APPENDIX 1
Detailed descriptions of procedures and parameters in SPIRALL

Description of procedures

This section includes a description of the procedures in SPIRALL. They are described in the order in which they are executed during a run. Running SPIRALL involves two steps, each of which is made up of multiple procedures. The first step is the setting up of the model which is done using the button 'Setup' in the user interface. A number of variables that are a part of the setup are user defined and need to be selected before initiating this step. 'Setup' specifies the spatial domain of the model and the attributes of the agents. Once these are defined, the next set of procedures, called by the button 'Go' within the user interface, can be initiated.

SETUP

The procedures that follow are non-looping i.e., they do not repeat each month.

Load Layers

This procedure loads spatial datasets that define the extent and attributes of the world within which agents operate. The following four spatial datasets are read in to represent the heterogeneity in demographic, cultural and livelihood characteristics across Kenya.

- Population density: Raster layer representing population density of the region for the year 2000 (SEDAC, 2016).
- Land cover: A raster dataset representing 10 land cover classes: tree cover areas, shrub cover areas, grasslands, croplands, aquatic vegetation or flooded areas, sparsely vegetated areas,bare areas, built up areas, snow or ice covered areas and open water (ESA, 2017).
- Kenya Livelihood Zones: A vector dataset composed of polygons delineating multiple livelihood zones within Kenya with an attribute table detailing multiple social, economic and livelihood characteristics of interest FEWSNET, 2017.
- Kenya Counties Map: A vector dataset composed of polygons outlining counties in Kenya. County boundaries represent ethnic group boundaries and thereby areas over which pastoralist agents may exhibit cooperative behaviors. For example, conflicts are likely when pastoralists move their herds beyond county boundaries, whereas they may be more likely to share resources and practice gifting with fellow county residents (FEWSNET, 2017).
- Protected areas: A vector dataset composed of polygons showing protected areas (IUCN category I - VI and other protected patches) within the study region based on the World Database on Protected Areas (UNEP-WCMC and IUCN, 2018)

The extent of the raster datasets and the spatial grain are then used to define the spatial domain ('world' in NetLogo parlance) and the size of individual patches within the world (Fig.A1.1).

