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Of Animal Husbandry and Food Production—A First Step towards a Modular Agent-Based Modelling Platform for Socio-Ecological Dynamics

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Abstract: Agent-based models provide detailed, bottom-up approaches to investigate complex socio-ecological systems. This study presents a first step towards a modular agent-based simulation that is based upon empirical data, as well as environmental suitability maps and an assessment of livestock units. To illustrate the capabilities of our simulation, we use a geographically explicit approach to simulate a component of the production of animal products of a rural settlement in the lower Bakırçay catchment, western Turkey. The model structurally couples various agent types representing several elements and processes of the animal husbandry and food production value chain, such as sedentary herders—practising daily, short-distance pastoralism—and their flocks of goats and sheep, as well as milking and slaughtering. The modelling tool captures the fundamental socio-ecological dynamics of animal husbandry and food production in rural settlements. Therefore, the tool is valuable as a basis to discuss hypotheses regarding the number of animals that are needed to cover the requirements of different growing populations.

Keywords: multi-agent-simulation; pastoralism; human impact; grazing; landscape

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1. Introduction

The transparent modelling of complex interactions between interrelated components, such as herders and their flocks, is a big challenge for simulating socio-ecological dynamics [1]. For this purpose, different simulation approaches have evolved over the years [2,3]. Besides GIS-based land use and land cover simulations, e.g., [4,5], cellular automata (CA), e.g., [6–8], and agent-based modelling (ABM), e.g., [9,10], are widely used methods. In contrast to cellular automata and GIS-based approaches, the agent-based representation of the decision-making and feedback between agents and their environment enables bottom-up approaches for studying complex socio-ecological systems [11]. This method allows for the simulation of an individual's specific behaviour, as well as its actions and interactions with the environment. Therefore, the individual's properties and their linkages within a population or community can be examined [12]. Due to the flexibility of ABMs, a wide range of modelling approaches has evolved that allows for the study of socio-ecological systems and human–environment interactions, e.g., [1,13], as well as animal husbandry and pastoralist land use practises, e.g., [14–16].

In this study, we present an empirical-based agent-based model on flock demography based on ethnographic evidences collected by Dahl and Hjort [17] as a first step towards an open platform of modular modelling components. The individual components can be used to simulate and explore dedicated aspects of human–environment interactions. The components are designed to be linked together so that—given sufficient computing resources—a socio-ecological model of entire human settlements can be created. This model can be used in various contexts, from which, we present the specific context of a single settlement and its developing, empirical-data-based reference population. In order to illustrate the capabilities of our currently implemented approach, we use distinct empirical, as well as geographically explicit, datasets to simulate the processes and dynamics of animal husbandry and the production of animal products of a rural settlement in the lower Bakırçay catchment, western Turkey.

In addition, we examine the effects of abstract external disruptions and different diet compositions on these processes and dynamics. Due to the geographic explicitness of the simulation, we also map the impact of the modelled land use and herding practices on the visited grazing areas.

1.1. Agent-Based Modelling

Agent-based modelling has been used for decades and is continuously gaining more and more importance in the study of socio-ecological systems, cf. [1,13,18]. In contrast to general equilibrium approaches or classical multivariate statistics that only capture the global dynamics of socio-ecological systems [19,20], agent-based modelling approaches are able to capture both global, as well as local, dynamics [20]. Simulations are based on actions and decision rules of single individuals or groups and their interactions with the environment [1,13]. Besides, multiple scales and constant interactions within or between different agents are possible. Agents are abstract and could, e.g., represent humans, animals or cities. The environment is considered as a virtual world that is able to influence the agent's actions and its interaction [21].

Classical models investigating the interactions between humans and the environment are:

- The 'Long House Valley' model, which explores the relationship between climatically determined resource availability, settlement location and population growth in the period between 400 and 1450 CE [22,23]. The model simulated Puebloan households practising maize farming in a valley, located in modern Arizona, USA. During the model runs, the growth of households was accompanied by a degradation of the environment, causing the eventual collapse of the society [24];
- A geographical-information-system-based approach with a focus on environmental dynamics and erosion was employed in the Mediterranean Landscape Dynamics (MedLanD) Project [25]. It is designed to study the long-term effects of small-holder agropastoralist land use activities on the evolution of *barrancos* in Mediterranean Spain by coupling a spatially explicit (cellular automata) model of landscape evolution with an agent-based simulation of land use [26–28].

Furthermore, agent-based modelling has been used to simulate and gain insights into (agro-)pastoralist movements and land use patterns, e.g.:

- To simulate decision-making processes of mobile pastoralists in the Logone floodplain in the Far North Region of Cameroon [29]. It is shown that pastoral systems can be managed sustainably. Individual autonomy, freedom of movement, habitat and suitable technology are crucial prerequisites for this;
- Dressler et al. [30] used an agent-based model to capture the dynamics and feedback between pastures, livestock and household livelihood in South Africa. Their simulation shows that not only heterogeneities in household wealth, but also the effects of climate and demographic change can lead to the polarisation of even homogeneous households;
- Pastoral migration in response to conflict or environmental variability on a monthly basis in northern Somalia was studied by Nelson et al. [16]. Their results show that agent-based models can be useful tools to understand the behaviour of individuals in a spatial and temporal context. Furthermore, climate-related environmental conditions, such as droughts and conflicts, e.g., over land use, are identified as possible triggers for migration.

These studies use aggregated agent types to simulate pastoralist camps and, e.g., draw the number of cattle per herd from a normal distribution, or the number of herds from a Poisson distribution [29], or use a single type of agent representing a pastoralist household with livestock, reproducing a fixed birth rate [30]. In contrast to these studies, we simulate our agents—e.g., herders, goats, sheep—as *individuals* with a distinct and empirical-based reproduction cycle [17], offering the possibility to investigate potential emergent patterns and thus using the full potential of ABMs.

1.2. Pastoralism

Pastoralism is characterised by a large continuum in the degree of mobility, reliance on agricultural production and types and numbers of livestock, as well as political organisation [31]. Mobility, grazing practices and feeding can be directly investigated by analysing isotopes from human and animal dental and skeletal tissues, cf. [32]. The subsistence practices of pastoralist societies range from a combination of plant cultivation and herding to a nearly exclusive practice of herding animals. These further include practices such as nomadic and specialised forms of mobile pastoralism, as well as the more common village-based herding [33]. Additionally, practised movement patterns range from a sedentary use of rich pastures (little migration) to transhumance (seasonal migration), semi-nomadic (permanent homestead) and nomadic pastoralism (frequent homestead movement) [33].

According to Salzman [34], pre-industrial pastoralist herders often combined their animal husbandry practice with farming, as well as hunting, gathering and fishing. This 'multi-resource' pastoralism or agropastoralism allowed for the herders to change their production according to changing local and regional conditions [35].

1.3. Study Area

The study area is located in western Turkey, c. 100 km north of İzmir (Figure 1; for a detailed environmental description of the study area and its development, see, e.g., [36,37]).

The location of the simulated agropastoralist settlement corresponds to the modern village Tekkedere (Figure 1). The Tekkedere valley in the Yuntdağ mountains is intensively used for pastoralism, in combination with terrace-based olive cultivation. The village is small, with c. 200 inhabitants (2010: 260 people [38]; 1840: 185 people ([39], p. 125)). The watershed of the creek flowing through the village was continuously settled since the Bronze Age [40]. With the establishment of the settlement of Yukarı Kışlak on the northeastern edge of the valley in late-to-post-Byzantine times, a development of the settlement shifting to the west is documented. This extends via Aşağı Kışlak and Eski Tekkedere to the present-day village of Tekkedere, which was erected in the middle of the 20th century at its current location [41].

The study area's climate is a typical Mediterranean hot and dry summer climate of the temperate regions (Cs after Köppen and Geiger, see cf. [42]). Due to moist western winds, the winters are humid and temperate, whereas the summers are hot and dry (Figure 1, bottom right; [43]). The annual average temperature is around 16 °C. These general climatic characteristics were established during the mid-Holocene and also occurred during prehistory ([44], p. 46), ([45], p. 142), with a temporary aridisation around 100 BCE to 0 CE [46].

In the research area, pastoralism is linked directly to the agricultural regime of cereal, olive tree or vine cultivation, and is rarely separated from agricultural land use activities [47]. The husbandry of small sheep and goat herds has a millennial-long history, as documented by animal bones found in the cisterns of ancient Pergamon [48]. Therefore, we assume that agropastoralist settlements in the research area practised husbandry of goats and sheep. Additionally, due to the high soil fertility of the Bakırçay floodplain, these settlements also relied on additional agricultural products, such as corn, legumes and olives, cf. [36,49,50].

