A SIMPLE AGENT-BASED MODEL OF THE TRAGEDY OF THE COMMONS

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ABSTRACT

The Tragedy of the Commons by G. Hardin is a famous metaphor for social dilemmas in common-pool resource use. In his famous article from 1968 he argued for an abstract common-pool pasture that the pasture must become depleted as herdsmen have higher incentives to add cattle than to remove, due to the shared nature of the common. However, Hardin built his argument on the assumption of purely selfish and profit-oriented behavior of humans. For this article, we therefore hypothesized that the integration of other human values can lead to sustained use of the common. We test both of these questions via an implementation of Hardin's pasture as an agent-based model, which allowed us to simulate Hardin's pasture system over time. Simulation results verify both Hardin's argument and our hypothesis.

INTRODUCTION

In his article on the "Tragedy of the Commons", Hardin (1968) argued that an abstract common-pool pasture must become depleted if users are free to choose the number of cattle stocks. In specific, he based his argument on the observation that users are trapped in a social dilemma, where the cost of increased cattle stocks are shared among users while the benefit remains personal. Such biased payoffs, according to Hardin (1968) would deduce users to add more and more cattle, notwithstanding the observable but less-rated cost. Though, this argument was entirely based on the presupposition that the users are strictly profit-oriented. Other social values such as fairness, group welfare, institutions of remuneration and punishment, or more personal values such as risk aversion, were not considered. For this article, we therefore sought to validate Hardin's line of thought under the assumption of strict profit orientation, and to test if and under what conditions the common could be sustained when allowing social and personal non-profit values in addition. Since such social and personal values or dispositions influence and are influenced by others' and one's own past actions, we decided to implement Hardin's tragedy in an agent-based model, which allowed us to both implement feedback between the pasture and users, and social feedback between users.

In the next section, we present the model structure of a simple model of the Tragedy of the Commons, and describe the social and personal dispositions that are implemented and tested. In the subsequent section, we present simulations results. Simulation results verify the initial argument of Hardin when only the selfish disposition is active, and that the consideration of other dispositions can lead to a sustainable use, each in the way intuitively suggested.

MATERIALS AND METHODS

Agent-based modelling is an approach for modelling the actions and interactions of single entities called agents, with a view to testing their effects on the system as a whole. Thereby, agents can be spatial patches representing a gridded space, or mobile agents having the ability to move along space. Thus, agent-based modeling has the inherent capacity to model social and human-environment systems from the bottom-up in discrete time steps by specifying their constituent parts. Here, we implemented an abstract pasture close to the one described by Hardin (1968). Accordingly, in the model, human agents can decide in each time step to add or subtract their cattle stock by one cattle head, or leave it constant. Feedback between human agents and their biophysical environment consists of the effects of stocking rates on future grass growth, and of an integration of this cost in the stocking-rate choice. Social interactions are reflected in the stocking decision in terms of what stocks others have and what actions others have played in the previous round.

Model overview

The model that we developed was programmed in NetLogo (Wilensky 1999) and represents a square virtual pasture in a grid of 33 x 33 individual patches, a user-defined number of non-moving herdsman agents randomly located in space, and a user-defined number of moving agents representing cattle, each randomly assigned to a herdsman agent as owner. Over time, cattle graze, grass regrows, and agents update their stocks, forming an annual time loop. During the grazing routine, cattle move to the nearest grass patches and clear the grass cover of these patches. In order to

