John, F., Toth, R., **Frank, K.**, **Groeneveld, J.**, **Müller, B.** (2019):

Ecological vulnerability through insurance? Potential unintended consequences of livestock drought insurance

Ecol. Econ. **157** , 357 – 368

http://dx.doi.org/10.1016/j.ecolecon.2018.11.021

Ecological vulnerability through insurance? Potential unintended consequences of livestock drought insurance

Felix John,[1] Russell Toth,[2] Karin Frank,[1,3,4] Jürgen Groeneveld,[1,5] Birgit Müller[1*]

[1] Helmholtz Centre for Environmental Research – UFZ, Dept. of Ecological Modelling, Leipzig, Germany

[2] University of Sydney, School of Economics, Australia

[3] University of Osnabrück, Institute of Environmental Systems Research (USF), Osnabrück, Germany

[4] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Germany

[5] TU Dresden, Institute of Forest Growth and Computer Science, Tharandt, Germany

[*] Corresponding author. Contact details: Helmholtz Centre for Environmental Research - UFZ, Permoserstr. 15, 04318 Leipzig, Germany; phone: +49 341 235 1708; e-mail: birgit.mueller@ufz.de

Preprint Version

Access the final version at https://doi.org/10.1016/j.ecolecon.2018.11.021

Cite this article as

John, F., Toth, R., Frank, K., Groeneveld, J., Müller, B., 2019. Ecological Vulnerability Through Insurance? Potential Unintended Consequences of Livestock Drought Insurance. Ecological Economics 157, 357-368, https://doi.org/10.1016/j.ecolecon.2018.11.021.

The implementation of the ABM is available to download at COMSES NET:

https://www.comses.net/codebases/5948/releases/1.2.0/

Abstract:

Increasingly frequent and severe droughts pose one of the greatest challenges for dryland pastoralists in the Horn of Africa. Livestock drought insurance (LDI) has been proposed as a means to manage these risks. However, LDI may have unintended side effects, such as inducing unsustainable herd sizes leading to long-term pasture degradation. These issues are infeasible to study empirically given that none of the emerging LDI programs have existed at scale for any extended period of time. Thus, we study the potential long-term effects of LDI on pasture conditions at scale with the help of an agent-based model. We particularly consider the possibility that if insurance is taken up at scale, the quick herd size recovery that insurance enables after droughts can disrupt natural pasture recovery dynamics, with the potential to degrade the long-run carrying capacity of the vegetation. Our results show that, especially if pastures are very sensitive to grazing, insurance can indeed cause and/or intensify ecological instability. Furthermore, unfortunately, these unintended ecological consequences are most likely where insurance is needed the most. Designing the insurance product in the light of these insights may dampen these effects.

Keywords: index-based insurance, risk-coping strategies, pastoralism, grazing, East Africa

1. Introduction

In the last decade, microinsurance has emerged as a popular instrument in development policy to manage disaster risks and increase resilience in the developing world. Main areas of application are climate and weather-related risks. Various initiatives highlight the appeal and magnitude of such microinsurance programs. For example, during their 2015 Elmau summit, the G7 countries announced their "InsuResilience" initiative that would provide insurance coverage against climate risks for 400 million additional people in the most vulnerable developing countries from a commitment of 420 million US dollars (G7, 2015a; G7, 2015b). Similarly, the Global Index Insurance Facility (GIIF), funded by the European Union as well as the governments of Germany, Japan, and the Netherlands, and managed by the World Bank Group, facilitates access to agricultural and disaster insurance for over 7 million people, with about 178 million US dollars in assets insured (GIIF, 2017). Developing countries also have started to implement insurance schemes to manage climate risks. For example, the government-led Kenya Livestock Insurance Program (KLIP), reinsured by SwissRe, started in 2015 and released payouts totaling roughly 2 million US dollars to over 12,000 vulnerable pastoral households after a severe drought in February 2017 (SwissRe, 2017). This was the largest livestock insurance payout in Kenyan history (ILRI, 2017).

To date, the attention of both policy makers and scientists usually centers on the short-term impacts of insurance programs, whereas long-term, and especially system-wide, effects are largely neglected (e.g., Müller et al., 2017; see also the more detailed literature discussion in the next section). This is not surprising, since the main goal of these insurance programs is to provide payouts to enhance short-to-medium term resilience and enable recovery after a shock. Furthermore, long-term data on such programs at scale are not available, due to the relatively recent emergence and scaling of such programs. For example, the KLIP only launched in the mid-2010s and reached more than 10,000 pastoralists, out of 4 million across northern Kenya, as of late 2015. Yet, especially in dynamic resource-use contexts, long-term effects can be considerable, since decisions today may influence the availability of the resource in the future.

In this paper, we contribute to the literature by exploring whether livestock drought insurance (LDI) has the potential to lead to unintended ecological instability at scale. More precisely, we investigate the impact of LDI on long-term herd and pasture dynamics, and address it with a suitable agent-based modeling framework that captures the essential system dynamics. The main mechanism we examine is as follows: in order to avoid livestock loss and its adverse socio-economic consequences, insurance aims to maintain livestock numbers at pre-drought levels, or restore them to those levels as quickly as possible. Pastures, on the other hand, are usually in bad condition after a drought and need time to recover. In that regard, livestock losses during a drought create a “natural resting period” in absence of LDI. If, for a significant share of pastoralists, livestock losses are prevented, or drastically shortened through LDI, these post-drought resting and recovery periods will diminish. Over time, pastures may degrade. So while, at the individual level, it may be optimal to cushion the immediate effects of a drought by purchasing LDI, on the community level, this may lead to unsustainable over-use of pastures in the long run.

To explore this possibility, we develop an agent-based model (ABM) that depicts the rangeland management practices of mobile dryland pastoralists in a stylized way. The model encompasses a settlement of households who move their herds between wet and dry-season common-property grazing areas. The model also features an insurance scheme through which pastoralists receive a payout if a certain amount of rainfall is not met. By employing a dynamic simulation model, we can depict the nonlinear interactions between the consumer (livestock) and resource (biomass) dynamics, as well as the impact of economic decisions (insurance). Furthermore, we discipline the analysis by calibrating the model with data from the Horn of Africa where some of the largest LDI programs are currently in place. Thereby, we analyze both economic and ecological effects as well as their interdependencies, and ensure that our parameterizations are applicable to a real-world policy space.

Our approach can overcome two practical challenges which cannot be solved otherwise. First, it enables us to observe processes that would materialize only in the medium and long run and for which there is currently no empirical data, since there is no LDI program that has operated at significant scale for more than 5-10 years, much less the timescale of decades. Thus, with our model we can point to potential unintended consequences before they become reality. Second, it is possible to use the model as a "virtual lab" (Seppelt et al., 2009; Magliocca et al., 2013; Magliocca and Ellis, 2016). In it, we explore different scenarios (e.g., different ecological conditions or rainfall values) and analyze their effects. The "virtual lab" approach can highlight and explain qualitative structural changes in long-term development.

The interplay of insurance with ecological factors has mainly been analyzed in analytical theoretical models thus far. In an analytical model, Bhattacharya and Osgood (2014) elaborated two distinct effects that can arise from insurance: a substitution effect and an income effect. The former refers to households diverting resources from their production activity towards the insurance premium. In pastoral systems, this reduces pressure on the common-property resource (i.e., the pasture). The income effect, on the other hand, follows from the insurance payout in case of a drought, which increases farmers' well-being and can prevent them from dropping out of the system. For pastoral systems, this could lead to an increase in environmental pressure, as the natural self-correcting mechanism of outward selection is muted. They conclude that it remains an empirical question which effect will be stronger, which they cannot address since they analyze a fully general parameter space. However, their model essentially represents a one-time decision of whether to purchase insurance and thus cannot take consumer-resource interactions and long-term dynamics into account that accumulate over time. Müller et al. (2011) assessed the effects of LDI for a single private-property livestock farmer in a dynamic simulation model. They showed that insurance designs with low payout thresholds (i.e., a payout is triggered even for modest droughts) created incentives to use the land in a less sustainable way and therefore they advocated insuring only severe droughts.

Our work goes beyond existing studies on the effects of LDI in several ways. First, by including multiple agents, we account for the common-property management regime, which also makes our model of pasture growth more realistic since grazing pressure also depends on how many herders use a pasture at the same time. Second, by including different pasture types, grazing dynamics can be modeled more realistically. We differentiate between wet-season grazing areas where usually all herds of the settlement graze together, and their dispersal onto different grazing areas during dry seasons, a grazing distribution that characterizes a number of the pastoralist systems in the Horn of Africa. Third, we systematically consider different rainfall patterns to examine the robustness of our results. Fourth, instead of only comparing expected livestock numbers, we also analyze their variation over time.

Our study also contributes a new case to a broader literature on the adverse ecological effects of rangeland management policies. Campbell et al. (2000) highlight the increased likelihood of environmental degradation for a tight tracking policy in Zimbabwe. This herd management strategy relies on frequent purchasing and selling of livestock aiming to maintain their numbers in equilibrium with the available feed resources. Hobbs et al. (2008) argue that landscape fragmentation (typically not a land-use policy in itself, but a related side-effect) results in a tight coupling of animals and plant resources, which is very hard to manage in environments with large climatic variability (such as semi-arid and arid rangelands) and can ultimately lead to "deleterious changes" in vegetation composition, primary productivity and soils. James et al. (1999) compile evidence of vegetation degradation and changes in species composition around artificial watering points in rangelands.

The remainder of this article is structured as follows: In the next section, we shed some light on mobile pastoralism in the Horn of Africa and review previous research on LDI and its analysis through simulation models. In Section 3, we introduce our model and explain our analysis methods. Then, we present the main findings from our simulations in Section 4, which we discuss in Section 5. Finally, we draw some conclusions.

2. Mobile pastoralism and livestock drought insurance

In arid and semi-arid dryland areas, highly variable rainfall – both in space and time – causes fluctuations in resource availability, and thus often renders immobile land-use options like crop agriculture or sedentary livestock breeding difficult. Therefore, mobile livestock keeping is often identified as the best-suited land-use strategy, as it can quickly adapt to spatial heterogeneity in the available resources (McGahey et al., 2007). Even though droughts have always been an inherent feature of these arid and semi-arid regions in the Horn of Africa, their numbers and repercussions have increased in recent years due to climate change (Niang et al., 2014). They are also identified as one of the greatest challenges by pastoralists in the area (McPeak et al., 2012;

Alemu and Robinson, 2015). Droughts cause forage scarcity, and thus, can entail substantial livestock losses. Between 1980 and 2001, recurring droughts killed 37 to 62% of all cattle in the Borana Plateau of South Ethiopia (Desta and Coppock, 2002: Jensen et al., 2014). While there is evidence of informal risk sharing whereby clan members help each other out in case of need, these informal arrangements operate at a much smaller scale and cannot compensate the losses from large covariate shocks like droughts (Huysentruyt et al., 2009). As a consequence, households can be caught in poverty traps (Lybbert et al., 2004; Toth, 2015). These poverty traps are induced by a critical minimal herd size. Below that critical herd size mobile pastoralism is not viable. Assuming that reproduction is also low for small herds, people become trapped in a destitute situation.

LDI can be a suitable means to address these issues. Most microinsurance schemes in rural areas in developing countries are index-based, which means that a payout is triggered if a predefined threshold of rainfall, or vegetation cover, is not met over a given period of time. This avoids case-by-case damage assessments, and hence, greatly lowers the cost of the product.

In Kenya and Ethiopia, a pilot program called Index-Based Livestock Insurance (IBLI) was introduced in 2010 and 2012, respectively, mainly by the International Livestock Research Institute and Cornell University with funding from USAID and has been closely monitored ever since (Chantarat et al., 2013). IBLI relies on an index of remotely-sensed vegetation data (i.e., Normalized Difference Vegetation Index, NDVI). A payout is determined based on actuarial calculations, calibrating a strike level (i.e., the critical index value that triggers a payout) to the remotely-sensed data. In the original *asset replacement* design, the index on which payouts were based was predicted average livestock mortality. Payouts were made shortly after the drought, i.e., after losses had already occurred. Advancements in vegetation forecasting made it possible to predict dry-season forage availability during the vegetation growth period. This also allowed shifting payouts to before the (predicted) drought sets in, so herders may prevent losses, e.g., by purchasing supplementary fodder from unaffected regions (*asset protection* design).

Previous studies on the impact on index-based insurance focused primarily on direct economic impacts at the beneficiary level. Mobarak and Rosenzweig (2013) found that Indian farmers who were insured against weather risks took significantly less action to mitigate risks. Cole et al. (2016) similarly showed in field experiments that, with insurance, farmers shifted their production to crops with higher yields, but also higher sensitivity to rainfall. Ghanaian farmers with insurance additionally invested significantly more in their farming operation (Karlan et al., 2014). Other work strives to explain low uptake rates of index-based insurance in drylands (Binswanger-Mkhize, 2012; Mobarak and Rosenzweig, 2013; Karlan et al., 2014; Cole et al. 2016) and basis risk (Jensen et al., 2014, 2016).

Analyzing how IBLI helps manage drought shocks, Janzen and Carter (2013) found that IBLI policy holders were considerably less likely to sell livestock and to cut back on their current food consumption. Jensen et al. (2016) reported that IBLI coverage reduced households' exposure to risk from large covariate shocks by roughly 63%. Interestingly, Toth et al. (2017) found that insured pastoralists had higher stocking rates than their uninsured peers. They argued that insurance made holding livestock more attractive by reducing investment risks and also pointed to the potential of increased environmental degradation. These results show that IBLI is effective in cushioning immediate economic effects of droughts. The long-term effects of insurance on livestock numbers and pasture conditions, however, have not been studied so far, mainly due to lack of data. In a recent review on the impact of agricultural insurance, Müller et al. (2017) found that resilience does not always increase through insurance and call for a more holistic impact assessment of insurance programs that also includes social and ecological factors.

3. Methods

To analyze the effects of LDI on the pastoral system, we use a stylized agent-based model that we will briefly introduce before describing our analysis methods. The model assesses the long-term impact that the provision of LDI at scale has on livestock numbers and pasture conditions. While the model is aligned to the environmental context the pastoralist groups straddling the border between Ethiopia and Kenya and provides a highly stylized characterization of their rangeland management practices, it is not our intention to make quantitative predictions. Instead, our model intends to generate insights into qualitative changes in the dynamics due to the provision of insurance that are still general enough to potentially extrapolate to other regions. The stylized calibration to that specific setting is merely meant to provide some discipline to the analysis, by providing an empirical context to pin down a number of key parameters.

3.1. Model description

3.1.1. General structure and processes

In the following, we describe the main features and processes of the model; for a complete description please refer to the ODD+D protocol (Overview, Design Concepts, Details + Decision-making; Grimm et al., 2006; Müller et al., 2013) in the appendix. Figure 1 shows the overall structure of the model. It depicts the rangeland practices of a pastoralist settlement with 10 households and runs in discrete quarter-annual time steps. This temporal resolution follows the four weather seasons over the year: long rain (Apr - Jun) – long dry (Jul - Sep) – short rain (Oct - Dec) – short dry (Jan - Mar). Rainfall varies from one year to the next as explained below.

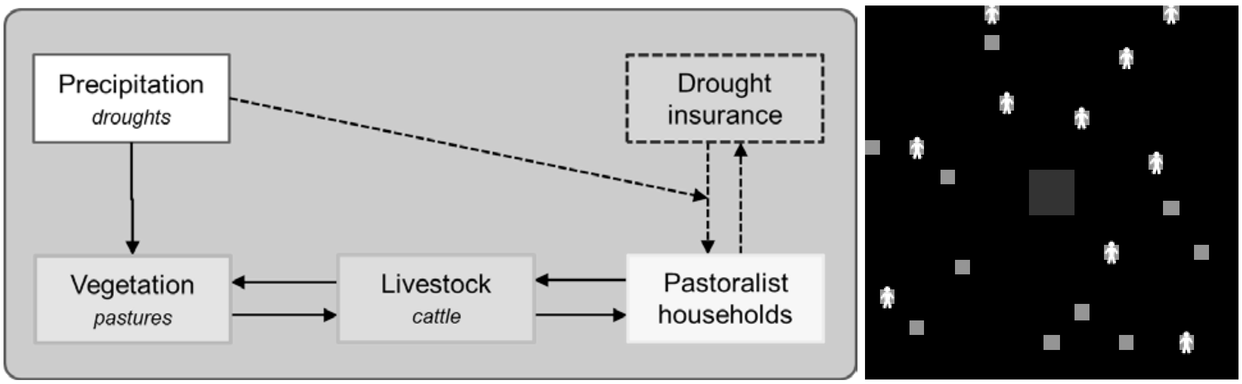

Fig. 1: Structural overview of model components and their relationships (left) and illustration of the spatial configuration (right). Herders (white) move their herds back and forth between the rainy-season pasture (dark grey) and the more remote dry-season pastures (light grey). The black space in between can be considered as land unsuited for grazing.

Agents (herders) are considered as homogeneous households who keep cattle and move their herds between rainy-season and dry-season pastures, as is consistent with numerous pastoralist systems in the Horn of Africa (Helland, 1997; McPeak et al., 2012; Wario, 2015). While during the rainy seasons, all herds graze together on one large patch,[1] they spread out onto 20 different remote grazing areas in dry seasons. At the beginning of dry seasons, herders move in random sequential order to the pasture with the highest available biomass and feed their herds there.[2] In

[1] Since distance does not formally matter in the model it is not essential that this be a single patch; the main feature is just that this patch provides relatively abundant resources during the wet season. Additionally, we assume the total areas covered by rainy and dry-season pastures resp. to be equal. Since the model implementation forces us to set a ratio, we chose a balanced ratio for a start. Preliminary analyses showed that this ratio does have an effect (as it shifts the limiting factor from one pasture type to the other). We see exploring this ratio as an interesting next step for further research (either by reducing the number of dry-season pastures or their relative size).