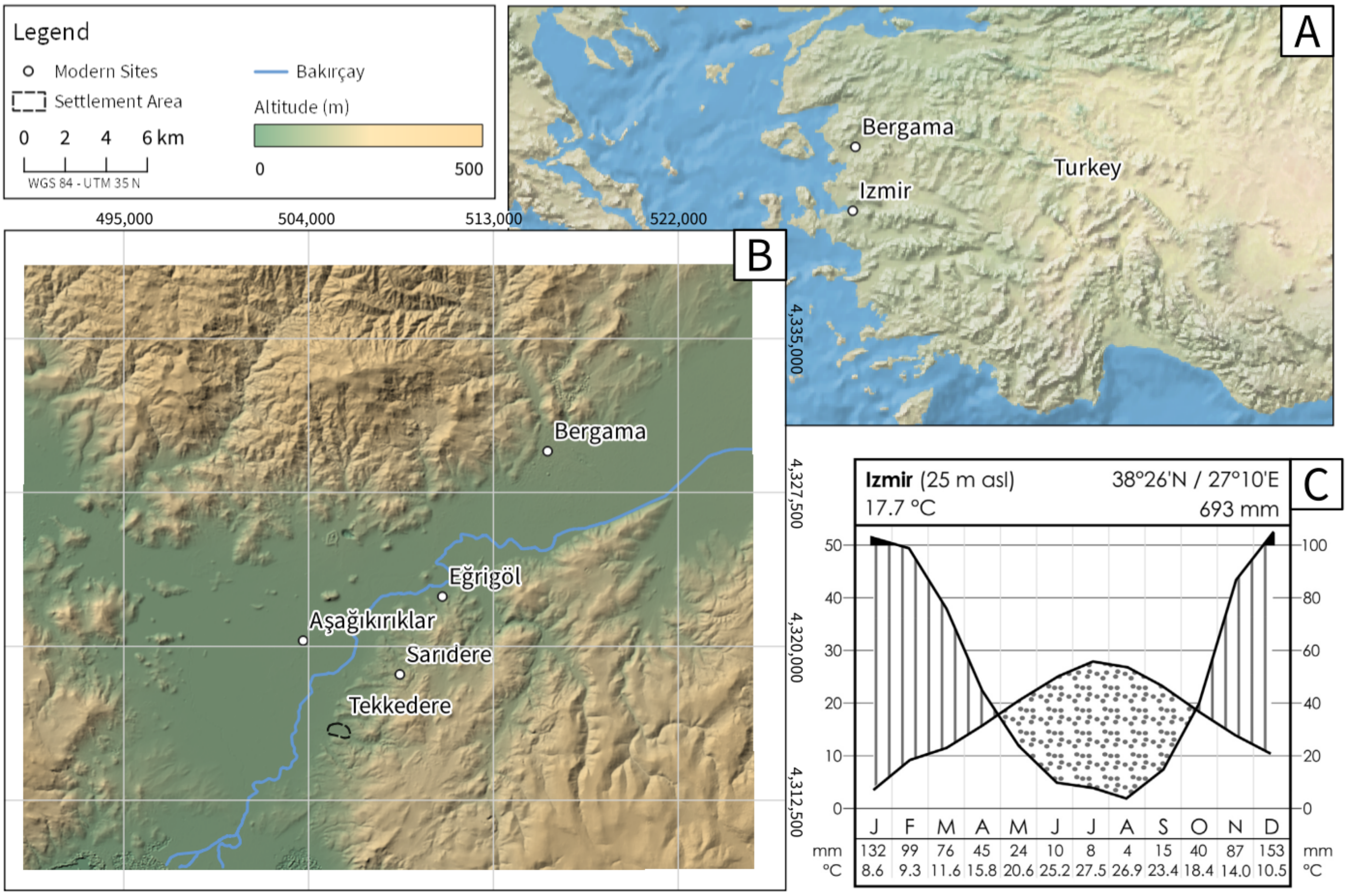

Figure 1. (**A**) The general setting of the study area in the vicinity of Bergama in western Anatolia (Turkey); (**B**) a regional overview showing the location of Tekkedere at the transition between the fertile, intensively agriculturally used Bakırçay plain and the Yunt-Dağ mountains; (**C**) climate diagram of İzmir for the period 1961–1990 (based on Sträßer [51], nr. 146).

2. Methods

2.1. Biomass Quantification and Dynamics

In order to model the impact of grazing activities on the biomass, an inventory of the biomass in the form of a raster is necessary. Due to the lack of such information for pre-industrial times, we approximate these using modern conditions and a remote-sensing-based index, i.e., normalise difference vegetation index (NDVI; see Chapter 1 of the Supplementary Materials for details on its calculation).

We transformed the mean NDVI values into biomass for grazing, applying the concept of livestock units (*LU*; [52]). We assumed that one hectare of grassland can provide one *LU* with its yearly fodder requirement [53]. One sheep or goat corresponds to 0.1 *LU* [52], so that one hectare of grassland can feed up to ten goats or sheep.

In our simulation, one individual goat or sheep is able to graze for maximum of eight hours on a usual day; thus, it can consume up to eight units from the biomass raster per day, i.e., 2920 units per year. Herders started their days at dawn and tended their flocks to nearby pasture areas and returned with them in the evening (a practice documented since antiquity, e.g., in Varro rust. 2, 10, 1; [54]). In the study area, we have, on average, 11.37 sun hours per day [55], leaving plenty of time to move between settlement and pasture and still provide eight hours to graze.

Combining *LU* and grazing time, one hectare of grazing land provides enough biomass units to feed 10 goats or sheep for one year. This corresponds with data of Hakyemez et al. [56], who also reported stocking densities of 10 goats per ha. One pixel of the employed biomass raster has an area of c. 1 ha; thus, it provides fodder for 10 goat or sheep agents, which is equivalent to c. 29,200 biomass units per cell and year.

These maximum biomass units have to be adjusted to the local environmental characteristics. The basis for *LU* calculations are recent grasslands used by farmers in the USA [53], whose average yield is 10.65 t/ha. This is nearly three times as high as can be expected for western Turkey, as research of Albayrak et al. [57] on forage yield under rainfed conditions in the Isparta province shows yields for pure grass areas of 3.1 to 3.5 t/ha. Therefore, the maximum NDVI-derived cell value is equivalent to c. 33% of the 29,200 biomass units, which is equal to c. 9733; this value is also used as an upper limit for the biomass regrowth. The locally adjusted potential biomass raster is multiplied with the mean NDVI raster in order to connect vegetation characteristics with potential biomass.

2.2. Activity Areas

In addition to biomass, a data set on the suitability of the study area can also be integrated into the simulation. Detailed information regarding the simulated activities of the agents are required for this purpose. If the required information is not available, the simulation can be run without this dataset (see Chapter 4 in the Supplementary Materials for a comparison between a simulation run with and without integrated suitability).

To relate the pastoral activities to the homestead of the herders, a map of the grazing area accessibility was created integrating empirical data on environmental characteristics, as well as topographic information via fuzzy variables (for concept of fuzzy variable see, e.g., [58]) using the R package FuzzyLandscapes [59]. We employed the following fuzzy sets to define our grazing zones:

- Pastoralists compete with agricultural production for arable land [60]. According to Forbes [61], p. 101, herders and owners were liable for any damages. Therefore, areas in walking distance of up to 1.5 km from the settlement were assumed to be less suitable, because they might have rather been used for agricultural production than for grazing, and thus would result in potential conflicts between farmers and pastoralists. (Figure 2A; [60]);
- Research on movement patterns of pastoralists in Greece has shown that herders—not considered as nomadic pastoralists—move distances of 10 to 15 km on a daily basis [47]. Therefore, areas in walking distance larger than 15 km were treated as unsuitable, because this distance is too large for the simulated daily short distance pastoralism (Figure 2A);
- Over- and early spring grazing—especially in sloping fields—destroys vegetation and causes erosion, leading to a loss of available pasture areas and biodiversity in general [62]. Slope gradients steeper than 25% lead to a significant increase in soil erosion [63]. Therefore, due to a higher sensitivity to erosion [64], too steep areas were treated as little suitable (Figure 2B);
- Pastoralist herders prefer spots from which they can oversee the surrounding area, and can thus visually control their flocks. Therefore, the *Positive Topographic Openness* [65] was calculated using SAGA GIS [66]. It is a measure of the portion of a circle that is visible at a certain position along a topographic section (Figure 2C);
- Topographical features also influence microclimate of a grazing spot. Humid conditions favour the occurrence of diseases such as foot rot [67]. For our grazing zones, the connection between terrain features and humid conditions was not considered.

Based on these rules, maps of the grazing suitability were derived and integrated into the map of potential grazing sites, i.e., all available locations independent of their suitability. From this set, the pastoralist agents select the grazing spots to model inherent processes and information (see below).

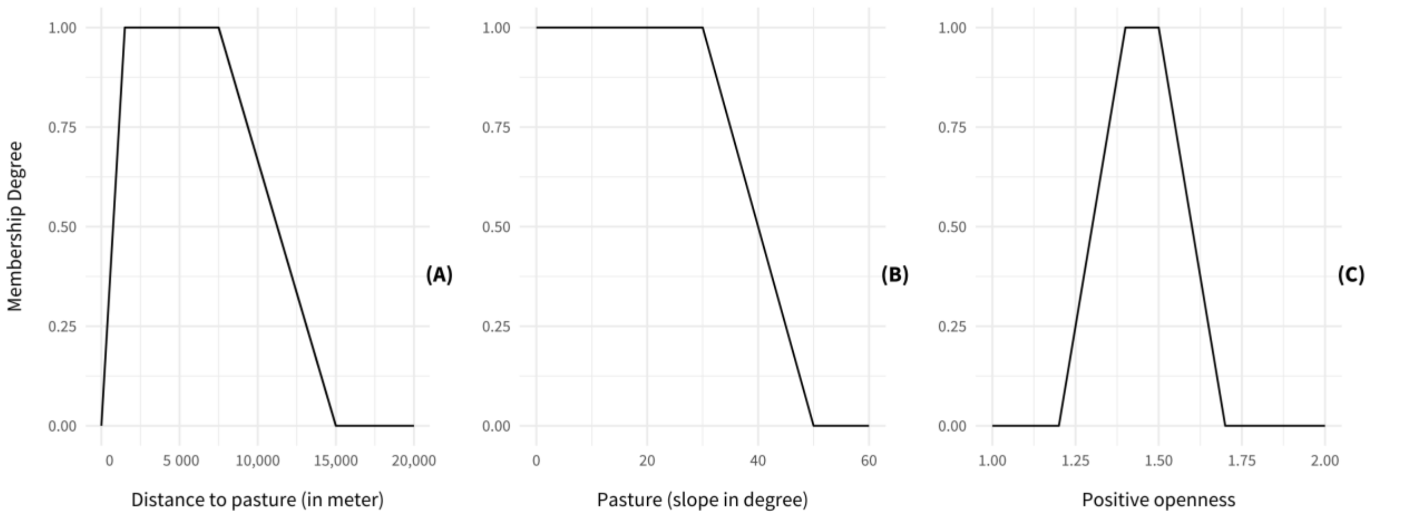

Figure 2. Fuzzy sets as employed in the analysis. Each set represents the suitability for pastoralist grazing of (**A**) distance to pasture, (**B**) slope and (**C**) positive openness.