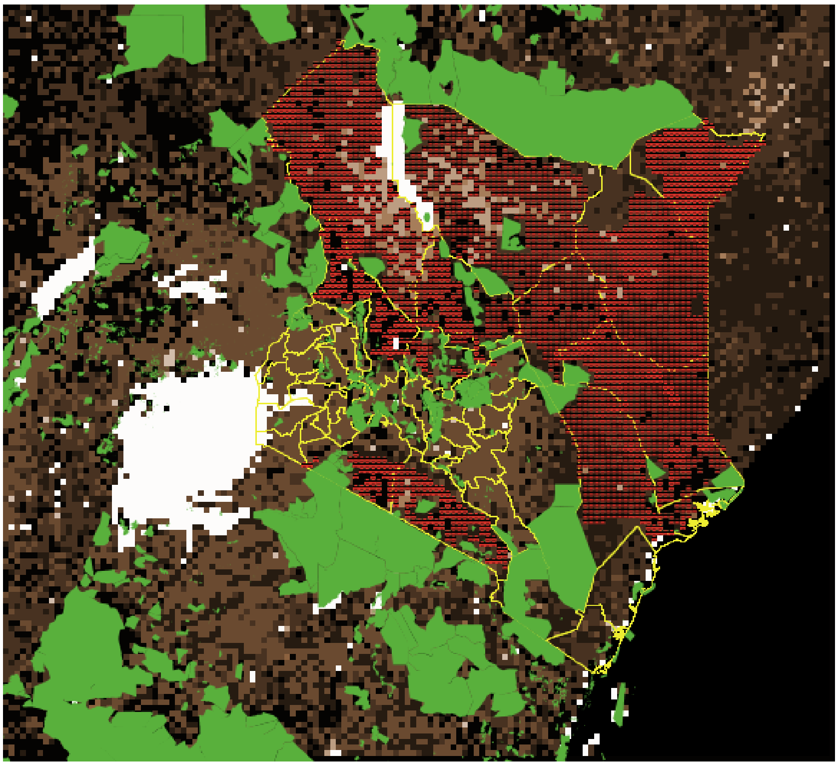

Figure A1.1: SPIRALL- The region of interest as rendered in NetLogo. The region includes a large swath of eastern Africa. Kenya and its counties are outlined in yellow. The patches are 100 km^2 each. Patch colors represent the underlying land cover. Agents (pastoral households) are represented in red. The number of agents on each patch is based on the underlying population density of that patch as well as the mean household size. Green polygons represent protected areas (IUCN category I - VI and other protected patches)

Load Agents

Agents are individual autonomous households. A chooser located on the model interface allows users to pick from among two livelihood options to be represented by the agents. Users may choose to represent "Pastoralists", or"Farmers". The option to represent both livelihoods also exists. Depending on the option selected, agents are distributed on appropriate patches. Spatial distribution of each agent type is guided by the livelihood zone, population density and land cover associated with a patch. A user controlled parameter 'Sample', present in the user interface, can be used to set the fraction of the population to be represented. Pastoralist agents are distributed within livelihood zones where pastoralism is the principal form of livelihood and where the underlying land cover class is either grasslands, shrublands, or croplands. Similarly, if selected, farmer agents are distributed on patches dominated by agricultural land cover and within zones where farming is the dominant livelihood option. Hereon, we only describe procedures relevant to pastoralist agents.

Each household is assigned members across six age-sex classes ensuring that every households has at least one male and female member over the age of 17. The total number of individuals in a household is represented in term of adult equivalents (AE; Appendix 2). Each household is assigned a livestock herd. The composition of the livestock herd is based on the livelihood zone the household is located in. Four types of livestock (cattle, sheep, goat and camel) are assigned, with their numbers varying randomly around a mean value unique to each livelihood zone. For each household, herds belonging to each species are divided into three age-sex classes; weaned males, weaned females, and pre-weaning young. The proportion of individuals within each age-sex class for each livestock species is based on Mwanyumba et al. (2015). Each individual head of livestock is assigned an age as well as an age-specific weight. Age-specific weights are assigned using species-specific Brody curves (Brody and Lardy, 1946) with an added random deviation (Fig. A1.2). Total livestock holdings of each household is summarized in terms of Tropical Livestock Units (TLU), where an adult camel is 1.25 TLU, adult cattle are 1 TLU each, and adult sheep and goats are 0.1 TLU each.