[2] The order in which agents are selected (i.e. who moves first and gets the best pasture) is random. Since the grass that would be consumed by the livestock of one agent is deducted immediately, the next agent selects the pasture with the highest available biomass factoring in movement decisions of previously selected agents. In reality, patch

rainy seasons, they always return to the large rainy-season pasture. Distances between dry-season pastures and the settlement are not considered explicitly in the model, and do not play a role in pasture selection on the temporal scale we model. Even though these distances can be substantial in some pastoralist systems at up to 100 km, the smallest temporal units in our model are seasons (roughly three months). Therefore, the movement is easily completed within a time step.

Herds feed on grass and, once a year, they reproduce at a constant growth rate.[3] Herd sizes are modeled as floating-point values in tropical livestock units (TLU).[4] Herders let their herds grow through natural reproduction for as long as pastures provide enough fodder to sustain all animals. If a pasture does not provide enough fodder, however, pastoralists are forced to destock animals. Since, in rainy seasons, all animals share the relatively abundant grazing area, agents destock their herds in equal proportions (i.e., all herds are destocked by 10%, for example).[5] However, below a certain herd size (in our case, 5 TLU), mobile pastoralism is not viable anymore (Lybbert et al., 2004; Toth, 2015). Accordingly, whenever a herd falls below this threshold, the herder becomes sedentary and keeps their livestock near the settlement throughout the year (McPeak et al., 2012). Furthermore, sedentary herds are exempted from destocking as a community effort to protect the destitute. Households without any animals are forced to abandon pastoralism completely and leave the system. Since we do not allow the entry of new herders or

---

selection is likely to be non-random, with priority given to larger herds, or based on community norms (Helland, 1997). We abstract from this level of realism.

[3] Herd growth, as we interpret it in our model, describes the net change in herd size, thus comprising calve births as well as animals deaths/slaughters. Thereby, we implicitly assume that fertility rates and off-take are constant over time and linear in herd size, which is a simplification to keep model complexity manageable.

[4] Tropical livestock units (TLU) are a standardized measure to provide equivalent estimates of livestock biomass. One TLU represents an animal of 250 kg live weight. Conversion factors are 1 TLU = 1 cow = 10 goats or sheep = 0.7 camels.

[5] Destocking can be considered to capture a number of processes, including offselling in anticipation of a drought, livestock death, or impeded reproduction due to adverse conditions. We abstract from social norms or other mechanisms that might lead to heterogeneous destocking.

the splitting of herds, the exit of a herder entails that there is an additional dry-season pasture which is not grazed. On this patch, biomass can accumulate, which, as a consequence, may lead to a higher level of resources available to the remaining herders.

Grass growth is based on an established rangeland vegetation model (Müller et al., 2007; Martin et al., 2016; Dressler et al., 2018a, 2018b) where the vegetation of each patch resembles a generic type of perennial grass with two components: green and reserve biomass. Green biomass comprises the photosynthetically active parts like leaves, and is consumed by animals. It sprouts from reserve biomass – the brown storage parts above and below ground like roots and other below-ground tissue – depending on rainfall. Green biomass development is described by the following difference equation:

(I) $$G_t = \left(1 - m_g\right) * G_{over,\, t-1} + rain_t * RUE \ * R_{t-1} \qquad \text{with} \quad G_t \leq \lambda R_{t-1}$$

Current green biomass G_t depends on two aspects: First, ungrazed green biomass of the previous year (i.e., the portion of green biomass left over from the previous year, $G_{over,\, t-1}$), reduced by green biomass mortality $m_g \in [0, 1]$, and second, the growth of new shoots. This second aspect is driven by current rainfall $rain_t$ multiplied by the conversion factor RUE and the reserve biomass from the last period, R_{t-1}. Green biomass may, however, not exceed a threshold value λR_{t-1}, which is the maximum capacity of green biomass that can grow from a certain amount of reserve biomass.

Reserve biomass $\boldsymbol{R_t}$ is modelled through the following difference equation (based on Martin et al. 2016):

(II) $$R_{t+1} = R_t + w\left[gr_1 * \left(G_t - G_{over,\, t}\right) + G_{over,\, t}\right]\left[1 - \frac{R_t}{R_{max}}\right] \ - \ \left[\left(m_r + gr_{2,t}\right)R_t \ \right]$$

Reserve biomass growth is density dependent. It depends on the growth rate w, the green biomass of the previous period, and the proximity to carrying capacity (R_{max}). Grazing can vary in its impact on pasture growth (expressed by the model parameter $gr_1 \in [0, 1]$). Since, technically speaking, gr_1 measures how strongly green biomass which is consumed in that year contributes to reserve biomass growth, we define "sensitivity to grazing" as 1 - gr_1. So a sensitivity to grazing near 1 denotes a strong impact of grazing, and thereby, low regeneration. In reality, the impact of grazing depends on several factors. These factors comprise, in particular, vegetation characteristics (e.g., morphological traits and chemical traits of the vegetation affecting the robustness towards grazing). In that regard, sensitivity to grazing can also be interpreted to represent different ecosystems. Reserve biomass is reduced by a natural mortality rate m_r as well as animal consumption. If the amount of fodder needed cannot be met by the available green biomass, parts of the reserve biomass are consumed too ($gr_{2,t} \in [0, gr_2]$, gr_2 describing the maximum consumable reserve biomass).

While this stylized description of the grazing system abstracts in a number of ways from the complexity of pastoralist systems, it is sufficient for the purposes of our modeling exercise, as we have distinct wet and dry season locations, with resource constraints relatively more binding on the dry season locations. Hence we can broadly cover a number of northern Kenyan pastoralist systems (McPeak et al., 2012), along with the large Borana system straddling northern Kenya and southern Ethiopia (Helland, 1997; Reda, 2016; Wario, 2015; Wario et al., 2016). In any case, recent trends such as bush encroachment and other land use restrictions (Wario et al., 2016; Reda, 2016) will likely intensify resource scarcity during dry and drought periods, and thus, tend to exacerbate the broad, system-wide dynamics that we aim to capture.

3.1.2. Insurance

To this baseline model, we add an insurance feature (cf. dotted lines and boxes in Fig. 1). When it is active, all mobile households will purchase insurance[6] for an exogenously set amount of animals each year (or the entire herd if it is smaller than that).

The insurance is actuarially fair and is purchased at the beginning of each year. When rainfall remains below a certain threshold, agents will receive a payout at the end of the year – regardless of their actual losses. If agents lose animals they will use the payout to restock, otherwise they store it to pay future premiums. Agents aim to restock their herds to the average size of the last three years.

Conceptually, it does not make a difference whether one argues that the indemnity payment is used to compensate the animals lost during drought (as in the initial *asset-replacement* design) or whether supplementary fodder is purchased to keep these animals alive (as intended by the *asset-protection* design). The crucial point for our model is that, under either approach, livestock holding will be much larger over the drought and immediate post-drought period than would have been the case in absence of insurance. It is true that if asset replacement insurance were to be scaled, eventually there would be a point at which restocking demand would overwhelm the livestock market, however with the move to an asset protection model that minimizes livestock losses entirely, the implications of our model are even starker.

3.1.3. Rainfall

Highly variable rainfall is a system-immanent feature of semi-arid rangeland areas that has been playing an important role in shaping the ecological conditions as well as the established

[6] Insurance is not introduced until year 15, because the first years are considered a transient phase.

rangeland management practices. Based on a historical 47-year rainfall data set from Laisamis, Marsabit County, North Kenya, we inferred that rainfall approximately follows a lognormal distribution with a mean of 180 mm/a and a standard deviation of 80 mm/a. So, in our model, rainfall is drawn from such a lognormal distribution. Seeing that droughts roughly occur every six to seven years, we interpreted draws of 100 mm/a or less ($P(X \leq 100 \text{ mm/a}) = 0.1206$) as droughts.

Due to nonlinearities in biomass dynamics, it is not only the moments of the rainfall distribution (such as mean, variance, and skewness) that matter, but also the order in which rainfall events occur over time. To gain a mechanistic understanding of the effect that the structure of the rainfall time series (esp. temporal correlation) has on the system dynamics, we chose a controlled way instead of working with random time series. To systematically assess the broad range of rainfall time series, we drew six representative yearly rainfall values from the random distribution which were then assigned to the individual seasons in fixed proportions. We made sure the sample included exactly one drought and was representative in terms of sample mean as well as standard deviation. We then brought the sampled values in a certain order (see below) and continuously repeated the obtained sequence throughout the simulation (see Figs. 2 and 4D for examples). As is often done in simulation experiments (e.g., Wichmann et al., 2003), we chose those orders that allowed us to analyze a wide range of weather events. The chosen rainfall scenarios are: (i) ascending and (ii) descending order (yielding the highest positive autocorrelation) as well as (iii) a strongly alternating rainfall pattern (highest negative autocorrelation). These scenarios represent opposite ends of all potential orders and thus can be assumed to cause the most diverse system dynamics.

The scenarios are also expected to drive different rangeland dynamics: Ascending rainfall entails that high-rainfall years occur well after the drought when herds have had sufficient time to recover and grow. Descending rainfall, on the other hand, may allow pastures to replenish very quickly after a drought because of the exceptionally high rainfall in the first post-drought years which coincides with low stocking rates. Finally, alternating rainfall may increase the buffering capacity throughout the simulation, as low-rainfall years will limit herd growth creating a biomass surplus in the subsequent high-rainfall year (high rainfall leads to a growth of more green biomass than will be consumed by livestock).

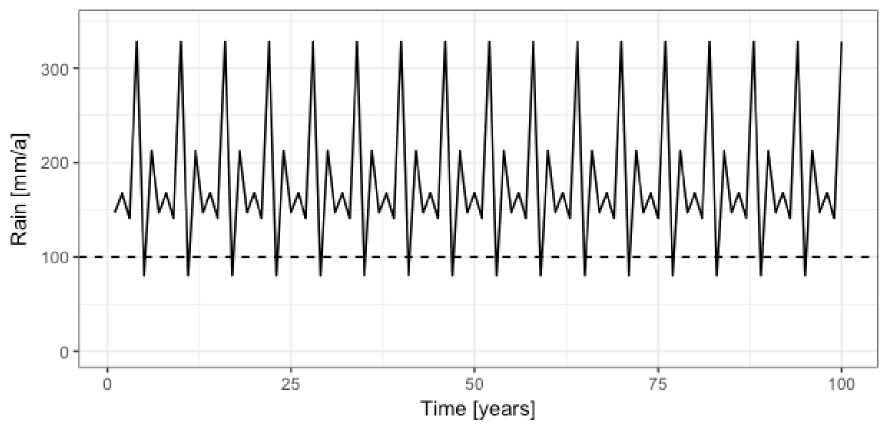

Figure 2: Rainfall time series generated from a repeated 6-year sequence of rainfall values (here in the order with the highest negative autocorrelation). The dashed line at 100 mm/a indicates the drought threshold.

3.2. Model analysis

We analyzed the effects of an at-scale introduction of LDI on long-term pasture and herd dynamics for different economic and ecological parameters. On the economic side, we varied the insurance sum (i.e., the number of animals covered by insurance) from 0 to 50 TLU. Since our simulations showed that herd sizes never exceeded 50 animals, an insurance sum of 50 TLU is equivalent to always insuring the entire herd. Note that the insurance sum is the maximum amount of animals that herders would insure, but they never insure more animals than they actually have. On the ecological side, we varied the pastures' sensitivity to grazing. If it is 0, grazing does not have any impact on the pasture development; if it is 1, biomass rebuild of grazed pastures is very low.

We then ran the model for 1000 years which is necessary to see whether results are stable and because some of the methods we used gain accuracy if fed with more data. To compare scenarios, we evaluated results against two criteria: (i) the long-term mean of livestock numbers and (ii) the downside risk (see below for an explanation). For the former, we took the total number of livestock and calculated its mean over the last 900 years. We cut off the first 100 years of each simulation considering them a transient phase. By comparing each scenario to the one without insurance, we thus isolated the long-term effect of LDI on the mean livestock numbers. This metric, however, ignores variation over time, which is why we also analyzed the downside risk. Downside risk (*DR*) measures the spread of outcomes *x* below a critical threshold $\tilde{X}$, in our case the long-term mean of livestock numbers for the scenario without insurance. Downside risk is thus calculated according to the following formula:

$$DR = \sqrt{\frac{1}{900}\sum_{t=101}^{1000} \min(x_t - \tilde{X}, 0)^2}$$

In other words, downside risk indicates how likely it is to fare worse than without insurance. Focusing on potential losses makes sense if one assumes that livestock keepers tend to be risk-averse.

Additionally, we analyzed differences in system dynamics. Since we investigate complex consumer-resource interactions (between livestock and pastures), different temporal patterns can emerge. They can result in the formation of oscillations which are overlaid by stochasticity. To better understand the likelihood of oscillations induced by internal interactions as well as their determinants, we conducted a Fourier transformation of the livestock trajectory. Again, we used the last 900 years. A Fourier transformation is a useful tool to identify qualitative differences in time series data (Cowpertwait and Metcalfe, 2009). It is a method from mathematics that decomposes a time series into the frequencies that it is made up of. As a result, it yields the amplitudes of the underlying frequencies. Thus, it can detect regular cyclic patterns such as the accumulation and breakdown of herd sizes and in which intervals they occur.

We then assigned simulation runs to one of the following broader system orders:

1. *Collapse*: Either at least one household was forced to leave the system (because all their livestock had died and they did not have the means to buy new animals) or during the last 100 years of the simulation there was always less than 1 animal in the system (i.e., all households had between 0 and 1 animals).

2. *Oscillation*: The Fourier transformation detected a pronounced cyclic pattern with a wavelength between 40 and 200 years. As a relevance criterion, we considered only those cycles with a Fourier transform (i.e., an amplitude) of at least 400 000.

3. *Quasi-stationarity*: Variables fluctuated on a small scale within a constant interval (i.e. all runs that do not fall in any of the other categories).

The utilized model parameters (see ODD+D protocol in the appendix) correspond to the ones used in Müller et al. (2007) and Martin et al. (2016) (vegetation sub-model) or are based on personal communication with empirical experts (livestock sub-model). For an extensive sensitivity analysis of the vegetation sub-model (such as impact of vegetation parameters gr_1 and rain use efficiency as well as the impact of rainfall parameters on vegetation), see Schulze (2011). We additionally performed a local sensitivity analysis on the effect of herd growth, which can be found in the appendix. The model was tested using desk and documentation checking, face validation, walkthroughs with modelers, ecologists and economists, module testing as well as debugging. A check for inter-run variability revealed that the model produces identical results regardless of the random seed. Therefore, we run the model only once for each parameter constellation.

4. Results

In this part, we first explore the temporal dynamics for individual model runs to get a first impression from the functioning of the overall system. We then go over to the main goal of this paper, i.e., the identification of chances and risks of the introduction of livestock drought insurance (LDI) in semi-arid rangelands. We do this by a systematic model analysis which compares the outcomes of scenarios with and without LDI and assesses the relative influence of ecological (esp. ecosystem characteristics), economic (esp. design of the insurance contract) and climatic factors (esp. different rainfall scenarios).

4.1. Insurance can alter rangeland dynamics substantially

According to our simulations, the impact of insurance on the dynamics of the coupled social-ecological system is qualitatively different for different ecological conditions. This can be best seen by looking at the trajectories of livestock and biomass for individual model runs with different ecological settings.

In ecosystems where grazing has a medium or low impact on vegetation growth (i.e., sensitivity to grazing < 0.6), our simulations show that livestock follows boom-and-bust cycles (e.g., Fig. 3A). Such cycles describe a steady growth of herd size that is repeatedly interrupted by shocks and are frequently observed in reality (e.g., Desta and Coppock, 2002). Hence, the model matches the system dynamics of the real world, which serves as a reasonability check for our model. It can also be seen that these drops often coincide with drought years. In other words, the system is primarily driven by rainfall variability.