2.3. *Agent-Based Model*

In order to ensure a geographically explicit and performant simulation , the agent-based model was developed using the Julia programming language [68], as well as the packages *Agents.jl* [69], *CSV.jl* [70], *CSVFiles.jl* [71], *DataFrames.jl* [72] and *GeoArrays.jl* [73]. In order to enable reproducibility of the simulation and its results, the complete code and the input data, including a detailed model description, following the second update of the 'ODD' protocol [74], are available online at https://doi.org/10.5281/zenodo.5141854, accessed on 7 December 2021. To further establish the simulation's reproducibility, the simulation environment was set up and can be instantiated using *DrWatson.jl* [75].

In the following paragraphs, the model and its core functions are briefly described and visualised (Figure 3).

2.3.1. Model Purpose and Agent Types

The model was developed to simulate the processes and dynamics of animal husbandry and the production of animal products. Due to the required level of detail, we derived data from various pre-industrial ethnographic sources, spanning various regions, cultures and periods. In the context of this study, we used the model to simulate the animal husbandry and the production of animal products of the inhabitants of a pre-industrial settlement, whose production of animal products depends on sedentary herders. These herders practise daily and short-distance pastoralism. Furthermore, the simulation locates spots with high grazing intensities, possibly leading to an increased risk of erosion. Therefore, the number of times a cell was used for grazing was counted.

The simulation ran for 50 years. Based on recent population data [38], we assumed that c. 150 to 200 people lived in the study area. The simulation runs in ticks, defining distinct time steps and representing, for the sake of computational efficiency, a quarter of a day. In each tick, an agent follows a routine of predefined tasks [21].

The model itself consists of five different agent types (Figure 3) representing elements of the agropastoral value chain. Stochasticity is used to soften sharp thresholds, which trigger corresponding actions.

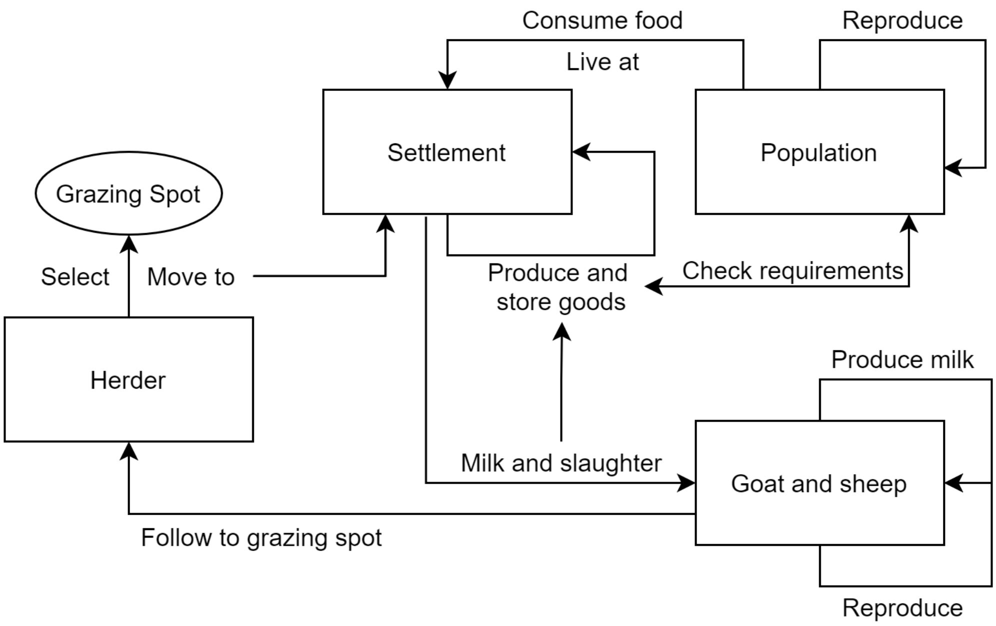

Figure 3. Overview of the agent types and the main dynamics of the agent-based model.

Population agents want to reproduce and therefore have to eat. They adapt to the current availability of food at their home settlement and eat more of another good, if the stored amount of one good is not sufficient. In the context of this simulation, we assume that the population agents have to cover the proportion of animal products on their daily calorie requirements in order to reproduce. Therefore, the population agents have an energy level which increases by 1 if they were able to cover at least 75 % of their requirements. If the agent could only cover less than 25 % of its requirements, the energy level decreases by 1. Otherwise, it stays the same. In this simulation, the female population agents' energy level must be at least 50 % of their maximum energy level to meet the requirements for a pregnancy.

The initial population of the settlement consists of 100 people. In order to simulate basic population dynamics, the population agents are able to reproduce, following their individual reproductive cycle, e.g. female population agents are able to become pregnant if their age is above 14 [76] and their calorie requirements are covered. After that, the agent is 'pregnant' for about 9 months, after which one population agent is created. A 9 % chance of stillbirth or miscarriage ([77], p. 390) is implemented.

Of all the initial 100 population agents, three adult population agents are assumed to be working as pastoralist *herders* (the number changes according to the number of herder agents). These population agents consume and reproduce in place of the pastoralists, while the pastoralists take care of their herds. Other population agents might be working as, e.g. farmers, but the corresponding processes are not yet simulated.

At least since antique times (see, e.g., Varro rust. 2, 10, 1 [54]), agricultural work began at dawn and ended at dusk, herders tending a flock in nearby pasture areas returned in the evening. Therefore, in the morning, the pastoralist agents and their herds move from the settlement to a selected *grazing spot*. Initially, each herd consists of 100 sheep and 100 goats. The selection of the grazing spot is based on the spot's suitability and the amount of biomass required to feed the agent's herd for at least half of the day. The agents stay at their selected spots for the day and return to the settlement in the evening

Goat and sheep agents want to reproduce and therefore have to eat. Accordingly, this agent type follows their pastoralist agent to the selected grazing spot. If the animal agents reach their grazing spot selected by the pastoralist agent, they try to 'eat' for two simulation steps, i.e., they reduce the value of biomass at their current position. If the biomass value is higher than the agent's hunger, the biomass gets reduced. If this is not the case, the agent starts moving randomly into one of eight directions (left, right, down, up, up-left, up-right, down-left and down-right). The distance of this move is also randomly set. To assure that the agents move to another cell, the minimal distance is 101 m, i.e., 2 pixels. In this way, the agents can move up to 505 m per tick.

In order to enable lactation and reproduction, the goat and sheep agents run through a simulated life cycle. This includes age- and sex-specific values for meat yield ([17], p. 202), milk yield ([17], p. 212) and reproduction ([17], p. 90). In this context, a 10% chance of stillbirth or miscarriage [78] is also implemented. The herd's initial demographic composition is derived from (Dahl and Hjort [17], p. 96). The ratio between male and female newborns is equal ([17], p. 88). We assume that a pastoralist (agent) can only herd a certain amount of animals without a dog, which ranges between 300 and 400 animals in total ([17], p. 255). The values differ between 150 and 200 for each agent and are randomly set during initialisation of the simulation. In order to keep its herd herdable, each pastoralist (agent) can slaughter goat and sheep (agents) as soon as their numbers grows too strong. As long as the goat and sheep herds grow, this procedure ensured a continuous and sustainable supply of meat.

Environmental conditions and possible diseases also influence the number of juvenile goats and sheep. According to Dahl and Hjort [17], p. 95, 30.5% of juvenile lambs die under six months. A similar value of 29.54% is reported for juvenile goats under 6 months. Therefore, c. 30% of both juvenile goat and lamb agents die during each simulated year due to environmental conditions and diseases. Due to the fact that death rates for older animals are lacking ([17], p. 95), only the environmentally induced death of juveniles is implemented.

The animate agents are supplemented by an *inanimate settlement agent*, which is the starting and end point of the daily pastoralist routine. It also acts as a place to store the produced animal products, which, in return, are consumed by the population agents. For all food production processes, a loss of 10% is assumed, which is a value also used by Hughes et al. [79]. An explicit decay of stored products is currently not implemented. In order to ensure the population agents' 'survival' during the months until the first 'lactation' period of the goat and sheep, a predefined amount of meat and cheese is stored at the settlement (see Table 1).

Table 1. The initial food storage of the settlement.

