Supplementary Materials

Gerrit Günther[1], Thomas Clemen[2], Rainer Duttmann[1], Brigitta Schütt[3], Daniel Knitter[1]

[1] Department of Geography, Physical Geography, Christian-Albrechts-Universität zu Kiel, Ludewig-Meyn-Str. 8, 24098 Kiel, Germany
[2] Department of Computer Science, Hamburg University of Applied Sciences, Berliner Tor 7, 20099 Hamburg, Germany
[3] Physical Geography, Department of Earth Sciences, Institute of Geographical Sciences, Freie Universität Berlin, 12249 Berlin, Germany

This document provides a the supplementary materials of the study by **Guenther2021**. If you have any questions, please feel free to contact me (Gerrit Günther) via email (guenther@geographie.uni-kiel.de).

1 NDVI Calculation

It is common to use the Normalized Difference Vegetation Index (NDVI) to estimate pasture resources or preferred herding areas using remote sensing imagery [**Frachetti2006**, **Honeychurch2007**, **hammerLocalLandscapeOrganization2014**].

Furthermore, **moritzIdealFreeDistributions2014** used the NDVI as an indicator of the quality and quantity of forage and **anyambaAnalysisSahelianVegetation** find this index very useful as a relative measure of green biomass in the same area at the same time.

We derived the NDVI from Landsat 8 imagery (obtained from the USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) on demand interface). Since the majority of the annual precipitation in the research area falls in winter and early spring (December–April) during which uncultivated vegetation is most likely to have been healthy, only images from within this time span and with less than 10 % cloud cover were used [**hammerLocalLandscapeOrganization2014**]. The NDVI was calculated via (see also e.g. [**Huete1999**]):

$$NDVI = \frac{NIR - red}{NIR + red}. \quad (1)$$

However, indexes like the NDVI have limitations like saturating asymptotically at high biomass values [**huete2002overview**, **diaz2016long**]. These flaws can be reduced by using seasonal NDVI time-series, which therefore enable a more accurate above-ground biomass estimation and less saturation than using a single NDVI [**zhuImprovingForestAboveground2015**]. Subsequently, the mean of the six selected years (2013–2019) was calculated, ranging between -1 (non-vegetated areas) to $+1$ (vegetated areas) (Figure **??**).

We employed R Programming Language [**RLanguage**] and the package raster [**RPackageRaster**] for the calculations.