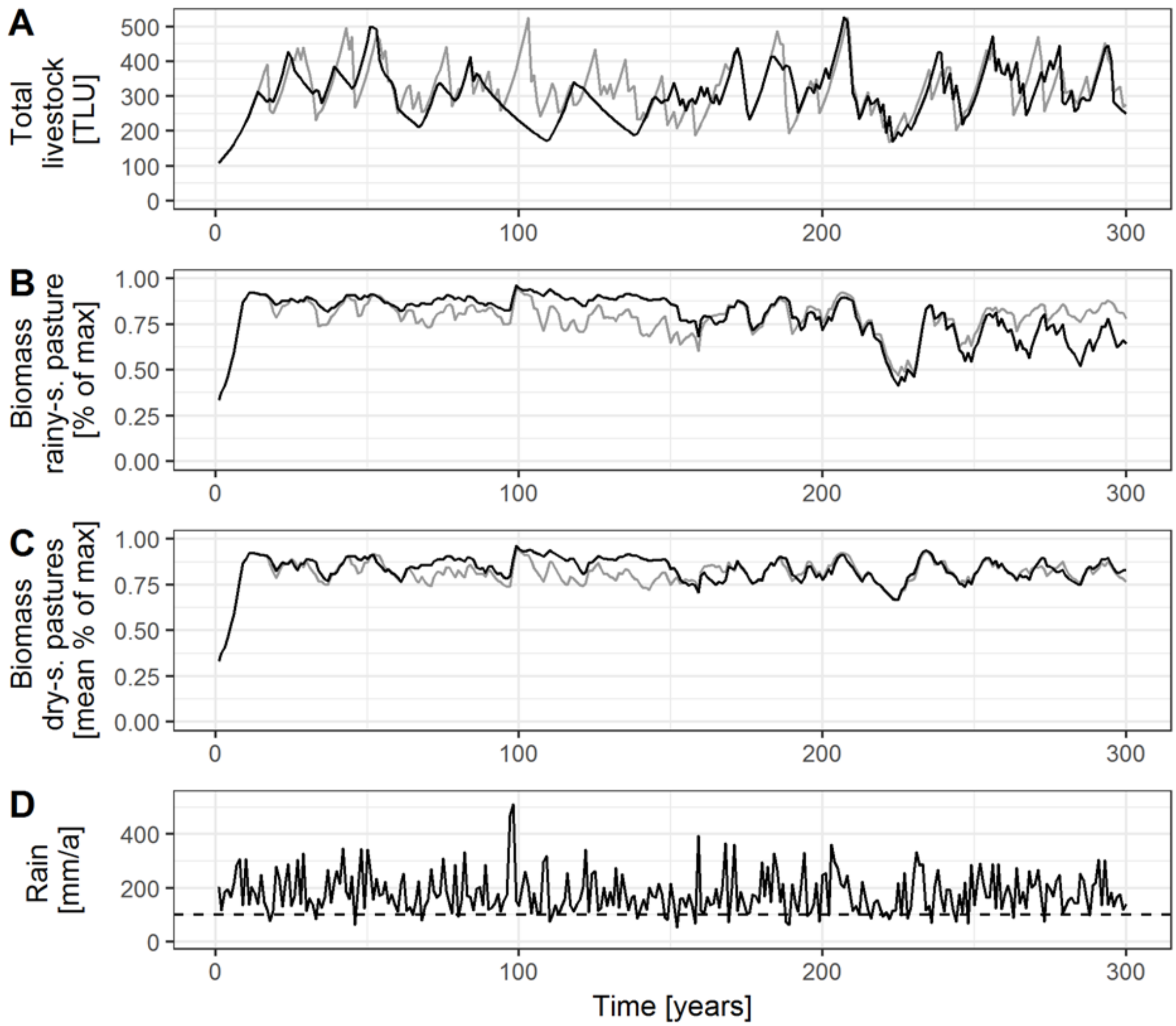

Fig. 3: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time for random rainfall (drawn from a lognormal distribution with mean = 180 mm/a and sd = 80 mm/a). Graphs depict the situation without insurance (grey graph) and with an insurance of 40 TLU (black graph), sensitivity to grazing is low (0.25) and both simulations are generated with the same random seed. Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

However, running the model with random rainfall (i.e., not using the sequences explained above, but randomly drawing from a lognormal probability distribution instead, see Fig. 3D) indicates that the effects of a particular drought on livestock numbers and pasture conditions strongly depend on the particular circumstances at that time (e.g., in terms of grazing pressure, time since previous drought, insurance payout, etc.). The high level of path-dependence is caused by overlapping nonlinearities in the consumer-resource interaction, the biomass accumulation, and the differential grazing pressure on dry and rainy-season pastures, which we disentangle in more detail below. This also influences how well insurance can buffer the shocks arising from droughts. Figure 3 shows two representative simulation runs with identical rainfall time series – one without LDI (grey graph) and with an LDI of 40 TLU (black). While in some cases (e.g., between years 200 and 250) trajectories of both scenarios quickly converge again after the drought, in others (e.g., around year 100) they evolve very differently thereafter.

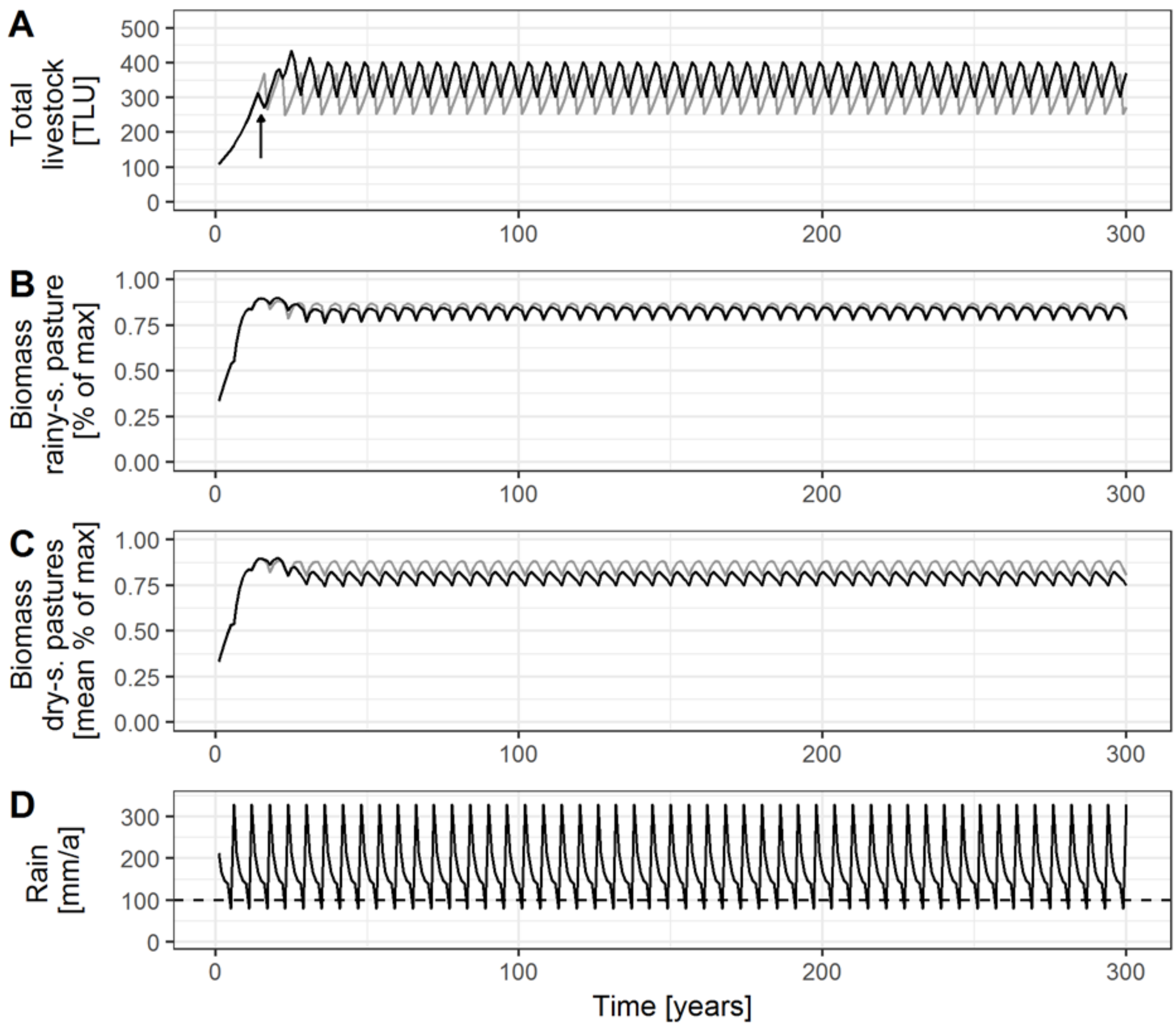

Fig. 4: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with low sensitivity to grazing (0.25) for "descending rainfall" scenario. Graphs depict the situation without (grey) and with an insurance of 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

Systematically exploring the simulated rainfall scenarios helps disentangle the overlapping dynamics. Fig. 4 depicts the situation for the "descending rainfall" scenario with low sensitivity to grazing. Without insurance (grey graphs), a stable cyclical pattern emerges where livestock numbers are building up steadily interrupted by droughts. Introducing insurance in this context (Fig. 4, black graph) slightly changes the dynamics: In our simulation, insurance is introduced after 15 years (arrow in Fig. 4A), and we see that, first, immediately after introduction, households have to sacrifice some of their herd growth in order to pay the insurance premium. This reduces grazing pressure on the pastures so they could accumulate more biomass. Therefore, pastures are able to sustain more animals during the next years (until the next drought hits in year 24). Additionally, during the drought, pastoralists use the insurance payout to maintain their herd size high. After the drought, herds have enough forage to grow, but, in the scenario with insurance, they have a head start relative to the scenario without insurance. Then the dynamics converge to a stationary pattern in both cases: Without insurance, the typical boom-and-bust cycle emerges. Here, the drought reduces livestock numbers to the level at which they have been at the beginning of the cycle. Yet with insurance, a different boom-and-bust cycle forms: Livestock accumulates immediately after the drought, but hits the carrying capacity of the remote dry-season pastures. Therefore, pastoralists have to destock in the last two years leading up to the drought. In the "descending rainfall" scenario, rainfall steadily declines towards the drought, so the amount of available grass also decreases. The insurance payout, however, is then used to reverse the previous destocking. As a result, if pastures' sensitivity to grazing is low (as in Fig. 4; where it is 0.25), the system may be able to support the additional grazing pressure through LDI (which stems from the quick restocking after the drought).

If the sensitivity to grazing is high (0.9), dynamics change (Fig. 5). Again, the grey graph depicts the simulation without insurance. Here, the pattern is less regular. It is visible, however, that the boom-and-bust cycle establishes over a period of two droughts, because livestock numbers break down so heavily during one drought that enough biomass can accumulate thereafter to buffer the effects of the next one.

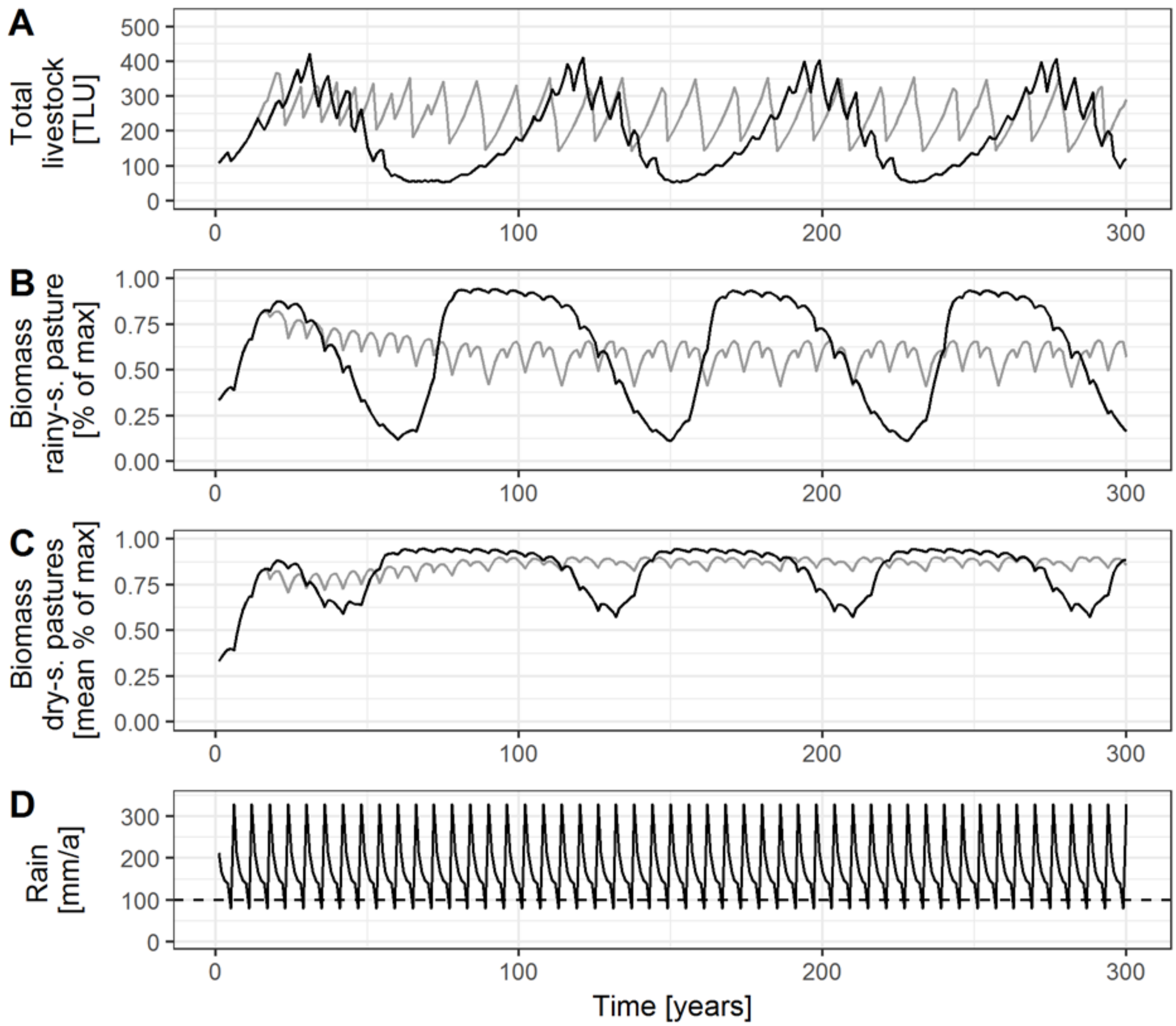

Fig. 5: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with high sensitivity to grazing (0.9) for “descending rainfall” scenario. Graphs depict the situation without (grey) and with an insurance of 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

Introducing LDI under these conditions turns the quasi-stationary system into an oscillating one where, over a time span of about 80 years, herds experience a long-term cycle of decline and recovery. Immediate restocking after the drought exerts a high pressure on pastures that leads to gradual degradation. Figures 5B and 5C show that biomass cannot really recover after a drought. While the remote grazing areas can recover after a couple of droughts, wet season grazing areas take considerably longer. Only at very low herd sizes (5 animals per herd) do the dynamics turn round and pasture recover. Yet the system cannot stabilize at the level of the no-insurance run. Instead, it overshoots and immediately enters in the next degradation phase. This shows that introducing the LDI causes a regime shift with qualitatively different systems dynamics which are characterized by long-term changes between phases of degradation and recovery. The time-scale of these long-term processes is an emergent property that subsumes the combined effect of all the factors considered.

4.2. Ambiguous long-term effects of insurance

We now assess the long-term effects of varying insurance sums as well as varying levels of sensitivity to grazing. We choose these factors to test the effects of insurance in different ecological and economic conditions.

The insurance sum is the main decision criterion that policy holders have. Insuring more animals, or even the entire herd, poses a trade-off, as it entails high yearly premium payments, but also ensures that all potential livestock losses are covered no matter how severe the drought. More risk-tolerant herders may insure only parts of their herd in order to reduce premiums, potentially assuming that not all their animals will be lost in the same drought, or only seeking to insure a minimal, biologically regenerative, herd size.

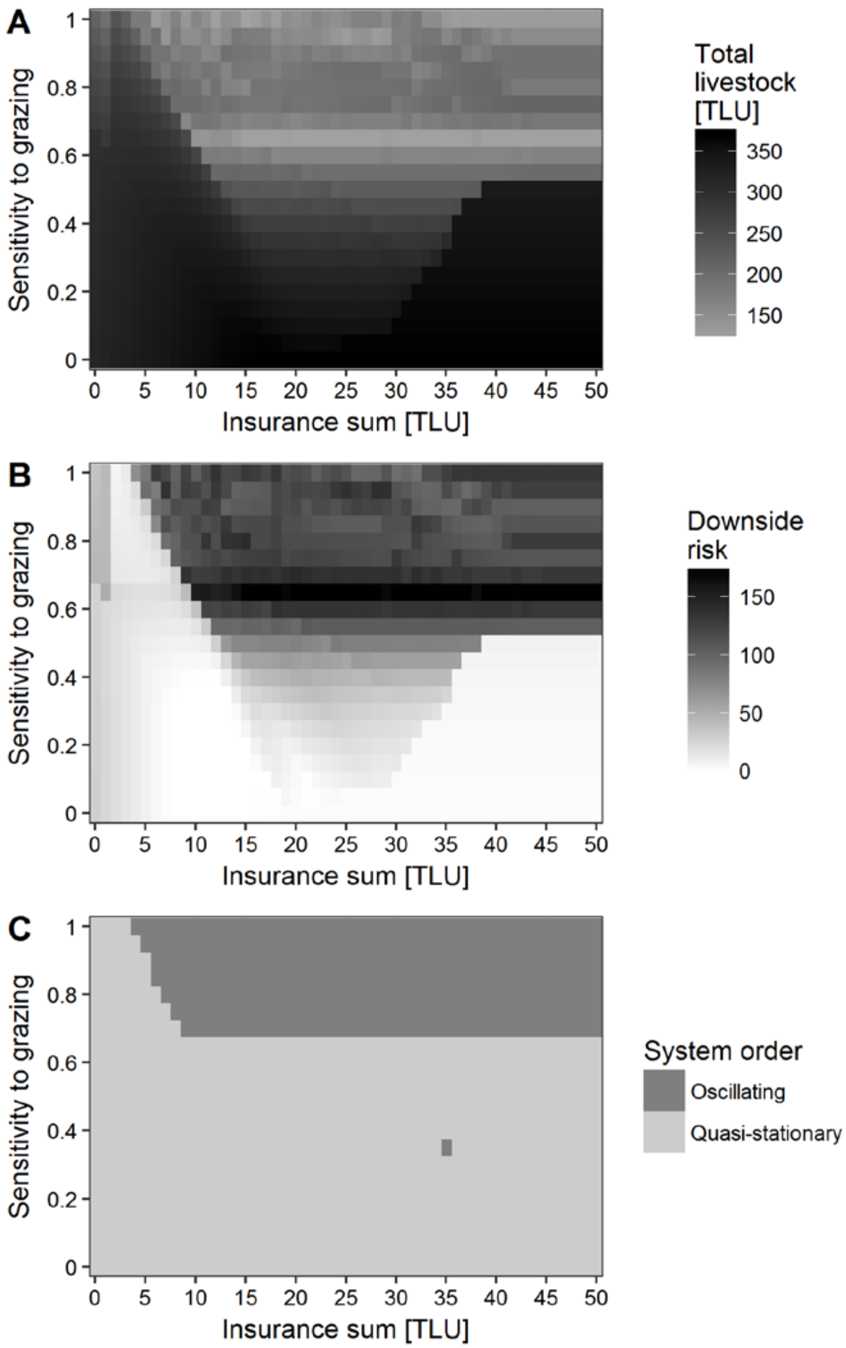
A
Sensitivity to grazing
Insurance sum [TLU]
Total livestock [TLU]
350
300
250
200
150
B
Downside risk
150
100
50
0
C
System order
Oscillating
Quasi-stationary
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35
40
45
50

Fig. 6: Long-term mean of total livestock numbers (A), downside risk of falling below the livestock mean of the simulation without insurance (B), and the resulting system order[7] (C) for descending rainfall dependent on the sensitivity to grazing and insurance sum. Data generated based on a single run.