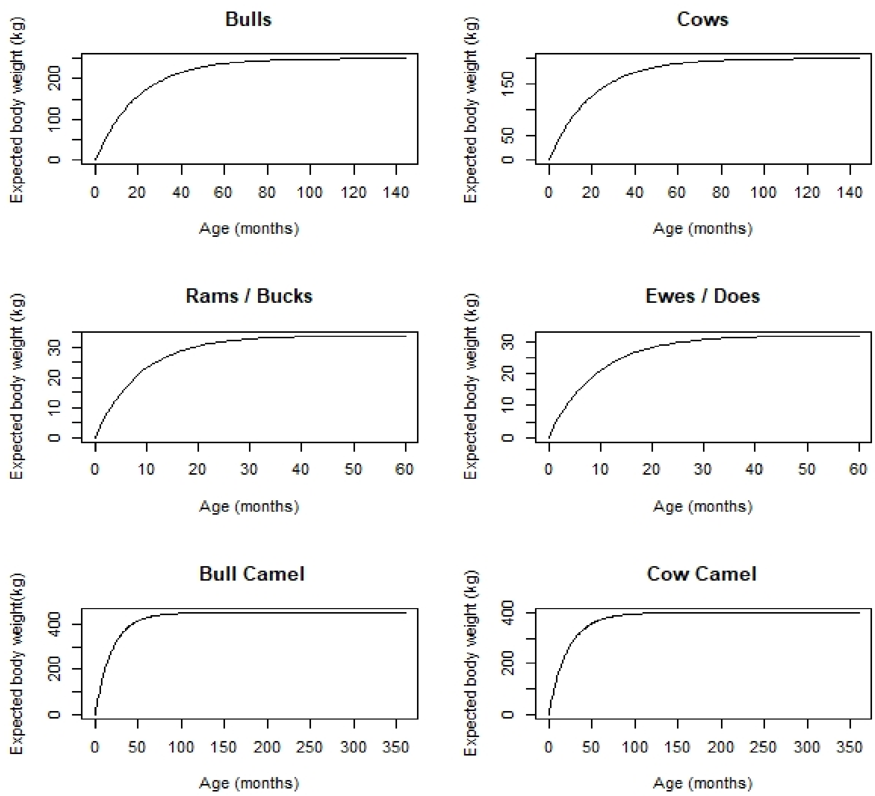

Figure A1.2: Species-specific Brody Curves. When the model is initiated, individual heads of livestock are assigned a weight based on their age. Expected body weights are determined and a random deviation is added to introduce variability. For each species, the upper limit of the x axis also represents the assumed maximum age of survival.

Households are also randomly classified as 'sedentary' or 'non-sedentary', based on the proportions of such households within each livelihood zone FEWSNET, 2017. Sedentary pastoralist agents located on agricultural lands within pastoral livelihood zones are further classified as agropastoralists. All pastoralist households are also initialized with a random sum of cash (Kenyan Shillings) and food in the form of maize stocks. This represents balance income and food reserves from the previous month. Agropastoralist households are randomly assigned a parcel of agricultural land of a random size (range 0.25 - 2 ha). Household income and livestock holdings is set proportional to household size. Households are categorized into three wealth classes based on per-capita livestock holdings as poor (< 3 TLU / AE), middle income (≥ 3 & ≤ 6 TLU /AE) and wealthy (> 6 TLU /AE). Each household is assigned an ethnic identity dependent on the county they are located in. Finally, each household is assigned a social network composed of other households sharing the same ethnic identity. This represents the family of the household with whom social interactions such as gifting can occur.

Load parameters

Model parameters controlling household and patch behaviors are loaded (see Appendix 2 for a complete list of model parameters).

GO

Procedures associated with this step repeat every month.

Load forage

The model links with L-Range, by reading in patch-specific biomass values for each of 8 biomass pools. These pools represent biomass associated with green herbs (gh), dead herbs (dh), green shrubs (gs), dead shrubs (ds), fine branches of shrubs (sb), green trees (gt), dead trees (dt) and fine branches of trees (tb). Once the biomass pools are read in, for each patch, maximum stocking densities for cattle and camel are calculated as follows.

$$\text{Cattle Stocking Density} = \frac{(\text{gh} + \text{dh}) \times (1 - \text{unavailable})}{225}$$

$$\text{Camel Stocking Density} = \frac{(\text{gs} + \text{ds} + \text{gt} + \text{dt}) \times (1 - \text{unavailable})}{360}$$

In the above equations, cattle stocking density is the total number of cattle that can be stocked on a 1 km^2 patch given the total herbaceous biomass on the patch ($gh + dh$) and that an adult bull weighing 250 kg consumes this biomass at a daily rate of 3% of its body weight. Similarly, for camel, stocking density is calculated using the non-herbaceous biomass ($gs + ds + gt + dt$) and assuming that a camel weighing 400 kg will consume this biomass at a daily rate of 3% of its own body weight. For each patch, only a fraction ($1 - unavailable$) of the total biomass simulated by L-Range is considered as available for grazing. We set this fraction at 3% i.e., 97 % of the simulated biomass within each pool is considered unavailable for off take by herbivores each month.

