# Dartmouth in Namibia

**Dartmouth College, Environmental Studies Program, Hanover NH USA**

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# Assessing the carrying capacity of the Kuiseb River ecosystem for Topnaar livestock

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## Abstract

Carrying capacity is important for understanding ecosystem balances and sustainable population dynamics. The purpose of this study was to estimate the carrying capacity of the Kuiseb River ecosystem for Topnaar livestock, and to better understand the relationship between spatial distributions of cattle and pod-producing tree species. Two different census methods and body condition scores were used to assess the abundance and relative health of cattle in the system, and a series of tree productivity measurements were used to extrapolate the most productive areas of the riverbed. We found that cattle abundance increased with increasing relative abundance of *Faidherbia albida* trees, but mean *F. albida* pod production decreased with relative species abundance. We conclude that carrying capacity has not yet been breached within our study area, but monitoring of the riparian vegetation and livestock numbers will be important in the face of climate change and intensification of extreme weather events.

## Introduction

Competition for limited resources is widespread in both natural and human systems, and can often act as a point of conflict at the interface between the two. Resources may be limiting for wildlife populations and have widespread impacts on economic systems. Recognizing an ecosystem's limits is critical for the sustainability of socio-ecological systems on both global and local scales. When a system's capacity to support a population is exceeded, resource dynamics can be altered, sometimes permanently, via environmental degradation (Tuffa & Treydte 2017). The idea that the limits of an ecosystem can be exceeded informs our understanding of what regulates populations, and forms the basis of the concept of an environment's *carrying capacity*.

There are many factors that determine the maximum population sizes that an ecosystem can support without exceeding its capacity. The dietary and nutritional needs of animal species must be met to sustain healthy populations. Water is another critical resource not only because animals need to drink, but also because the amount of water is a critical determinant of primary productivity available to consumers, and thus indirectly to the rest of the food web. In addition to resource availability, inter-species competition resulting from spatial and dietary overlap has a profound effect on population sizes. As one population increases, the pressure it exerts on an ecosystem reduces the availability of resources for other populations.

The idea of carrying capacity and its various determining factors are especially pertinent to the study and practice of pastoralism, as livestock are integral to many cultures and socioeconomic systems. Like humans and wildlife, livestock are equally dependent on an ecosystem's natural resources. They are therefore subject to population limitations imposed by finite resources. Above all other livestock species, cattle are predominantly valued by people around the world not only as sources of food- but also as a form of investment and economic stability. Thus, it necessary to consider their needs as a component of carrying capacity. Cattle have specific nutritional requirements that intensify with extreme heat or cold, making some rangelands more suitable for them than others. They require a wide variety of vitamins and minerals, such as calcium, phosphorus, and vitamins A, D, and E (Gadberry 2010). A high quantity of protein is also essential to their diet, particularly during lactation and towards the end of gestation periods (Lalman et al. 2007) and thus have a large impact on population productivity.

The ability for cattle to fulfill their resource requirements is hindered by the challenges in resource-scarce environments. Our study focuses on livestock management along the Lower Kuiseb River, one of twelve ephemeral rivers traversing the Namib Desert in Namibia. The desert is characterized by minimal rainfall and low primary productivity. Rainfall averages at less than 10 mm per year, and many organisms depend predominantly on fog and groundwater because rainwater is not a reliable water source (Eckardt et al. 2011). These environmental factors limit the abundance of life that can survive in this harsh ecosystem. However, animals can access higher abundances of key resources sequestered in ephemeral rivers. The Kuiseb provides sources of food and water for plants, wildlife, and livestock, forming a biodiverse riparian ecosystem, or "linear oasis" (Kok & Nel 1996). Two seed pod producing trees, *Acacia erioloba* and *Faidherbia albida*, are key resources affecting carrying capacity as wildlife and livestock rely on their seed pods as their primary food source (Moser 2006). Per annum, an *A. erioloba* tree produces an average of 135 kg of pods, while a *F. albida* tree produces an average of 120 kg. These pods are high in protein and carbohydrates, and they have sufficient levels of calcium and phosphorus to fulfill the nutritional requirements of cattle (Jln et al. 2017). Due to the crucial role that these trees have in forage provisioning, part of our study assessed their relative abundance and pod productivity.

Despite the aridity of the surrounding desert environment, these pod producing trees, and the nutrients they provide, enable the pastoralist lifestyles of local communities to persist. For the Topnaar, an indigenous Namibian people who live along the Lower Kuiseb River, pastoralism is entrenched as a cultural and economic practice. The Topnaar people have lived in the Lower Kuiseb River region for nearly 800 years, raising livestock under extreme desert conditions (Desert Research Foundation of Namibia 2015). Historically, the Topnaar were nomadic, but their mobility has become increasingly limited by expanding human populations, international borders, exclusion from conservation areas, and decreased access to water (Jacobson 1995). Those who have not found work in urban centers continue to dwell along the Kuiseb river, where they keep a variety of cattle, goats, sheep, and donkeys. Although Topnaar livestock management practices have been successful in the past (Desert Research Foundation of Namibia 2015), it is unclear whether the Kuiseb can support the current number of livestock. For instance, in the past year, it was reported that livestock numbers significantly decreased in the Lower Kuiseb River (J. Kooitjie, *pers. comm.*, 27 October 2017), which might indicate that livestock have exceeded the Kuiseb's carrying capacity. Understanding the degree to which livestock can be supported by key resources in the Lower Kuiseb is critical for assessing the sustainability of this socio-ecological system and for the continuation of Topnaar pastoralism.