Fig. 6A shows the resulting long-term means of total livestock numbers for different sensitivities to grazing and varying insurance sums. The sensitivity to grazing describes the regeneration capacity of reserve biomass under grazing. A darker shade of grey indicates a higher long-term mean of livestock numbers. The figure shows absolute values for the different insurance sums, with the left-most column displaying the reference case without LDI. So comparing a cell with the left-most one for the same sensitivity to grazing (i.e., in the same row) indicates the effect of LDI. One general trend is that a lower sensitivity to grazing (i.e., going down on y-axis) can support more animals in the long run in the case without insurance.

The effect of LDI, however, differs greatly. For a low sensitivity to grazing (< 0.4), the effect of insurance is mixed and a trade-off becomes visible. Even though long-term degradation (i.e., oscillations) does not occur for any insurance level, two contrary effects can be observed: For low insurance sums, payouts can cushion the effects of a drought without compromising pasture regeneration, thereby allowing higher livestock numbers. Large insurance sums, on the other hand, entail high premiums which can often only be paid through destocking. This reduces grazing pressure and allows pastures to regenerate as well. Medium insurance sums result in destabilization manifested in reduced mean livestock numbers and enlarged downside risks.

[7] In the run with a sensitivity to grazing of 0.35 and an insurance sum of 35 TLU, the system jumps from one quasi-stationary state into another after about 350 years. In the Fourier transformation this jump is interpreted as a very low-frequency oscillation, which is why it is classified as ‘oscillating’.

With a high sensitivity to grazing, the situation is qualitatively different. For a high sensitivity to grazing (≥ 0.7) and low insurance sums, the payout after a drought is not high enough to substantially increase pressure on the pastures. So the replaced animals can contribute to a faster herd growth. Therefore, it can have a slightly positive effect on livestock numbers also in the long run. But increasing the insurance sum turns the system dynamics from quasi-stationary to oscillating (Fig. 6C). The resulting repeated breakdowns of livestock numbers reduce their long-term mean compared to the case without insurance.

For sensitivities to grazing that are slightly smaller than the threshold that triggers the oscillations (i.e., values between 0.5 and 0.7) and medium to high insurance sums, long-term livestock means are considerably lower than in the reference case without LDI. Here, the pressure on the pastures reduces their biomass levels during the first years of the simulation (i.e., the transient phase) and the system settles into a quasi-stationary state with low livestock numbers.

Interestingly, downside risk and long-term means of livestock numbers show very similar results (Figs. 6A and 6B). Whenever only a small number of animals can be sustained, this also increases the risk to be worse off by purchasing LDI.

4.3. Effect of insurance for different rainfall patterns

We now do the same analyses for different rainfall patterns and find similar effects. As already explained above, we take the scenarios with the strongest negative and positive temporal autocorrelation. Strong negative autocorrelation results in an alternating pattern of high and low rainfall years (Fig. 3 above); whereas the strongest positive autocorrelation is achieved by bringing the values in descending or ascending order. So far, we have presented results for a descending rainfall scenario (i.e. rainfall values are ordered from highest to lowest, starting again with the highest after a drought) where the very wet years after the drought contribute to a quick recovery of biomass and maybe even the build-up of a buffering capacity.

For negatively autocorrelated values, this buffer effect is largely absent (Fig. 7; see also Figs. A1 and A2 in the appendix that show – analog to Figs. 4 and 5 above – the temporal dynamics of individual runs). The most prominent feature is that for a sensitivity to grazing smaller than 0.7, LDI does not seem to have any effect on neither livestock numbers nor system order. For higher sensitivities to grazing, effects seem erratic. Long-term oscillations occur in almost all cases, sometimes they even lead to a total collapse, i.e., herders lose all their animals (Fig. 7C).

Results for ascending rainfall are not shown here (instead see Figs. A3-A5 in the appendix), because on an aggregated level (e.g., as shown in Fig. 7) they are qualitatively very similar to the ones with alternating rainfall.

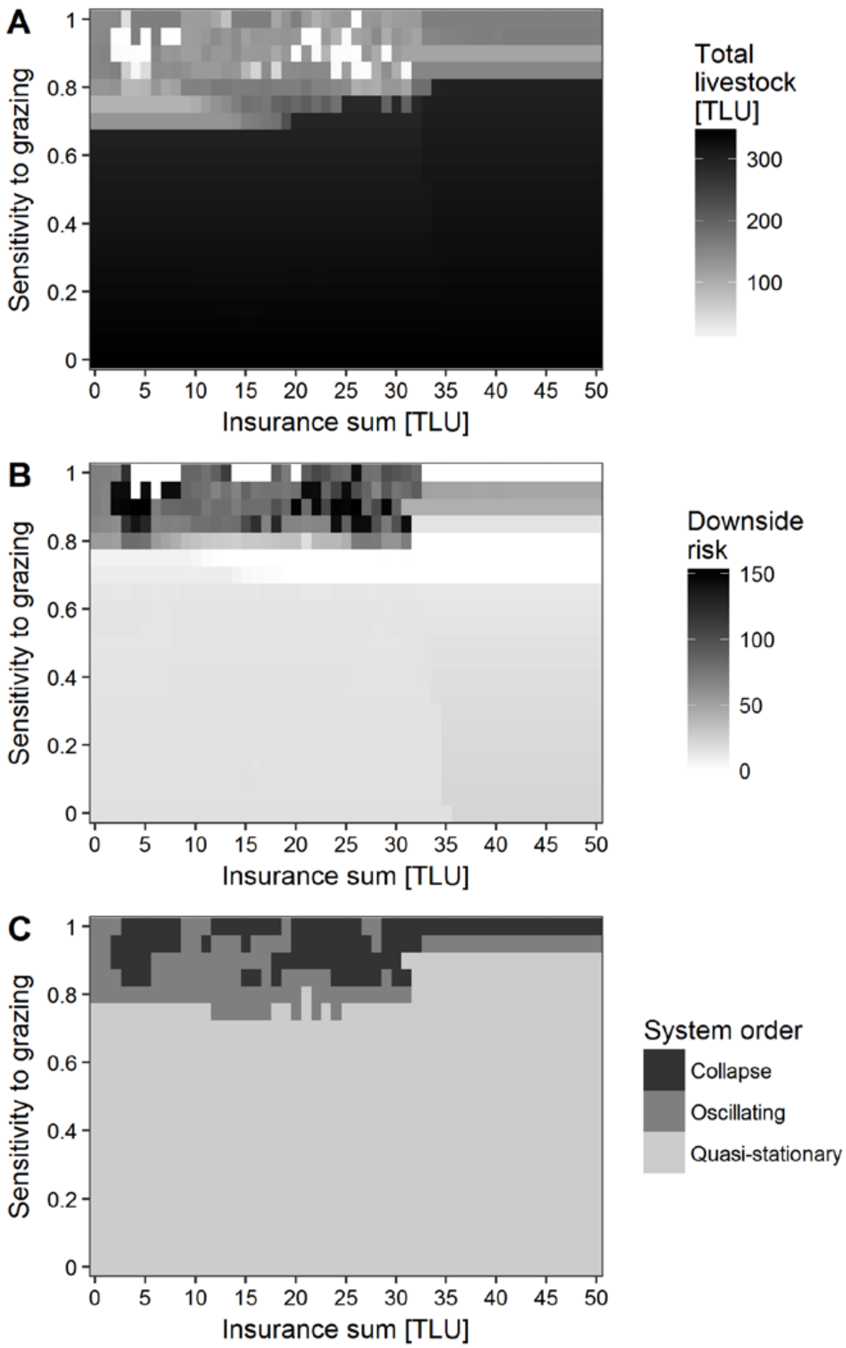

Fig. 7: Long-term mean of total livestock numbers (A), the downside risk of falling below the livestock mean of the simulation without insurance (B), and the resulting system order (C) for alternating rainfall dependent on the sensitivity to grazing and insurance sum. Data generated based on a single run.

5. Discussion

Our results show that – within the assumptions of our model – insurance can both stabilize and destabilize the common property pastoral system, depending on the interplay of ecological and economic factors. Insurance can prevent hunger and poverty by cushioning shocks, but it can also leave pastoralists worse off by potentially causing long-term degradation.

Without insurance, drought reduces livestock numbers, which slowly recover in subsequent years through boom-and-bust cycles. Insurance mitigates livestock losses caused by drought, which leads to higher stocking rates immediately thereafter. If pastures can recover sufficiently fast, they may sustain higher livestock numbers also in the long run. If, however, pastures cannot handle the high post-drought grazing pressure, unsustainable overgrazing may occur, from which a slow but steady degradation may emerge.

5.1. Impact of insurance

LDI is typically only assessed in terms of short-term economic impacts and at the level of the individual beneficiary. In dynamic resource-use contexts, however, insurance has indirect effects as well, that materialize in the interplay of different land users and their environment. So the impact of LDI can be framed as a trade-off between the individual preference to avoid negative shocks, and a community-wide interest to manage pastures sustainably. Insurance is a means to achieve the former, but at the expense of ecological buffering capacity. It is possible that, empirically, this systemic feedback effect will manifest only if insurance is taken up at significant scale. Even though LDI coverage is still relatively low at the moment, our results should raise caution. Adverse ecological effects can be substantial and may take very long to be reversed. This call for caution is all the more justified as our simulation results show that unintended ecological consequences unfold gradually and may not be detected at once.

Prior studies have found effects of insurance that could also bring about unintended consequences. Studies with Indian farmers showed that those farmers who have insurance take on higher-risk, higher-return investments (Mobarak and Rosenzweig, 2013; Cole et al., 2016). While this may be beneficial to the farmers, on average, it can be bad for the laborers who end up facing higher wage risks (but do not necessarily get the upside benefit of the higher returns) (Mobarak and Rosenzweig, 2014). This could be called a "pecuniary unintended consequence" of insurance, whereas our findings represent a "socio-ecological unintended consequence". Our results support the findings of Bhattacharya and Osgood (2014) that households with LDI divert some assets from their production activity to insurance (*substitution effect*). We can also observe the *income effect* in that foregone income of the households may be more than compensated by LDI payoffs in case of a drought. The most obvious case here is that the payout can keep pastoralists in the game when a drought would have killed all their animals. But Bhattacharya and Osgood's (2014) two-period model simply attributes negative impacts of insurance on the common-property resource to the income effect outweighing the substitution effect. Our model, on the other hand, takes into account the dynamic nature of pasture development and delivers a more nuanced picture. To assess the ecological sustainability of the pastures, the question is not whether insurance increases grazing pressure, but whether pastures can cope with it. Our results show that insurance can also lead to an increase in livestock numbers that is ecologically sustainable (Fig. 4). We identify the sensitivity to grazing as a key factor for this. If pastures are very sensitive to grazing and "natural resting periods" after droughts are diminished, Bhattacharya and Osgood's income effect does endanger sustainability.

Interestingly, our results suggest that the risk of obtaining unintended consequences is highest under those conditions when insurance is needed the most, that is when sensitivity to grazing is high. In these cases, droughts are more likely to cause livestock losses, since grazing already reduces the ecological buffering capacity in non-drought years. Accordingly, pastures need more time to recover. Forgoing pasture resting can thus lead to unintended consequences, as has already been shown by Müller et al. (2007). On the other hand, when grazing has little effect on biomass growth, pasture buffering capacity is high. Pastures are not damaged as much by droughts, and moreover, they will recover faster. Under these circumstances, expected livestock losses will be lower. Therefore, insurance is not only less necessary, but, if taken up, would also have smaller ecological consequences.

5.2. Design of insurance

To find an optimal balance between the desired economic, and unintended ecological, effects, a thorough assessment of pasture conditions would be needed. Unfortunately, it is not possible, or at least very costly, to pinpoint this optimal state. Therefore, a practical second-best solution could be to restrict the amount of animals that can be insured by each household in the system. This limit should be high enough to ensure that farmers do not get caught in poverty traps, which develop around 5 TLU (Lybbert et al., 2004; Toth, 2015), but not as high as to cause substantial ecological damage in the aggregate. Interestingly, this is exactly what the Kenya Livestock Insurance Program (KLIP) does. In 2015, the Kenyan government started to offer LDI of 5 TLU to vulnerable pastoralists for free (SwissRe, 2017).

Furthermore, our results hold for both designs of IBLI (i.e., asset replacement and asset protection). In the model, herds are destocked in case of forage scarcity and then restocked after payouts have been made at the end of the year (corresponding to the end of the short dry season in March). While this resembles the asset replacement design, the argument is even stronger for asset protection. In this case, early payouts aim at maintaining original livestock numbers throughout the drought (e.g., by fodder supplementation), so that there would be no periods of reduced stocking. Consequently, the risk of over-grazing is also higher. This reasoning is backed up by modeling studies which show that supplementing fodder only during droughts to reduce destocking can have detrimental ecological effects (Müller et al., 2015; Schulze et al., 2016). Furthermore, the results would also hold for indemnity-based insurance, and whether based on an asset replacement or asset protection model.

5.3. Potential and Limitations

Even though we use a stylized qualitative model that cannot make reliable quantitative prediction of future conditions, there are a number of insights that go beyond a purely theoretical thought experiment. The model indicates qualitative changes in system dynamics (e.g., where the system moves from a quasi-stationary to a oscillatory state (such as shown in Fig. 6C). The model also allows us to disentangle overlapping mechanisms (e.g., insured herders have to sacrifice some of their herd growth in order to pay the insurance premium, which leads to lower herd sizes in the first years after the introduction of insurance, but larger herd sizes in the long run). Furthermore, the model enables us to systematically vary parameters (e.g., sensitivity to grazing and insurance sum) and analyze their effects as well as their interactions. Finally, we can explore the impact of temporal rainfall patterns with the model. These result in different response surfaces for long-term livestock averages (cf. panel A of Figs. 6, 7, and A5), their variation of herd sizes over time (panel C) and the risk that insurance leaves you worse off (panel B).

Our model also has a number of limitations which point to the need of further research and generalization. First, we assume an artificial rainfall time series. We use statistical moments from empirical rainfall data, but limit the complexity by creating simplifying scenarios. We additionally assume a constant intra-annual rainfall distribution. So the yearly rainfall is assigned proportionally to the different seasons. This also entails that in case of a drought, both dry seasons have very little rainfall. Hence, our model delivers qualitative results, whereas policy makers might want fully quantitative predictions. Second, we consider spatial structure only implicitly. While it is important that we distinguish between different grazing areas, their distances do not matter. Including movement costs may make dry-season pastures that are closer to the settlement more attractive and increase grazing pressure there. Thereby these pastures might experience stronger degradation, whereas those farther away become more unattractive and get rested more often, which could strengthen or weaken our results, depending on the distribution of pastures' sensitivity to grazing. Third, we do not address the question of who takes up insurance, which is hotly debated (e.g., Hazell and Hess, 2010; Binswanger-Mkhize, 2012). Instead, we assume that all households purchase LDI to analyze the effects on a larger scale. Explicitly considering the decision of insurance uptake would greatly increase model complexity, which is why an in-depth analysis is beyond the scope of this paper, though heterogeneity in take-up patterns could strengthen or weaken our results. But we do acknowledge that analyzing the uptake decision posits a very interesting research question, and hence, a valuable model extension for future studies. Fourth, and in a similar vein, our model does not allow for endogenous, community-wide coordinated responses to the dynamics we model. For instance, if insurance scaled and this was generating real degradation, the community might get together and implement rules to mitigate these effects (e.g., by limiting herd sizes, controlling grazing patterns, escape mobility, etc.; Oba and Lusigi, 1987). Lastly, model validation and parameter estimation is often difficult for this type of model, since a number of parameters that are needed in the model are not easy to observe in reality (e.g., rain-use efficiency, the conversion factor of rainfall into biomass growth, is hard to measure). Therefore, we rely on sensitivity analyses for these parameters and validate them only qualitatively.

There are additional features like household heterogeneity or probabilistic herd growth which we do not take into account for sake of simplicity. While we see that these features would make the model more realistic, we do not believe that they would qualitatively change our results.

