

# Linking Spatial and Temporal Modeling: A Case Study from the Eastern Pamir, TJ

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## Abstract

The Eastern Pamir of Tajikistan is a remote high mountain region located in the east of Tajikistan. Today, a great share of the Eastern Pamir's local energy demand is satisfied by dwarf shrubs (*Krascheninnikovia ceratoides* and *Artemisia* spp.) and animal manure. Besides of their energetic potential, dwarf shrubs are an important nutrient source for local livestock. It is assumed that overuse of local dwarf shrub stands leads to a degradation of pastures. With decreasing pasture quality, potentially, less livestock can be kept by locals. Besides of the economic losses associated with a decrease in livestock numbers, yields of manure also decline. In order to compensate the missing manure yields, locals may harvest even more dwarf shrubs. Thus, potentially a self-reinforcing functional chain exists in this system. Breckle and Wucherer (2006) refer to the degradation of pasturelands due to excessive dwarf shrub harvest in the Pamir Mountains as *teresken syndrome*. In a field study, we identified typical current energy carrier usage patterns in the village of Alichur, the second largest settlement in the Eastern Pamir. We then used a System Dynamics and Geographical Information Systems combining hybrid approach to analyze the energy system of Alichur and we modeled two scenarios of the system: one pessimistic in terms of dwarf shrub growth and one optimistic. Both scenarios show that in the short to medium term a collapse of the energy system of Alichur is unlikely to happen. The optimistic scenario indicates that resource consumption currently is sustainable in terms of pasture quality and dwarf shrub balance. The assumed self-reinforcing functional chain could not be confirmed. After all, the model provides strong indications that the *teresken syndrome* does not apply for Alichur. In addition to these findings, the case study shows, that combining SD and GIS in one model, allows for a conceptual understanding of the modeled system (mainly SD part), mass-balance simulations (SD and GIS parts) and visualization of model results (GIS part). Thereby, in addition to the case study results, this work demonstrates that System Dynamics and Geographical Information Systems combining hybrid approaches are a powerful tool for case study analysis, model simulation and result presentation. The approach is able to clarify structural assumption on the regional Social-Ecological-System and to support management decision.

## 1. Introduction

The Eastern Pamir of Tajikistan (*rajon* Murghab) is characterized by arid plateaus at elevations of between 3,700 m asl and 4,000 m asl situated between mountain peaks of mostly 5,000 m asl to 5,500 m asl (Yusufbekov and Kasach, 1972). Precipitation rates of 60 mm to 120 mm per year (Tsatsenkin and Kasach, 1970) and average annual temperatures below 0°C (Yusufbekov and Kasach, 1972) allow only a short vegetation period of no more than a few months. Thus, vegetation is very sparse. A large part of the Eastern Pamir is covered by an *Artemisia ceratoides* kryophyt desert. Dominating plants are the dwarf shrubs *Krascheninnikovia ceratoides* (*teresken*) and *Artemisia* spp. (*shyvak*). Agriculture is not possible at this rough high mountain climate. Therefore, livestock farming plays an important role for the

local population. Locals keep Yak, sheep and goats. In terms of energy supply, the *rajon* Murghab today is a nearly self-sufficient region (Hohberg et al., 2015). This is caused by its remote location as well as by the political development, which has significantly restricted the exchange of goods with neighboring regions after independence from the Soviet Union in 1991. Following an aera of external energy supply with coal and diesel during soviet regime, now the energy demand of the Eastern Pamir's local population is mainly satisfied by the two dwarf shrubs *teresken* and *shyvak* as well as by dried animal manure. According to Breckle and Wucherer (2006), dwarf shrubs are not only one of the main energy carriers, but also local livestock's main source of nutrition, resulting in a competitive

utilization of dwarf shrubs. Moreover, Breckle and Wucherer (2006) point out that past thermal utilization of dwarf shrubs has caused degradation of pastures in the periphery of settlements. They bring up the term *teresken syndrome* to describe the degradation of pasturelands due to dwarf shrub harvesting for energetic purposes. Assuming the *teresken syndrome* influences the quality of pastures in the Eastern Pamir in the way described by Breckle and Wucherer (2006), it is only reasonable to expect also livestock density and therewith the amount of animal manure available to the local population to decrease. This, in turn, increases the pressure on the local dwarf shrubs and may finally cause a collapse of the current energy supply in the region. Kraudzun et al., (2014) point out that the *teresken syndrome* possibly does not apply for the Eastern Pamir. On the one hand, the share of dwarf shrubs in the local energy mix has been reduced to the advantage of animal manure during the last years. On the other hand, degradation effects as described by Breckle and Wucherer (2006) so far have not been quantitatively proven. Consequently, Kraudzun et al., (2014) conclude that the utilization of dwarf shrubs needs to be analyzed on a temporal and spatial resolution and that the interdependence between pasture quality and dwarf shrub harvest should be subject to further research.

It is the aim of the research reported in this contribution<sup>1</sup> to quantitatively analyze the *teresken syndrome* in a representative case study. To do so, we develop a model, which is not only spatially and temporally resolved, but also takes into account feedbacks in the system as described above. As a case study we describe, model and analyze the energy system of Alichur, the second largest settlement of the *rajon* Murghab and home of about 1,800 inhabitants. The target of the analysis is to formulate quantitative statements on stability, sustainability and possible developments of the Social-Ecological-System (SES) (Ostrom, 2009) in regard to energy resources for Alichur and similar high mountain SES, and thus to give recommendations on an improved SES management (Figure 1).

## 2. Methodology

### 2.1 System Dynamics

System Dynamics (SD) (Forrester, 1961) is an approach used for understanding the nonlinear behavior of complex systems over time. A core element of SD is the consideration of feedbacks within systems. Quantitative SD models visually delineate systems using stocks, flows and variables. While a stock represents any entity that

accumulates or depletes over time, a flow is the rate of change in a stock. Variables regulate flows through impacts. Classic examples for the application of SD are the fields of business cybernetics and social sciences. Beyond that, however, SD today is an established and accepted method in analysis of environmental systems and finds applications e.g. in the case of environmental impact assessments or in the area of resource management (Xu and Coors, 2012). Primarily, SD has not been developed for spatial modeling.