Table 1: External parameters of the model

Parameters	Domain	Explanation
Cov	$[0, 100]$	Initial percentage of patches covered by grass
N	$\mathbb{N} \setminus \{0\}$	Total number of herdsman agents
C	$\mathbb{N} \setminus \{0\}$	Initial number of cattle agents
$rate_{growth}$	$\mathbb{R}^+ \setminus \{0\}$	Net relative grass growth rate near zero vegetation
P_{cow}	$\mathbb{N} \setminus \{0\}$	Cattle price
$requ_{cow}$	$\mathbb{N} \setminus \{0\}$	Annual forage requirement of cattle agents in patches
$rate_{learn}$	$\mathbb{N} \setminus \{0\}$	Total number of herdsman agents
$level_{self}$	$(0, 1)$	The tendency to favor actions that support personal financial benefit
$level_{coop}$	$(0, 1)$	The tendency to favor actions that support group financial benefit
$level_{fairself}$	$(0, 1)$	The tendency to refrain from actions that make the agent worse off than others
$level_{fairother}$	$(0, 1)$	The tendency to refrain from actions that make the agent better off than others
$level_{negrec}$	$(0, 1)$	The tendency to favor actions that penalize others
$level_{posrec}$	$(0, 1)$	The tendency to favor actions that reward others
$level_{conf}$	$(0, 1)$	The tendency to favor actions similar to the past behavior of the group
$level_{risk}$	$(0, 1)$	The tendency to favor actions that reduce financial risk

reflect the idea to integrate an environmental cost estimate in the stocking choice, we chose to represent subsequent grass growth by a logistic growth function that is dependent on the grass cover that remains after browsing. Finally, agents update their stocks.

In an earlier agent-based version of the Tragedy of the Commons (Schindler 2012), we assumed that during each time step, agents' actions converge to a Nash equilibrium. In this earlier version, we therefore identified the agents' actions by a random (Pareto-optimal) Nash equilibrium of the strategic game in the current time step, where payoffs were weighted by dispositions. The disadvantage of this version, however, was threefold: First, we believe using Nash equilibria does not realistically represent human behavior in the proposed setting, as we expect that herdsmen are not constantly engaged in a strategic game throughout the year but rather behave in a "trial and error" mode and revisit stocking decisions only once or twice a year. Second, the use of an extension to calculate Nash equilibria every time step was very costly in terms of computation speed. Third, the way how the dispositions influenced payoffs was complicated and not entirely intuitive. For this version, we therefore decided to straighten these shortcomings, i.e. build reactive instead of strategic agents, with a transparent and simple way to integrate social and personal dispositions.

These comprised eight dispositions, i.e. selfishness vs. cooperativeness, fairness concerning oneself vs. fairness concerning others, positive vs. negative reciprocity, conformity, and risk aversion (Table 1). The range of dispositions is inspired by Ebenhöh and Pahl-Wostl (2006). Accordingly, we identify selfishness and cooperativeness with the tendency to favor decisions that improve the agent's own or the entire group's financial benefit, respectively; fairness concerning oneself or others with the tendency to favor own decisions that reduce unfair cattle stock distributions towards the agent himself or towards others; positive and negative reciprocity with the tendency to factor own decisions that reward others' actions or punish others' actions, respectively; conformity with the level of favoring actions that are similar to others' past actions; and risk aversion with the tendency to avoid financial risks caused by the uncertainty of others' behavior.

Model details

Each herdsman agent i is endowed with an individual probability of adding one cattle to its stock ($prob_{add}$), and the corresponding counter-probability of subtracting one cattle ($prob_{subt}$). These probabilities are updated according to how the conditions induced by past actions match with the social and personal dispositions. According to these probabilities, a choice is made in each time step, denoted by x_i, while k_i denotes the current size of the cattle stock. The cattle agents are endowed with an owner variable indicating the owning herdsman agent ($owner \in \{1, \cdots, N\}$), and a feeding status ($feedstat \in \mathbb{N}$) indicating the number of patches browsed in the current time step. The patches are characterized by a variable ($cover \in \{no\ grass, grass\}$) indicating whether the patch is covered by grass or not, whereby the cover of a browsed patch is turned from grass to no grass.