These livestock populations and this ecosystem provide an ideal sample for assessing carrying capacity because the variables in an arid environments that affect carrying capacity are especially clear and their effects are particularly profound. Furthermore, there are less confounding factors contributing to population pressures than in other socio-ecological systems. Understanding carrying capacity can help prepare pastoralists here and in other arid environments for adaptive livelihood strategies, given the inevitable effects of climate change. Therefore, we have taken a multiphase approach to studying population pressures and environmental conditions as they relate to livestock carrying capacity in this system. We first estimated the current livestock population size, utilizing two different methods. We then evaluated the spatial patterns of pod producing trees, as well as livestock distributions and health, and the relationships between them. In doing so, we aim to determine whether the region's carrying capacity has been exceeded and the implications for Topnaar pastoralism along the Kuiseb River.

Regarding the census, we hypothesize that there will be approximately 400 cattle in the lower Kuiseb region based on the most recent approximations. With regards to the spatial patterns of pod producing trees and livestock, we hypothesize that there will be a positive correlation between tree pod productivity and cattle density, as well as an increased density of productive trees and cattle further upstream because of greater water availability resulting from the geomorphology of the Kuiseb. Cattle health will also correlate with higher densities of productive trees. Finally, we hypothesize that cattle have reached, or are close to reaching, carrying capacity in the lower Kuiseb river region due to limited access to key resources.

## Methodology

### *Study area description*

Our study area encompassed a 55 kilometer stretch of the riverbed previously identified by Morgan (2017; see figure 1). It was extended to 65 kilometers in order to further expand the reach of our cattle census. The study area was selected in order to build upon previous research and existing data. The portion of the Lower Kuiseb River that comprises our study area contains the Topnaar settlements Kharabes, Soutriver, Natab, Oswater, and Homeb, which allows for analysis of our variables in relation to community locations.

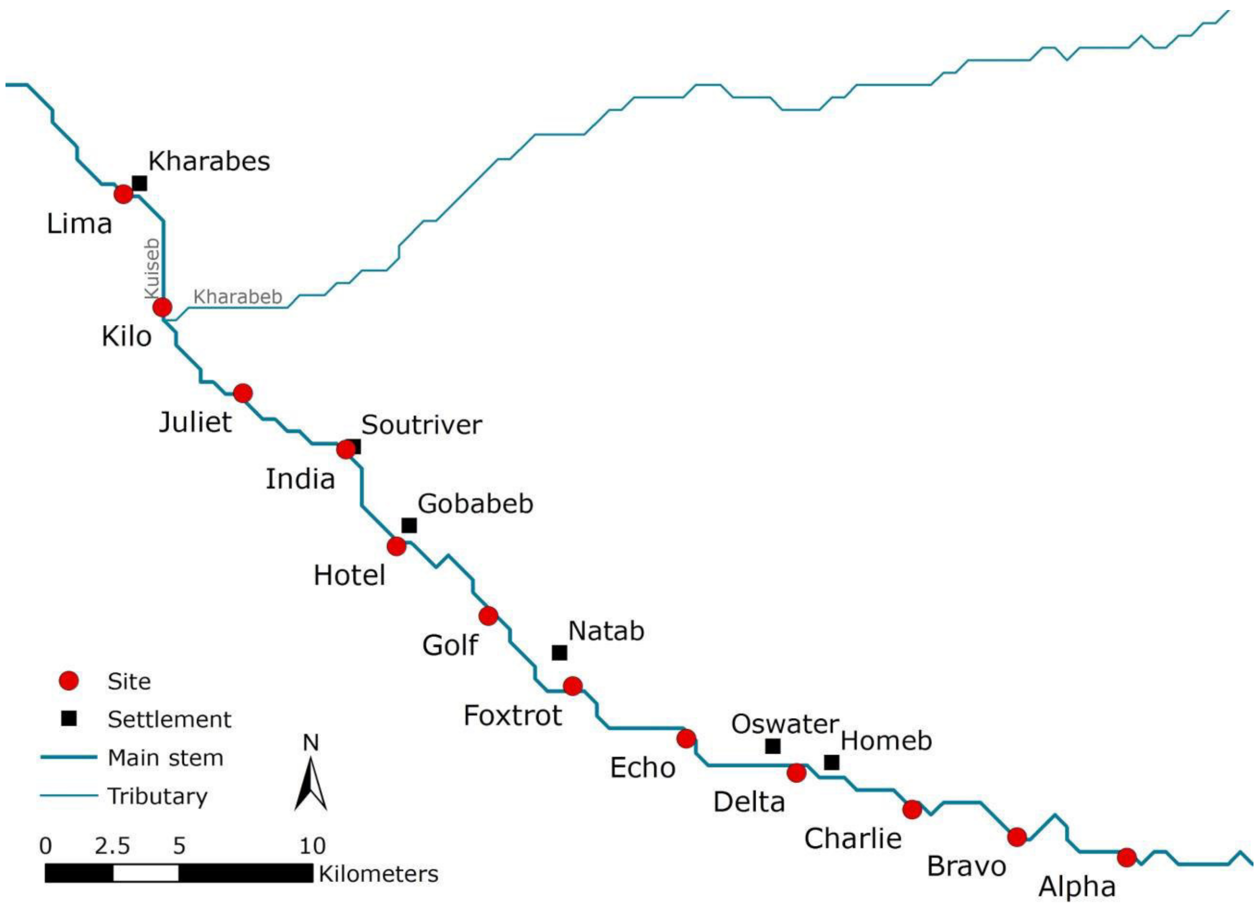


**Figure 1.** The 65-kilometer study area stretch showing transects and settlements (Source: Morgan 2017).

### *Cattle Abundance and Health*

*Complete Enumeration*

In order to gauge the populations of wildlife and livestock species a complete enumeration of all animals was performed. Starting upstream 5 kilometers above transect Alpha, every cow, sheep, goat, donkey, and wild ungulate species observed from the track we traveled along the Kuiseb riverbed was recorded as we drove downstream, ending 5 kilometers past our final transect Lima. For this census method the study site was expanded by 10 km in order to include livestock that had wandered into the area immediately outside of the initial study area. The enumeration was done in the span of one day to prevent recounting.