### 2.2 Realization of the Spatio-Temporal Hybrid Model

Linking Geographical Information Systems (GIS) - which is excellent for spatial modeling, but is extremely limited in respecting time - and SD in a hybrid spatiotemporal model creates a powerful tool for simulating the behavior of a SES. To combine SD and GIS in a hybrid-model we a) disaggregate space in grid cells, b) replicate the SD model (create model instances) for each grid cell and c) assign the SD-model calculation of each instance to its related grid cell. Therefore, in the hybrid-model each (GIS) grid cell corresponds to one (SD) model instance as illustrated in Figure 2. Spatiotemporal simulation thus operates as a spatially distributed calculation of a non-spatially resolved dynamic model. In the spatially explicit SD model, cell neighborhoods are defined and neighborhood effects are respected. Reference tables are used to transfer spatial data between GIS and SD model instances. In the reference tables, table rows represent model instances of the SD model or respectively the cells of the GIS grid. Table columns contain IDs that allow for the assignment of grid cells to model instances, as well as information on the current cell state (dwarf shrub biomass, grazing capacity etc.) and invariable cell characteristics (e.g., cost distance, biomass potential, type of vegetation). After simulation in the SD model, model variables of all model instances are exported from the SD model and visualized in GIS. For programming of the hybrid spatio-temporal model we used the software Simile (Muetzelfeldt and Massheder, 2003), GIS procedures are implemented by ESRI/ArcGIS 10.3/ArcTools/Model Builder.

### 3. The Energy System of Alichur

After literature analysis, the energy supply and demand situation of the village of Alichur was analyzed during several field campaigns in the years of 2013 and 2014.

<sup>1</sup>HÖBERG (2015) provides a more detailed report.

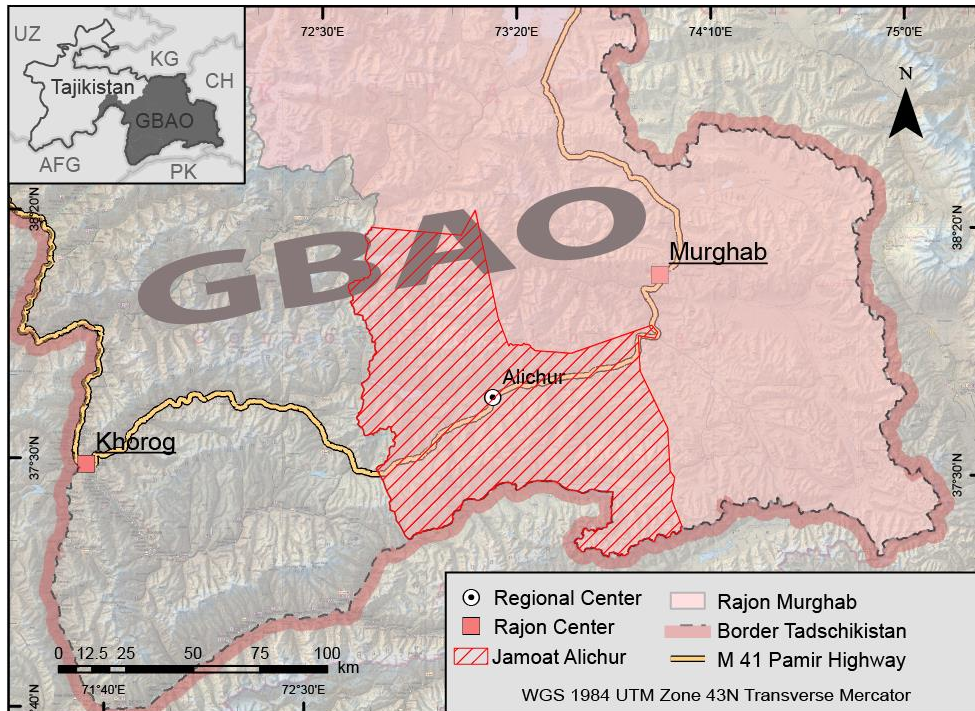


Figure 1: Rajon Murghab and the case study area located in the Eastern Pamir. GBAO = Gorno Badakshan Autonomous Region, Source: Hohberg (2015)

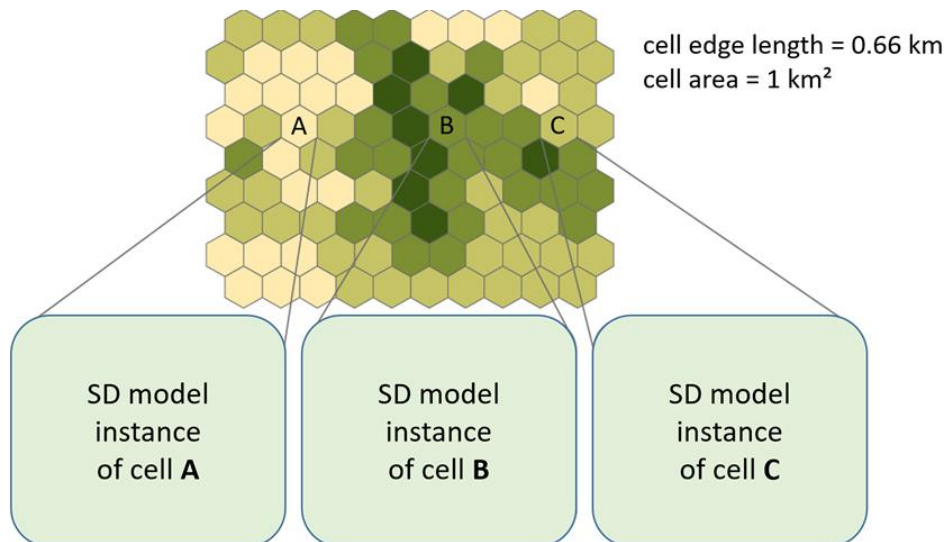


Figure 2: The SD model receives its spatial reference through disaggregation and assignment of model instances

During the field campaigns, we conducted a census of all 210 households in Alichur, took samples of energy carriers for thermal analysis, held expert interviews and recorded harvesting tracks by GPS in order to gain a comprehensive understanding of the local energy and harvesting system. Later on, SD was used for system analysis.

### 3.1 Model Structure

Figure 3 depicts the model structure resulting from the performed system analysis of Alichur's energy system. At the core of the model, we consider the energy mix of Alichur. The energy mix describes the share of the energy carriers *manure*, *dwarf shrubs* and *coal* used to cover the overall energy demand of Alichur.