Product	Amount (Unit)
Goat Cheese	300 (kg)
Sheep Cheese	300 (kg)
Goat Meat	300 (kg)
Sheep Meat	300 (kg)
Goat Milk	300 (L)
Sheep Milk	300 (L)

Goats and sheep are often referred to as "capital on the hoof" ([80], p. 44). To avoid overexploitation, only small amounts of goats and sheep are slaughtered besides the ones due to herd growth. If the amount of meat produced by slaughtering surplus animals is not sufficient to cover the population agents' requirements, the settlement agent can also slaughter animals. If the storage drops below 125 g of meat per inhabitant, the settlement agent starts to slaughter as some kind of backup. This amount of meat is sufficient to cover the minimum share of animal calories in the assumed diet. In the simulation, the culling of young males—a typical pastoralist management method [81]—is practised. This means that, if the amount of meat stored at the settlement is not sufficient, preferably male juvenile goats and sheep are slaughtered. If there are no juvenile males, the entire herd is considered for slaughter and the individual with the highest weight was selected.

This agent also checks the goat and sheep herds for lactating individuals. Then, the selected agents are milked in descending order of quantity of milk. Following the description of Degen [82], approximately 50 goats and sheep can be milked each day, and the milk is stored at the settlement.

At the end of each day, the available amount of milked is used to produce cheese. In the context of the simulation, we assume and simulate the production of a traditional, long shelf life type of cheese, such as Kashar cheese ([83], p. 14). After 3–6 months ripening, this type of cheese may be stored for 2–3 years ([83], p. 14). After the ripening period, the corresponding amount of cheese is stored at the settlement.

2.3.2. Demography

In order to model the demography of our simulated population, we use a reference family ([17], p. 140) as a basis. This reference consists of a 30-year-old father and a pregnant mother of 25. They have two children of 3 and 8. Additional workers—a female of 15 and a male of 18—are attached to the household ([17], p. 141). In order to add a certain degree of variation, the age of the adult males is set to a random value between 25 and 32, and the age of the adult females to a random value between 20 and 28. The age of the juveniles ranges between 3 and 8, and the age of the young adults ranges between 15 and 18. The agents age and die a natural death according to the life expectancy of pre-industrial times at an age between 35 and 45 [84], and reproduce over time.

2.3.3. Calorie Requirements

In our simulation, a member of the pastoralist community requires an average of 2000 kilocalories on a daily basis. This amount roughly fits to the results of Brown [85], p. 69, who describes a pastoralist "(...) as an active individual doing no heavy work". Further, he ascribed a daily need of only 2300 kilocalories to a standard male pastoralist, adding that "(...) even this may be too high, for pastoralists are often very slim light people who may not eat as much as a standard European subject". As stated by Dahl and Hjort [17], p. 141, the pastoralist life and its easiness displays great variations between different pastoralist settings.

The population agents have an activity level, representing an individual person's daily activity level, that is derived from empirical studies, cf. [86]. In order to represent a heterogeneous society, including children and elderly people with varying degrees of activity, this level randomly changed each day between 'sedentary', 'moderately active' and 'active'. During pregnancy, c. 400 additional kilocalories are required per day [87], which are added to the pregnant agent's daily requirements.

2.3.4. Food Consumption

In general, the dietary composition and the availability of food depend on many factors, such as demography, social dynamics and the individual's social status. Therefore, the precise proportion of animal products on the populations' consumption used in the simulation is likely to differ from reality, especially when keeping the continuum of different pastoralist practices and the spatially varying availability of resources in mind [31].

The diet structure of the population in our agropastoralist settlement is based upon empirical data synthesised in Hughes et al. [79]. According to this, the food consumption is mainly dependent on agricultural products, such as cereals and legumes, which made up approximately 80% of the diet. From this dataset, we took the proportion of meat in the diet, which is around 4%, whereas another 5% was accounted for by dairy products [88,89]. In this simulation, the consumed dairy products are summarised as cheese. A detailed overview of the food requirements used for the simulated scenarios can be found in Table 2.

2.3.5. Surplus Goods

The simulated animal husbandry and food production systems can lead to the production of surpluses. To avoid stockpiling several thousand tonnes of dairy products, an abstract surplus management is implemented. In the context of this simulation, we refer to the surplus management as 'trade'. Specific and interesting aspects of trade, economy and markets are not (yet) implemented.

In order to store dairy products, goat and sheep milk is processed into cheese. Even cheese can only be stored for a limited time; in our case, 2–3 years [83]. Sedentary communities in Central Anatolia store c. 15–20 kg per family for consumption during winter [90]. In our simulation, the population agents stockpile an amount of cheese sufficient for 1 month, which is 3 kg of goat cheese and 4.5 kg of goat cheese per person.

According to Greek writers of the imperial period, weekly markets (*agora*) were held ([91], p. 40). In the context of the simulation, varying quantities of surplus cheese are traded. The agents trade the goods on an exemplary regional market, occurring every eighth day.

2.3.6. Biomass Regrowth

Over the course of the simulation, the goat and sheep agents 'graze' or reduce the amount of available biomass. Therefore, an algorithm simulating biomass regrowth had to be implemented. Considering our approach of estimating the study area's initial amount of biomass, certain assumptions were made:

- Biomass regrowth is limited to the vegetation period [92]. According to, e.g., Atalay [93] and Taner et al. [94], the vegetation period in the study area is determined according to the daily temperature being equal or greater than 8 °C;
- During this period, the biomass regrow factor per tick is 1.5% of the current value [95]:

$$Biomass = Biomass + (Biomass * 0.015); \tag{1}$$

- We assume a homogeneous biomass regrowth;
- We further assume that the biomass regrowth is capped by the initial maximum biomass value of c. 9700.

To show the model's capability of integrating climate data, we use modern climate data derived from Fick and Hijmans [96] at a spatial resolution of 30 arc seconds. At the current set-up of the model, the specific climate data does not have an influence on the environment, and thus on the model dynamics.

To simulate daily fluctuations and climatic variability, each cell's daily value varied by up to 10% of the monthly value:

$$\begin{aligned} Daily\ Temperature\ &= Monthly\ Temperature\ +\ (rand(Monthly\ Temperature)\ *\ 0.1) - \\ &\quad (rand(Monthly\ Temperature)\ *\ 0.1). \end{aligned} \tag{2}$$

In this case, the *rand* function randomly selects a value between 0 and the average monthly temperature derived from Fick and Hijmans [96]. Corresponding to the calculated daily temperature and the current amount of biomass, the biomass value either increases or decreases.

2.4. Modelled Scenarios

In order to explore the system's elasticity and reactions to external disruptions, two different scenarios—mirroring average and high resource requirements—were created to investigate the social-ecological dynamics of the settlement (Tables 2 and 3). The scenarios differ in the proportion of animal products on the population agents' consumption. For the *Average Requirements* scenario, the proportion of the goods on the consumption is based on the information described in Section 2.3.4. For the *Higher Requirements* scenario, we doubled the requirements. Thereby, the proportion of dairy products equals the one of the 'elite' diet by Hughes et al. [79]. The proportion of meat is still 53% smaller than the proportion of the 'elite' diet by Hughes et al. [79]. Since this information does not distinguish between the individual products, we have assumed the values listed in the table. At the current state, agricultural production is not simulated. We further assume the production and consumption of field crops, such as barley, wheat or lentil. During both scenarios, varying quantities of surplus cheese are traded.

Furthermore, in order to explore the animal husbandry and food production systems' reaction to pressure, we implemented two abstract external disruptions (in years 14 and 35 of the simulation)—probably caused by cultural, environmental and societal changes [45,97,98]—due to which, c. 30% of the animals are lost for human consumption.

Table 2. Food data used as input for the simulation.

Product	Proportion (%) per Scenario	
	Average Requirements	Higher Requirements
Goat Meat	3.00	6.00
Sheep Meat	1.00	2.00
Goat Cheese	3.00	6.00
Sheep Cheese	2.00	4.00

Table 3. Initial number of agents used for the simulations.

Agent Type	Initial Number
Settlement	1
Population	100
Herder	3
Goat	300
Sheep	300

To reduce the influence of stochasticity, 10 simulation runs were conducted for each scenario. The values shown are the average results of the runs performed for the respective scenarios (see Table S3 in the Supplementary Materials for the standard deviations of the simulation's core variables).

3. Results

In general, only small differences in the population dynamics of the two scenarios become apparent (Figure 5). The herd dynamics and the population agents' consumption show marked differences between the dynamics of the modelled scenarios (compare Figures 6–10). In general, the results of both scenarios show stable, but fluctuating dynamics that remain stable even under external disruptions. The consumption patterns of the *Average Requirements* scenario enable the trade of high amounts of surplus goods. Due to the consumptive behaviour of the *Higher Requirements* scenario, fewer amounts of goods could be traded during the short periods of high availability (Figure 9).

3.1. Assumed Initial Biomass Distribution and Areas Suitable for Grazing

The results of the assumed initial biomass show spatial variations (Figure 4, left), with medium and medium-high amounts of biomass in the plain and in the elevated regions. Especially west of the settlement, high amounts of biomass that correspond to the course of the Bakırçay river are located. Patches of low biomass are scattered in the elevated regions in the northern and the southern part of the study area, coinciding with low NDVI values (compare Figure S1 in the Supplementary Materials).

In terms of grazing activities, large parts of both the plain and the elevated regions in the east are highly suitable (Figure 4, right). Only small areas in the valleys of the mountainous part, as well as areas that are close to and very distant from the settlement, are assumed to be less suitable, mirroring the constraints defined in the fuzzy sets.