*Mark and recapture*

In addition to complete enumeration, we used the mark and recapture method along with the Lincoln-Peterson estimator to approximate the amount of cattle in the study site. This method is suitable for this study site because the system is closed and a proportion of the cattle are marked with unique identification ear tags. By writing down identification numbers we essentially “marked” cattle, and by writing down the total number of cattle sighted, we were able to determine the specific proportion of these marked to unmarked cattle.

The formula for the Lincoln-Peterson estimator is listed below:

$$N = Kn/k$$

Where N is total population size, K is the number of animals captured on the second visit, n is the number of animals marked on the first visit, and k is the number of animals recaptured that were marked.

On day one between the hours of 16:00 and 19:00 starting at transect Alpha and ending at transect Hotel every head of cattle was recorded, along with every identification number. On day two between the hours of 16:00 and 19:00 starting at transect Hotel and ending at transect Lima every head of cattle was recorded, along with every identification number. This data was compared with the data from our complete enumeration day, in which we also recorded cattle identification number along with total cattle counts. We then applied the Lincoln-Peterson estimator (Lettink & Armstrong 2003) to approximate total number of tagged cattle and multiplied this by the proportion of untagged to tagged cattle to ascertain cattle population size.

*Cattle Body Condition Scores (BCS)*

We used a body condition score index template to determine the health of cattle that were identified during the 3-day livestock census (Appendix 1). Individuals were scored with values 1-5, with 5 indicating the most body fat and suggesting highest health. Cattle were scored using the same template regardless of age, sex, or position. This information was useful for evaluating the effects of tree pod productivity and settlement proximity on cattle health. Since each cow’s geographic location was recorded, the spatial distribution of body index scores may reveal existing correlations between cattle health, distance from Topnaar settlements, and proximity to areas of high pod productivity.

***Abundance and Productivity of Acacia erioloba and Faidherbia albida***

*Kuiseb River Transects and Pod Productivity Measurements*

To assess the overall pod productivity of *A. erioloba* and *F. albida* trees in the Kuiseb River study area, we first divided the river into 12 transects identical to those used by Morgan (2017), designated as Alpha, Bravo, Charlie, Delta, Echo, Foxtrot, Golf, Hotel, India, Juliet, Kilo, and Lima in an upstream to downstream order (Figure 1). We chose to utilize these transects due to the abundance of ecological data previously collected from them. In studying the pre-existing transects, we were able to build upon the wealth of knowledge developed by Morgan (2017). Within each transect, we employed four different productivity measurements on both tree species. These measurements were conducted during the morning between 8:00 and 13:00 over a four-day period. Pod density was evaluated via sample pod counts for every tree. Tree trunk circumferences were recorded at approximately breast height. Trees were subjectively rated on a productivity scale of 1-5 based on their pod density, and “herbivory plots” were cleared under one *F. albida* tree from each transect. The “herbivory plots” measured 3x3 meters and were revisited after a period of 48 hours to ascertain fallen pod counts and livestock activity. Five *A. erioloba* trees and five *F. albida* trees were randomly selected in each transect, for a total of ten trees per transect. However, tree selection was partially influenced by trunk accessibility, as many *A. erioloba* and *F. albida* trees were enveloped in brambles, making it logistically unfeasible to measure trunk circumference.

*Tree Pod Counts*

We recorded four sample pod counts for each sample tree to assess pod productivity by using a 10x10 cm cardboard square as an to estimate pod density. The purpose of the cardboard square was to confine the observational field of view to a uniform volume, in which we could more easily count pods to estimate pod density. To ensure consistency and eliminate additional variables, one group member was selected to conduct pod counts throughout the entire data collection period. This group member stood at four evenly spaced positions around the base of each tree, from which the square was held at arm’s length and the total number of individual pods that laid within the square’s borders was counted. Individual counts were then averaged to obtain an area specific pod count to indicate each tree’s pod density. These pod counts were intended to correlate with the subjective productivity rating we assigned to each tree.

*Subjective Rating*

Subjective tree pod productivity ratings were based on a ground level observation of pod density. Subjective ratings for both *A. erioloba* and *F. albida* were assigned using the uniform 1-5 rating scale, with 1 being the lowest pod density and 5 being the highest pod density. Both tree species were assessed using the same standards, instead of being assessed relative to their own species despite differing phenologies. These subjective productivity ratings were expected to positively correlate with tree pod counts.

*Trunk Circumference*

Tree trunk circumferences were measured and recorded using a rolling measuring tape. Circumferences measurements were collected at approximately breast height. This method was intended to help us determine whether a correlation exists between tree circumference and the other metrics of productivity that we tested, such as the average pod density, subjective rating, and canopy cover size. Subjective tree pod productivity ratings were expected to positively correlate with tree pod counts from method 1.

*Canopy Cover*

The canopy cover areas of the *A. erioloba* and *F. albida* trees that we sampled were determined using imagery collected from an unmanned aerial vehicle (UAV) in 2016. The coordinates we gathered using the GPS device were mapped on the UAV-derived orthophotos at each site. The area of each tree crown was then calculated by drawing a polygon to represent each crown and calculating its area in ArcMap 10.4.1. This was used to develop a relationship between canopy size and our pod density measurements, which could be applied to other trees in the study area to estimate pod productivity at a broader scale. If a correlation were to exist between canopy cover and our pod density measurements, canopy cover could potentially be used as a proxy for predicting pod productivity over larger expanses of the Kuiseb River, which would streamline similar studies in the future.