The essential characteristics of the energy mix are determined by the sub-models *dwarf shrubs* and *grazing*, which specify the availability of the energy carriers dwarf shrub and manure. The sub-model *dwarf shrubs* is a spatially resolved model, whereas the sub-model *grazing* defines the availability of manure as the sum of the pasture capacities of all relevant pasture areas without spatial resolution. For spatial resolution, a 1 km<sup>2</sup> hexagon raster was chosen (Figure 2). The sub-models are parameterized by a series of exogenous input parameters, some of which are spatially resolved (e.g. shrub biomass). The model accounts for feedback during simulation: The amount of dwarf shrubs, which were extracted from the system for thermal utilization during a previous time step, directly affects the present and future availability of that resource. Excessive harvesting of dwarf shrubs leads to a degradation of pasture capacity, which causes a decrease in livestock numbers and available manure. Target variables of the model concern the energy mix of Alichur (consumption of manure, dwarf shrubs and coal), pasture capacity, the remaining dwarf shrub biomass and the difference between dwarf shrub biomass

growing and biomass harvested as an indicator for sustainability *S*.

### 3.2 Model Inputs

#### 3.2.1 Energy Demand

The 2012 census combined with calorific analyses of energy carriers yields a total energy demand of 34.0 TJ per year for the village of Alichur. For the single energy carriers, the following values resulted: 17.8 TJ (52.4 %) manure, 12.9 TJ (37.9 %) dwarf shrubs, 3.2 TJ (9.3 %) hard coal and 0.1 TJ (0.4 %) electricity.

#### 3.2.2 Forms of dwarf shrub harvest

We identified two main types of harvesting relevant for the inhabitants of Alichur: Individual Harvest (IH) and Group Harvest (GH). IH describes the collection of dwarf shrubs within close distance to the village of Alichur, mostly performed by single individuals. Presently people walk up to 6.5 km to harvesting sites. Harvested dwarf shrubs are bundled and brought to Alichur by donkey. GH is performed by up to eight persons, who in a common effort drive by truck to harvesting areas with high dwarf shrub densities.

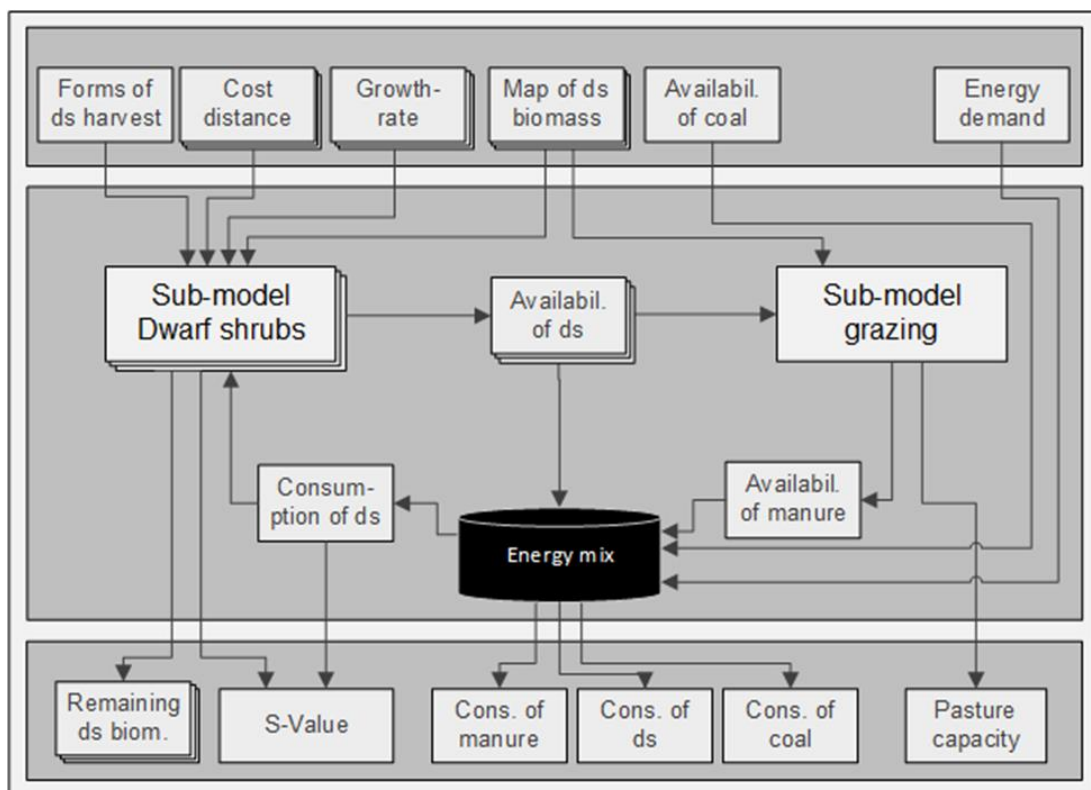


Figure 3: Energy system of Alichur as modeled in the SD-GIS-hybrid model, components depicted with multiple frames were modeled spatially, Source: Hohberg (2015)

Currently harvesting groups drive to distances located up to 45 minutes from the village of Alichur for harvest. For simplification and due to its marginal occurrence, dwarf shrub mass harvested by motorcycle was assigned to IH and GH equally shared, dwarf shrub mass harvested by shepherds on summer pastures was assigned to GH. In 2012, 71 % of the harvested dwarf shrub amounts were brought to Alichur by GH and 29 % by IH.

### 3.2.3 Harvesting map

The harvesting map fulfills two functions: 1. it is needed to identify the total area potentially available for dwarf shrub harvest around the village of Alichur and 2. It allows to delimit harvesting areas from each other. By the help of the harvesting map, the origin of the dwarf shrub biomass harvested, can be spatially located. We generated the harvesting map of Alichur using a multi-stage procedure of mapping (on the base of historic map data and satellite images) and checking on site (by locals). The resulting harvesting map consists of 61 harvesting areas and covers a total area of about 2,000 km<sup>2</sup>.

### 3.2.4 Spatial model for dwarf shrub harvest

During our field studies, we found that the location of the site of dwarf shrub harvest depends mainly on three site characteristics: (1) Slope, (2) distance to Alichur (in terms of time needed to reach the site) and (3) stand density. We assumed that all site characteristics differ for the two forms of harvesting IH and GH. In order to derive the movement characteristics of each harvesting form, we evaluated seven GPS harvesting tracks of IH and 14 GPS tracks of GH activities, which had been recorded by locals. It was found, that for GH, the formal and informal road system in the region was crucial for travel time, while travel time for IH mainly depends on slope. Rivers act as barriers for both, IH and GH. Statistical analyses showed that both harvesting types are performed on slopes of up to 20° of inclination. Masking all areas reachable via slopes no steeper than 20° in the harvesting map of Alichur, reduces the area available for dwarf shrub harvest to about 1,000 km<sup>2</sup>, which is half the area of the total harvesting map. Travel speed for harvest by foot (IH) is detected between 4.1 km/h and 5.2 km/h and for harvest by truck (GH) between 13 km/h and 36 km/h on road and 8 km/h off road. Using this information, cost raster layers were calculated with the help of the ArcGIS model builder for both IH and GH.