6. Conclusion

In dynamic resource-use contexts like common-property pastoralist communities, introducing livestock drought insurance at scale can have systemic impacts. Insuring weather shocks may be desirable from the perspective of the individual beneficiary, but at the system level such interventions have the potential to stimulate unsustainable resource over-use, such as overgrazing. Our simulation results corroborate this hypothesis by showing that, where grazing has a large impact on vegetation dynamics, insurance may increase grazing pressure too much and trigger a phase transition to long-term oscillations. These oscillations unfold in cycles of 80 to 100 years and swing back and forth between a near-collapse of the system and subsequent "recovery". From an economic standpoint, the oscillations are not desirable, as they lead to lower average livestock numbers in the long run and extended periods of threateningly low asset levels. The phase transition sets in gradually, which makes it all the more difficult to detect in reality.

A strength of our dynamic modelling approach (e.g., the introduction of repeating rainfall time series) was to disentangle different dynamics and to separate the impact of insurance from naturally occurring randomness in rainfall. We could thereby detect qualitative differences in the behavior of the social-ecological system depending on ecological parameters (e.g., sensitivity to grazing) and characteristics of the insurance contract (insurance sum).

These potential socio-ecological feedbacks have to be kept in mind when designing insurance products to avoid unintended consequences. Since our results are based on a theoretical simulation model that naturally comes with a set of simplifying assumptions, we can merely point to this possibility and call for caution. Additionally, we'd like to encourage empirical researchers to test our hypothesis in the field.

Acknowledgments

We would like to thank the members of the junior research group POLISES as well as two anonymous reviewers for helpful comments on previous versions of this paper. We would also like to thank the International Livestock Research Institute for their hospitality. FJ wishes to thank Niklas Hase for helpful discussions and comments during model building and analysis. FJ and BM gratefully acknowledge funding by the German Federal Ministry of Education and Research (BMBF-01LN1315A) within the Junior Research Group POLISES. RT gratefully acknowledges funding support from AusAID through the AusAID Development Research Awards Scheme under an award titled "The human and environmental impacts of migratory pastoralism in arid and semi-arid East Africa".

The views expressed in this publication are those of the authors and not necessarily those of the institutions that they are working for or that provided funding. The Commonwealth of Australia accepts no responsibility for any loss, damage or injury resulting from reliance on any of the information or views contained in this publication.

References

Alemu, T., Robinson, L.W., 2015. Systems Analysis for Rangeland Management in Yabello, ILRI Workshop Report. International Livestock Research Institute, Nairobi, Addis Abeba.

Bhattacharya, H., Osgood, D., 2014. Weather Index Insurance and Common Property Resources. Agricultural and Resource Economics Review 43, 438-450.

Binswanger-Mkhize, H.P., 2012. Is There Too Much Hype about Index-based Agricultural Insurance? Journal of Development Studies 48, 187-200.

Campbell, B.M., Doré, D., Luckert, M., Mukamuri, B., Gambiza, J., 2000. Economic comparisons of livestock production in communal grazing lands in Zimbabwe. Ecological Economics 33, 413-438.

Chantarat, S., Mude, A.G., Barrett, C.B., Carter, M.R., 2013. Designing Index-Based Livestock Insurance for Managing Asset Risk in Northern Kenya. Journal of Risk and Insurance 80, 205-237.

Cole, S., Giné, X., Vickery, J., 2016. How does risk management influence production decisions? Evidence from a field experiment. Review of Financial Studies 30, 1935-1970.

Cowpertwait, P.S., Metcalfe, A.V., 2009. Introductory time series with R. Springer Science & Business Media.

Desta, S., Coppock, D.L., 2002. Cattle Population Dynamics in the Southern Ethiopian Rangelands, 1980-97. Journal of Range Management 55, 439-451.

Dressler, G., Hoffmann, F., Breuer, I., Kreuer, D., Mahdi, M., Frank, K., Müller, B., 2018. Polarization in (post-)nomadic resource use in Eastern Morocco: insights using a multi-agent simulation model. Regional Environmental Change. https://doi.org/10.1007/s10113-018-1412-9.

Dressler, G., Groeneveld, J., Buchmann, C.M., Guo, C., Hase, N., Thober, J., Frank, K., Müller, B., 2018. Implications of behavioral change for the resilience of pastoral systems—Lessons from an agent-based model. Ecological Complexity.

G7, 2015. Joint Statement on InsuResilience, Paris, 5 December 2015. http://www.bmz.de/g7/includes/Downloadarchiv/G7_Joint_Statement_InsuResilience.pdf, last accessed: 24 August 2017.

G7, 2015. Think Ahead. Act Together. Leaders' Declaration G7 Summit. Elmau, 7-8 June 2015. https://www.g7germany.de/Content/EN/_Anlagen/G7/2015-06-08-g7-abschluss-eng_en.pdf?__blob=publicationFile&v=3, last accessed: 24 August 2017.

GIIF, 2017. Global Index Insurance Facility – Overview. https://www.indexinsuranceforum.org/overview, last accessed: 24 August 2017.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115-126.

Hazell, P.B.R., Hess, U., 2010. Drought insurance for agricultural development and food security in dryland areas. Food Security 2, 395-405.

Helland, J., 1997. Development interventions and pastoral dynamics in Southern Ethiopia, in: Hogg, R. (Ed.), Pastoralists, ethnicity and the state in Ethiopia. Haan, London, pp. 55-81.

Hobbs, N.T., Galvin, K.A., Stokes, C.J., Lackett, J.M., Ash, A.J., Boone, R.B., Reid, R.S., Thornton, P.K., 2008. Fragmentation of rangelands: Implications for humans, animals, and landscapes. Global Environmental Change 18, 776-785.

Huysentruyt, M., Barrett, C.B., McPeak, J.G., 2009. Understanding Declining Mobility and Inter-household Transfers among East African Pastoralists. Economica 76, 315-336.

ILRI, 2017. Record payouts being made by Kenya Government and insurers to protect herders facing historic drought. International Livestock Research Institute, Nairobi, 21 February 2017. https://news.ilri.org/2017/02/21/record-payouts-being-made-by-kenya-government-and-insurers-to-protect-herders-facing-historic-drought/, last accessed: 16 March 2018.

James, C.D., Landsberg, J., Morton, S.R., 1999. Provision of watering points in the Australian arid zone: a review of effects on biota. Journal of Arid Environments 41, 87-121.

Janzen, S.A., Carter, M.R., 2013. The Impact of Microinsurance on Consumption Smoothing and Asset Protection: Evidence from a Drought in Kenya. Presented at the Annual Meeting of the Agricultural and Applied Economics Association, Washington, D.C., 4-6 August 2013.

Jensen, N.D., Barrett, C.B., Mude, A.G., 2016. Index Insurance Quality and Basis Risk: Evidence from Northern Kenya. American Journal of Agricultural Economics 98, 1450-1469.

Jensen, N.D., Mude, A., Barrett, C.B., 2014. How basis risk and spatiotemporal adverse selection influence demand for index insurance: Evidence from northern Kenya. Working paper, December 2014, https://ssrn.com/abstract=2475187, last accessed: 24 August 2017.

Karlan, D., Osei, R., Osei-Akoto, I., Udry, C., 2014. Agricultural Decisions after Relaxing Credit and Risk Constraints. The Quarterly Journal of Economics 129, 597-652.

Leblois, A., Quirion, P., 2013. Agricultural insurances based on meteorological indices: realizations, methods and research challenges. Meteorological Applications 20, 1-9.

Lybbert, T.J., Barrett, C.B., Desta, S., Coppock, D.L., 2004. Stochastic wealth dynamics and risk management among a poor population. Economic Journal 114, 750-777.

Magliocca, N.R., Brown, D.G., Ellis, E.C., 2013. Exploring agricultural livelihood transitions with an agent-based virtual laboratory: global forces to local decision-making. PLoS One 8, e73241.

Magliocca, N.R., Ellis, E.C., 2016. Evolving human landscapes: a virtual laboratory approach. Journal of Land Use Science 11, 642-671.

Martin, R., Linstädter, A., Frank, K., Müller, B., 2016. Livelihood security in face of drought – Assessing the vulnerability of pastoral households. Environmental Modelling & Software 75, 414-423.

McPeak, J.G., Little, P.D., Doss, C.R., 2012. Risk and social change in an African rural economy: livelihoods in pastoralist communities. Routledge.

Mobarak, A.M., Rosenzweig, M., 2014. Risk, insurance and wages in general equilibrium. NBER Working paper No. 19811, June 2014. National Bureau of Economic Research.

Mobarak, A.M., Rosenzweig, M.R., 2013. Informal Risk Sharing, Index Insurance, and Risk Taking in Developing Countries. American Economic Review 103, 375-380.

Müller, B., Frank, K., Wissel, C., 2007. Relevance of rest periods in non-equilibrium rangeland systems – A modelling analysis. Agricultural Systems 92, 295-317.

Müller, B., Quaas, M.F., Frank, K., Baumgärtner, S., 2011. Pitfalls and Potential of Institutional Change: Rain-Index Insurance and the Sustainability of Rangeland Management. Ecological Economics 70, 2137-2144.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environmental Modelling & Software 48, 37-48.

Müller, B., Schulze, J., Kreuer, D., Linstädter, A., Frank, K., 2015. How to avoid unsustainable side effects of managing climate risk in drylands — The supplementary feeding controversy. Agricultural Systems 139, 153-165.

Müller, B., Johnson, L., Kreuer, D., 2017. Maladaptive outcomes of climate insurance in agriculture. Global Environmental Change 46, 23-33.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Oba, G., Lusigi, W.J., 1987. An overview of drought strategies and land use in African pastoral systems. Working Paper 23a, March 1987. Agricultural Administration Unit, Overseas Development Institute.

Reda, K.T., 2016. Dynamics in pastoral resource management and conflict in the Borana rangelands of southern Ethiopia. African Security Review 25, 31-43.

Schulze, J., Frank, K., Müller, B., 2016. Governmental response to climate risk: Model-based assessment of livestock supplementation in drylands. Land Use Policy 54, 47-57.

Schulze, J., 2011. Risk Measures and Decision Criteria for the Management of Natural Resources Under Uncertainty - Application to an Ecological-Economic Grazing Model. Diploma Thesis. University of Greifswald, Germany.

Seppelt, R., Müller, F., Schröder, B., Volk, M., 2009. Challenges of simulating complex environmental systems at the landscape scale: A controversial dialogue between two cups of espresso. Ecological Modelling 220, 3481-3489.

Solomon, T.B., Snyman, H.A., Smit, G.N., 2007. Cattle-rangeland management practices and perceptions of pastoralists towards rangeland degradation in the Borana zone of southern Ethiopia. Journal of environmental management 82, 481-494.

SwissRe, 2017. Facts on the Kenya Livestock Insurance Program (KLIP). http://media.swissre.com/documents/KLIP_Facts_on_the_program.pdf, last accessed: 24 August 2017.

Toth, R., 2015. Traps and Thresholds in Pastoralist Mobility. American Journal of Agricultural Economics 97, 315-332.

Toth, R., Barrett, C.B., Bernstein, R., Clark, P., Gomes, C., Mohamed, S., Mude, A., Taddesse, B., 2017. Behavioural Substitution of Formal Risk Mitigation: Index Insurance in East Africa. Working paper, November 2017.

Wario, H.S., 2015. An integrated assessment of resource use strategies in the Borana pastoral system of southern Ethiopia. Ph.D. dissertation, University of Kassel, Germany.

Wario, H.S., Roba, H.G., Kaufmann, B., 2016. Responding to mobility constraints: Recent shifts in resource use practices and herding strategies in the Borana pastoral system, southern Ethiopia. Journal of Arid Environments 127, 222-234.

Wichmann, M.C., Johst, K., Moloney, K.A., Wissel, C., Jeltsch, F., 2003. Extinction risk in periodically fluctuating environments. Ecological Modelling 167, 221-231.

Appendix

A. Supplementary figures

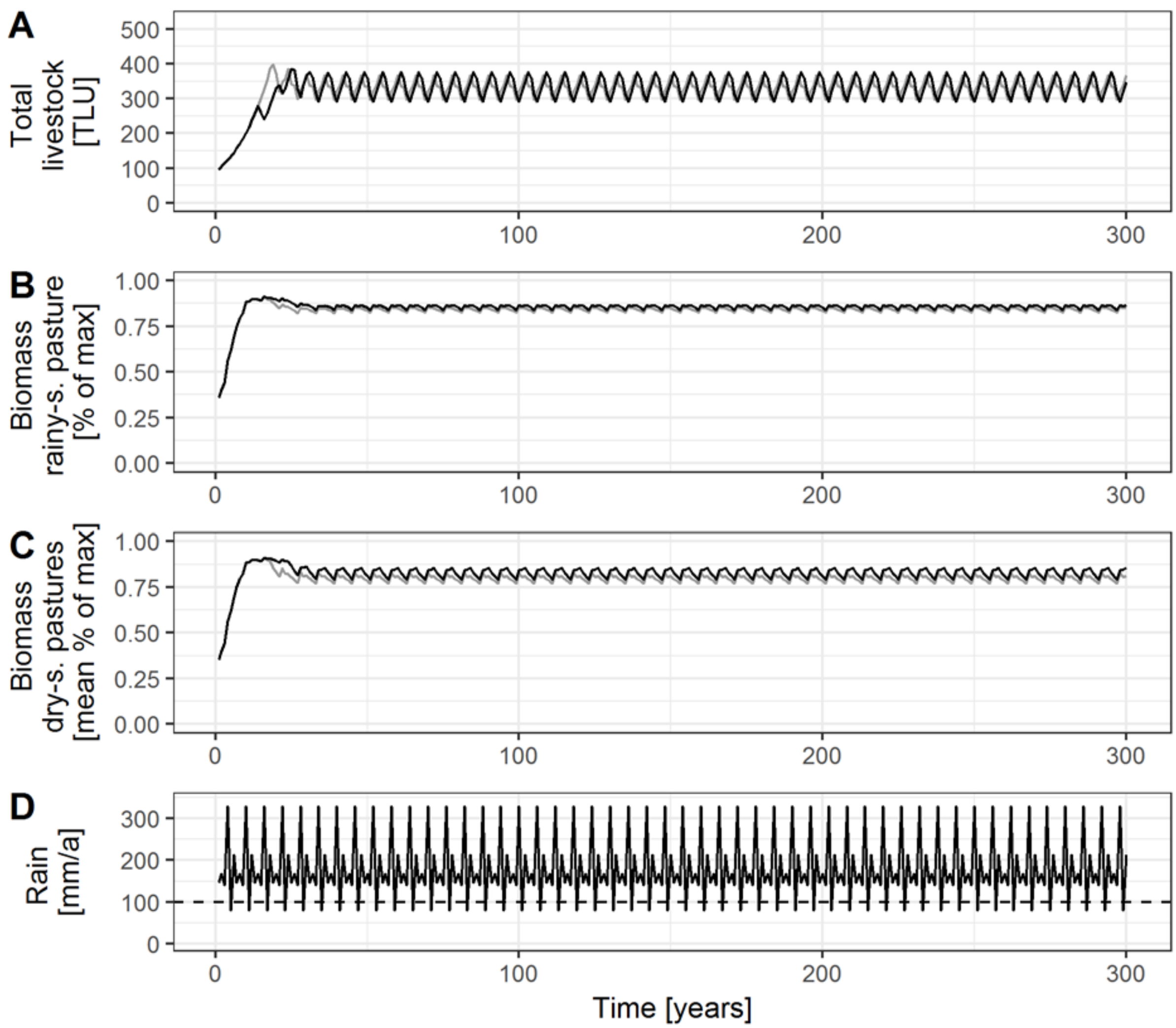

Fig. A1: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with low sensitivity to grazing (0.25) for "alternating rainfall" scenario. Graphs depict the situation without (grey) and with an insurance of up to 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

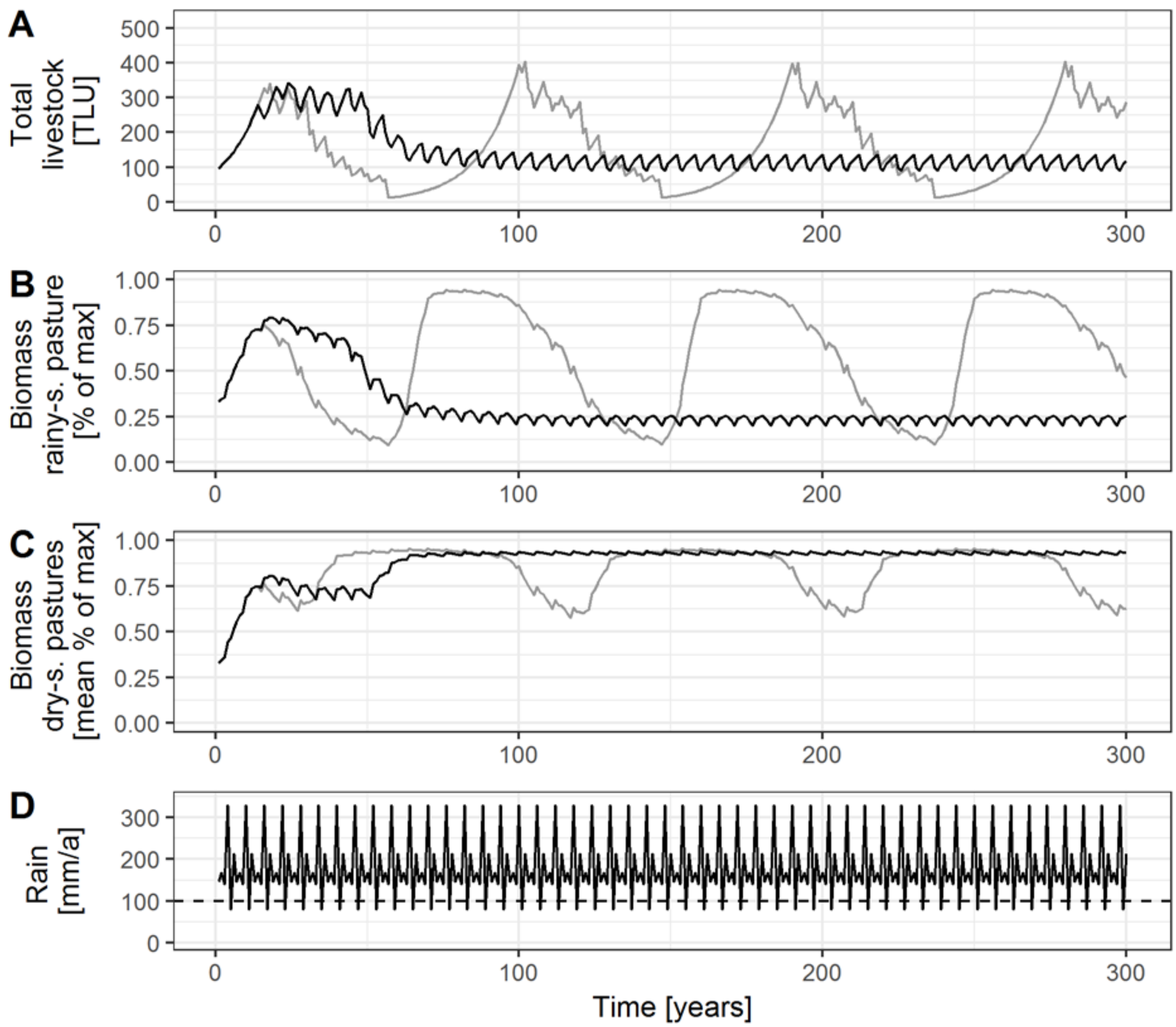

Fig. A2: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with high sensitivity to grazing (0.9) for "alternating rainfall" scenario. Graphs depict the situation without (grey) and with an insurance of up to 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