### ***Relationships between livestock and pod-producing trees***

#### *Tree and Livestock Distributions*

In addition to obtaining a complete census of livestock within our study area, we recorded every animal's geographic location at the time we encountered them on a GPS device. Plotting these coordinates on a satellite imagery map allowed us to acquire a visual representation of where cattle and other livestock were most abundant along the lower Kuiseb River. Coordinates were also recorded for the *A. erioloba* and *F. albida* trees that were measured for pod productivity. Plotting these data sets on a satellite imagery map and comparing their respective distributions to one another helps inform an understanding of the relationships between tree distribution, cattle distribution, and their respective distances from Topnaar settlements. A visual representation of cattle and tree distribution, and tree pod productivity in relation to settlement location may simultaneously answer two questions: 1). Are cattle and other livestock most abundant in areas of high pod productivity? and 2). How far are cattle inclined to travel away from settlements in order to access areas of high pod productivity?

#### *Sampling Spatial Heterogeneity in Transects (SSHIT) Method*

In order to assess livestock activity and utilization of tree pods, as well as tree pod productivity, we conducted research using the SSHIT method, which was established by Grotz et al. during the Dartmouth program in 2015. Unlike prior studies utilizing this method in 2015 and 2016, we focused solely on the enumeration of cow and donkey dung, and of *F. albida* and *A. Erioloba* pods. For this method, we examined a 20 km section of the Lower Kuiseb River by traveling 10 km upstream and 10 km downstream from the Gobabeb Research and Training Center campus. Mirroring the 2016 Dartmouth group's SSHIT method application, this river section was divided into increments of 2 kilometers (Freehafer et al. 2016). Collecting data from the same transects would allow us to compare our findings to those from previous years and make inferences about tree pod utilization and livestock movement. At each of these 10 sites, we collected data from 50x2 meter transects situated behind the first line of trees, and from parallel transects 20 meters farther from the channel (see figure 2). Thus, for each site along the river, four transects were studied.

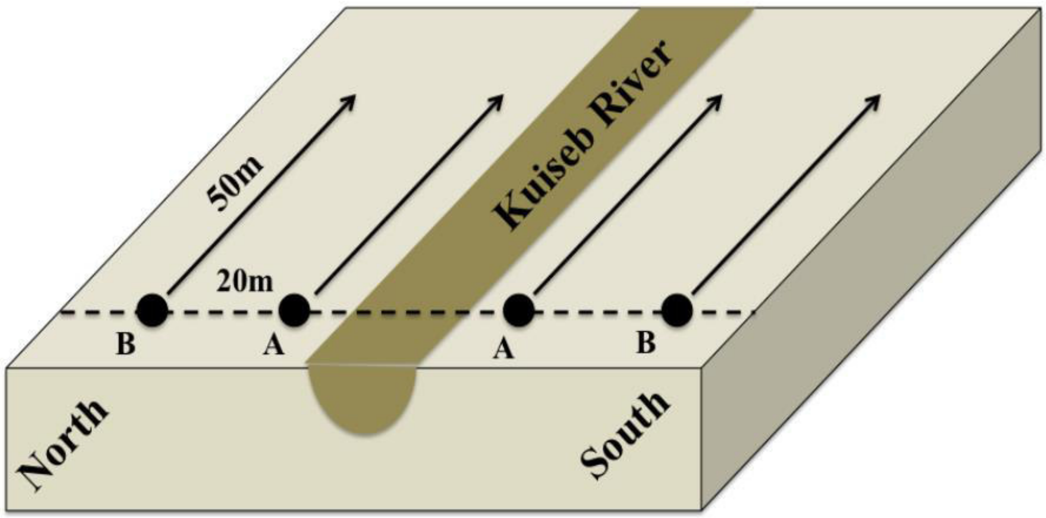


**Figure 2.** Diagram of the Kuiseb River transects used in each of the eleven 2 km sections during SSHIT method data collection (Source: Grotz et al. 2015).

*Herbivory plot*

Herbivory plots were made by clearing 3x3 meter areas underneath one *F. albida* from each transect. *F. albida* was selected because it was in the midst of its most pod productive time of year. These plots were intended to assess both livestock utilization of tree pods as a food source and tree pod production. Markers were placed in each corner of the plots in order to make them more recognizable and easier to locate upon revisitation. The total number of pods were counted prior to clearing of the plot, and preexisting dung, tree pods, and other debris were then removed. Once cleared, the plots were left and revisited after approximately 48 hours. Upon revisitation, we recounted the number of tree pods, identified and counted dung from various livestock species, and noted any livestock or wildlife tracks traversing the plot.

***Methods for Determining Carrying Capacity***

We employed a commonly used method for determining a rough short term estimate for livestock carrying capacity (Frost 2017). Using the data we gathered and data from the literature, annual forage production in the study area was calculated and divided by one standard animal unit year. A standard animal unit month is the amount of forage needed for one lactating 494 kg cow in one month, this number was multiplied by 12 to get a standard animal unit year (Meehan et al. 2016). In order to estimate the total number of individual *A. erioloba* and *F. albida* trees in the study area, the species densities of these pod-producing trees in each of our transect blocks (same as Morgan 2017, the source for tree numbers) were applied to approximately ten 500-meter segments spanning 2.5 kilometers in either direction along the river bed. These densities were multiplied by the width of each 500-m segment to estimate the number of trees in each segment. The sums of these segment counts were used as the estimates of the total number of *A. erioloba* and *F. albida* in the entire study area. All this information on resource availability and resource needs were inputted into the following equation to generate an estimate of study area carrying capacity in standard animal units per year:

$$C = (AN + Fn) / (U(12))$$

Where C is standard animal units per year, A is the yearly yield of pods per one *A. erioloba* tree in kilograms, N is the number of acacia trees, F is the yearly yield of pods per one *F. albida* tree in kilograms, n is the number of *F. albida* trees and U is the kilograms of dry matter consumed per month for one animal unit month.