Find pasture

Once stocking densities for cattle and camel are determined for each patch, households sequentially assess whether the patch they are currently located on can accommodate their cattle and *n* or camel herds. If not, pastoralists move their herds or entire households to other patches. This movement is governed by a step-wise decision making process that takes into account household characteristics (e.g., sedentary *n* non-sedentary) as well as social considerations such as ethnic group boundaries (Fig. A1.3 and A1.4). Patch-specific stocking densities are not absolute. Households that are not able to find suitable patches that can accommodate their herds, may chose to remain on a patch (or move to a patch) where cattle or camel numbers are at the estimated stocking density. This decision making process assumes perfect knowledge of potential and actual stocking densities for each patch within the movement radius, as in an Idea Free Distribution (IDF) scenario. This assumption is tenable because pastoralists are known to make use of communication networks that allow them to learn about the condition of far away pastures. A recent study has also shown that pastoralist use of grazing commons resembles an IDF (Moritz et al., 2015).

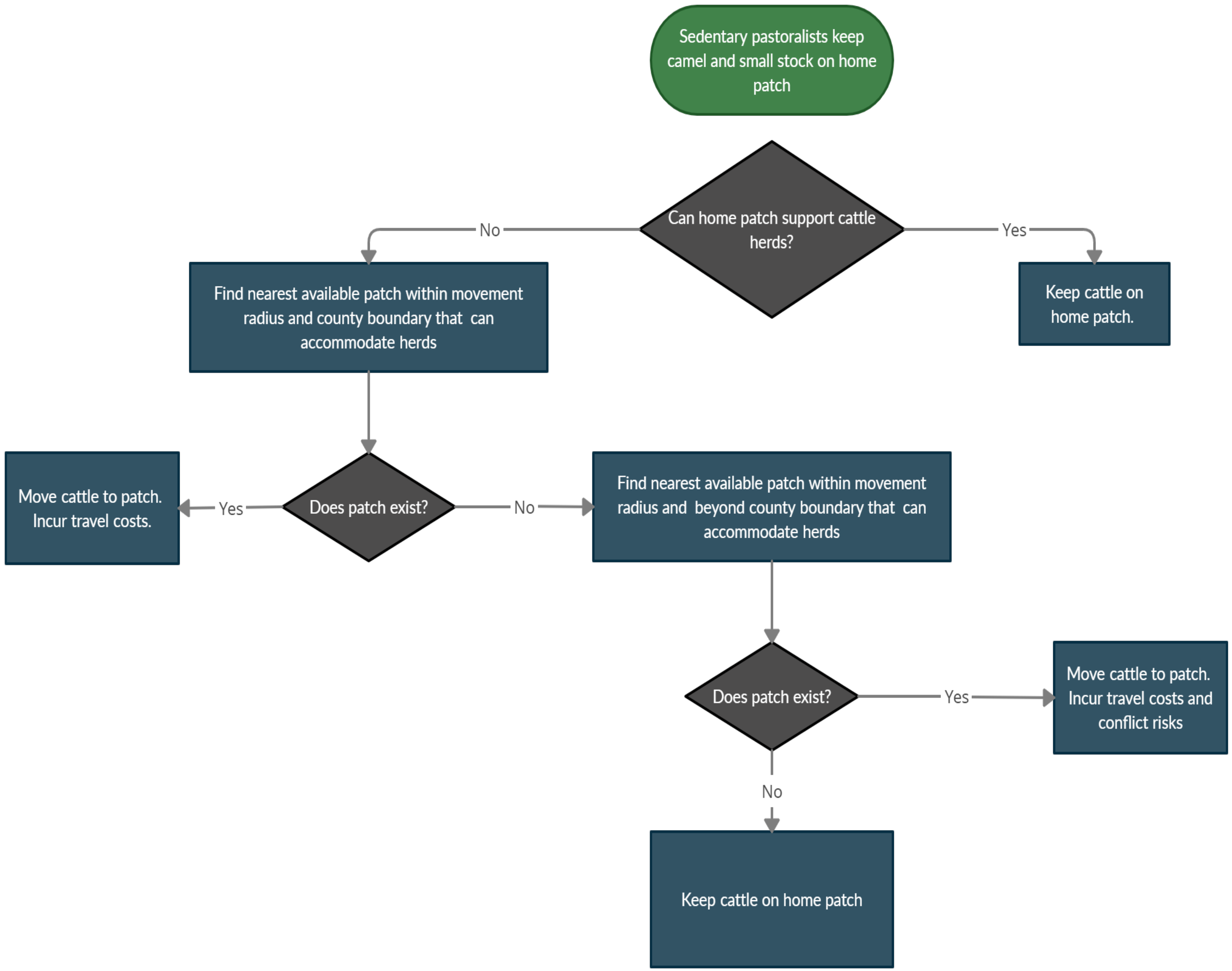

Figure A1.3: Herd splitting by sedentary pastoralists and agropastoralists. Unlike non-sedentary pastoralists, cattle herds of sedentary pastoralists do not return to the home-patch during the long rains unless the patch is found to be suitable