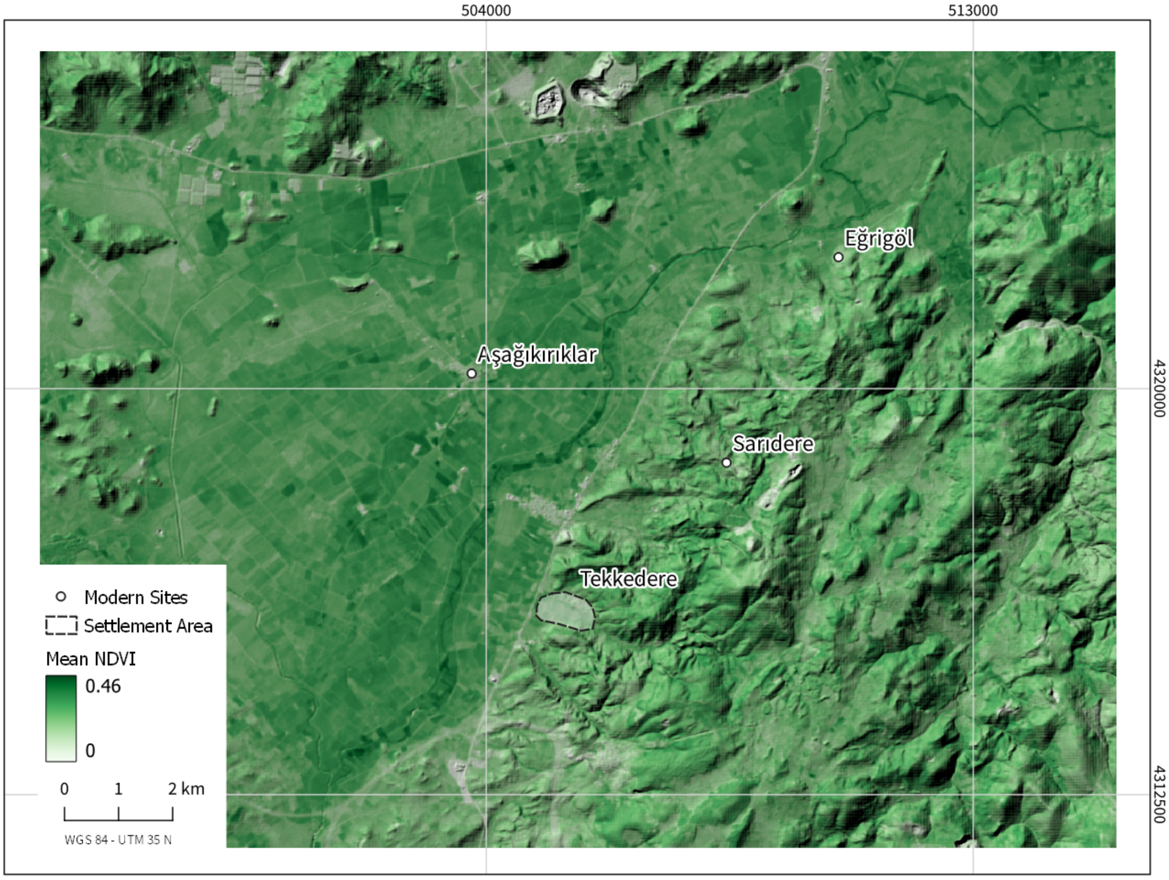

Figure 1: Calculated mean NDVI of the study area. Database: TanDEM-X digital elevation model [**rizzoli2017generation**, **wessel2018accuracy**].

2 Increased Number of Animals

To further investigate the dynamics of the agent-based model and to examine the effects of over-exploitation, we performed additional model runs. These model runs use the same number of initial population and settlement agents, as well as the same dietary composition as the *Average Requirements* scenario. However, these model runs are initialised with 6 herder agents and 600 goat and sheep agents.

2.1 Population Dynamics

Over the course of the simulation, the population agents age, reproduce and die. The results follow the same cyclical pattern of increasing and decreasing population numbers as in other scenarios (Figure **??**).