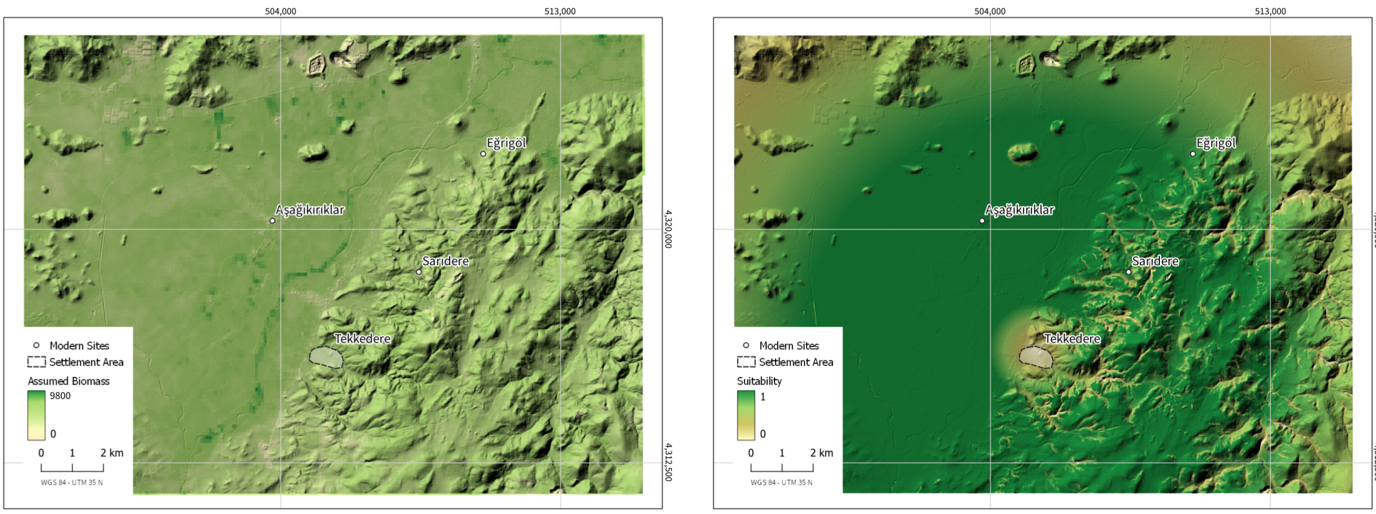

Figure 4. Assumed initial biomass distribution based on derived NDVI values and livestock units (**left**) and areas suitable for pastoralist grazing (**right**). Elevation data: TanDEM-X digital elevation model [99,100].

3.2. Population Dynamics

Over the course of the simulation, the population agents age, reproduce and die. For both scenarios, the results show a similar pattern of increasing, decreasing and settling population numbers (Figure 5).

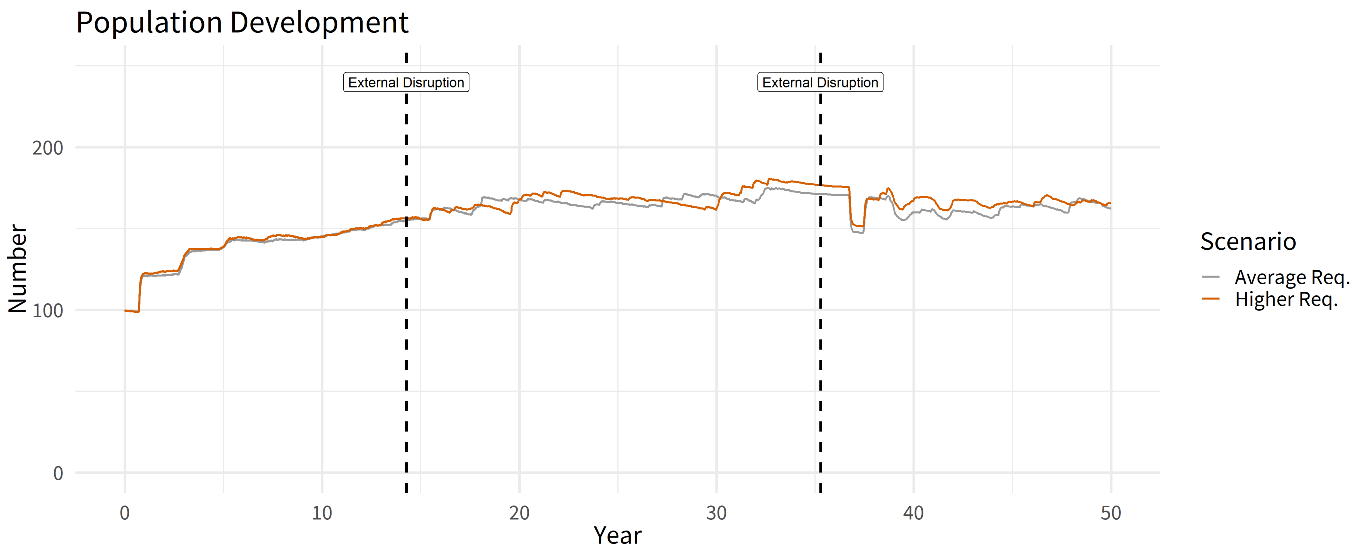

Figure 5. Simulated population dynamics of the *Average Requirements* and the *Higher Requirements* scenario.

3.3. General Calorie Requirements

In the context of the study, we differentiate between a required and a consumed amount of calories. We use the term required for a targeted consumption of goat and sheep products, as defined in Table 2. If there is less than the targeted amount of sheep or goats products available, they have to be substituted by another, non-animal good (e.g., corn) not modelled here. The difference between the required and consumed good shows the amount of these replacement goods.

For both scenarios, the results show increasing calorie requirements over the course of the simulation (Figure 6, top). In general, the calorie requirements during the *Average Requirements* are lower than the ones during the *Higher Requirements* scenario. Throughout the simulation, and despite the strong dynamics in the consumed calories—especially during the *Higher Requirements* scenario—the calorie requirements were fulfilled almost all of the time (100% in the *Average Requirements* scenario, 96% in the *Higher Requirements* scenario; see Table S1 in the Supplementary Materials).

The external disruptions during the 14th and the 35th year only have a small effect on the population agents' consumption, especially during the *Higher Requirements* scenario.

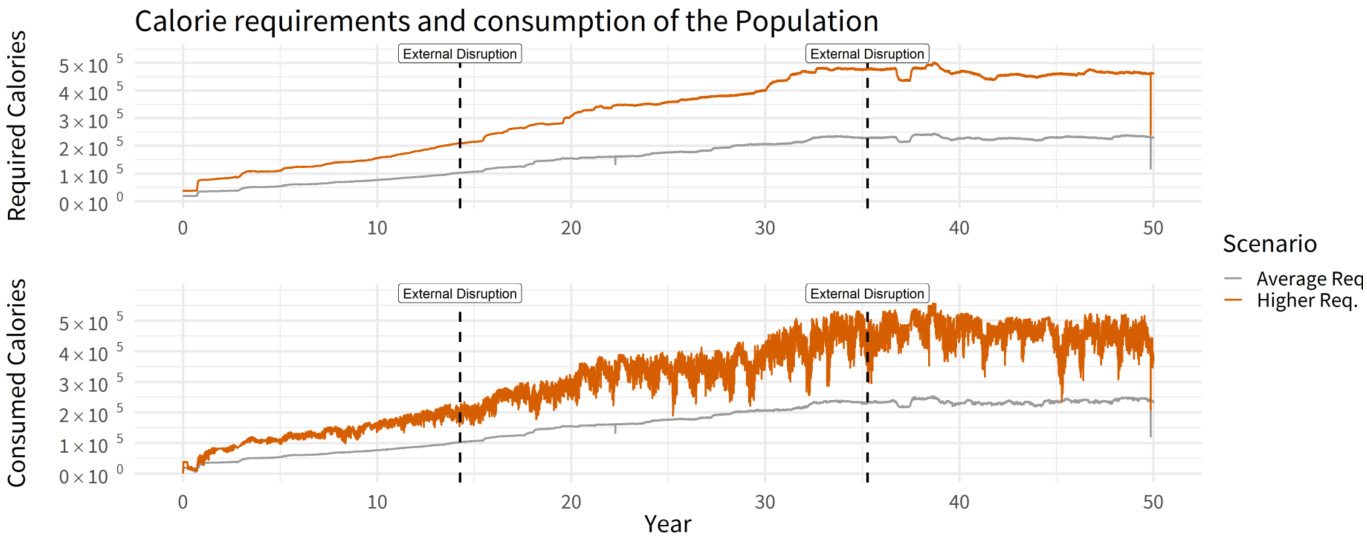

Figure 6. Calorie requirements (**top**) and consumption (**bottom**) during the *Average Requirements* and during the *Higher Requirements* scenario.

3.4. Coverage of the Calorie Requirements with Goat and Sheep Products

Agents are able to substitute a deficit in meat with cheese, as long as it is available. The results show that the mean consumption of goat products fluctuates between the scenarios and over the course of each simulated scenario (Figure 7). Higher fluctuations in cheese consumption resemble the additional effect of herd demographics, such as reproductive cycles and related milk production. As a result of the external disruptions during the 14th and 35th year, almost no goat meat is consumed in each following year. Overall, a trend of increasing meat consumption is visible until the middle of the year, followed by a decline towards the end of the year. An opposite trend can be observed in the consumption of cheese, indicating that the population agents were able to covered their calorie requirements by the consumption of cheese, in case meat was not available.

The pattern looks different for the consumption of sheep products (Figure 8). Over the 50 years of the *Average Requirements* scenario, results show that the population agents were able to constantly cover their requirements by consuming both sheep meat and cheese. During the *Average Requirements* scenario, the external disruptions during the 14th and the 35th year only have a small effect on the population agents' consumptive behaviour.