User-defined parameters of the model comprise the settings for initialization (i.e. total number of herdsmen, initial total number of cows, and initial grass cover), one parameter for each of the time-loop procedures of grazing, grass regrowth, and taking action (the annual forage requirement of cattle in terms of number of patches, the grass growth-rate near zero vegetation, the price per cattle), and factors determining the decision-making process, comprising the adaptation speed, i.e. how fast the agent responds to evaluations, and the eight social and personal dispositions (Table 1).

Cattle agent routine
Each cattle agent moves and browses patches: One-by-one each cattle agent tries to fulfill its demand of grass patches (i.e. $requ_{cow}$). In this process, the agent moves to the nearest grass patch and browses it, upon which the state of the patch is turned to "no grass". This procedure is repeated until a cattle's demand is fulfilled or cannot be fulfilled due to grass patch depletion. In this latter case, the cattle agent is automatically removed from the pasture. When this grass-patch search has terminated for a cattle agent, the search for a different cattle agent is initiated. Thus, one-by-one, all cattle agents sequentially try to fulfill their demand, while the sequence is random.

The removal of cattle due to grass depletion is automatic and thus is independent of the herdsman agent decision-making process. It is based on the assumption that insufficiently fed cattle can be sold in time, thus involving no cost for the herdsman agent, but simply reducing his cattle stock. This is based on the rationale that under normal market conditions herdsmen will not wait for their cattle to die but will and are able to take action.

Patch routine
Noy-Meir (1978) suggests that for the type of simplified pasture like the one that we assume here (i.e. a pasture consisting of one plant species grazed by a herbivore population with a constant physiological status of intake), the growth rate of green biomass can be described by a function which is dependent on the current available green biomass. thereby increasing at a low biomass level, and decreasing at a high level. Using such a function, the cost of degradation can be incorporated in the model. Noy-Meyr (1978) proposes four growth functions that fulfill these requirements, among them the logistic growth function that we used in MASTOC (see equation 1). However, different growth functions can theoretically be built into the model.

$$g(Veg) = Veg \cdot (1 + (rate \cdot Veg \cdot (1 - (Veg/Vegmax)))) \quad (1)$$

with Vegmax = 1089 (total number of patches). The cover variable of patches is updated by:

1. Update variable Veg
2. Ask (g(Veg) - Veg) patches with cover = no grass: set cover grass

Herdsman agent routine
The herdsman agent routine consists of the update of the cattle stocks. For that, first rewards for the dispositions are calculated, being either 1 or -1 for each disposition. Then, the total weighted reward is calculated. Finally, the choice probabilities are updated accordingly, and an action is chosen according to these probabilities.

Calculate disposition-oriented rewards

Selfishness and cooperativeness
We identify selfishness with the tendency to favor actions that are personally financially beneficial, where we denote $benefit^i_{self}$ with the financial benefit of the previous action of agent i, which is revenue minus cost caused by the action (equation 2). It is important to note that this benefit solely refers to the benefit caused by *changing* the cattle stock, and not of the entire cattle stock as such, since we are interested in calculating rewards for *actions*.

$$benefit_{self} = x_i \cdot P_{cow} - cost(K + \sum_{j \neq i} x_j, K + \sum_j x_j) \quad (2)$$

where P_{cow} is the cattle price, K the current total number of cattle on the pasture, and $cost(x, y)$ is the cost function, representing the financial loss of pasture potential in this time step caused by increased/reduced grazing pressure in the last time step:

$$\begin{aligned} cost(x, y) \;\; := \Big[& g(max(0, Veg - x \cdot Requ)) \\ & - g(max(0, Veg - (x + y) \cdot Requ)) \Big] \cdot \frac{P}{Requ} \end{aligned} \quad (3)$$

where x is the previous number of total cattle agents, y the current number, and g the vegetation update function (equation 1). The reward of the past action is simply 1 if the benefit was positive, and -1 if the benefit was negative.

$$r_{self} = \begin{cases} 1 & if\ benefit_{self} > 0 \\ -1 & if\ benefit_{self} < 0 \end{cases} \quad (4)$$