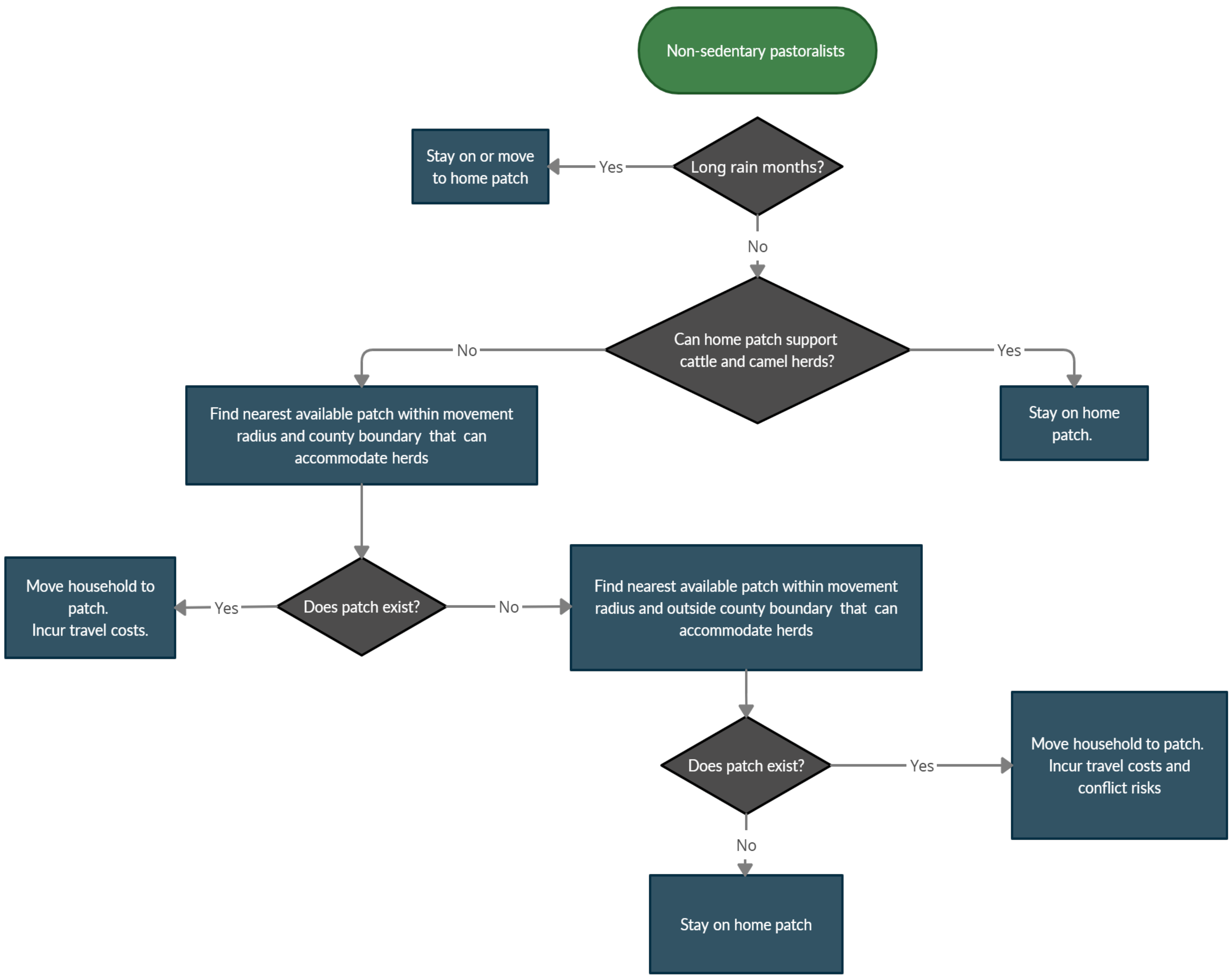

Figure A1.4: Movement decisions by non-sedentary pastoralist households. During the long rain months, non-sedentary households return to their home-patches.Protected areas within the movement orbits can be accessed at any point in baseline simulations

Deplete Patch

Once livestock and households redistribute themselves, this procedure determines forage consumption by individual heads of livestock. For each patch, the total available herbaceous and browse forage is tallied. Of the total biomass estimated for the patch by L-Range each month, a fraction that equals the fraction of the pastoral population being represented (user-controlled parameter 'Sample') is considered as available. Each month,a fraction ('Unavailable'- a user defined parameter) of this biomass is conserved and considered not available for grazing. The total biomass across the eight pools that is available on a patch is then divided among the four livestock species on the basis of their preference for each pool (Appendix 2) and their relative abundance within the patch (TLU). This is then used to calculate per-capita availability of biomass for each species. Following the calculation of availability, the maximum quantity of forage that individual heads of livestock can consume is calculated as 2% of their body weight. Each month, animals lose or gain weight depending on the amount of forage consumed and the weight loss resulting from body maintenance requirements and travel.

$$\text{Wt loss from maintenance} = \frac{\text{BMR} \quad \text{body wt}^{0.75} \quad 30 \quad 239}{5600}$$

The parameter BMR is specific to each livestock species (Appendix 2). Energy lost estimated in Megajoules (MJ) is converted to kilo calories by multiplying by 239 and a loss of 5600 calories results in 1 kg of weight loss.

The following equations are used to determine the total distance traveled by individual heads of livestock and the resulting weight loss.