Finally, based on the cost raster layer, the cost distance (time necessary) to reach a grid cell from the village center of Alichur was derived using ArcGIS tool *cost distance*. Figure 4 shows the resulting cost distance map for GH.

The relation of a stand's current biomass to its biomass potential is referred to as stand density. In field studies we found that after IH stand density decreases down to 0.2, whereas after GH mostly stand densities of more than 0.5 remain. Furthermore, GPS-track analysis showed, that IH takes place on any sufficiently stocked stands and GH spares winter pastures. According to locals involved in GH, shepherds do not allow for GH on their winter pastures, which confirms the findings from GPS-track analysis.

### 3.2.5 Dwarf shrub biomass and growth characteristics

Zandler et al. (2015) provide a dwarf shrub biomass map of the Eastern Pamir of Tajikistan (Figure 5). The dwarf shrub biomass map is product of an allometric model, which correlates dwarf shrub coverage from satellite images and dwarf shrub biomass sampled in the field. According to Zandler et al. (2015), dwarf shrub biomass in the case study region varies between 0 kg/ha and 10,000 kg/ha with a mean of 1,574 kg/ha. At elevations of 4,000 m asl up to 4,400 m asl, dwarf shrub stands with biomass densities between 2,000 kg/ha and 5,000 kg/ha are frequent.

The logistic equation describes the net growth of populations, such as dwarf shrubs, in environments with limited resources. Basis of the logistic equation is an exponential growth model in which the annual growth of a stock is a product of the growth coefficient  $r$  and the population size  $N$ . In order to consider competition in the equation, the growth coefficient  $r$  is inversely proportional to the population size  $N$ . For population sizes that are, in relation to the carrying capacity of their environment  $K$ , of very small size, growth is exponential. However, the closer the population size  $N$  approaches its environment's carrying capacity  $K$ , the smaller the growth coefficient  $r$  becomes. For populations whose size has reached their environment's capacity  $K$ , growth is ultimately zero. Figure 6 shows the growth rate of a population in an environment of limited resources as a function of population size (a) and the resulting development of population size over time (b). The logistic equation is suitable to describe the growth of dwarf shrub stands in the Eastern Pamir.

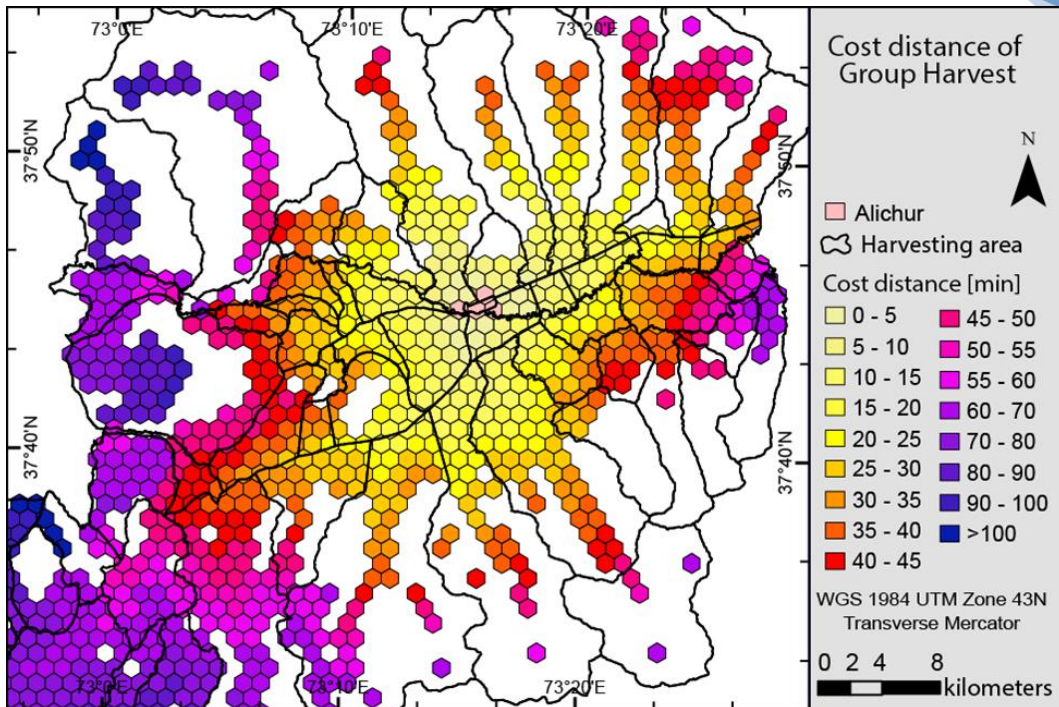


Figure 4: Cost distance raster for group harvest

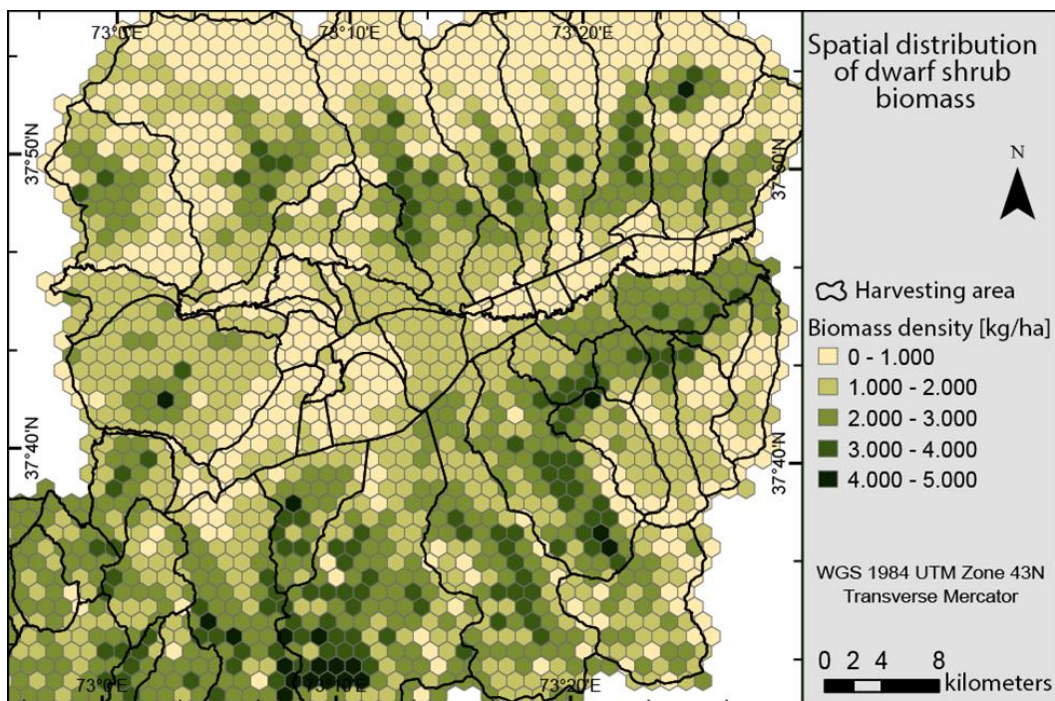


Figure 5: Dwarf shrub biomass in the case study region. Data: Zandler et al., (2015)