***Statistical analysis and GIS Mapping***

We used JMP Pro 10.13.1 to determine if there were statistically significant relationships between different variables collected in our data. Linear regression was used to analyze the relationship between various tree productivity measurements.

We collaborated with Bryn Morgan to construct spatial maps using ArcGIS 10.4.1. Satellite imagery was used to pinpoint settlement locations, and species locations were placed on the map using GPS coordinates.

## Results

***Abundance and Health of Cattle***

*Complete Enumeration*

We sighted 290 cattle and 277 goats in the riverbed during three census drives upstream and two downstream. The spatial distribution of cattle is presented in Figure 3 while the spatial distribution of goats is in Figure 4, with both showing marked heterogeneity in their space use. Because the censuses were conducted over the course of four days, many individuals are likely incorporated into these figures more than once. On the last day, however, we avoided duplicate counts by driving down the entire 65-kilometer study site, reflecting a complete enumeration of cattle (130 individuals) visible from the riverbed.

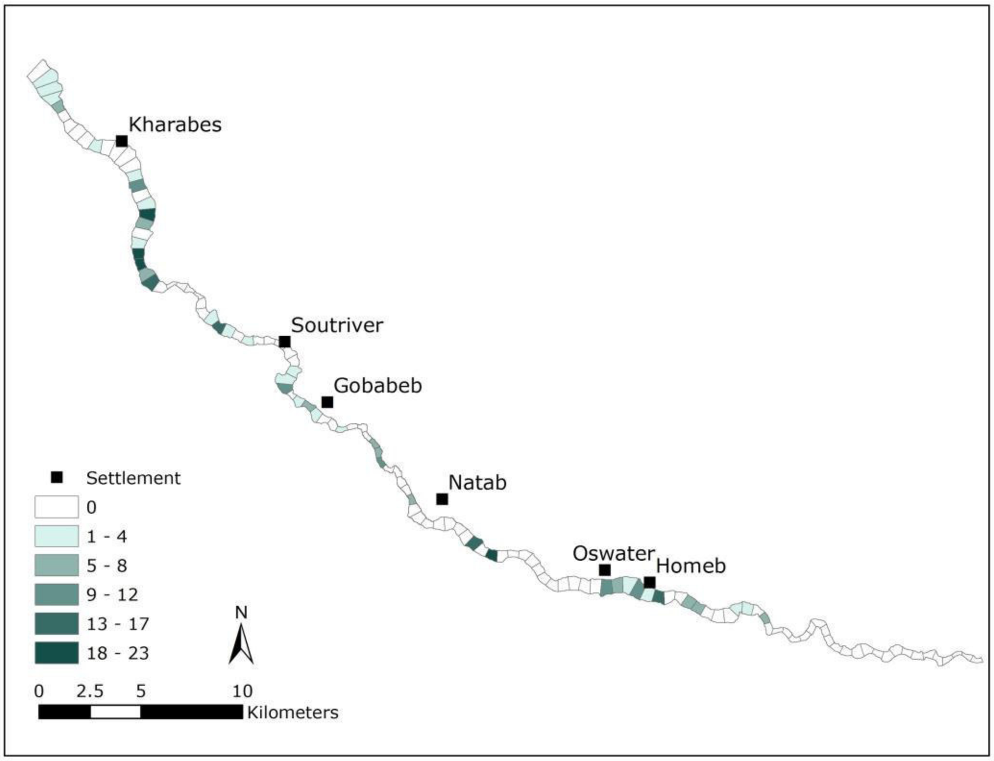


**Figure 3.** Heat map showing the distribution of cattle spottings (N = 290). The top left corner is the furthest downstream point of the study site, and the bottom right corner is the furthest upstream point.