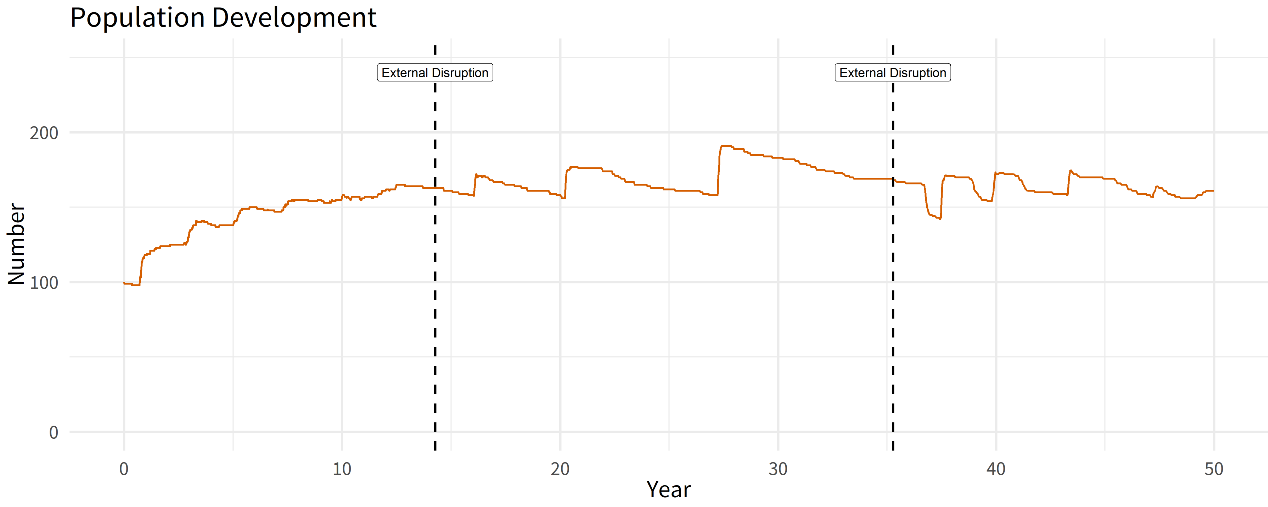

Figure 2: Simulated population dynamics of the additional model runs.

2.2 Coverage of the Calorie Requirements

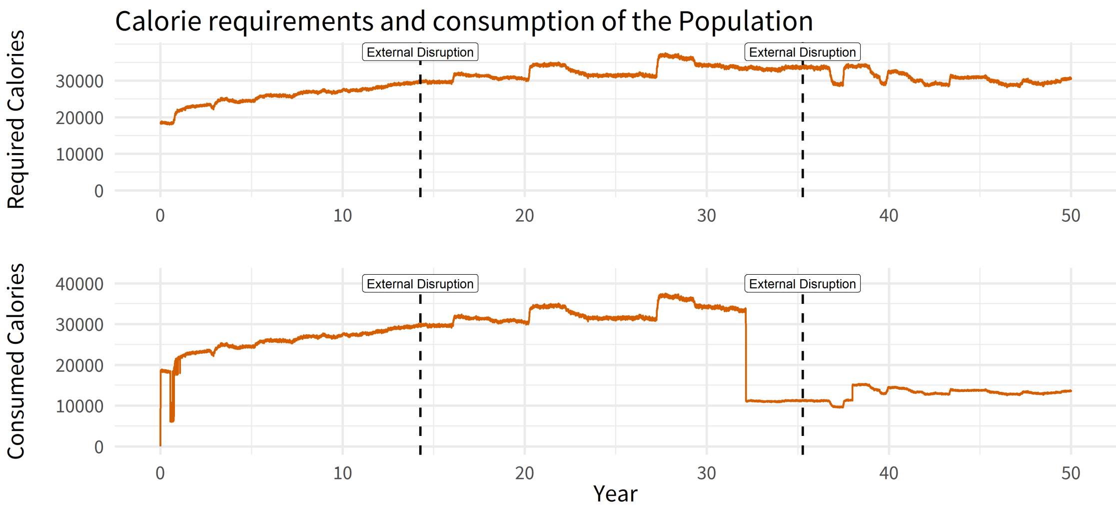

Figure 3: Calorie requirements (top) and consumption (bottom) during the additional model runs.

Comparing coverage to the calorie requirements, the results show that the population agents were able to cover their requirements of the produced goods until the c. 32nd year of the simulation. The calorie consumption strongly drops at this point and then stabilises for the rest of the simulation.

2.3 Coverage of the Calorie Requirements with Goat and Sheep Products

The results show that the mean consumption of goat products fluctuates over the course of the simulation (Figure **??**). The consumption of goat meat fluctuates heavily and decreases to 0 as a result of the first external disruption