$$\text{Total distance traveled} = \text{Travel to current patch} + \text{Travel within patch}$$

$$\text{Wt loss from travel} = \frac{\text{Total distance traveled} \quad 12 \quad \text{body wt} \quad 0{:}01}{5600}$$

For each species, the total distance traveled within a patch in a month is a function of the frequency with which the species need to be watered, and a randomly defined distance to a water source within the patch. We assume that cattle are watered every two days, sheep and goat every three days and camel every 5 days McCabe, 2011. Each month the weight gained by each head of livestock is tallied using the following equation.

$$\text{Wt gained from forage} = \frac{\text{Forage consumed} \quad \text{Energy content of forage} \quad 239}{5600}$$

The energy content of each kilogram of forage is assumed to be different for each livestock species (Appendix 2). The change in weight at the end of the month for each head of livestock is given by the difference between weight lost during the month and weight gained from forage consumption. At the end of this procedure the fraction of each biomass pool depleted by foraging by livestock is tallied. Once all procedures are done running, a single file containing information on the fraction of each biomass pool on each patch that is lost to livestock is written out for use by L-Range.

Grow Herds

The simulated weights of individual heads of livestock is compared against an idealized species and age-specific weight determined using Brody curves (Fig. A1.2). A body condition score for each animal is estimated as the ratio between the simulated weight and the idealized weight. For each species, an asymptotic function relates body condition scores to monthly survival probability (Fig. A1.5). Household herds are thinned by removing individuals that do not survive. The ages of individuals that survive the month is incremented. Finally, individuals of each species in the pre-weaning cohort that have survived the month and reached weaning age are transitioned to the post-weaning cohort.