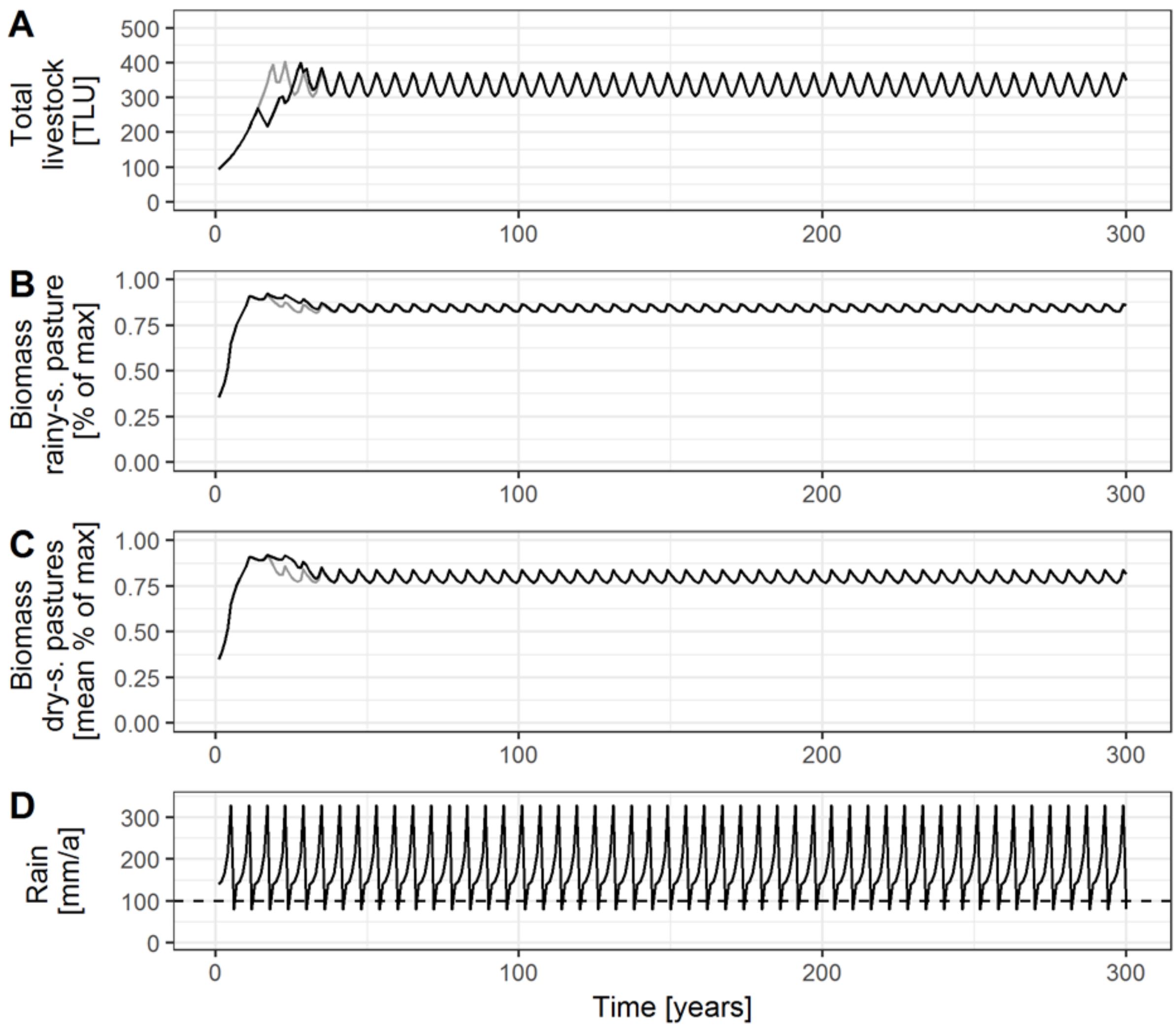

Fig. A3: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with low sensitivity to grazing (0.25) for “ascending rainfall” scenario. Graphs depict the situation without (grey) and with an insurance of up to 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

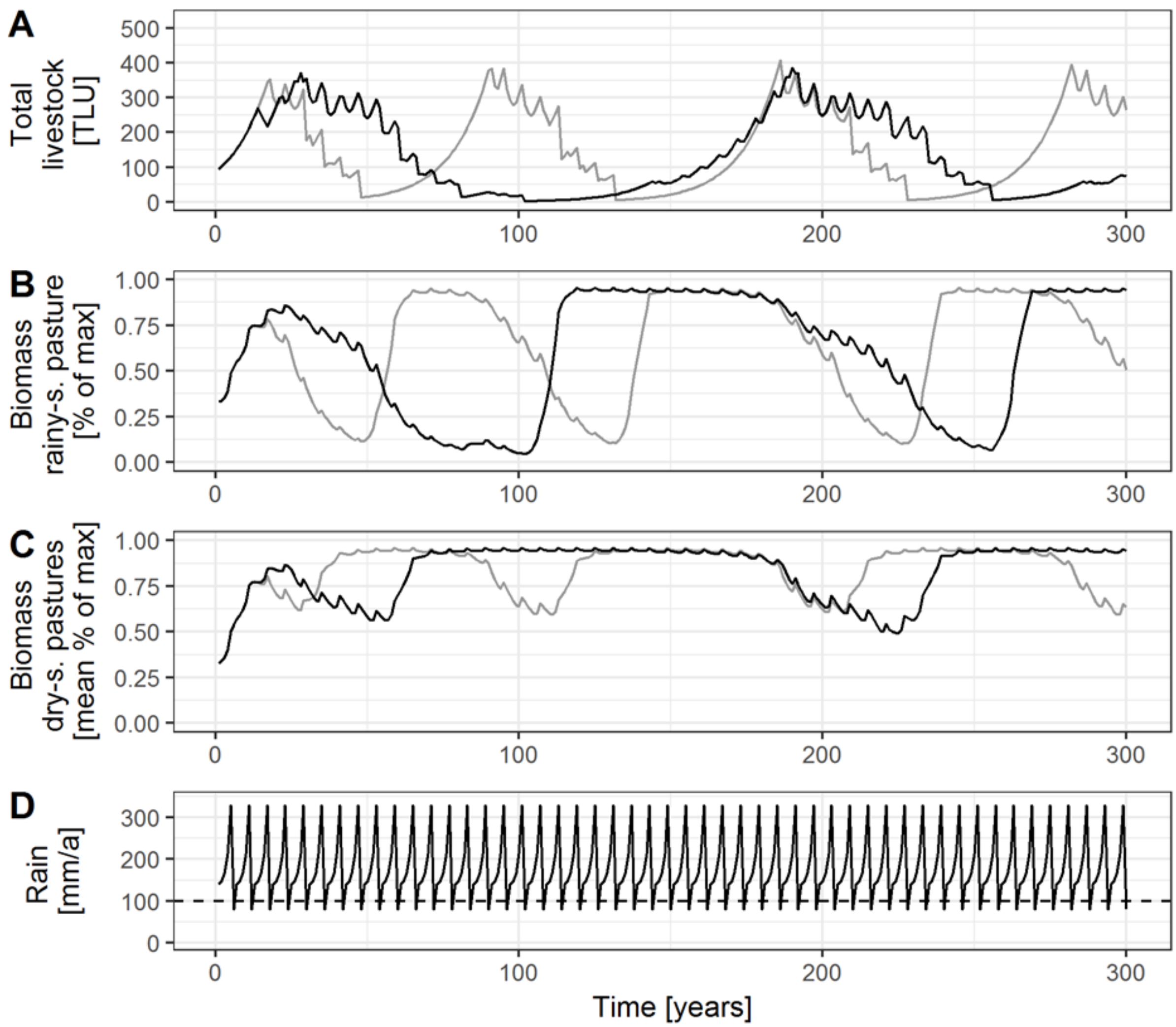

Fig. A4: Development of livestock numbers (A), reserve biomass of rainy-season (B) and dry-season pastures (C) as well as rainfall (D) over time with high sensitivity to grazing (0.9) for "ascending rainfall" scenario. Graphs depict the situation without (grey) and with an insurance of up to 40 TLU (black). Biomass values are normalized to the maximum reserve biomass. The dashed line in panel D represents the drought threshold.

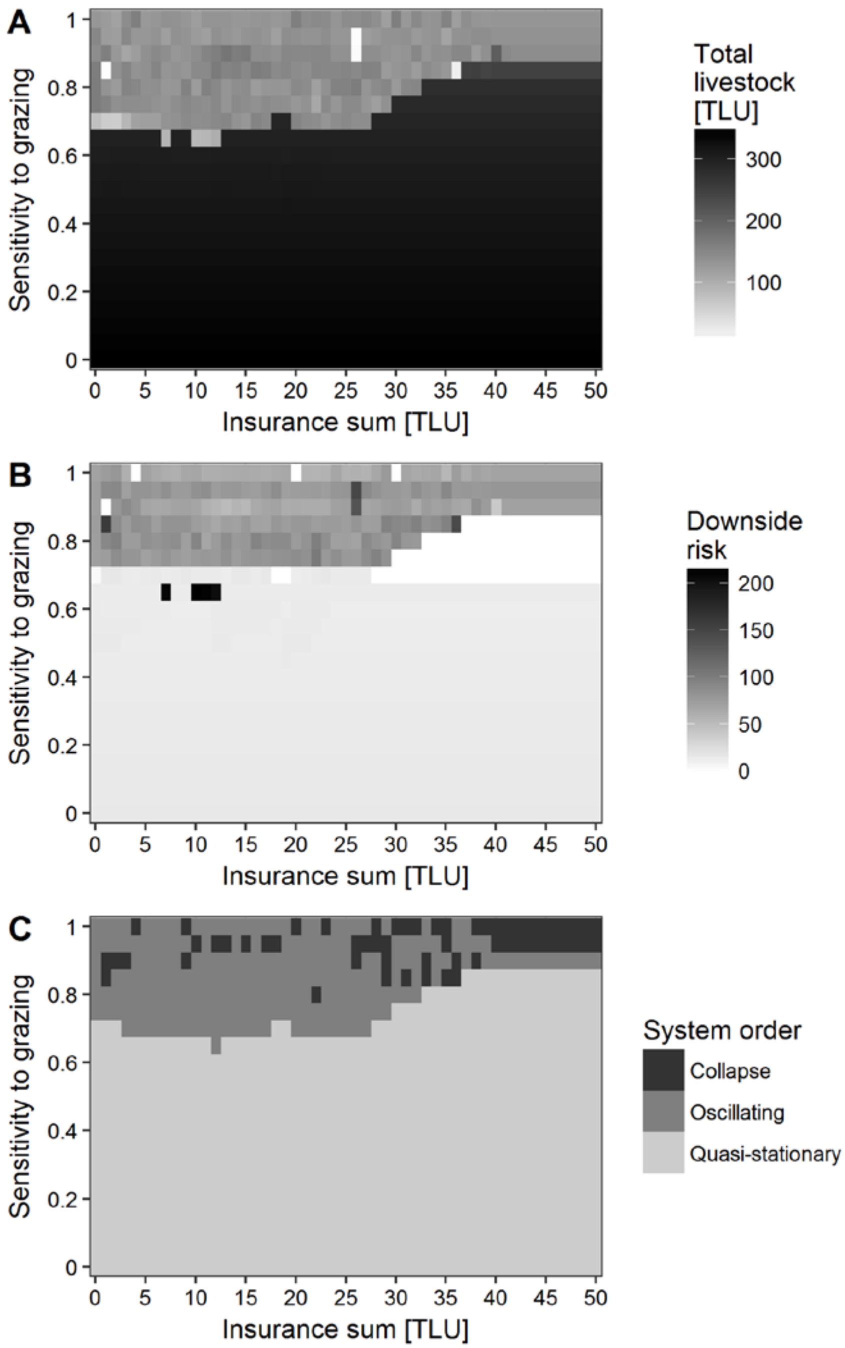

Fig. A5: Long-term mean of total livestock numbers (A), downside risk of falling below the livestock mean of the simulation without insurance (B), and the resulting system order (C) for ascending rainfall dependent on the sensitivity to grazing and insurance sum. Data generated based on a single run.

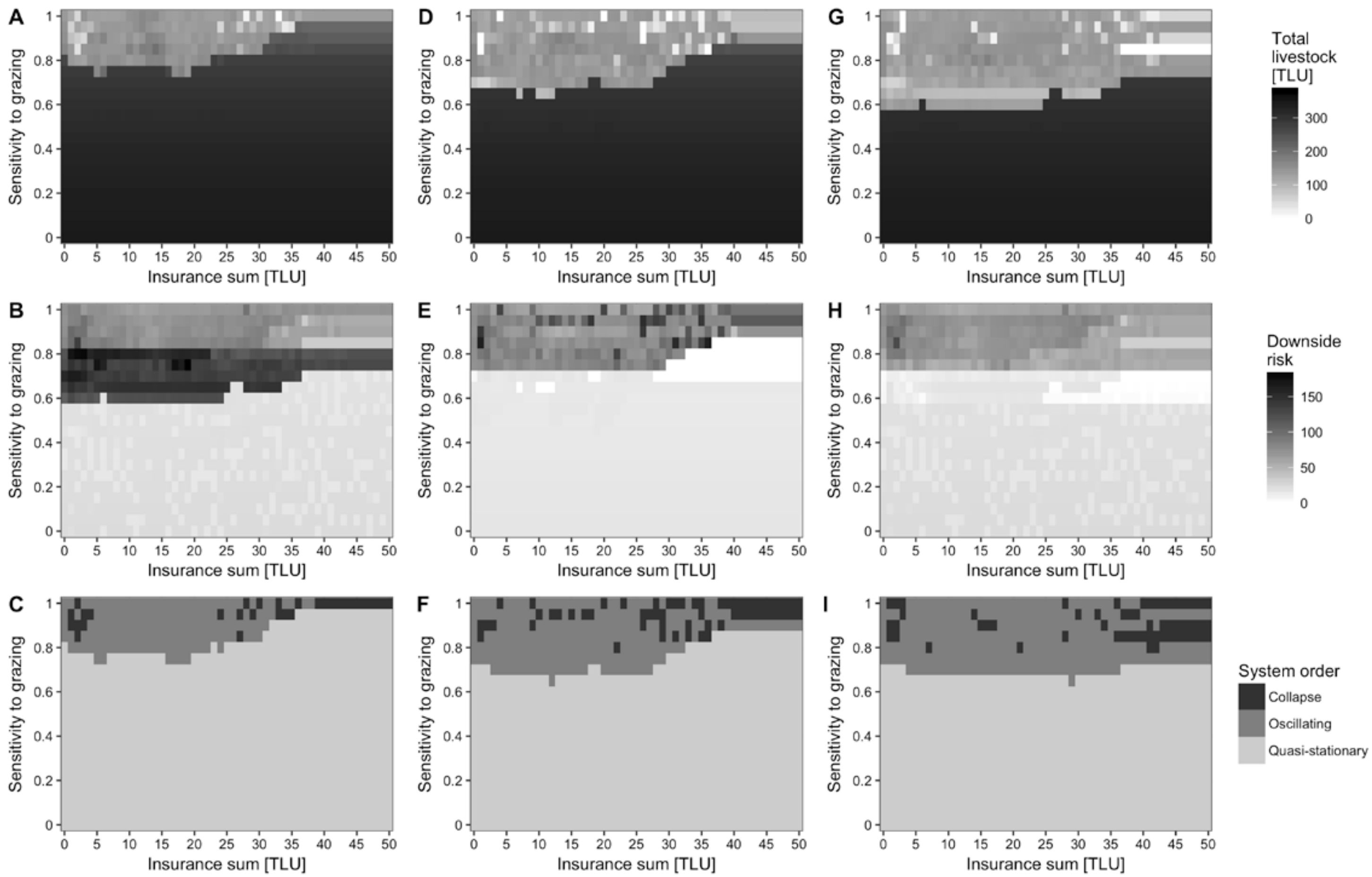

Fig. B1: Sensitivity of results to changes in livestock growth rate for ascending rainfall dependent on the sensitivity to grazing and insurance sum. The left column (panels A, B, C) shows the results for a livestock growth rate 10% below the default value, the middle column (D, E, F) for the default livestock growth rate, and the right column (G, H, I) for a 10% increase in livestock growth rate. The first row (A, D, G) depicts long-term means of total livestock numbers; the second row (B, E, H) the downside risk of falling below the livestock mean of the simulation without insurance; the last row (C, F, I) the resulting system order. Data generated based on a single run.