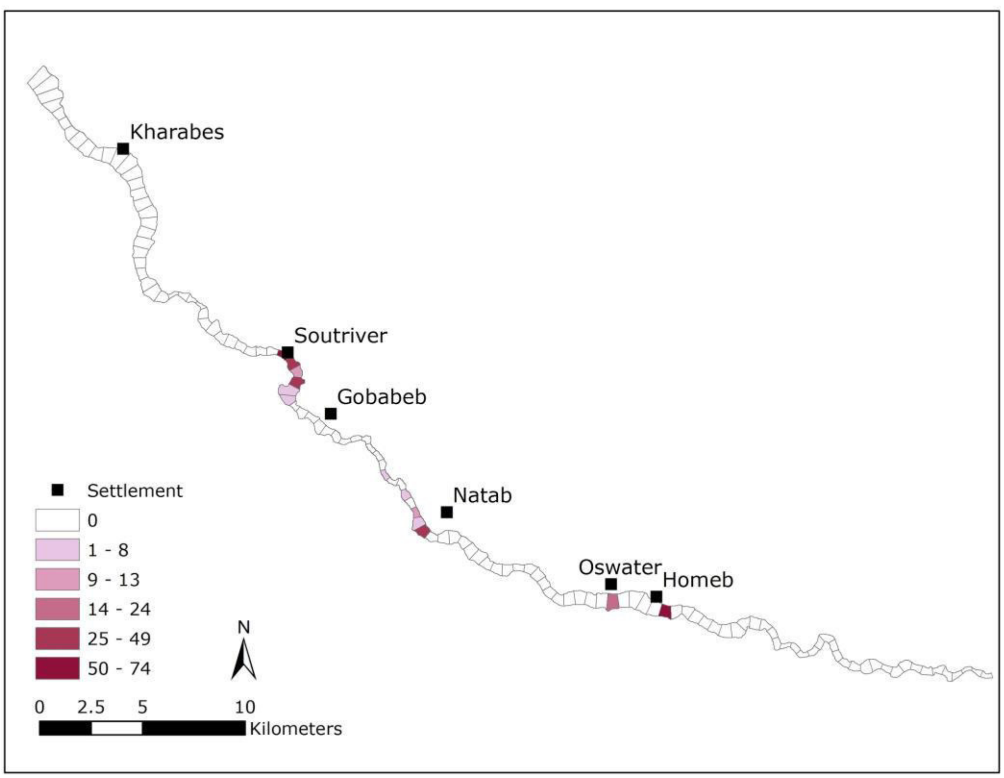

**Figure 4.** Heat map of goats along the study site (N = 277).

*Mark and Recapture Method*

We saw 41 tagged cattle on the first day and 43 tagged cattle on the second day. Out of the 43 tagged cattle observed on the second day, 18 had previously been recorded. Knowing this information allowed us to apply the Lincoln-Peterson estimator:

$$N = Kn/k$$

$$N = (43)(41) / (18)$$

$$N = 98$$

We determined the total population size of tagged cattle to be approximately 98. The proportion of total cattle to "recaptured" cattle on the second day was 3.22:1, so by multiplying this proportion by the estimated total population of tagged cattle we determined the total population of cattle in the study region to be approximately 316.

*Wildlife Sightings*

In addition to the cattle and goats, we recorded observations of eleven other species on the census drives (see Table 1).

**Table 1.** The 12 different animals encountered in the study area and their frequencies (N = 791).

| Species | Sightings |
|---|---|
| Cattle | 290 |
| Donkey | 97 |
| Goat | 277 |
| Sheep | 12 |
| Dik dik | 1 |
| Oryx | 11 |
| Springbok | 15 |
| Ostrich | 2 |

| | |
|---|---|
| Jackal | 3 |
| Guinea Fowl | 3 |
| Rooster | 2 |
| Dog | 1 |

Wildlife sightings occurred more frequently towards the ends of the study site away from the settlements and also away from the livestock groups. A herd of springbok between Gobabeb and Natab was one exception, as seen on Figure 5.

