Last update: 14 April 2018

B. ODD+D protocol of the Pastoralist LDI model

B.1. Overview

B.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.

B.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).

B.1.3. Process overview and scheduling

Fig. B1 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.

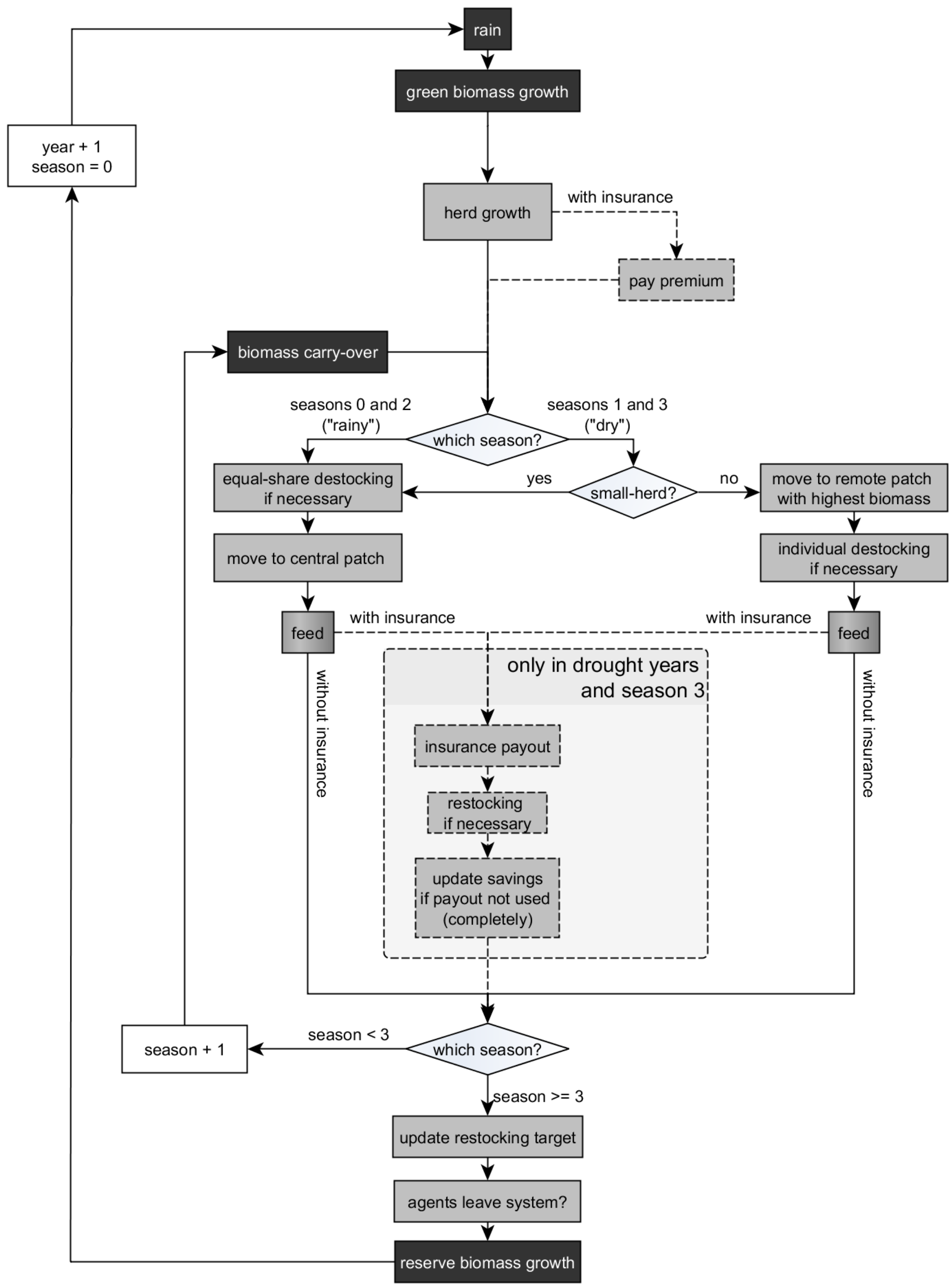

Fig. B1: Overview of model processes per year. Dashed lines refer to processes that are only applicable if agents have insurance. Patch processes are displayed in dark and agent processes in light grey. Agent processes take place sequentially for all agents in random order.