Numerous authors give suggestions for the growth rate of dwarf shrubs in the Eastern Pamir (among others: Breckle and Wucherer (2006), Clemens (2001) and Walter and Breckle (1986). Yet, none of the suggested values is based on long-time

observations. In order to account for the uncertainty of the growth rate  $r$ , we simulated two scenarios: one scenario assuming slow growth (pessimistic scenario) and one scenario assuming fast growth (optimistic scenario). We choose  $r = 3.6\%$  per year

and 5.6 % per year as growth coefficients. These values correspond to a maximum net biomass growth ( $N = 0.5 K$ ) of 45 kg/year and 70 kg/ha for dwarf shrub stands with a biomass potential ( $K$ ) of 5,000 kg/ha. The sub-model *dwarf shrub initially contains* the dwarf shrub biomasses shown in Figure 5. During simulation dwarf shrub biomasses increase due to growth (as described by the logistic equation) or decrease due to harvest (by GH or IH).

The natural biomass potential of anthropogenic influenced stands was approximated on harvesting area level as we assume that growth conditions are similar within harvesting areas. We approximate the natural biomass potential of simulated cells based on the harvesting area level. In the model, a cell's biomass potential is either 50 % of the highest biomass density found in the harvesting area, or, if the current biomass density of the cell is higher than this value, the cell's current biomass density.

### 3.2.6 Competition between dwarf shrub harvest and livestock keeping

Vanselow (2011) examines the vegetation of the Eastern Pamir in detail. He identifies six different vegetation classes in the case study region. Each of the vegetation classes consists of a different composition of the vegetation components *dwarf shrubs*, *herbs and grasses* and *cushion plants*. Sheep, yak and goats kept by locals have different demands on fodder plants. Goats for example are able to digest about 50 % of proteins contained in cushion plants, whereas sheep and yak are not able to digest these pasture components at all (Vanselow, 2011). Using Vanselow's (2011) vegetation classification in combination with the nutritive values that he

provides for each vegetation component, the pasture potential for yak, sheep and goat was derived. For simplification, we considered average herds representing the average livestock composition found in the census in our model. The average herd consists of 1 yak, 1.7 sheep and 1.2 goats.

The limiting factor for livestock keeping in the region is the availability of winter pastures. Currently, at least 23 winter pastures are used by the inhabitants of Alichur (Kraudzun, unpublished). Based on the findings of Vanselow (2011) we assumed an average range of movement of 2.8 km around each pasture camp and a maximum inclination of  $36^\circ$  for winter pastures in the sub-model *grazing*.

Figure 7 shows the winter pastures and the vegetation classes prevailing on them. In total about 40,000 ha of Alichur's vicinity are winter pastures. While in the sub-model *grazing*, the nutritive value of the vegetation components *herbs and grasses* and *cushion plants* is fixed, the nutritive value of the vegetation component *dwarf shrubs* depends on the current dwarf shrub biomass given from the sub-model *dwarf-shrubs*. A decrease in dwarf-shrub biomass on a winter pasture due to harvest therefore causes a decrease in pasturing potential. Currently about 1,700 average herds are kept on Alichur's pastures. Given the pasture potential derived using the data on average nutritive values of Vanselow (2011), the livestock can be fed for 9.8 month per year on the winter pastures. Pasture potential and manure availability are directly linked. We estimated the average annual production rate of manure for energetic purposes based on the statements of local livestock farmers on animal specific manure production rates.

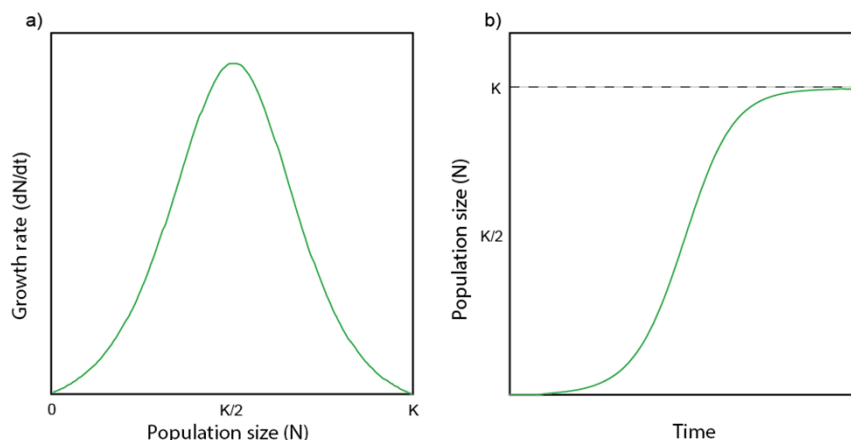


Figure 6: a) Logistic growth function with growth rates of 0 at population sizes of 0 and  $K$  and a maximum growth rate at  $K/2$ . b) S-shaped growth curve of a population as resulting of the logistic growth model