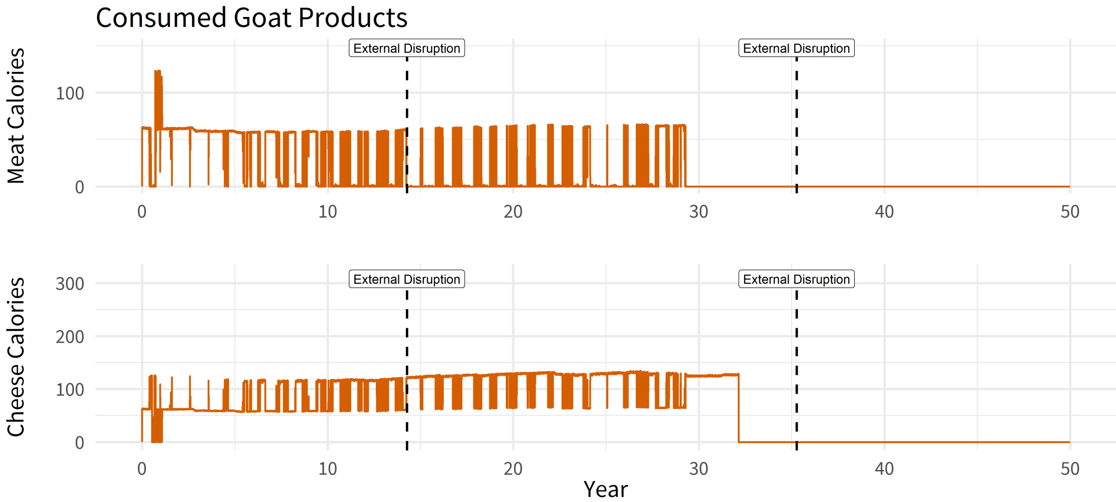

Figure 4: Calorie intake due to goat meat (top) and goat cheese (bottom) during the additional model runs.

in the 14th year. Due to this, the consumption fluctuates even more heavily. Further on, the consumption of goat meat stops as a direct result of the goat herd collapse around the 29th year of the simulation.

Higher fluctuations in cheese consumption resemble the additional effect of herd demographics. Furthermore, the consumption fluctuates to compensate for the meat deficit. Further on, the consumption of goat cheese stops as a delayed result of the goat herd collapse around the 32nd year of the simulation.

In contrast, the consumption of sheep meat is steady until the c. 37th year of the simulation. From this point, the consumption of sheep meat stops as a result of the strong decline of the sheep herds. The consumption of sheep cheese is also steady, but increases to compensate for the meat deficit from the c. 37th year of the simulation, and stabilises after this point. The external disruptions during the 14th and the 35th year have no visible effect and do not change the general patterns of sheep products (Figure **??**).

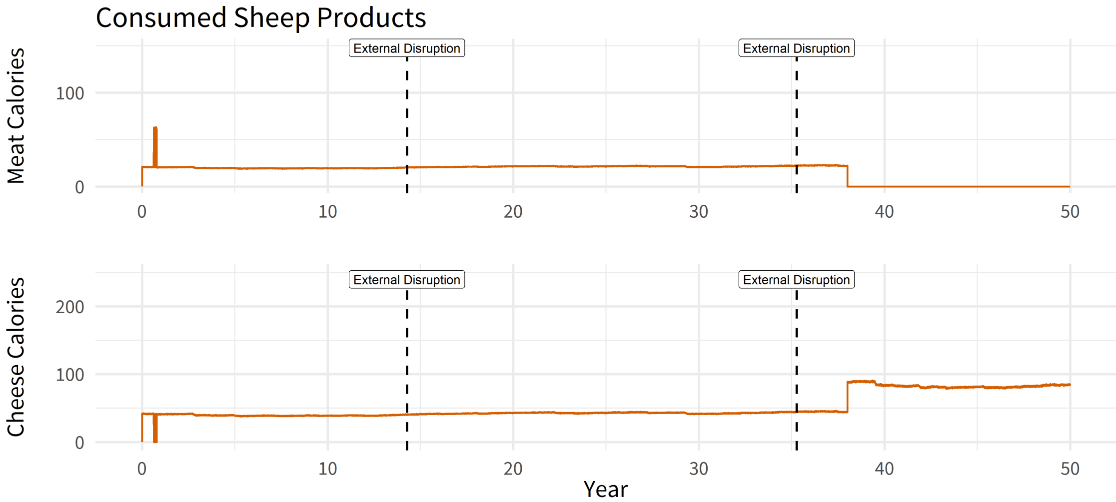

Figure 5: Calorie intake due to sheep meat (top) and sheep cheese (bottom) during the additional model runs.