Cooperativeness
Equivalently, cooperativeness is the tendency to favor group actions that are financially beneficial for the entire group, where we denote $benefit^i_{coop}$ with the the share of the group benefit for agent i. This share is the shared group action revenue minus cost caused by the group action (equation 5). Here again, the benefit solely refers to the benefit caused by the action, not of the entire cattle stock.

$$benefit_{coop} = (\sum_{j \neq i} x_j) \cdot \frac{P_{cow}}{N} - cost(K)(K + \sum_j x_j) \quad (5)$$

$$r_{coop} = \begin{cases} 1 & if\ benefit_{coop} > 0 \\ -1 & if\ benefit_{coop} < 0 \end{cases} \quad (6)$$

Fairness towards oneself and towards others
If fairness towards oneself is considered and an unfair situation existed for agent i in terms of cattle stocks, previous actions that increased the own cattle stock were rewarded, while a reduction was punished (equation 7).

For fairness towards others the procedure is equivalent (equation 8).

$$r_{fairself} = \begin{cases} 1 & \textit{if } mean_{j \neq i}\ k_j > k_i \textit{ and } x_i = 1 \\ -1 & \textit{if } mean_{j \neq i}\ k_j > k_i \textit{ and } x_i = -1 \end{cases} \quad (7)$$

$$r_{fairother} = \begin{cases} 1 & \textit{if } mean_{j \neq i}\ k_j < k_i \textit{ and } x_i = -1 \\ -1 & \textit{if } mean_{j \neq i}\ k_j < k_i \textit{ and } x_i = 1 \end{cases} \quad (8)$$

Positive and negative reciprocity
If the tendency for positive reciprocity is considered, i.e. non-zero, and the majority of actions was a reduction of cattle, the past action of agent i is rewarded if it was a deduction, too, and punished otherwise (equation 9). The procedure for negative reciprocity is equivalent (equation 10).

$$r_{posrec} = \begin{cases} 1 & \textit{if } mean_{j \neq i}\ x_j < 0 \textit{ and } x_i = -1 \\ -1 & \textit{if } mean_{j \neq i}\ x_j < 0 \textit{ and } x_i = 1 \end{cases} \quad (9)$$

$$r_{negrec} = \begin{cases} 1 & \textit{if } mean_{j \neq i}\ x_j > 0 \textit{ and } x_i = 1 \\ -1 & \textit{if } mean_{j \neq i}\ x_j > 0 \textit{ and } x_i = -1 \end{cases} \quad (10)$$

Conformity
Conformity works like an amplifier of others' actions: The agent's actions are rewarded if they are the same as the majority's past actions, and punished otherwise (equation 11).

$$r_{conf} = \begin{cases} 1 & \textit{if } mean_{j \neq i}\ x_j < 0 \textit{ and } x_i = -1 \\ 1 & \textit{if } mean_{j \neq i}\ x_j > 0 \textit{ and } x_i = 1 \\ -1 & \textit{if } mean_{j \neq i}\ x_j < 0 \textit{ and } x_i = 1 \\ -1 & \textit{if } mean_{j \neq i}\ x_j > 0 \textit{ and } x_i = -1 \end{cases} \quad (11)$$

Risk aversion
If risk aversion is non-zero and there was any financial risk for the agent due to the uncertainties of others' agents' actions, a reduction of the cattle stock is rewarded, and punished otherwise (equation 12).

$$r_{risk} = \begin{cases} 1 & \textit{if } cost(K)(K+N) > P_{cow} \textit{ and } x_i = -1 \\ -1 & \textit{if } cost(K)(K+N) > P_{cow} \textit{ and } x_i = 1 \end{cases} \quad (12)$$

Calculate total weighted reward Subsequently, the final weighted reward is calculated (equation 13).