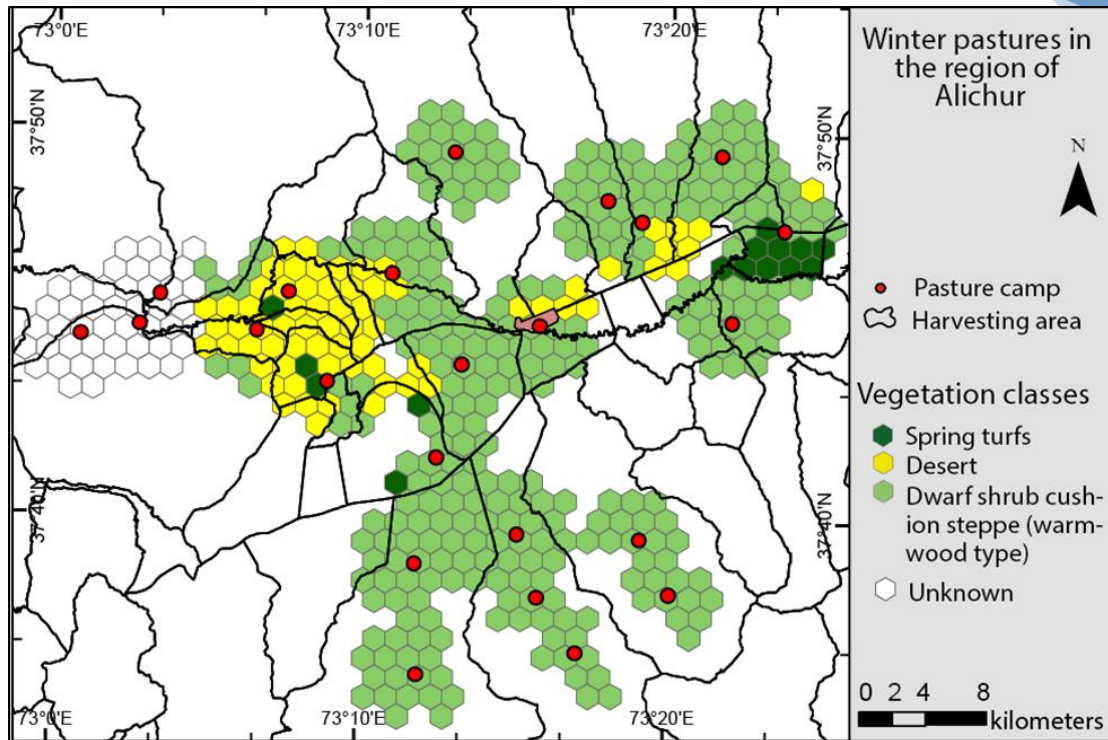


Figure 7: Winter pastures in the region of Alichur. Data: Vanselow (2011) and Kraudzun (unpublished). Graphic own work

We found that an average herd produces on average 747 kg/a of energetic utilizable manure. Since currently winter pasture potential is completely utilized, a decrease in winter pasture potential automatically reduces the amounts of average herds kept in the region and thus the manure available for burning. In our interviews, locals reported that a decrease in available manure is compensated by dwarf shrubs. This pictures the core assumption that the *teresken syndrome* is a self-enforcing feedback.

### 3.3 Scenario Simulation

#### 3.3.1 Model setup

Dwarf shrub biomass is simulated on a 1 km<sup>2</sup> hexagon grid. For the initialization of IH, all grid cells with dwarf shrub biomass densities of at least 1,000 kg/ha (upper limit) within a range of 90 min. travel distance from Alichur (according to the IH cost-distance raster) are harvestable. Once dwarf shrub harvest in a grid cell has started, the cell can be harvested until a minimum of 500 kg/ha (lower limit) remain. For GH, all grid cells with a minimum biomass density of 2,500 kg/ha (upper limit) are harvestable. After harvest at least 1,850 kg/ha (lower limit) dwarf shrub remain. In each time

step, dwarf shrub harvest (IH and GH) takes place in the harvestable cells that have the least cost distance relative to the village of Alichur. While IH is performed in any grid cell holding sufficient dwarf shrub biomass, GH spares cells that are winter pastures. The availability of manure is specified by the total carrying capacity and the resulting number of average herds available at each time step. If the availability of manure decreases, the total demand for dwarf shrubs increases proportionately. Simulation time is 100 years, or, if a deficit in harvestable dwarf shrubs by IH occurs, until the time the deficit appears. While a deficit of biomass harvestable by GH can be compensated through IH in the model, we interpret a deficit in harvestable dwarf shrubs by IH as a collapse of the energy system. At this time, people are not able to satisfy their energy demand anymore. According to the period input data, the simulation starts in the year of 2013. To evaluate sustainability of the system modelled, we derive a sustainability factor  $S$ , which is defined as the quotient of biomass growth rate and biomass harvest rate (Equation 1). If  $S \geq 1$  we define the system to sustainable. An unsustainable state of the system is indicated by  $S < 1$ .

$$S(t) = \frac{\frac{dN}{dt}(t)}{\frac{dE}{dt}(t)}$$

with  $\frac{dN}{dt}$  is biomass growth rate and  $\frac{dE}{dt}$  is biomass harvest rate

Equation 1

### 3.3.2 Model evaluation and model validity

Numerical models of environmental systems cannot finally be validated (Ford, 2009). Greenberger et al., (1976) argue that, for ecological models, the term *valid* represents the degree of trust in model behavior for a defined purpose and under defined conditions rather than an overall quality label. In modeling, the term *validation* typically is associated with the comparison of simulation results and historical data. Yet, this kind of validation is possible only when historical data is available. In environmental modeling, such data is often lacking. Using models without historical data implies a form of deductive reasoning (Beven, 2009). In models without available historical data, model findings fully depend on the (subjective) initial assumptions. The uncertainties of these assumptions carry forward through the whole model. *Forward uncertainty analysis* (Beven, 2009) describes the quantification of model quality by carrying forward initial uncertainties. For *forward uncertainty analysis*, it is essential to know which input parameters, model predictions are most sensitive to. This information is typically gained through sensitivity analysis. While Beven (2009) argues that the method of deductive reasoning has a long tradition in science and is a widely recognized procedure, Ford (2009) even considers the systematic varying of model parameters, as it is performed during sensitivity analysis, one of the most insightful validation tests.

Our model of Alichur's energy system is widely based on measured data, which was obtained during our field stays in the project region. Yet, as a model of an environmental system, numerous model inputs are uncertain. Furthermore, historical timelines were not available for most of the model parameters. We thus performed a *forward uncertainty analysis* for model validation. We used the parameter  $S$  as a target value for model evaluation. By performing the ANOVA F-test, we tested several model input and management parameters for sensitivity.

It turned out that in general, the sensitivity (F-value) of model input parameters is higher than the sensitivity of management parameters. Yet, with increasing model time, the sensitivity of the management parameters increases whereas the sensitivity of the input parameters is greatest for the simulation start.

This finding is reasonable, as it states that the earlier a management decision is taken, the stronger it influences the future state of the system. Furthermore, the charts of all tested model variables showed reasonable trends. Thus, the model properly represents the mechanisms of action in the case study region. For model calibration we varied the harvesting parameters *upper limit* and *lower limit* for GH and IH as to match the mean traveling times (cost distances) yielded from GPS-track evaluation. At the time of evaluation (in 2012), these were 43 minutes for GH and 42 minutes for IH.