During the *Higher Requirements* scenario, this pattern is again strongly amplified. After the first 5 years, there are periods in each year where no sheep meat is consumed. Furthermore, the effects of the external disruptions during the 14th and the 35th year have a large impact on the population agents' consumptive behaviour. The loss of animals leads to a period of 3–4 years during which no sheep meat is consumed.

The fluctuations in the consumption of goat and sheep products hint to a high uncertainty in meat supply. Only during the *Average Requirements* scenario was a sufficient supply with goat meat established (meat/cheese ratio of 1.18). In all other cases, available cheese had to substitute meat, mirroring unstable herd demographics (see Table S1 in the Supplementary Materials for all calculated ratios).

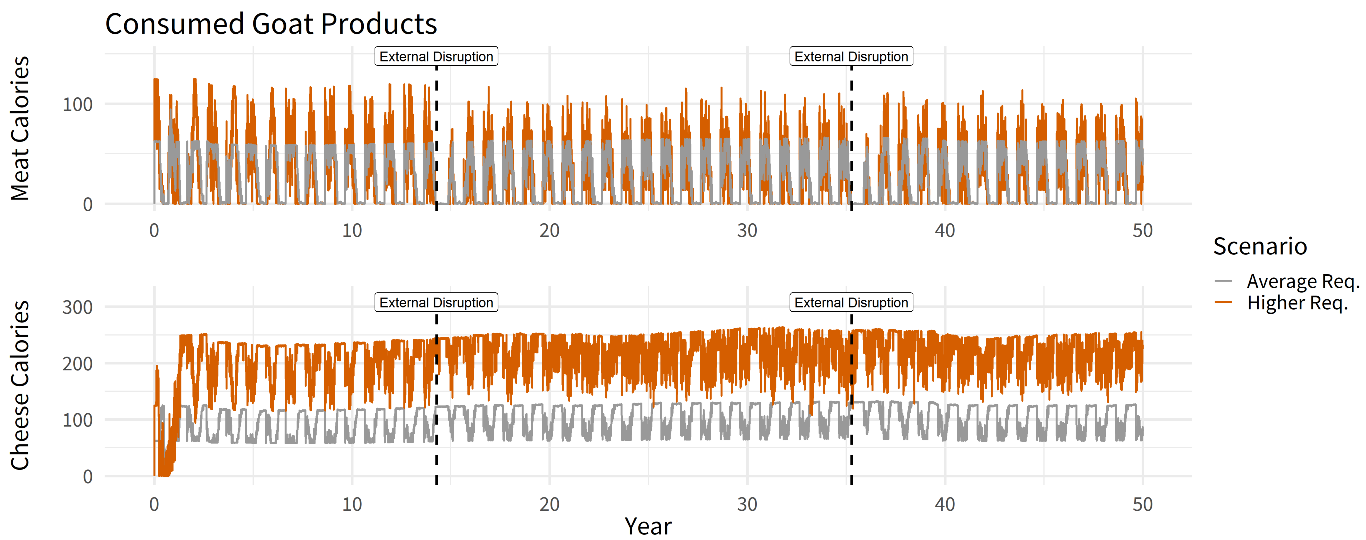

Figure 7. Calorie intake due to goat meat (**top**) and goat cheese (**bottom**) during the *Average Requirements* and during the *Higher Requirements* scenario.

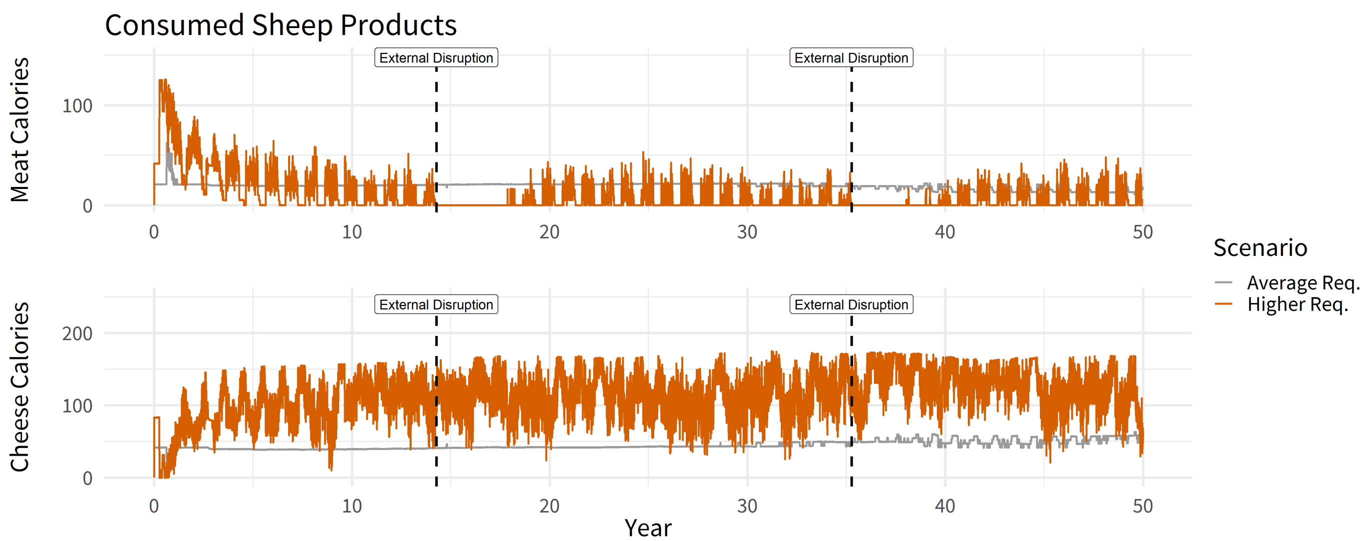

Figure 8. Calorie intake due to sheep meat (**top**) and sheep cheese (**bottom**) during the *Average Requirements* and during the *Higher Requirements* scenario.

3.5. Trade Dynamics

Over the course of the simulation, the surplus of cheese products is traded on an exemplary regional market, occurring every eighth day (Figure 9).

The sufficient supply of goods over the entire period during the *Average Requirements* scenario enabled a continuous trade with surplus cheese. This is not the case for the *Higher Requirements* scenario. Due to the higher consumption, fewer amounts of cheese were traded during the short periods of high availability.

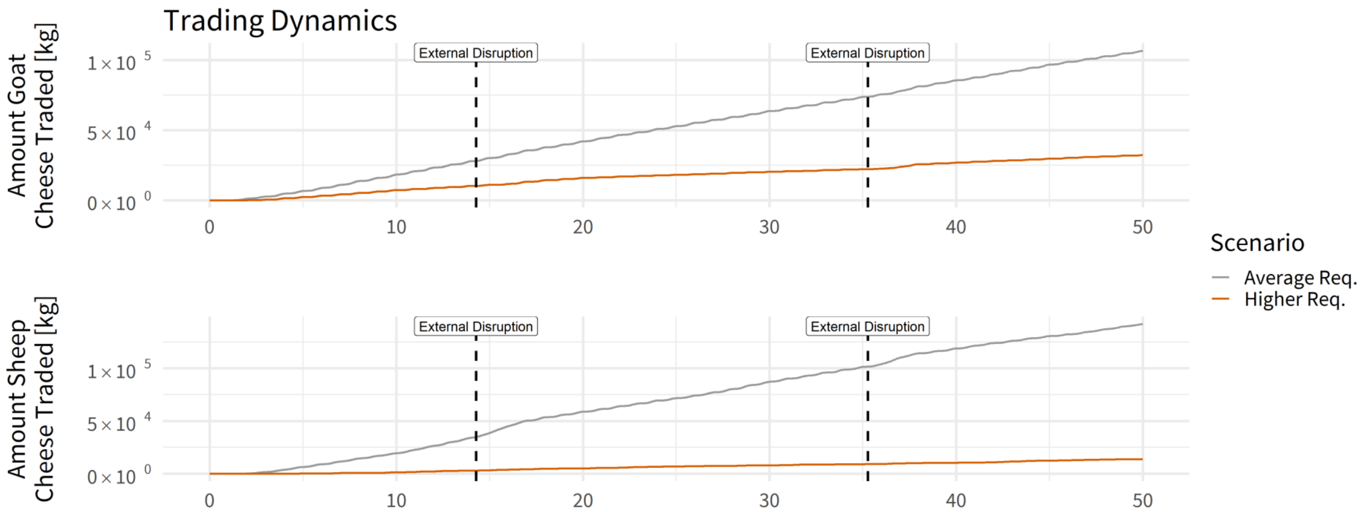

Figure 9. Amount of goat cheese (**top**) and sheep cheese (**bottom**) traded during the *Average Requirements* and during the *Higher Requirements* scenario.

3.6. *Herd Dynamics*

Goat and sheep agents run through a reproductive cycle, age and die over time. 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 10). During both scenarios, the number of goats is strongly amplified. As a result of the external disruptions during the 14th and 35th year, the numbers decrease, but recover during the following years. Therefore, the supply of goat products is guaranteed at all times. During both scenarios, the number of sheep agents is less strongly amplified and follows a similar pattern, but on different levels.

In general, the number of sheep agents is higher during the *Average Requirements* scenario than during the *Higher Requirements* scenario. In the first 14 years of the *Average Requirements* scenario, an increasing trend is visible. During the first decade of the *Higher Requirements* scenario, the numbers decrease. From this point, the numbers settle for c. 4 years. Due to the external disruption during the 14th year, the numbers decline strongly. After an additional 6 years, the numbers for both scenarios stabilise again. Only the numbers during the *Higher Requirements* scenario recover to a pre-disruption state, whereas the numbers during the *Average Requirements* scenario stabilise at a lower level. The same dynamics are visible at and after the external disruption during the 35th year. As for the goat products, the supply of sheep products is guaranteed at all times.