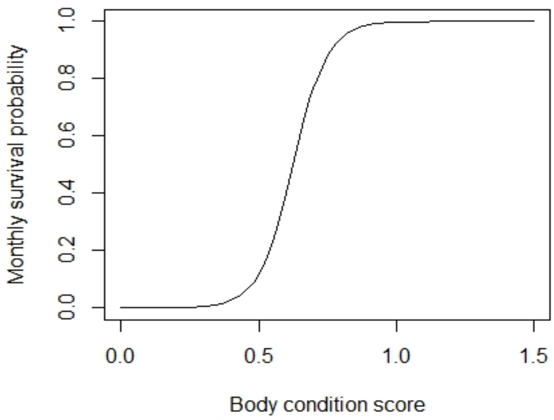

Figure A1.5: Relationship between body condition and monthly survival probability.The maximum monthly survival probability is set at 0.99, to reflect an annual background survival probability of 0.88

Reproduction

For each household, the total number of dead animals are tallied.If the month is a reproduction month, a fraction of the surviving females of each species with a body condition score greater than 0.8 reproduce. The fraction of reproducing individuals is based on the inter-birth intervals for each species (Appendix 2). If the month is a lactation month, then females that reproduced, produce milk proportional to their body condition score (Appendix 2). For each household, a variable tracks the total monthly milk production from lactating individuals of all species in the herd. If it is a harvest month, agropastoral households harvest maize, proportional to the green herb (gh) biomass on the patch

Count calories

For each household, the total calorie requirements for the month is tallied based on the total number of individuals in the house and age-sex-specific calorie requirements. Additional calories from opportunistic slaughter of livestock as well as calories from livestock that died naturally are also added together to tally total calories available from meat. Calorie requirements are met by sequentially extracting calories first from available milk, then meat, and finally maize. Where calorie requirements are not met by existing calorie reserves, households with cash in hand, may purchase additional calories from the store. Households that fail to meet 90% of their calorie requirements are classified as ”deficient”, while others are classified as ”sufficient”.

Cash flow

For each household, the total anticipated expenses over a three month period (inclusive of the current month) is tallied. Similarly, the total anticipated income over a three month period from diverse income sources is tallied. The ready cash with the household is updated based on the months income. Where the total anticipated expenses is greater than total income, households may chose to sell livestock if any are available. Those households that do not have livestock and have expenses that cannot be met are classified as ”assetless”. What animal is sold is dependent on the cash needed to meet anticipated expenses. When this need is below a threshold (Appendix 2) a small animal is sold (sheep or goat), or else a large animal such as camel or cattle or an appropriate number of small animals are sold. Following sale of animals, income earned is used to meet household expenses for the month. Each month households prioritize expenses towards buying food. Households that do not have adequate livestock to sell to meet the months' expenses, forgo these expenses and are designated as ”in debt”. The ”in debt” status is not carried over into the next month.

Similarly, when income exceeds expenses by a threshold , animals are purchased by households. Purchase decisions are governed by cash available in hand and the current composition of the herd. When cash in hand is below a threshold (Appendix 2), small animals are purchased, or else large animals are purchased.

Gifting

Households that have met their calorie requirements and have surplus milk may chose to sell it in a market, if markets are close. If markets are not available, households may gift milk to other households on the patch that are classified as ”deficient”. Similarly, households with at least 10 heads of cattle and goats (or sheep) may chose to gift livestock to a household within their social network that have lost all their animals (assetless). The total number of animals of each species with each household is updated to reflect changes resulting from the trading and gifting of livestock. The numbers and types of animals gifted each month is tracked.

Wrap up

Summaries specific to the current iteration are stored in variables, long term summaries are updated. When the final iteration is completed, summaries are exported to files.

Reset households

At the end of each iteration, households that are classified as 'assetless' are assigned a small number of livestock. This includes up to two cattle, sheep and goats.

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