### 3.3.3 Simulated scenarios

We modeled two scenarios: a pessimistic scenario (BAU\_a) and an optimistic Scenario (BAU\_b). Both scenarios simulate the energy system based on the current dwarf shrub management parameters (as described in the previous section) and assume them to stay constant in the future. Thus, scenarios are coded by BAU, which stands for Business-As-Usual. The difference between the two scenarios consists in the dwarf shrub growth factor  $r$  (under ideal conditions without competition), which is 3.6 % per year in the pessimistic scenario and 5.6 % per year in the optimistic scenario. The two scenarios respect the variance of growth conditions and thus consider a worst and a best case.

### 3.4. Simulation Results

*Pessimistic scenario (BAU\_a)*: Figure 8 and Figure 9 show the development of dwarf shrub harvest in scenario BAU\_a in time and space (Figure 8) and the development of the remaining harvestable biomass and  $S$  in time (Figure 10). During the first 30 years of simulation, the average time needed to reach harvesting sites for GH and IH increases continuously. It reaches 69 minutes for IH and 55 minutes for GH in the year 2043. Remaining harvestable biomasses for GH and IH simultaneously decrease in the simulation. In 2068, no harvestable dwarf shrub biomass remains, neither for GH nor for IH and the energy system collapses. Even though  $S$  continuously rises, it does not reach 1 before the biomass reserves are exhausted.

Dwarf shrub biomass densities above 2,500 kg/ha do only remain on winter pastures and on slopes that cannot be harvested. At the time of the system collapse, an average of 1,407 kg/ha dwarf shrub biomass remains in the system, which is only 6.8% less than in the beginning of simulation (2013). In 2068 1,677 average herds, are kept on the winter pastures, which is nearly the same amount as in 2013 (1,687 average herds). The stability in livestock numbers can be explained by the fact, that only IH takes place on winter pastures and that those pastures that can be accessed for IH are at the present already degraded. Due to the constant livestock numbers, the simulation also yielded a constant energy mix. Dwarf shrub utilization did not increase due to pasture degradation.

*Optimistic Scenario (BAU\_b):* The reason for this lies in  $S$ , which is from the start of the simulation on considerably higher in scenario BAU\_b as compared to scenario BAU\_a. With increasing model time,  $S$  approaches 1 and the remaining harvestable dwarf shrub biomass stabilizes at about 7,000 t. In the second half of the simulated period, an increasing number of previously harvested model cells are harvested again by both forms of harvest. Consequently, time needed to reach harvesting sites stabilizes at around 45 minutes for GH and 50 minutes for IH. The feedback between IH and livestock keeping does not play any role in this scenario. At the end of the simulated period, 1,690 average herds, two more than in 2013, are kept on the winter pastures in the region. The energy mix stays constant during the complete simulated period.