$$\begin{aligned} & reward = \\ & = level_{self} \cdot r_{self} + level_{coop} \cdot r_{coop} \\ & + level_{fairself} \cdot r_{fairself} + level_{fairother} \cdot r_{fairother} \\ & + level_{posrec} \cdot r_{posrec} + level_{negrec} \cdot r_{negrec} \\ & + level_{conf} \cdot r_{conf} + level_{risk} \cdot r_{risk} \end{aligned} \quad (13)$$

Update choice Probabilities and choose action

Finally, the probabilities are updated (equations 14), and according to the resulting probabilities, an action is chosen. If the reward compared to the previous time step is zero, the cattle stock remains the same.

$$\begin{aligned} & \textit{if reward} > 0 \textit{ and } x_i = 1: \\ & \quad Prob_{add} \mapsto Prob_{add} + (1 - Prob_{add}) \cdot rate_{learn} \\ & \quad Prob_{subt} \mapsto 1 - Prob_{add} \\ & \textit{if reward} < 0 \textit{ and } x_i = 1: \\ & \quad Prob_{add} \mapsto Prob_{add} \cdot (1 - rate_{learn}) \\ & \quad Prob_{subt} \mapsto 1 - Prob_{add} \\ & \textit{if reward} > 0 \textit{ and } x_i = -1: \\ & \quad Prob_{subt} \mapsto Prob_{subt} + (1 - Prob_{subt}) \cdot rate_{learn} \\ & \quad Prob_{add} \mapsto 1 - Prob_{subt} \\ & \textit{if reward} < 0 \textit{ and } x_i = -1: \\ & \quad Prob_{subt} \mapsto Prob_{subt} \cdot (1 - rate_{learn}) \\ & \quad Prob_{add} \mapsto 1 - Prob_{subt} \end{aligned} \quad (14)$$

RESULTS

We are mainly interested in the questions whether we can verify Hardin's line of thought via a simple and reasonably calibrated agent-based model, and how the consideration of dispositions as defined here influences the sustainability of the abstract common. To answer these questions, we varied the disposition values, while we selected reasonable values for the other six parameters as if it were a West-African rangeland. We chose the African case study just to be able to assign the parameters reasonable values - one could have equally chosen values from another region in the world. Doing so, we set the relative grass growth rate near zero ($rate_{growth}$) to 0.00496, which corresponds to a maximum annual grass growth factor of 2.2 as reported in Huffaker (1993), and set the forage requirement of 1205 $kg year^{-1}$ (Ohiagu and Wood 1979) to one patch, one patch thus equalling 0.44 ha if we assume an annual grass production of 3157 $kg ha^{-1} year^{-1}$ (Ohiagu and Wood 1979). The price was set to 133 US $ which corresponds largely to cattle prices in rural Ghana according to own data, and the initial grass cover was 100 %.

For testing Hardin's argument, we conducted 400 simulations with maximum selfishness, and all other dispositions set to zero. Number of herdsmen and number of initial cattle was thereby randomly varied between 2 and 20 and 0 and 500, respectively. Simulations verify Hardin's argument for more than 2 herdsmen agents and any cattle number. In each of these cases, the common broke down. However, in each of the cases where only two initial herdsmen agents were present, the common was always sustained.
For analyzing the second question, the number of herdsmen and initial cattle was varied within three scenarios (Table 2), while all dispositions were randomly set in units of 0.1. Correlation analysis showed that 7 of the 8 dispositions were significantly correlated with the sustainability of the common (Table 3), where a break-

Table 2: Parameter settings of selected scenarios

Parameters	Scenario 1	Scenario 2	Scenario 3
Initial percentage of patches covered by grass (Cov)	100	100	100
Total number of herdsman agents (N)	4	6	8
Initial number of cattle agents (C)	242	120	80
Net relative grass growth rate near zero ($rate_{growth}$)	0.00496	0.00496	0.00496
Cattle price (P_{cow}, \$)	133	133	133
Annual forage requirement in patches ($requ_{cow}$)	1	1	1
Total number of herdsman agents ($rate_{learn}$)	1.0	1.0	1.0