2.4 Herd Dynamics

The results show that the number of goat and sheep agents varies over the course of a single year as well as over the course of the entire simulation (Figure ??).

During the first c. three decades, the number of goat agents fluctuates between c. 700 and 500. Due to the first external disruption during the 14th year of the simulation, the number of animals decreases, but can increase during the following years. However, the goat herds collapse around the 30th year of the simulation and the number of goat agents drops to 0.

In contrast, the number of sheep agents increases to about 900 in the first 5 years and stabilises around this value for about 10 years. Due to the first external disruption in the 14th year of the simulation, the number of animals decreases, but may increase again in the following years. The number of sheep agents decreases around the 32nd year, but stabilises in the following years. The second external disruption also has a visible impact on the sheep herds, but the numbers increase again. With a delay of c. 9 years, the number of sheep also declines strongly around the 37th year and do not drop to 0 until the 44th year.

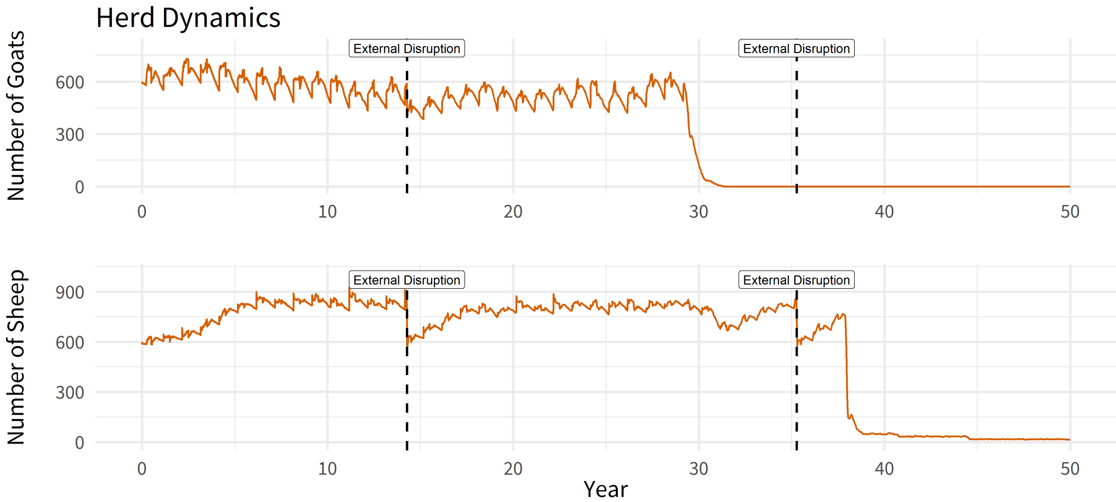

Figure 6: Total number of goat (top) and sheep (bottom) agents during the additional model runs.

2.5 Grazing Intensity

The grazing intensity is distributed over the highly suitable part of the modelled activity area and mirrors their pattern (see Figure **??**), what comes especially apparent in the areas close to the Bakırçay that were intensively used for grazing. However, even areas outside of the highly suitable areas—close to the settlement as well as in the north-west and in the east—were used for grazing. On the one hand side, these grazing activities are a side effect of the really high and towards the end really low number of animals. On the other hand side, grazing close to the settlement is a side effect of the implemented simplification of a rational thinking human being and the herder agents' behaviour as a *homo economicus*. If the herder agent can't find a suitable place providing enough biomass, it just selects the closest spot providing at least 50 % of the daily required biomass. Therefore, the spots close to the settlement were also frequently visited.