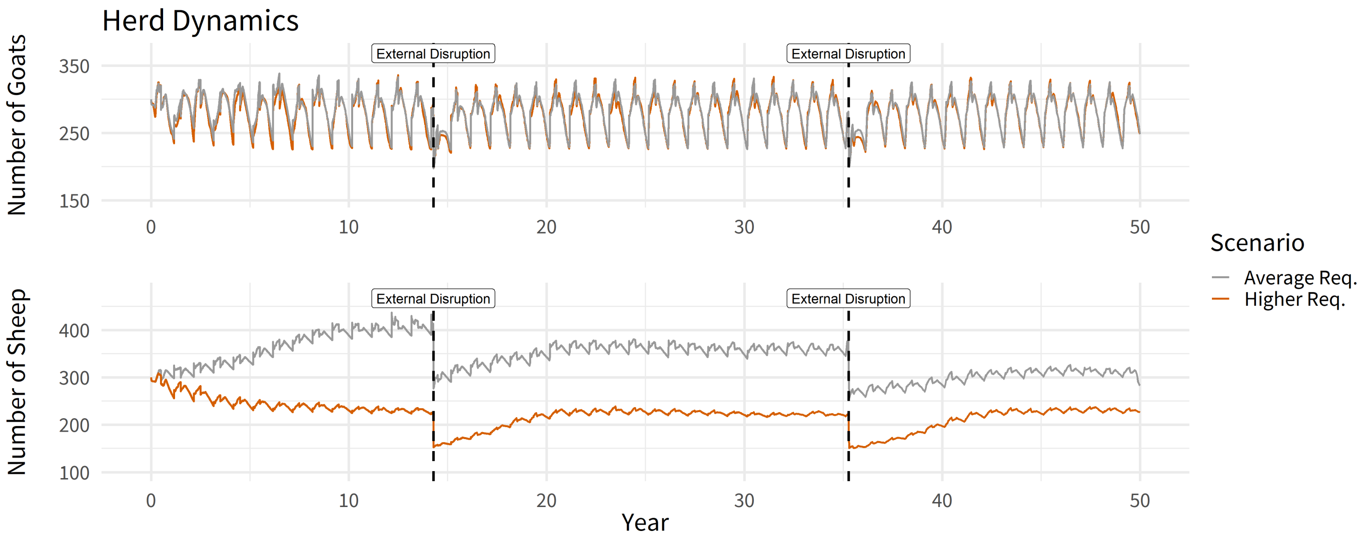

Figure 10. Total number of goat (**top**) and sheep (**bottom**) agents during the *Average Requirements* and during the *Higher Requirements* scenario.

Regarding the demography of the simulated herds, the results show that the herds of the *Average Requirements* scenario consist predominantly of female, adult individuals. For the herds of the *Higher Requirements* scenario, the ratio between male and female individuals is more balanced, whereas the proportion of juveniles remains almost similar, especially for the goat herds (Table 4).

Table 4. Age structure of the simulated male and female sheep and goat agents, as well as differences to the reference proportions from Dahl and Hjort [17], p. 96.

Type	Proportion (%) per Scenario Average req.	Proportion (%) per Scenario Higher req.	Data from Dahl and Hjort [17], p. 96	Differences Average req.	Differences Higher req.
Male Goats	12.3	19.6	23.6	11.3	4.0
Female Goats	87.7	76.4	80.4	−11.3	−4.0
Juvenile Goats	20.3	20.4	33.3	13.0	12.9
Male Sheep	8.6	60.9	22.2	13.6	−38.7
Female Sheep	91.4	39.1	77.8	−13.6	38.7
Juvenile Sheep	10.0	7.5	22.2	12.2	14.7

Due to the fact that the goat and sheep agents compete for the same resources, the synchronicity or the schedule of the simulation is an important factor. In our simulation, the sheep agent steps are executed before the goat agents, and are thus able to consume biomass before the goats and benefit from a higher availability of biomass.

3.7. Grazing Intensity

Grazing intensity corresponds to the number of times a cell was used for grazing (Figure 11). During the *Average Requirements* scenario, the intensity is distributed over the highly suitable part of the modelled activity area (see Figure 11, left), which becomes especially apparent in the areas close to the Bakırçay that were intensively used for grazing. Less suitable areas with a great distance to the settlement were less frequently used.

The grazing activity during the *Higher Requirements* scenario is located closer to the settlement, and extends less far into the plain during the *Average Requirements* scenario. Due to fewer animals—especially sheep—the utilised area was smaller, leading to a higher grazing intensity per cell (Figure 11, right).

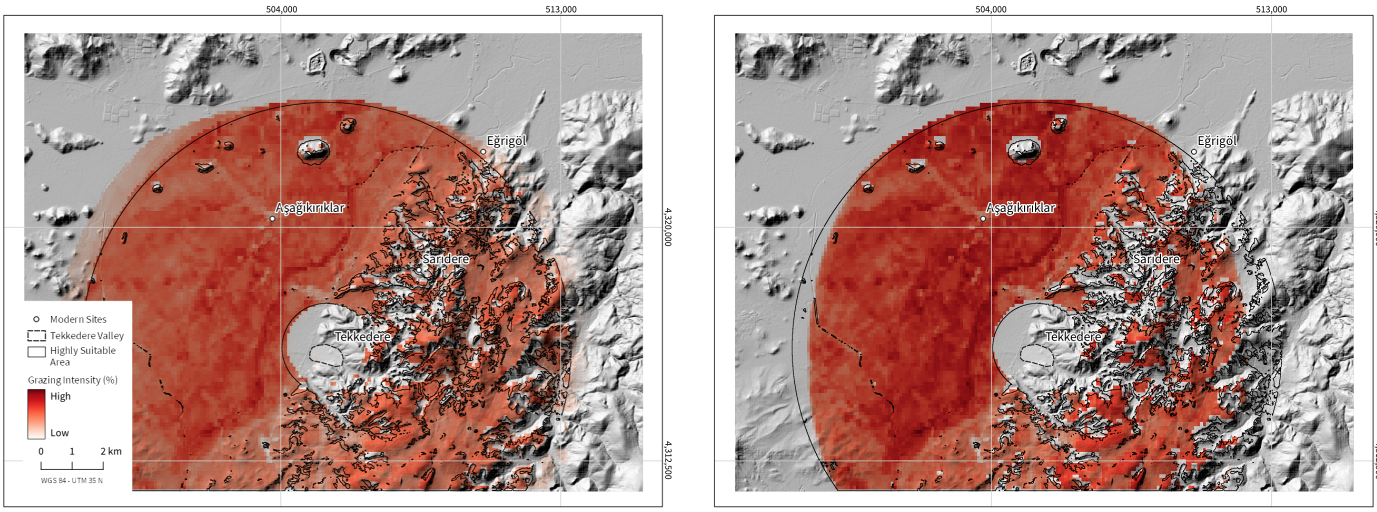

Figure 11. Simulated grazing intensity for the *Average Requirements* (**left**) and for the *Higher Requirements* (**right**) scenario. Highly suitable area corresponds to areas whose fuzzy value equals 1 (see Figure 4, right). Database: TanDEM-X digital elevation model [99,100].

4. Discussion

Due to the fact that archaeological and historical datasets often lack quantitative and vital information regarding population, food production and diets, models enable the exploration of hypotheses about the past [101]. Due to the open and flexible structure of our agent-based modelling approach, the simulation tool can be adapted to a wide range of research questions about animal husbandry and food production.

The results show that our agent-based modelling tool captures different processes of herd dynamics and consumption patterns of a settlement that are influenced by the dietary composition, and thus capture the socio-economic conditions of the population agents. Currently, the modelling tool and its assumptions are based on empirical archaeological data derived from the scientific literature. In this context, we use random numbers to accommodate for the inherent uncertainty of the empirical data. However, the more uncertainty and (real) randomness that are added, the higher the need for a proper sensitivity analysis.

The implemented animal husbandry practises, such as the culling of juvenile male sheep and goats established around the 8th millennium BC, are still commonly used by pastoral communities today [102–104]. Due to the simulation's level of detail, the data are derived from various pre-industrial ethnographic sources, spanning various regions, cultures and periods. Therefore, it is difficult to interpret the simulation's results in the context of approaches using, e.g., aggregated agent types, different food proportions or larger time frames. However, the small standard deviations of the results indicate a robust implementation of the input datasets. Nevertheless, there are some limitations regarding the implementation of, e.g., human behaviour and the input data sets.

4.1. Population Dynamics

The population difference between the scenarios is caused by the stochasticity implemented into the human reproductive cycle and into the mean life expectancy of people in pre-industrial times (see Chapter 3 in the Supplementary Materials for further experiments regarding population dynamics). The results indicate that an extrapolation of the reference family from Dahl and Hjort [17], p. 140, is sufficient to model a self-sustaining population.

4.2. Calorie Requirements and Intake

The assumed calorie requirements of the settlement's population are an important factor of the simulation. Combined with the number of agents, the requirements determine the necessary amount of food and the number of animals required to survive. The values used in the simulation are based on data from the U.S. Department of Agriculture (USDA) [86] and allow for a detailed assignment of calorie requirements based on age, sex and activity levels. In the simulation, age threshold values are used to assign the daily calorie requirements to the population agents. These sharp boundaries are the reason for the outliers around the 23rd year and towards the end of the simulation (see Figure 6, top). Combined with the implemented mean life expectancy of people in pre-industrial times, a considerable proportion of the initial population (agents) 'dies' during this period of time, but, in addition, new population agents are 'born'.