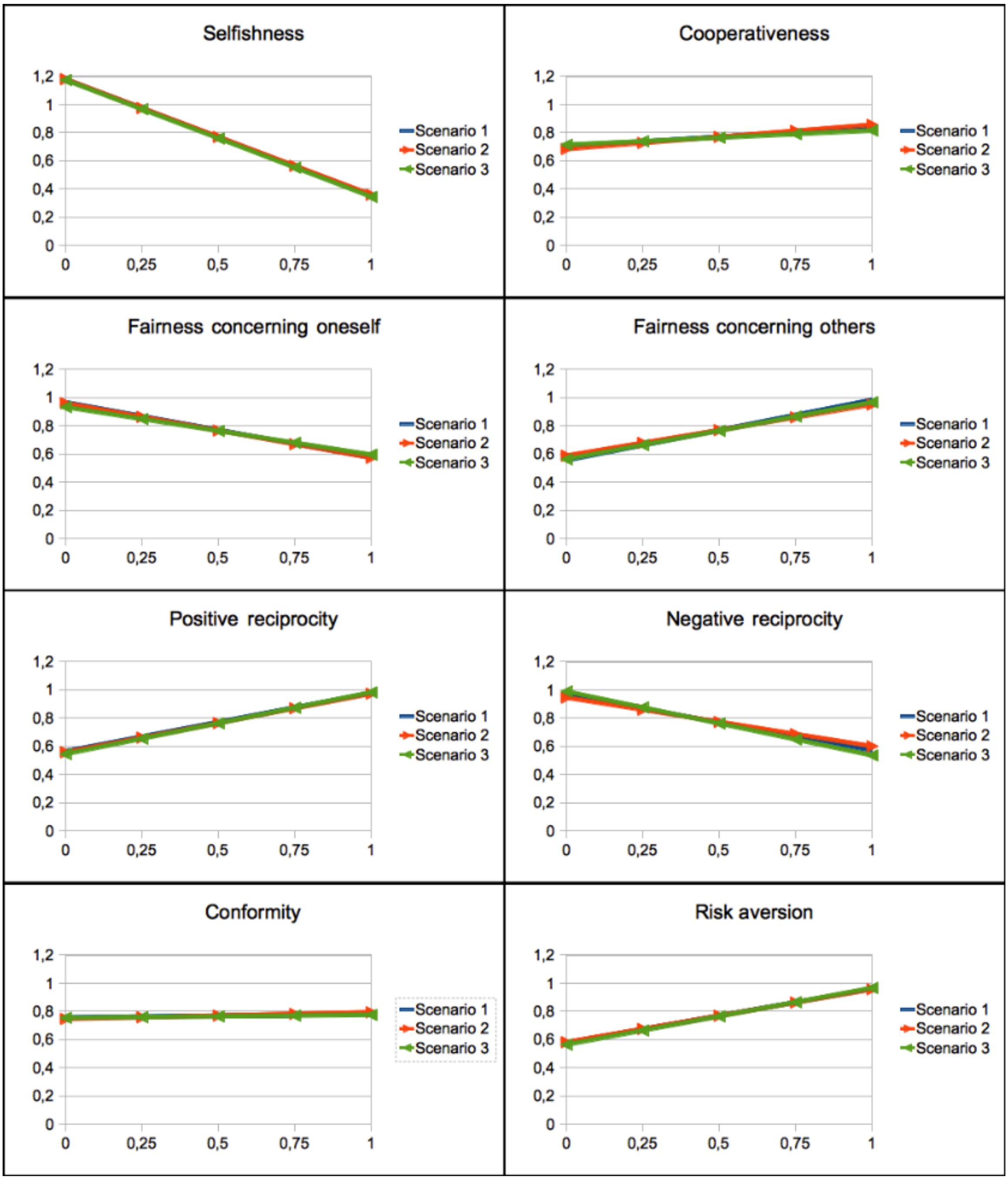

Figure 1: Simulation results of selected scenarios: Linear regression with sustainability value