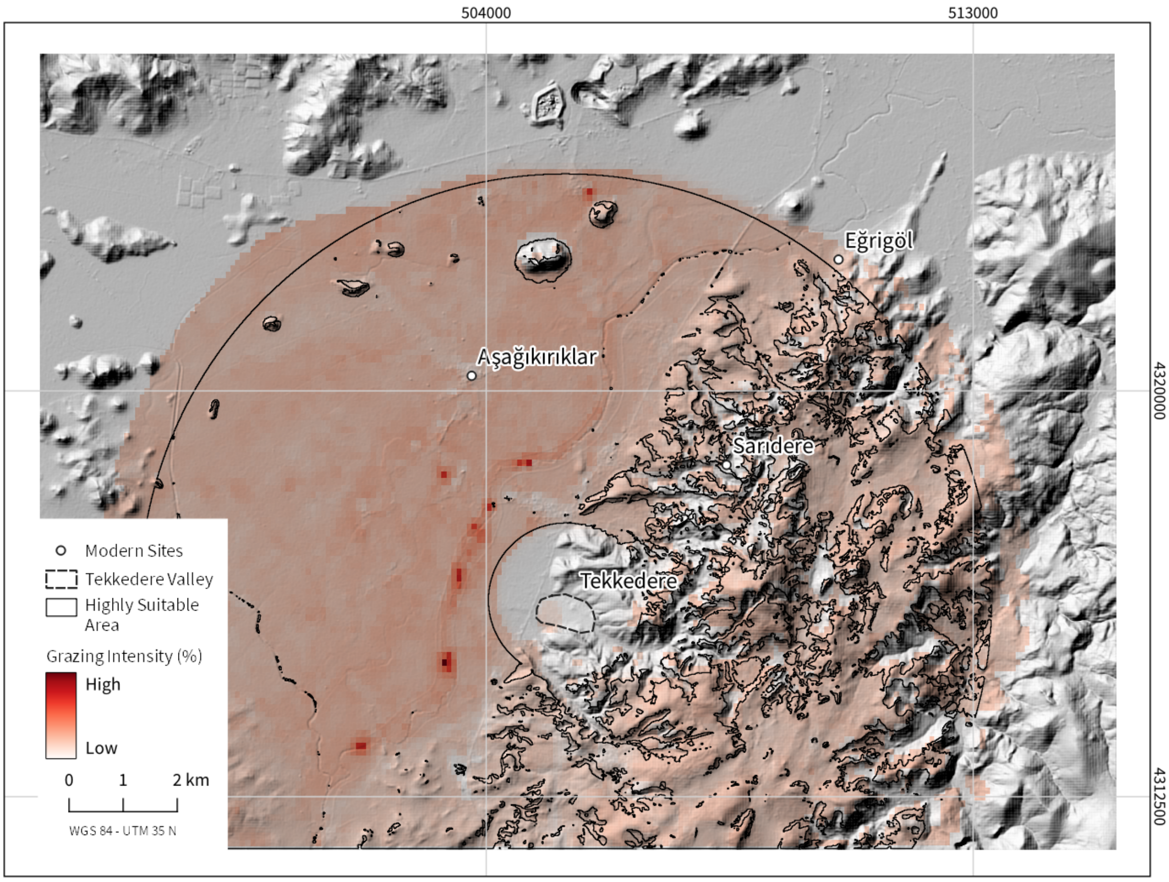

Figure 7: Simulated grazing intensity during the additional model runs. Database: TanDEM-X digital elevation model [**rizzoli2017generation**, **wessel2018accuracy**].

3 Long-term Population Dynamics

In order to explore long-term population dynamics created by a population of 100 people and a demography based on the reference pastoralist family by **dahlhavingherds**, we conducted additional simulation runs. In these runs, the population agents did age, reproduce and die regardless of calorie demand and consumption (Figure **??**).

The results show that the population sustains itself in the long term. This shows that an extrapolation of the reference family is sufficient to model a self-sustaining population.