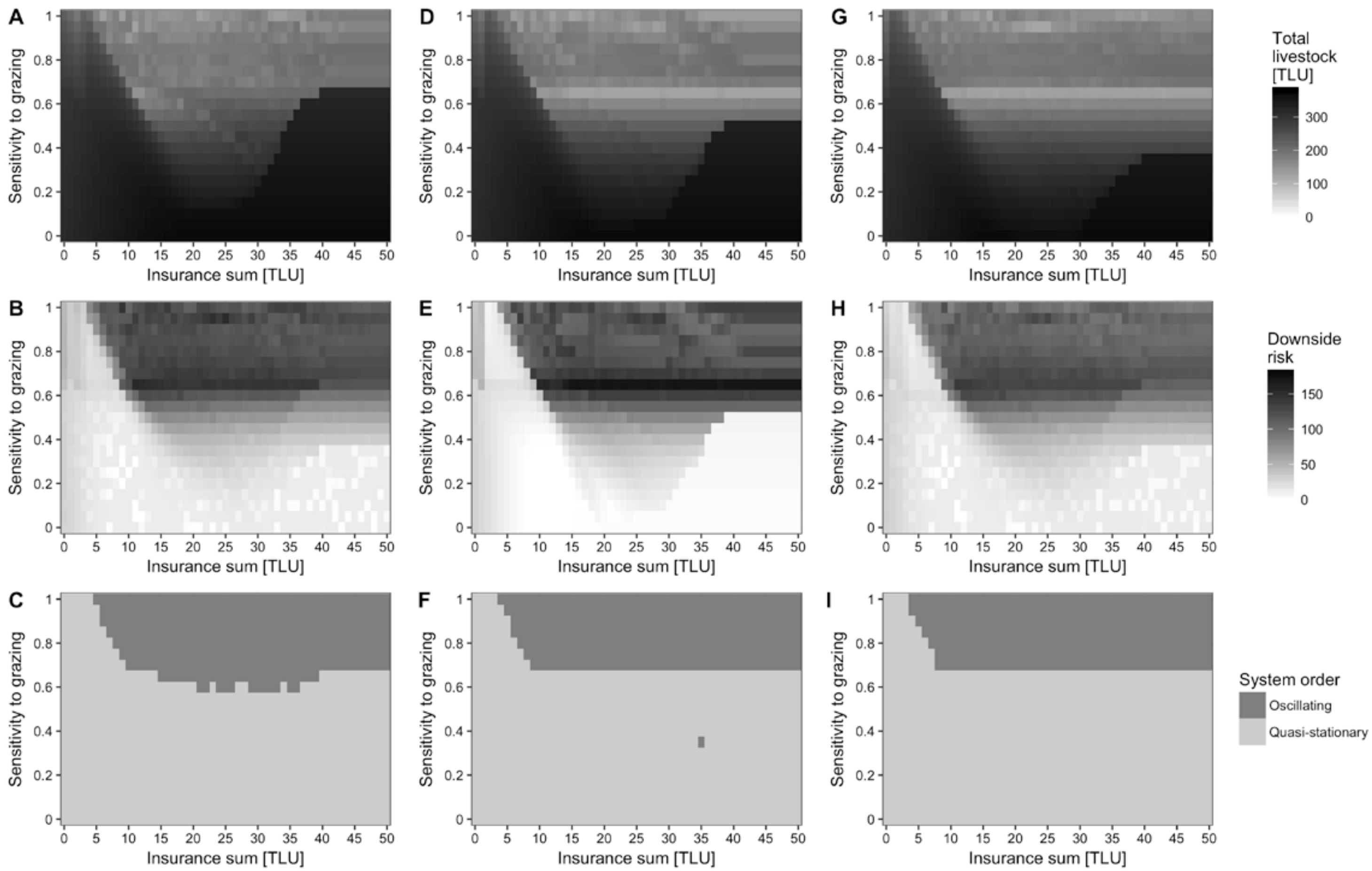

Fig. B2: Sensitivity of results to changes in livestock growth rate for descending rainfall dependent on the sensitivity to grazing and insurance sum. The left column (panels A, B, C) shows the results for a livestock growth rate 10% below the default value, the middle column (D, E, F) for the default livestock growth rate, and the right column (G, H, I) for a 10% increase in livestock growth rate. The first row (A, D, G) depicts long-term means of total livestock numbers; the second row (B, E, H) the downside risk of falling below the livestock mean of the simulation without insurance; the last row (C, F, I) the resulting system order. Data generated based on a single run.

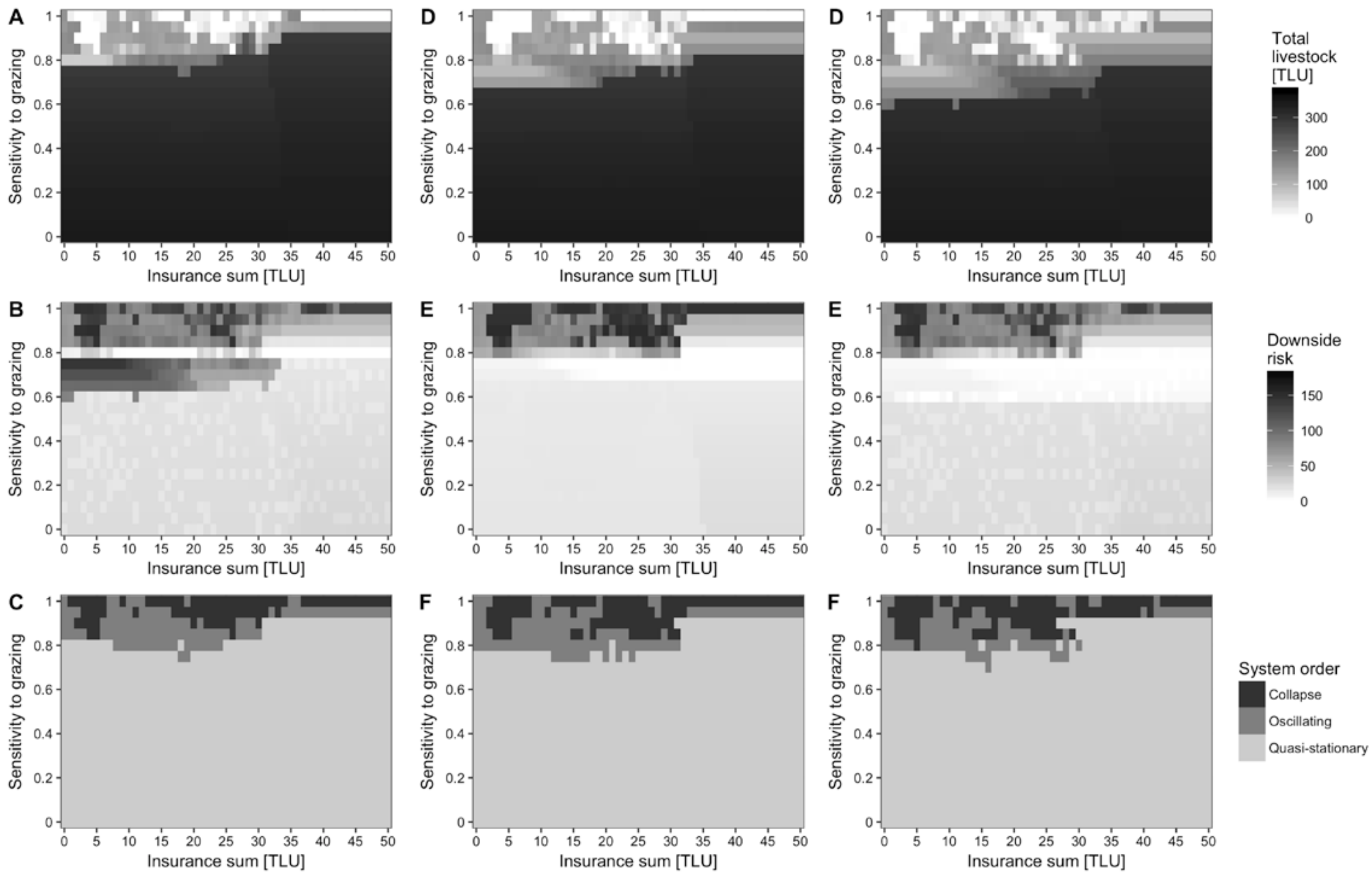

Fig. B3: Sensitivity of results to changes in livestock growth rate for alternating rainfall dependent on the sensitivity to grazing and insurance sum. The left column (panels A, B, C) shows the results for a livestock growth rate 10% below the default value, the middle column (D, E, F) for the default livestock growth rate, and the right column (G, H, I) for a 10% increase in livestock growth rate. The first row (A, D, G) depicts long-term means of total livestock numbers; the second row (B, E, H) the downside risk of falling below the livestock mean of the simulation without insurance; the last row (C, F, I) the resulting system order. Data generated based on a single run.

B. Sensitivity of results to livestock growth rate

In Figures B1 to B3, we show the sensitivity of the output variables analyzed in the paper to a 10% decrease and increase in livestock growth rate (left and right column, resp.). It can be stated that the general trends for the effects of insurance qualitatively hold independent of the livestock growth rate, namely that insurance may have negative long-term effects if sensitivity to grazing is high. However, for certain parameter ranges quantitative differences can be observed, mostly close to the phase transitions. In particular. for low sensitivities to grazing, far off the tipping points, all analyzed variables (i.e., average total livestock, downside risk and system order) are robust to changes in livestock growth rate across all three rainfall scenarios. Additionally, the phase space remains qualitatively relatively consistent, yet tipping points often move towards the bottom-right corner (i.e., systems start to oscillate already for lower sensitivities to grazing and higher insurance sums) the faster herds grow. This pattern can be observed for both system order and average total livestock numbers. We attribute both effects to the "natural resting periods", which become shorter the faster herds reproduce, but only become a relevant factor if grazing has a substantial impact on vegetation dynamics.

The effects on downside risk are a little harder to interpret. For the lower livestock growth rate, we often observe strong increases in downside risk near the phase transition. This effect can be explained by two factors. First, since downside risk essentially measures the risk to fall below a certain average livestock number (in our case, the one of the no-insurance scenario), this risk strongly depends on how high this reference value actually is. And especially in cases of considerable differences for low and high livestock growth rate, the reference values (which are the left-most cell for a given sensitivity to grazing in the top panel) also vary greatly. And if the reference value is already very low, it is harder to fall below it. Second, the livestock growth rate determines how fast herds can recover after a shock. So if herds decrease in size during a drought, and thereby fall below the reference value, they will regrow to that value more quickly with a higher livestock growth rate (assuming pastures provide enough resources). Furthermore, it can be observed that for both the increased and decreased livestock growth rates, downside risk shows an irregular pattern for low sensitivities to grazing in all rainfall scenarios. This pattern, observable through lighter and darker blotches in the middle row of Figures B1-B3 (left and right column), is absent for default values of livestock growth rate (middle column). Our interpretation is that in the default case there is a superposing effect or neutralizing interaction of effects that raises further questions, which we cannot analyze in depth at this point.

C. ODD+D protocol of the Rangeland insurance model

C.1. Overview

C.1.1. Purpose

The model was developed to study the long-term effects of index-based drought insurance on livestock and pasture development and especially potential unintended side-effects. Hence, its main purpose is system understanding.

The model resembles a semi-nomadic pastoral community in a dryland area which is adapted from the pastoralists groups in North Kenya/South Ethiopia. The model is primarily designed for the scientific community, but could ideally be modified to be also valuable to increase understanding of rangeland managers and political decision-makers.

C.1.2. Entities, state variables, and scales

The model is composed of mobile pastoralists with their herds and two different kinds of pastures: (i) wet-season grazing areas and (ii) more remote dry-season grazing areas.

The agents represent pastoralist households of a settlement. Each pastoralist owns one cattle herd of a certain size and decides where to move their herds. Livestock reproduces at a certain reproduction rate and needs a determined annual forage intake. Livestock is modelled as floating-point values. In the insurance scenario, each household disposes over a savings account (expressed in equivalent of cattle) from which all insurance transactions are made and a target for immediate restocking after a drought.

Rangelands are modelled as patches. There is one central patch in the center of the model world where also the pastoralists' settlement is assumed to be located and several more remote dry-season grazing areas. Each remote pasture is assumed to comprise an area of 100 ha (=1 km^2), whereas the central pasture has the size of all remote pastures put together. All patches are characterized by their reserve biomass and green biomass (the temporal biomass dynamics depends on several parameters which are explained in more detail below). Space is included implicitly, as there are different patches but their location and distances are irrelevant.

The model is driven by exogenous precipitation which is based either on a repeated pattern of a six-year rainfall sequence (see main paper for a more detailed description) or drawn from a lognormal distribution.

Time is operating at two nested scales: One time step in the model represents one year. Each year, however, is split up into the four seasons that can be empirically observed in the region (long rain – long dry – short rain – short dry).

C.1.3. Process overview and scheduling

Fig. C1 shows all model updating processes within one year in chronological order. Patch processes are displayed in dark and agent processes in light grey. Agent processes take place sequentially for all agents in random order.

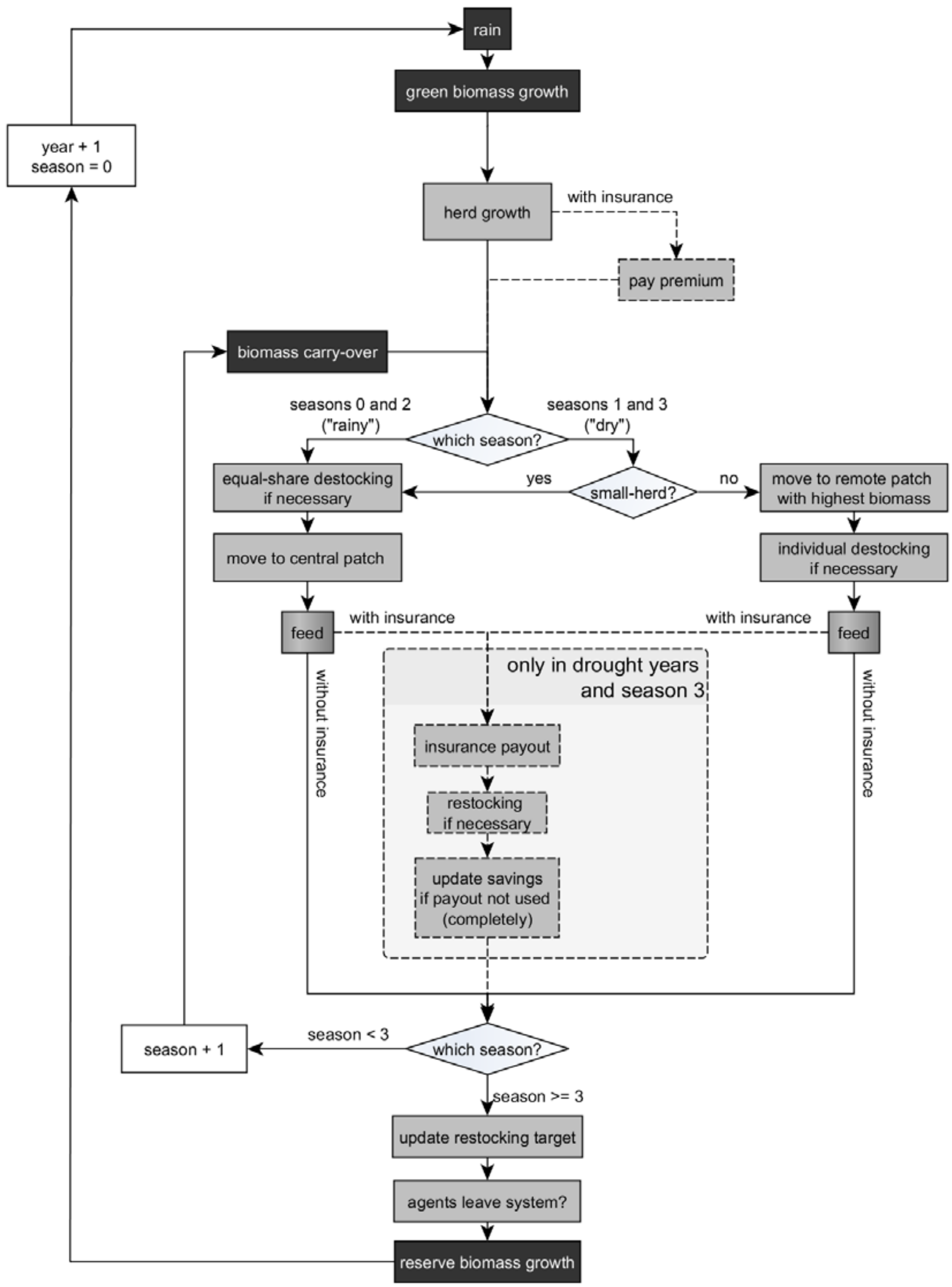

Fig. C1: Overview of model processes per year. Dashed lines refer to processes that are only applicable if agents have insurance. Patch processes are displayed in dark and agent processes in light grey. Agent processes take place sequentially for all agents in random order.