Table 3: Simulation results of selected scenarios

Scenario	Selfish-ness	Coope rative-ness	Fairness towards oneself	Fairness towards others	Positive recip-rocity	Negative recip-rocity	Confor-mity	Risk aversion
Scenario 1								
Correlation	- 0.409	0.067	- 0.193	0.213	0.206	- 0.179	0.013	0.190
Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.179	0.000
Scenario 2								
Correlation	- 0.411	0.085	- 0.192	0.180	0.208	- 0.172	0.023	0.188
Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.120	0.000
Scenario 3								
Correlation	- 0.402	0.049	- 0.166	0.197	0.217	- 0.224	0.010	0.196
Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.497	0.000

Table 4: Results of sensitivity analysis: Average sustained grass cover percentage for each disposition when set to values between 0 and 1 while other dispositions remain at their default values.

Value	Selfish-ness	Coope rative-ness	Fairness towards oneself	Fairness towards others	Positive recip-rocity	Negative recip-rocity	Confor-mity	Risk aversion
0.0	71	0	79	0	66	65	49	0
0.1	71	0	79	0	65	66	65	1
0.2	65	0	71	0	65	66	63	0
0.3	65	0	74	0	73	66	63	1
0.4	66	0	71	66	73	0	61	65
0.5	0	65	70	65	73	0	65	66
0.6	0	65	73	64	75	0	0	66
0.7	0	66	65	66	71	0	0	66
0.8	0	66	66	66	78	0	0	66
0.9	0	66	65	66	78	0	24	66
1.0	0	62	65	66	79	0	22	66

down was valued with 0, long-term sustainable use with 1, and removal of any cattle, i.e. exaggerated thoughtfulness, with 2. Only conformity did not show a significant correlation with the sustainability value, while all other dispositions behaved as intuitively suggested (Figure 1). While cooperativeness, fairness concerning others, positive reciprocity, and risk aversion significantly increased the sustainability level, selfishness, fairness towards oneself, and negative reciprocity decreased it, however, to different degrees. As such, a reduction in selfishness seems to have the greatest impact, while an increase in cooperativeness has only little. Identifying the reasons for these different degrees of impact is not straightforward, due to the complex interconnectivity of the dispositions' role in final action, therefore necessitating a simulation approach like the one conducted in this study.

Moreover, this complex nature has also other implications. If one is interested in management of a specific case study, it is necessary to look at the case-study dispositional values, which can cause behavior that violates the general statistical behavior of dispositions. To test this for a case study, we selected random disposition values using the scenario 2 (Table), which showed a sustainable system behavior. Then, we shifted each disposition in the respective direction that causes breakdown, until the system came to the point of breakdown. Starting with disposition values at this vulnerable point of breakdown, we conducted a sensitivity analysis, i.e. we separately shifted each value one-by one from 0 to 1 in steps of 0.1 and recorded the percentage of grass cover after as sufficient number of time steps (150). Each value combination was simulated 100 times. Results show that in this case study the increase of fairness towards oneself and the decrease of positive reciprocity did not lead to a breakdown of the system, but only to a reduction in the sustained grass cover (Table 4). In contrast, a shift of the other dispositions (apart from conformity) in their "negative" direction, i.e. the specific direction that leads to breakdown, caused a sudden switch from a sustained plateau to a system breakdown. For conformity, which does not have such a clear direction, we even obtained a significantly non-linear pattern of sustained grass cover. Moreover, in total, the land-cover levels seemed to cluster around two values of around 66 and 90 % (Figure), the reasons for which are not clear.