The fluctuations of goat and sheep products (see Figures 7 and 8) are linked to the amount of milk that is available for cheese production. This, in return, is directly linked to the number of birth-giving and lactating animals and their reproductive cycle. Regarding the abstract surplus management as a kind of trade and an integration of the regional economy, the results show that, during the *Average Requirements* scenario, a continuous trade of a large surplus of dairy products is possible. Due to the higher consumption, a considerable smaller amount of dairy products was traded during the *Higher Requirements* scenario. If, however, the simulated settlement of the *Average Requirements* scenario does not have access to regional markets, the surplus amounts, now considered as 'traded', would be treated as waste. In this case, the population of the *Higher Requirements* scenario would have consumed according to their production of animal products, while producing only small amounts of surplus and wasted goods.

At the current state, a social buffer in the form of long-term planning is not implemented in the population agents' eating behaviour. Under real world conditions, the population might react to declining numbers of goat and sheep with long-term slaughter and a ceasing of consumption until the numbers have increased again. Implementing planning algorithms, such as goal-oriented action planning (GOAP) [105], would enhance the population agent's eating behaviour. Due to this, the population agents would be able to choose a possible way to achieve their goal (eating a predefined amount) by consuming the available goods and replacing, e.g., goat meat, with other goats, sheep or agricultural products. A more dynamic eating behaviour would also enable a more dynamic, less input-data-dependent simulation of population dynamics.

4.3. Herd Dynamics

The number of c. 300 goats and sheep is sufficient to cover the calorie requirements of a population consisting of around 175 people during both scenarios (compare Figures 6, 7 and 10). These numbers are much smaller than the requirements of the reference family used to extrapolate our initial population ([17], p. 220). This is due to the meat-and-dairy-based diet simulated by Dahl and Hjort [17], p. 220, which strongly affects herd dynamics.

For both simulation runs, the herd demographics differ from the reference herd from Dahl and Hjort [17], p. 96, especially for the sheep herd demographics (Table 4). While the proportions differ during the *Average Requirements* scenario by around c. 13 percentage points, and both goat and sheep herds predominantly consist of female individuals, the differences are even higher for the *Higher Requirements* scenario, and are up to 38.7 percentage points, leading to sheep herds predominantly consisting of male individuals. This indicates that our simulation tool is not able to reproduce the demographic patterns of the reference herd. However, this also indicates that the demographics of the herds are strongly influenced by the population agents' consumption; especially the sheep herds, which differ more strongly. However, Dahl and Hjort [17] do not provide information regarding the consumptive behaviour of the communities who kept the flocks, and thus a comparison under the same food composition is not possible.

Moritz et al. [106] use agent-based modelling to examine threshold values and minimum numbers and dynamics of herd growth in the context of pastoralist communities. Their results show that herds have the potential to grow exponentially. However, this is only the case in a hypothetical world, in which pastoralist families do not use their animals for provisions. If the animals are used and sold for provisions—like in our model—the herds are likely to grow linearly. However, our simulated number of animals does not grow linearly but follows a cyclical pattern instead (Figure 10). This is due to the implemented limit of animals per herd, which triggers the slaughter of individuals. Until this limit is reached, the simulated goat herds grow almost exponentially, whereas the number of sheep agents grows linearly. Continuously growing flocks would require extended grazing areas and more labour input. As the models that are run with a higher number of animals show (see Chapter 2 in the Supplementary Materials), higher numbers of animals can also lead to a collapse of the flocks. Thus, an equilibrium must be found between the number of animals and the availability of biomass. For this, additional information regarding pastoralist herd management is necessary.

4.4. Effects of External Disruptions

To explore the effect of pressure on the system dynamics, we implemented external disruptions during the 14th and the 35th year of the simulation. As the results show, the sudden loss of 30% of the animals has a short term influence on the population agents' consumptive behaviour. However, it has no significant influence on the further course of the simulation (see Figures 5, 6 and 10). Over the course of the simulation, the systems fluctuate around an equilibrium state and are able to recover from both disruptions. Due to the different reproduction rates, the goat herds are able to recover within c. 1 year, whereas the sheep herds require c. 7 years to recover.

The model can also be used as a tool to simulate stronger disruptions, mirroring conditions such as the great Anatolian famine of the 1870s, due to which, parts of Turkey lost 90% of their animals during a major drought and freezing winters [107]. In addition to the pure loss of animals—as our results also show—these events also have a significant influence on the herds' growth rates, which can take up to a decade to catch up with the pre-disruption growth rate ([17], p. 199).

4.5. Grazing Patterns

Currently, the pastoralist agents are designed to select the closest grazing spot that is suitable and provides roughly enough biomass to feed its herd for the day. In our simulation, the pastoralist herders prefer the plain in the western part of the study area and rarely use the more elevated or mountainous regions (Figure 11). In this case, these regions provide sufficient amounts of biomass to graze the herd (Figure 4, left). The implemented suitability does not affect the herd dynamics because the highly suitable grazing spots, as well as the available biomass, are more or less ubiquitously distributed (see Chapter 4 in the Supplementary Materials for a comparison between a simulation run with and without integrated suitability).

The simulated patterns are contrary to typical grazing patterns for transhumance-practising herders. During the summer, these herders move to highland areas to benefit from high quality pastures [108–110]. Especially in western Anatolia, the mountainous and more humid landscape might have played a central role for pastoralist societies [111]. The results of Fuller et al. [112] indicate that pastoralist communities at Sagalassos (Turkey) during the Classical–Hellenistic and Byzantine periods also herded their goats along the mountainsides. However, the simulated herders do not practise transhumance, but practise short-distance pastoralism instead. Moreover, agricultural production is not part of the current model version. Only a small area close to the settlement is treated as less suitable, but can be used by the herders. Therefore, in our simulation, pastoralists and their herds do not have to compete with agricultural production for high-quality land. In order to represent these effects, a suitability raster would be used, which provides this information. Therefore, more detailed information regarding the agricultural production in the study area is required.

The pattern of the activity areas resembles that of higher biomass values and corresponds to the fuzzy rules (Figures 4 and 11). The biomass-rich plane and its humid conditions close to the Bakırçay favour the occurrence of diseases such as foot rot [67].

The risk of infection is increased by accumulating manure [113], e.g., due to frequent grazing activities. This side effect of the terrain features and humid conditions was not considered. As a result of this, the current method to map the activity areas should be enhanced by implementing parameters such as the Topographic Position Index (TPI) [114]. Thus, additional and more specific suitability considering the avoidance of areas due to parasites (e.g., foot rot) could be modelled as well.

The model can also be used to simulate different types of behaviour. Due to the simplification of a rational thinking human being and the herder agents' behaviour as a *homo economicus*, a smaller number of animals leads to a higher grazing intensity and thus might cause locally increased degradation. Due to the higher calorie requirements, the number of goat and sheep agents in the *Higher Requirements* scenario is significantly lower than in the *Average Requirements* scenario (see Figure 10). Therefore, the biomass required to feed the herder agent's herd is also lower. Due to the fact that the herder agents try to minimise their effort, they select the closest suitable grazing area that provides sufficient biomass. The higher grazing intensity and the smaller activity area of the *Higher Requirements* scenario are side effects of the assumptions that were made to develop the model.

If data are available, the simulation tool allows for more nuanced assumptions about human decision-making and, especially, the selection of grazing spots, allowing us to assess overgrazing vs. sustainable use (on overgrazing, see [61], p. 101). Nevertheless, mapping grazing intensity seems to be a promising starting point for future analyses of human impact on natural systems. Currently, our model and data are not sufficient to assess the impact of grazing activities on the environment. Therefore, additional algorithms and modules are to be developed and implemented in future model version. Due to the open source approach, users can implement additional algorithms on their own. Approaches such as those presented by Barton et al. [25] or by Robinson et al. [115] could be a useful basis for the further development steps of the model.

Another possible way to approach this side effect would be more dynamic activity areas. The modelled activity areas determine the selection of grazing spots and, therefore, can be a central aspect of the simulation. At the current state, this input dataset is modelled prior to the simulation run and does not change over the course of the simulation. Due to, e.g., erosion, intensive grazing is likely to reduce the suitability of a frequently used spot (e.g., the "Sahel Syndrome" [116]). Future model versions could implement annually changing activity areas to assess the ecological sustainability of the modelled pastoral system.

5. Conclusions

In this paper, we present an empirical-based agent-based model as a first step towards an open platform of modular modelling components. The tool itself shows the possibilities of an agent-based modelling approach, developed using the Julia programming language and the package *Agents.jl*. It also highlights the possibilities and emerging opportunities of simulating socio-ecological dynamics, using an agent-based model, that simulates agents as individuals with a distinct and empirically based reproductive cycle.

The tool allows for the simulation of different scenarios, including, e.g., a varying consumptive behaviour or different herding strategies, as well as stronger, less abstract external disruptions. The modelling tool captures the fundamental socio-ecological dynamics of animal husbandry and food production in rural settlements. Therefore, the tool is valuable as a basis to discuss hypotheses regarding the number of animals that are needed to cover the requirements of empirically based growing populations. The geographic explicitness of the simulation allows us to map the grazing intensity and human impact on natural systems. Thus, with this tool, a step towards the open and transparent modelling of complex interactions between interrelated components is achieved.

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