C.2. Design Concepts

C.2.1. Theoretical and Empirical Background

Annual rainfall follows a log-normal distribution. With its right-skewed shape it accounts for a high share of dry and average years, but also more rare very wet years. To better understand the effect of insurance in the face of fluctuating rainfall, we use artificial time series with mean and standard deviation matching the observed annual rainfall characteristics (mean = 180 mm/a, sd = 80 mm/a).

The pastures are assumed to consist of perennial grasses that are composed of reserve or storage biomass and green biomass. Green biomass comprises all photosynthetically active parts of the plant and represents the main fodder for livestock. Reserve biomass summarizes the storage parts of the plants below and above ground. Within each year, rainfall is bimodal so that the amount of newly-growing green biomass is different each season (see, e.g., Coppock, 1994; Desta and Coppock, 2002).

Borana pastoralists usually divide their herds in *warra* (lactating animals and calves that are kept near the settlements throughout the year) and *forra* herds (dry herds composed of other adults that are taken to the remote grazing areas). Here, we only consider *forra* herds, assuming the size of *warra* herds to be more or less constant over time, and thus, also their grazing pressure. Put another way, one could also say that we implicitly assume that *warra* herds graze on different pastures that are not included in the model.

The minimum amount of animals that an agent needs to engage in mobile pastoralism and secure their livelihood is 5 TLU (tropical livestock units), which is in line with empirical findings on poverty traps (Lybbert et al., 2004; Toth, 2015). Pastoralists with smaller herds become sedentary and keep their livestock near the settlements throughout the year, because it is not worthwhile to take them to the remote pastures.

Agents always select the remote patch with the highest available biomass. Furthermore, they know how many animals can be sustained at a given level of biomass and destock accordingly. These decision-making rules seem justified in this context, since pastoralists usually know their rangelands very well and are in frequent exchange on pasture conditions with other pastoralists (either in person or via phone).

The decision-making submodel is based on qualitative observations of pastoralist households.

C.2.2. Individual Decision Making

Each household makes the decision where to move their herds on their own. Since every household owns only one herd and intra-households decisions are not considered, this can be regarded as an individual-level decision-making process. Out of the set of all remote patches, each agent selects the one with the highest available biomass. The order in which households make that decision is randomized. Agents react to insufficient biomass availability by destocking.

If one wishes to put the agents' decision-making process into a larger theoretical context, it could be classified as utility maximizing (with utility defined by the capacity to feed livestock which depends on the available biomass), yet this would be a very simple utility function.

In the insurance scenario, agents additionally decide how much to restock immediately after a drought. This restocking target is modelled as the mean herd size of the last three periods and does not include any further calculation on part of the agent. Beyond that, there is no restocking.

The model is spatially implicit, so distances between patches do not play a role in decision-making. Neither do social or cultural norms. Agents have a memory: they keep track of their herd size over the last three years, but only to calculate the restocking target (see explanation of corresponding submodel below).

There is no uncertainty in the agents' decision making.

C.2.3. Learning

Individual or collective learning is not included in the decision-making process.

C.2.4. Individual Sensing

Agents sense the available biomass on all patches. This way they choose where to go and how many animals can be fed there. There are no costs to information gathering, since also in reality pastoralists are in contact with each other over mobile phones and get accurate information on pasture conditions.

The sensing process is always accurate.

C.2.5. Individual Prediction

There is no prediction of future conditions.

C.2.6. Interaction

All agents interact indirectly through the amount of biomass on each patch. Biomass that has been consumed by one herd is not available any more for another herd. During rainy seasons, all herds graze concurrently on a resource-abundant grazing area (modeled as one large patch). During dry seasons, however, herders decide sequentially on where to take their herds and the biomass required to feed their herd is immediately deducted. So it is possible that multiple herds graze on the same patch also during dry season, but only if that patch still has the most biomass available after the first herd is completely fed.

C.2.7. Collectives

There are no collectives of agents.

C.2.8. Heterogeneity

All agents are homogeneous in their properties and decision-making rules.

C.2.9. Stochasticity

If rainfall does not follow one of the scenarios (see section C.3.3. below and main text for details), it is drawn randomly from a log-normal distribution.

The order in which agents choose patches is random.

C.2.10. Observation

Model output contains herd size and savings account of each agent, green and reserve biomass for each pasture, the number of agents remaining in the system and annual rainfall. These values are collected on a seasonal basis.

A complex consumer-resource interaction between biomass and livestock numbers emerges: Both variables follow a boom-and-bust cycle in which they accumulate over time and then are strongly reduced during droughts. Furthermore, for certain parameterizations, grazing pressure can cause long-term cycles (with a length of 80 years and more) of pasture degradation and recovery.

C.3. Details

C.3.1. Implementation Details

The model has been implemented in NetLogo version 5.2.1, mainly on a machine running Windows 7 (partly also on Mac OS X 10.11) in the time between January 2015 and January 2017. The model code is available on the CoMSES Net (https://www.comses.net/codebases/5948/releases/1.2.0/).

C.3.2. Initialization

During model setup all model parameters are initialized and state variables are set to their initial values (see Table C1 below).

Depending on whether rainfall is random or set to a specific scenario (see C.3.3. below), the probability of an indemnity payout is calculated either by the proportion of drought events in 1,000,000 draws from the rainfall distribution (in the random rainfall scenario) or by taking the proportion of droughts in the input file. The model initialization is always the same. Initial values are chosen arbitrarily, but the system is not very sensitive to initial conditions as it quickly converges to the boom-and-bust cycle.

C.3.3. Input Data

During initialization, if rainfall is not random, the data of the corresponding scenario is loaded from an external file. Rainfall is based on a fix sequence of values that is continuously repeated. For that, a representative six-year sample was drawn from the log-normal distribution (including exactly one drought). The values within that sequence were brought into ascending (rain6yrsAsc.txt) or descending order (rain6yrsDesc.txt) or sorted such that they showed the highest negative autocorrelation (rain6yrsNegAC.txt). The corresponding file will be loaded according to the setting of “Rainfall-scenario”.

C.3.4. Submodels

Below, the submodels will be presented in the order in which they appear in Fig. C1.

Rain

In each year, rainfall is drawn from a lognormal distribution (if rainfall scenario is “random”) or obtained by iterating over the value sequence loaded during initialization.

Rainfall is identical for all patches.

Green biomass

Green biomass comprises all photosynthetically active parts of the plant, and, hence, those that are palatable for the livestock. Its development over time is modelled through a difference equation (based on Martin et al. 2016).

(A.I) $$G_t = \left(1 - m_g\right) * G_{over,\,t-1} + rain_t * RUE \, * R_{t-1} \qquad \text{with} \quad G_t \leq \lambda R_{t-1}$$

Current green biomass G_t depends on two aspects: First, ungrazed green biomass of the previous year (i.e. the portion of green biomass not consumed through grazing, $G_{over,\,t-1}$), reduced by green biomass mortality $m_g \in [0, 1]$, and second, the growth of new shoots. This second aspect is driven by current rainfall $rain_t$ multiplied by the conversion factor RUE and the reserve biomass from the last period, R_{t-1}. Green biomass may, however, not exceed a threshold value

λR_{t-1}, which is the maximum capacity of green biomass that can grow from a certain amount of reserve biomass.

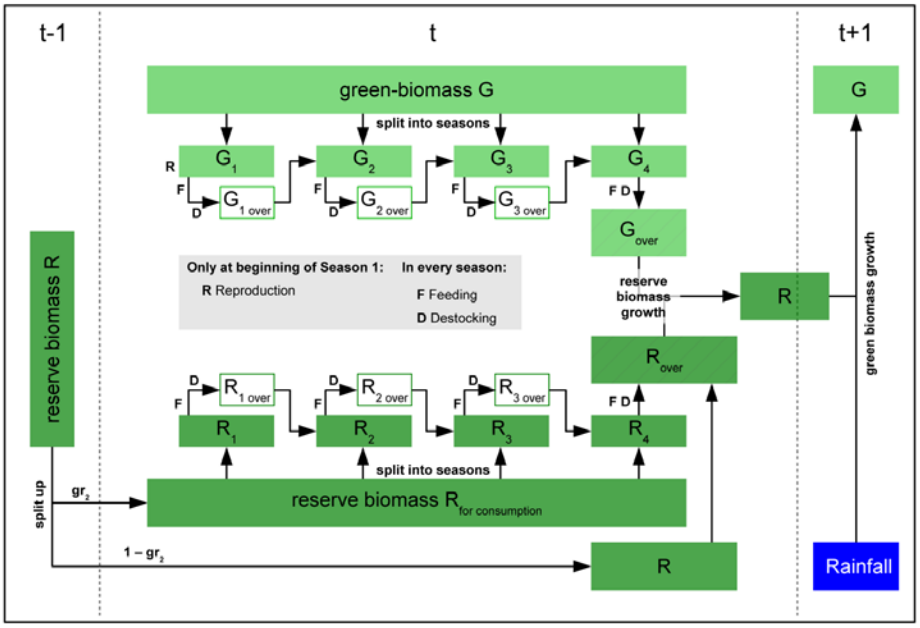

Fig. C2: Distribution of biomass onto the seasons. Indices (1-4) indicate the corresponding seasons of green biomass *G* and reserve biomass *R*.

The yearly amount of green biomass is split up into four seasons as follows, according to the rainfall distribution in each season (Toth, pers. comm., see also Fig. C2):

- G_1: Long rainy season (Apr-Jun): 50%
- G_2: Long dry season (Jul-Sep): 5%
- G_3: Short rainy season (Oct-Dec): 35%
- G_4: Short dry season (Jan-Mar): 10%

Biomass carry-over

Unconsumed green and storage biomass in one season will be directly added to the biomass available in the next season.

Herd growth

We interpret herd growth as the net change in herd size, thus comprising both fertility and mortality/slaughter. Herds evolve following a deterministic exponential growth function with a growth rate that is exogenously set. Thereby, we implicitly assume that fertility rates and off-take are constant over time and linear in herd size, which is a simplification to keep model complexity manageable.

Herd growth can be described by the following function:

(A.II) $livestock_t = (1 + g_{LS})livestock_{t-1}$

Premium payment

In the insurance scenario, agents purchase an actuarially fair insurance once a year. The premium is calculated in livestock units and will be deducted from the agent's savings account. If the account is not sufficiently covered, the agent has to sell a part of their herd accordingly.

Equal-share destocking

If the biomass available on the central patch is not sufficient to feed all animals, all agents destock an equal proportion of their herds.

However, there are some exceptions to this rule: Agents do not destock to less than the mobility threshold and agents with smaller herds are exempted from destocking. Yet if all agents are at or below this threshold and there is still not enough fodder for the remaining animals, all agents destock in equal proportions.

Example: Suppose there are only three herders A, B, and C on the wet-season pasture owning 4, 6, and 10 TLU of livestock, respectively. The pasture, however, only provides fodder for 16 TLU, which would mean that each herd would have to be reduced by 20% (i.e., destock 4 out of

20 TLU). But herder A is below the mobility threshold and is thus exempted from destocking. Therefore, the others would have to destock by 25% (i.e. 4 out of 16 TLU). In doing so, herder B would also fall below the mobility threshold. So, herder B only destocks to that threshold value of 5 TLU and herder C bears the rest. So the final livestock endowments would be 4, 5, and 7 TLU for herders A, B, and C, respectively.

Move to central patch

At the beginning of the rainy season, all pastoralists move to the central patch.

Move to remote patch with highest biomass

At the beginning of each dry season, each agent with a herd above the mobility threshold moves to the remote patch with the highest green biomass and feed. Agent movement is sequential (i.e. agents move and feed their herds immediately) in random order.

Feed

Livestock feeds on the green biomass which is available on the patch they are currently standing on. If green biomass is not enough for all animals, then a fraction of the reserve biomass (determined by gr_2) will also be consumed.

Insurance payout

In drought years, insurance pays out and the payment is transferred to the agent's savings account.

Restocking

If, in a drought year, the herd after destocking is smaller than the restocking target, the agent uses that year's insurance payout to immediately restock to their restocking target. If the payout is not large enough to reach the restocking target, the agent restocks as far as possible.

In the no-insurance scenario, there is no restocking from the market. This is effectively the assumption that household budgets (e.g., living costs, revenues from animal products or animal sales) are independent of insurance, but this is a valid first-order approximation due to very limited financial savings technologies and hence scarce post-drought financial resources in the setting we consider. We only model those changes in resources directly related to insurance (i.e., premiums and indemnity payments).

Herds below the mobility threshold, however, will always (that is also in non-drought years) be restocked to that threshold of 5 TLU, also using money that has previously been stored on the savings account.

Apart from these two conditions restocking is not included in the model.

Update restocking target

The restocking target determines up to which herd size an agent wants to restock immediately after a payout of the insurance. It is used as a means to determine whether the agent actually lost livestock due to the drought. The restocking target is the moving average of an agent's herd size. It is calculated based on the herd size at the end of current year and the two previous years, all with equal weights.

Agents leave system?

If even after restocking an agent still has no animals, s/he will exit the system.

Reserve biomass

Reserve biomass $\boldsymbol{R_t}$ denotes storage parts below and above ground (e.g. roots, stems). Its development over time is modelled through the following difference equation (based on Martin et al. 2016):

$$\text{(A.III)}\quad R_{t+1} = R_t + w\left[gr_1 * \left(G_t - G_{over,\,t}\right) + G_{over,\,t}\right]\left[1 - \frac{R_t}{R_{max}}\right] \; - \; \left[\left(m_r + gr_{2,t}\right)R_t\,\right]$$

Reserve biomass growth is density dependent. It depends on the growth rate w, the green biomass of the previous period (where the consumed biomass, $G_t - G_{over,t}$, contributes only to a lesser extent, regulated by grazing impact factor $gr_1 \in [0,1]$), and the proximity to carrying capacity (R_{max}). In the main text, however, we usually refer to the pastures' "sensitivity to grazing", defined as $1 - gr_1$, because it provides a more intuitive understanding. The sensitivity to grazing measures how strongly pastures are affected by grazing (with a high sensitivity (i.e., low gr_1) indicating a strong negative effect of grazing on pasture regrowth, and vice versa).

Reserve biomass is furthermore reduced by a natural mortality rate m_r as well as animal consumption. If the amount of fodder needed cannot be met by the available green biomass, parts of the reserve biomass are consumed too ($gr_{2,t} \in [0, gr_2]$, gr_2 describing the maximum consumable reserve biomass).

Table C1: Overview of parameters in the model, description and their values or ranges. In cases where the naming differs between source code and ODD+D, variable names from equations are put in brackets.

Parameter	Description	Value / range
number-timesteps	Number of years of a model run	1000 years
initial-number-nomads	Number of households at simulation start	10
initial-number-permanent-patches	Number of permanent remote patches	20
rain-mean	Mean annual rainfall	180 mm/year
rain-std	Standard deviation of rainfall	80 mm/year
rainfall-scenario	Feed in empirical rainfall data or draw rainfall from distribution	"random", "Rain6yrsAsc.txt", "Rain6yrsDesc.txt", "Rain6yrsNegAC.txt"
gr1 (gr_1)	Grazing impact factor – how much does grazed biomass contribute to reserve biomass growth	[0, 1]
gr2 (gr_2)	Direct take-off rate of reserve biomass by grazing – defines the amount of reserve biomass that can be consumed by livestock	0.1
w	Recovery rate of reserve biomass based on green biomass	0.8
rue (RUE)	Specific rain use efficiency how rain translates into green-biomass growth	0.002 1/mm
lambda (λ)	Maximum proportion of green to reserve biomass, capacity for green growth	2
Rmax-value (R_{max})	Maximum reserve biomass per patch	150 000 kg (1500 kg/ha * 100 ha patch size)
green-biomass-mortality (m_g)	Mortality rate of green biomass	0.3
reserve-biomass-mortality (m_r)	Mortality rate of reserve biomass	0.05
livestock-growth-rate (g_{LS})	Reproduction rate of livestock	0.085
Intake	Fodder intake of livestock	4500 kg/year per TLU
mobility-threshold	Minimum amount of livestock to avoid poverty traps and engage in mobile pastoralism	5 TLU

Parameter	Description	Value / range
strike-level	Rainfall value that triggers insurance payout	100 mm
ins-start	Length of transient phase before insurance sets in	15 years
max-ins-sum	Maximum number of animals insured	[0 TLU, 50 TLU]
State variable	**Description**	**Initial value**
Livestock	Herd size of each agent	10 TLU
savings	Money on the savings account of each agent	0 (measured in equivalent of cattle)
reserve-biomass	Amount of reserve biomass on each pasture	50 000 kg
green-biomass	Amount of green biomass on each pasture	0 kg
Memory	Memory of last three periods to calculate the restocking target	Initial herd size of that agent

References

Coppock, D.L., 1994. The Borana plateau of southern Ethiopia: synthesis of pastoral research, development, and change, 1980-91. ILRI Report (aka ILCA and ILRAD).

Desta, S., Coppock, D.L., 2002. Cattle Population Dynamics in the Southern Ethiopian Rangelands, 1980-97. Journal of Range Management 55, 439-451.

Lybbert, T.J., Barrett, C.B., Desta, S., Coppock, D.L., 2004. Stochastic wealth dynamics and risk management among a poor population. Economic Journal 114, 750-777.

Martin, R., Linstädter, A., Frank, K., Müller, B., 2016. Livelihood security in face of drought – Assessing the vulnerability of pastoral households. Environmental Modelling & Software 75, 414-423.

Toth, R., 2015. Traps and Thresholds in Pastoralist Mobility. American Journal of Agricultural Economics 97, 315-332.