B.2. Design Concepts

B.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.

B.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.

B.2.3. Learning

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

B.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.

B.2.5. Individual Prediction

There is no prediction of future conditions.

B.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.

B.2.7. Collectives

There are no collectives of agents.

B.2.8. Heterogeneity

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

B.2.9. Stochasticity

If rainfall does not follow one of the scenarios (see section B.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.

B.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.

B.3. Details

B.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/).

B.3.2. Initialization

During model setup all model parameters are initialized and state variables are set to their initial values (see Table B1 below).

Depending on whether rainfall is random or set to a specific scenario (see B.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.

B.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”.

B.3.4. Submodels

Below, the submodels will be presented in the order in which they appear in Fig. B1.

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

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.

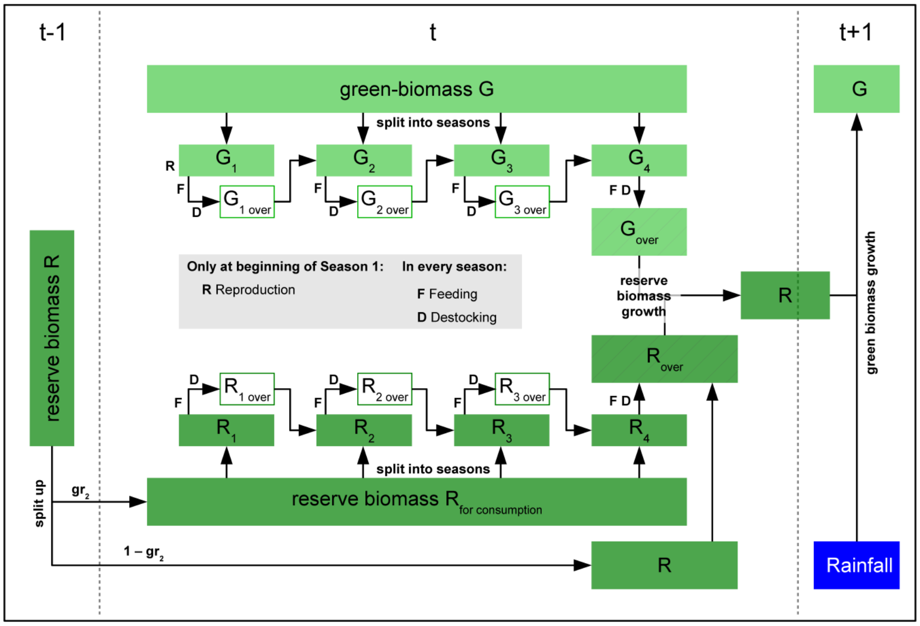

Fig. B2: Distribution of biomass onto the seasons. Indices (1-4) indicate the corresponding seasons of green biomass *G* and reserve biomass *R*.

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. B2):

- 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

Reproduction (defined as the net change in herd size) follows a deterministic exponential growth 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.

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 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):

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

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 B1 shows a complete list of parameters in the model, description and their values or ranges.

Table B1: Overview of parameters in the model, description and their values or ranges

Parameter	**Description**	**Value / range**
number-timesteps	Number of years of a model run	1000
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, the specific growth rate related to the reserve biomass	0.002 mm^{-1}
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
strike-level	Rainfall value that triggers insurance payout	100 mm

Parameter	Description	Value / range
ins-start	Length of transient phase before insurance sets in	15 years
max-ins-sum	Maximum number of animals insured	[0, 50]
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

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