DISCUSSION

With this model, we found an easy way to validate

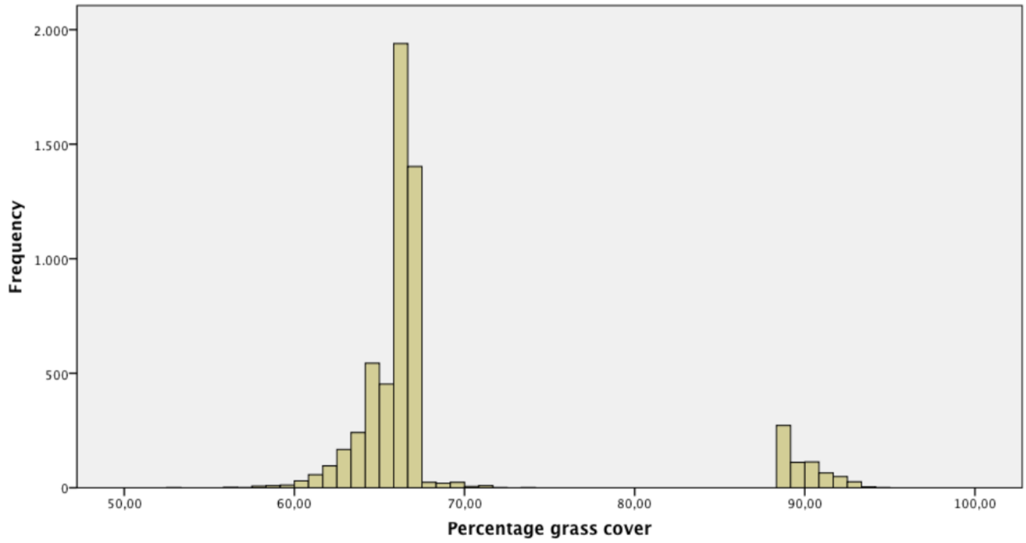

Figure 2: Frequencies of grass cover percentages of sustainable cases

Hardin's argument computationally, and validated the hypothesis that the consideration of other human values than pure profit orientation - as assumed by Hardin - can lead to sustained use of the common. We showed that statistically, these values or dispositions behave intuitively, but that this behavior can be counterintuitive and complex for specific case studies. This implies that when prosecuting to alter an existing endangered pasture system to a sustainable state, the specific behavior of this system should be studied via simulation. To do so, models with the ability to account for human behavior in human-environment interactions but with high computation speed are required. In contrast to a previous model version (Schindler 2012), which showed comparable results, this model fulfills this demand. While the computation load in the previous model version increased exponentially with increased herdsmen agent number, it increases here only linearly, which makes it suitable for real-world applications. This is due to the fact that this model calculates human behavior in a decentralized and reactive way, being the typical advantage of agent-based modeling, while the previous version used costly centralized calculation of equilibria to calculate human action. Having such a basic model may allow specification and adjustment to real-world applications, with the goal to strengthen those social norms that can make systems switch to sustainable states.

REFERENCES

Ebenhöh E. and C. Pahl-Wostl C. 2006. Agent-based modelling with boundedly rational agents. In J. P. Rennard, editor. Handbook of research on nature inspired computing for economy and management. Hershey-PA, USA.

Hardin G. 1968. The Tragedy of the Commons. Science 162:1243-1248.

Huffaker R.G. 1993. Optimal Management of Game and Forage Resources in a Private Fee-Hunting Enterprise. American Journal of Agricultural Economics, 75(3): 696-710.

Noy-Meir I. 1978. Stability in Simple Grazing Models: Effects of Explicit Functions. Journal of Theoretical Biology 71:347-380.

Ohiagu C.E. and T.G. Wood. 1979. Grass Production and Decomposition in Southern Guinea Savanna, Nigeria. Oecologia 40:155-165.

Schindler J. 2012. Rethinking the Tragedy of the Commons: The Integration of Socio-Psychological Dispositions. Journal of Artificial Societies and Social Simulation 15(1):4.

Wilensky U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo. Center for Connected Learning and Computer-Based Modeling. Northwestern University, Evanston, Illinois.

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