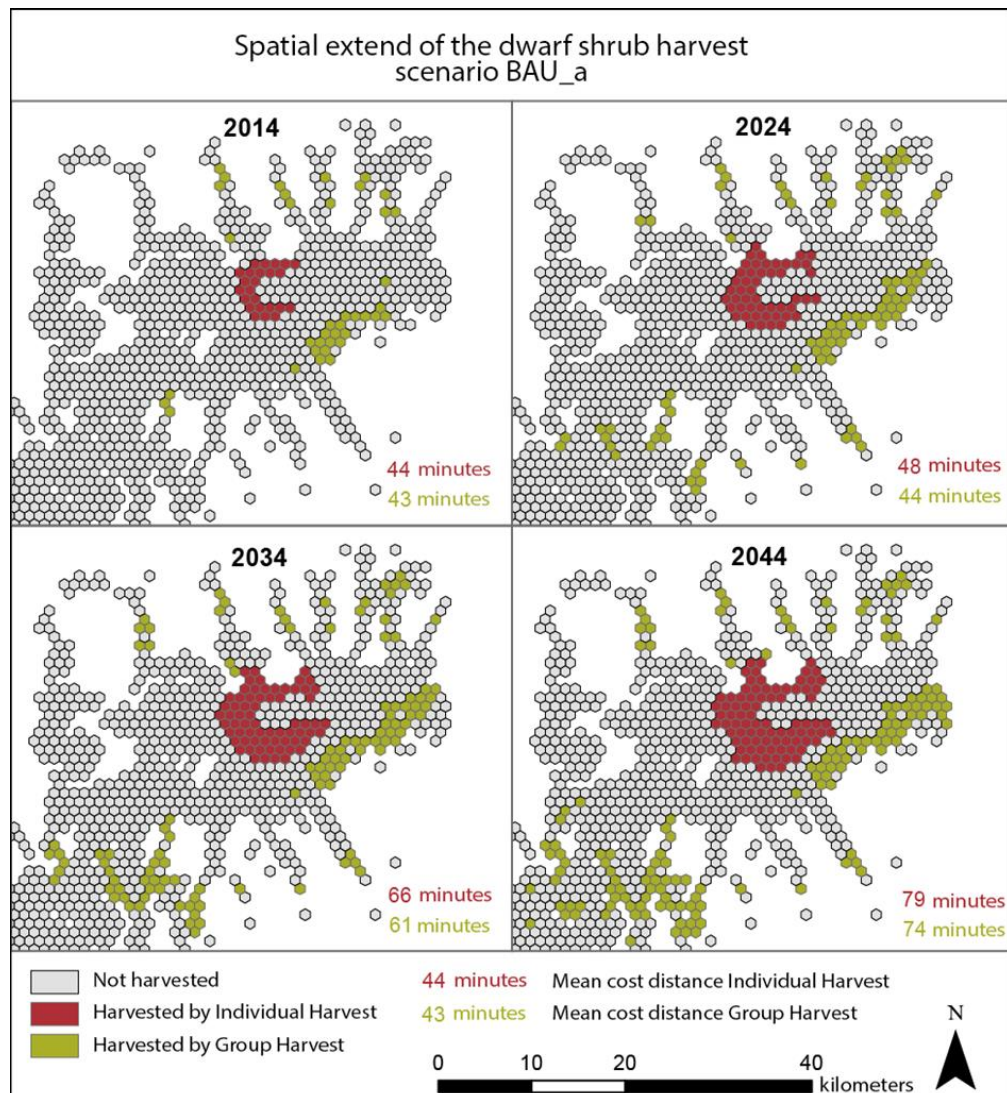


Figure 8: Spatial extend of IH and GH in scenario BAU\_a over time

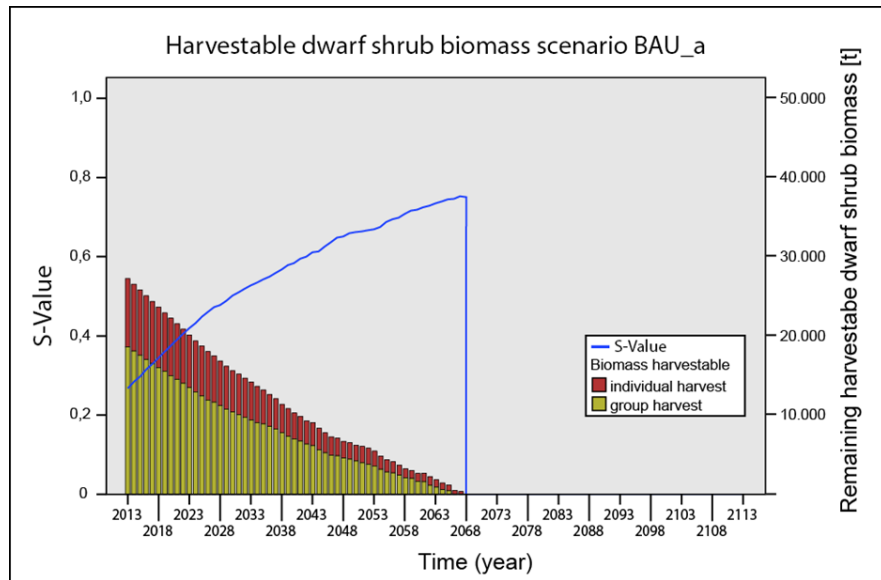


Figure 9: Remaining harvestable biomass and course of the S in the pessimistic scenario (BAU\_a). The vertical line represents the time of system collapse

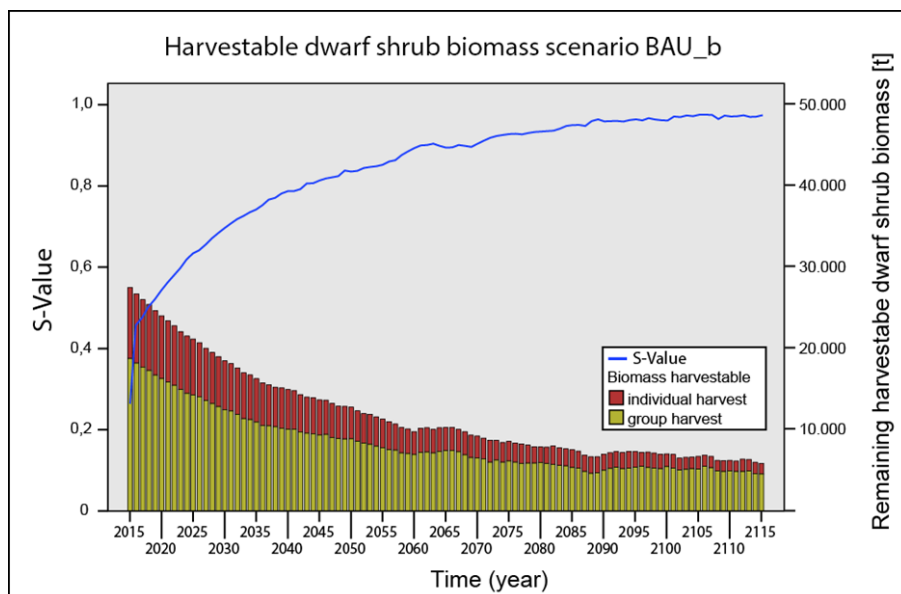


Figure 10: Remaining harvestable biomass and S in the optimistic scenario (BAU\_b)

## 4. Conclusion

### 4.1 Synthesis

By analyzing the energy system of Alichur and creating a spatiotemporal hybrid model, we clarified functional relations in the system. General dwarf shrub utilization patterns were identified and pictured in the model. Simulation results showed that the people of Alichur do not have to fear a collapse of their energy supply within the next decades. While the pessimistic scenario simulated indicates enough remaining harvestable dwarf shrub biomass for at least 50

years, the simulation results of the optimistic scenario even suggest that the current dwarf shrub usage pattern does not exceed regrowth of the plants and may thus be called sustainable in terms of dwarf shrub biomass balancing and pasture potential. Already in the system analysis it became clear, that a competing exploitation of the local dwarf shrub stands for firewood and for fodder is limited to the close surrounding of the village of Alichur. Changes in the energy mix did not occur. In the pessimistic scenario, after system collapse, more than 90 % of the initial

dwarf shrub biomass is available in the modeled area. We conclude that the term *teresken syndrome* does not adequately describe the situation in Alichur.

As habitat is a key element of every ecosystem, space plays a crucial role in the understanding a SES. Human interaction in a SES influences the state of ecosystems not only in space, but also in time. At the same time, the state of natural ecosystems influences management decisions of those who depend on ecosystem services. Thus, understanding ecosystem's dynamics over space and time is a crucial prerequisite for successful ecosystem management. With our case study, we demonstrated that a SD-GIS-hybrid can be an appropriate tool for ecosystem management when considering ecosystems in the wider context of SES.

#### 4.2 Critical Outlook

A model draws a simplified image of reality. As Box (1979) puts it: "All Models are Wrong, Some are Useful". The aim of modeling is to draw the big picture. To do so, it is important to identify and to consider only those aspects of reality that are of greatest importance to answer a research or management question. The energy model of Alichur, which has been described in this article, contains a strongly simplified structure as compared to the real world. We assumed uniform and constant dwarf shrub harvesting mechanisms. Yet, actually harvesting decisions are met by individual subjects and are based subjectively. Using a top-down approach, the energy model described does not consider subjective actors. Furthermore, the choice of energy carriers of some inhabitants of Alichur may differ from the mechanisms underlying our model, as there may be personal preferences for one or another energy carrier.

Despite our intense fieldwork, the entire model input parameters involve uncertainties. We tried to weaken this effect for the most uncertain input parameter, *dwarf shrub growth*, by considering two different scenarios. Apart of all uncertainties in the model, even uncertain models are valid to identify trends in a system, and, furthermore, the process of modeling itself is beneficial for the understanding of a system (Beven, 2009). Therefore, the model presented is to be seen as a step in a learning process. It should be adapted once more data becomes available for further validation. In this sense, the energy model of Alichur is a useful tool to understand resource management in the Eastern Pamir and to initiate and bring new insights into

the discussion on the future of the livelihood in the remote Eastern Pamirs.

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