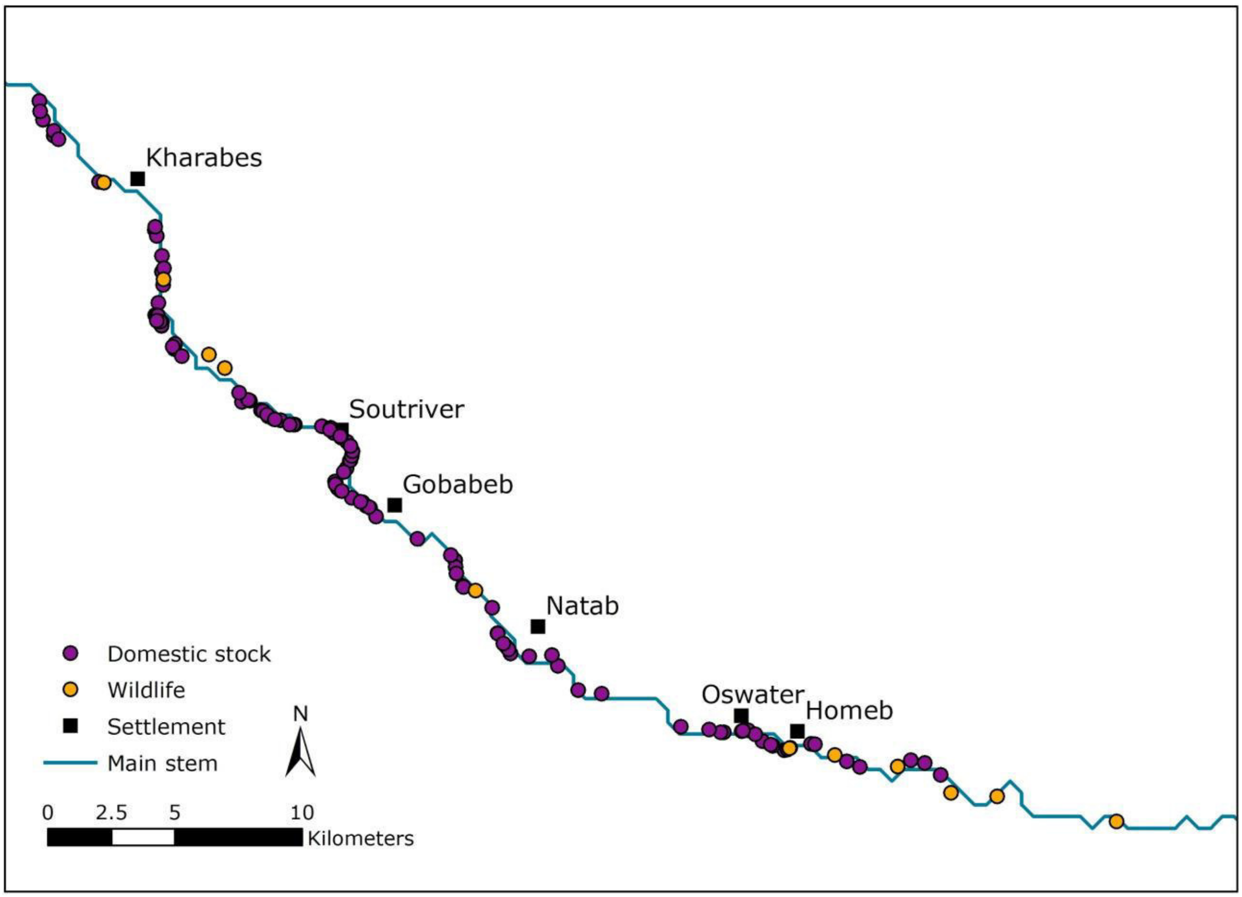


**Figure 5.** Map showing the spatial distribution of both wildlife and livestock (N = 788). The livestock species were cattle, goats, sheep, and donkeys.

On average, the wildlife were more than twice as far from the settlements than were livestock, a difference that was statistically significant (t-test, $N = 788$, $p < 0.0001$).

**Table 2.** average distance of animal types from their closest settlements. The livestock category includes cattle, goat, sheep, and donkeys.

| **Animal Type** | **Mean Distance from Closest Settlement** |
|---|---|
| Livestock | 3.212 kilometers |
| Wildlife | 8.048 kilometers |

We assigned each animal to its nearest transect and found that the most amount of cattle were found in Kilo and Delta, while the most goats were seen in India and Delta.

**Table 3.** The amount of animals found in or around each transect block (N = 793).

| | TRANSECT | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ANIMAL TYPE** | **Alpha** | **Bravo** | **Charlie** | **Delta** | **Echo** | **Foxtrot** | **Golf** | **Hotel** | **India** | **Juliet** | **Kilo** | **Lima** |
| COW | 0 | 5 | 15 | 47 | 20 | 15 | 28 | 15 | 17 | 28 | 83 | 28 |
| DIK DIK | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DOG | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| DONKEY | 0 | 0 | 0 | 22 | 11 | 6 | 2 | 11 | 21 | 28 | 2 | 10 |
| GEMSBOK | 10 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GOAT | 0 | 0 | 0 | 95 | 0 | 33 | 23 | 1 | 167 | 0 | 0 | 0 |
| GUINEA FOWL | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| JACKAL | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| OSTRICH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| ROOSTER | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| SHEEP | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 |
| SPRINGBOK | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 10 | 0 |

The number of cattle significantly decreased with distance travelled upstream (Figure 6; R square = .29, N = 12, p = 0.0020).

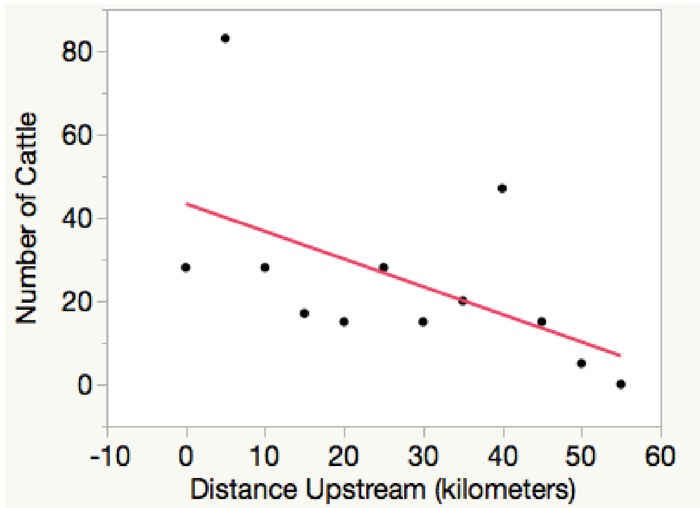


**Figure 6.** A moderate negative correlation between cattle abundance and kilometers upstream. Each point represents one transect (Alpha-Lima).

*Cattle Body Condition Scores (BCS)*

Out of our combined counts of livestock over the three-day data collection period, we assessed 102 cows for body condition. Most cows received a body score of 2 or 3, a few cows received a 1 or 4, and no cows received a score of 5. The average body score across all scored cattle was 2.7.

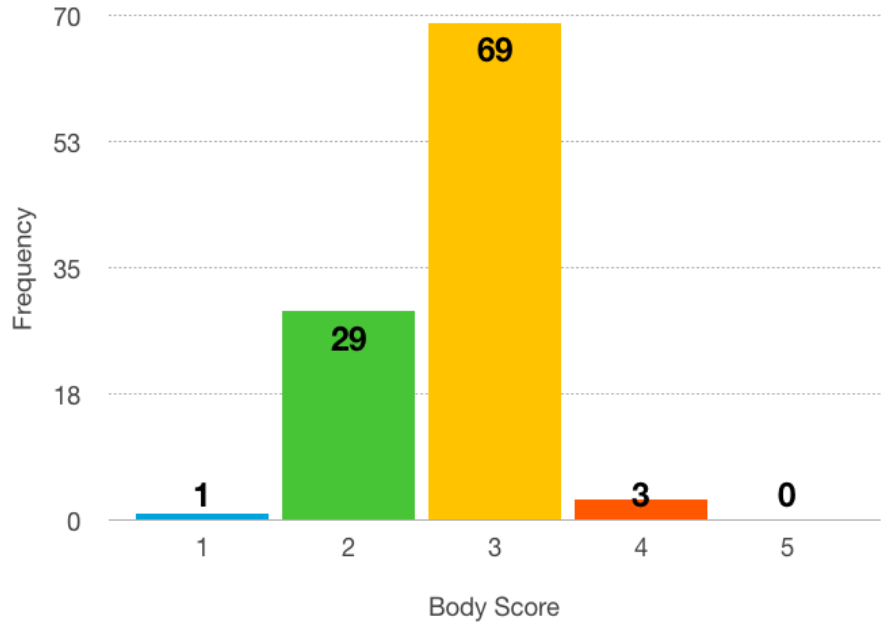


**Figure 8.** Frequency of individual cows' Body Condition Score recorded during census methods.

We found no significant relationship between body score and distance or angle from closest settlement. However, as shown in Figure 9, 80% of cows were spotted upstream from their closest settlement (mean angle from closest settlement less than the absolute value of 90 degrees, see Appendix 2).