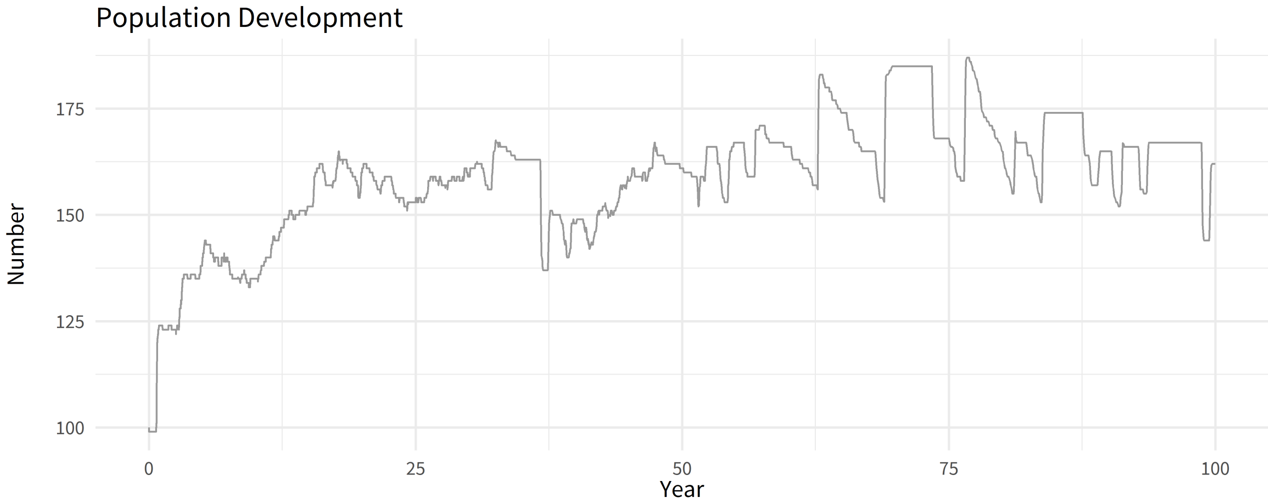

Figure 8: Simulated long-term population dynamics.

4 Effects of Suitability

Additional model runs were conducted to explore the effects of the integrated suitability raster on the simulated dynamics. The results show, that the spot selection based on suitability does not influence the herd dynamics (Figure **??**).

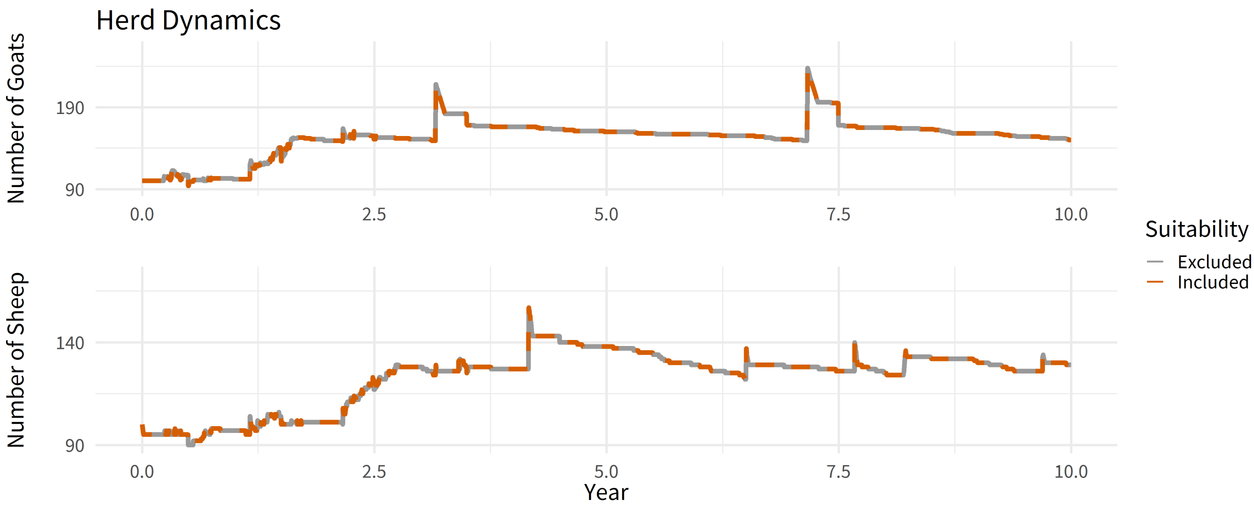

Figure 9: Comparison of a simulation with suitability data included and excluded. No difference between the simulation runs is visible.

However, a difference in the selection of grazing spots and therefore also in the grazing intensity is visible (Figure **??**).

When suitability is included, herders avoid areas close to the settlement, even though large amounts of biomass are present there. When suitability is excluded, a concentric grazing pattern originating from the settlement emerges.

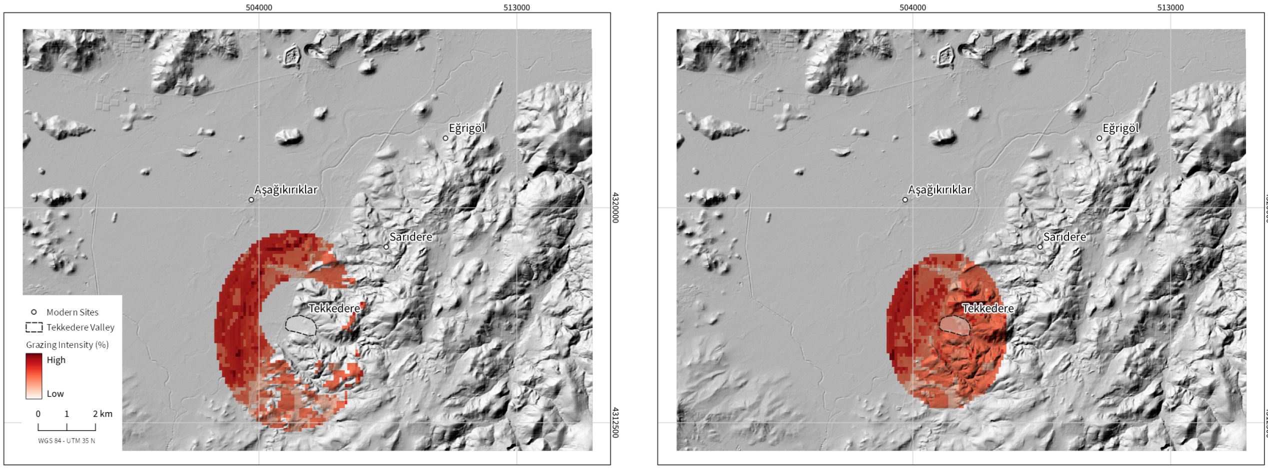

Figure 10: Simulated grazing intensity with suitability included (left) and suitability excluded (right). Database: TanDEM-X digital elevation model [**rizzoli2017generation**, **wessel2018accuracy**].

5 Additional Datasets

Table 1: Consumption ratios of the simulation runs with 2 herders.

Ratio	Scenario	
	Average requirements	Higher requirements
Calorie Requirements to Consumption	1.00	0.96
Goat Meat to Goat Cheese	0.35	0.22
Sheep Meat to Sheep Cheese	0.49	0.40

Table 2: Consumption ratios of the simulation runs described in the supplementary materials.

Type	Ratio
Calorie Requirements to Consumption	0.78
Goat Meat to Goat Cheese	0.48
Sheep Meat to Sheep Cheese	0.39

Table 3: Mean standard deviation of the simulation results

Ratio	Scenario	
	Average requirements	Higher requirements
Number of Goats	1.58	1.59
Number of Sheep	3.46	1.94
Population size	6.45	5.82