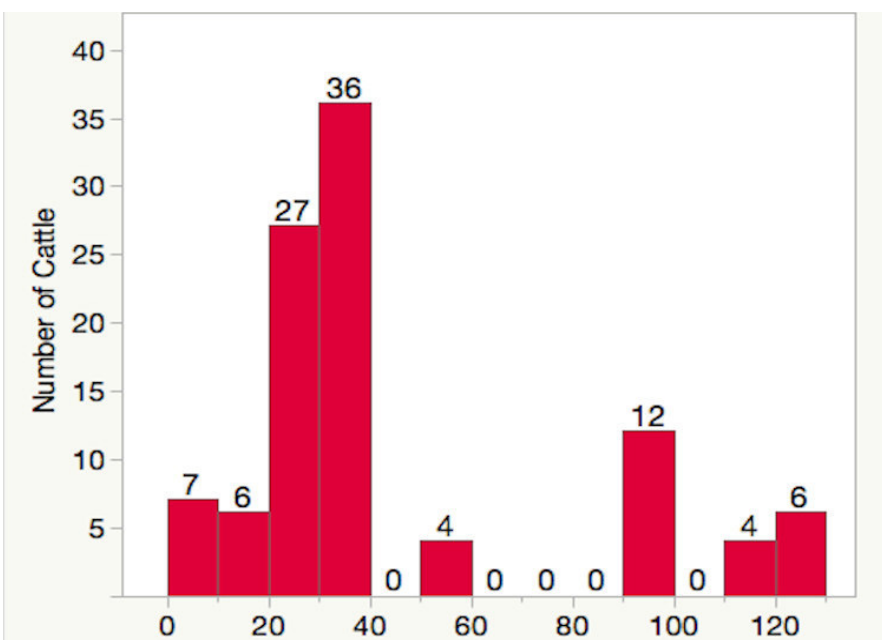

**Figure 9.** The absolute value of the angle cows were sighted at from the settlement they were closest to (N = 100).

### *Abundance and Productivity of Trees*

*Tree Productivity Measurements*

We collected data from 60 *F. albida* trees, but only 56 *A. erioloba* trees due to the low abundance of *A. erioloba* individuals in transect Juliet. The *F. albida* trees we examined had higher average pod counts (t-test, N = 116, $p < 0.0001$) and subjective productivity scores (t-test, $p < 0.0001$) for every transect. Two additional t-tests were conducted between the species and their mean productivity scores and mean trunk circumferences. The p-values were <.0001 and .0024 respectively, indicating statistically significant differences between these productivity measurements and tree species as well.

**Table 4**. The average pod count, productivity score, and trunk circumference for *F. albida* and *A. erioloba* trees in each transect (N = 116).

| | *Faidherbia albida* pods | | | | *Acacia erioloba* pods | | | |
|---|---|---|---|---|---|---|---|---|
| Transect | Mean Pod Count | Mean Productivity Score | Mean Trunk Circumference | Mean Canopy Size | Mean Pod Count | Mean Productivity Score | Mean Trunk Circumference | Mean Canopy Size |
| Alpha | 41.70 | 3.2 | 1.94 | 196.76 | 0.15 | 1.0 | 1.04 | 23.58 |
| Bravo | 27.55 | 2.6 | 1.92 | 432.30 | 0.15 | 1.0 | 1.84 | 65.42 |
| Charlie | 29.20 | 3.0 | 2.32 | 346.01 | 1.60 | 1.4 | 1.54 | 62.24 |
| Delta | 56.60 | 4.2 | 3.94 | 519.59 | 2.00 | 1.2 | 1.64 | 239.96 |
| Echo | 25.00 | 2.8 | 2.12 | 145.94 | 2.20 | 1.4 | 1.98 | 87.67 |
| Foxtrot | 27.65 | 3.0 | 3.30 | 340.86 | 0.90 | 1.2 | 2.36 | 141.74 |
| Golf | 32.75 | 3.2 | 3.48 | 295.87 | 3.20 | 1.6 | 3.62 | 183.88 |
| Hotel | 20.90 | 2.2 | 2.46 | 234.87 | 3.65 | 1.4 | 1.36 | 81.32 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| India | 23.35 | 2.8 | 5.34 | 633.56 | 0.15 | 1.0 | 2.86 | 212.12 |
| Juliet | 0.90 | 1.0 | 1.10 | 27.42 | 0.00 | 1.0 | 1.20 | 32.10 |
| Kilo | 1.65 | 3.2 | 3.36 | 436.69 | 1.65 | 1.2 | 2.00 | 134.48 |
| Lima | 15.75 | 2.0 | 2.04 | 115.42 | 0.60 | 1.0 | 1.58 | 30.84 |

We found that averaging the four pod count angles we recorded for each tree significantly correlated with the subjective productivity scores we assigned to each tree. The mean pod scores ranged from 0 to 79.25.

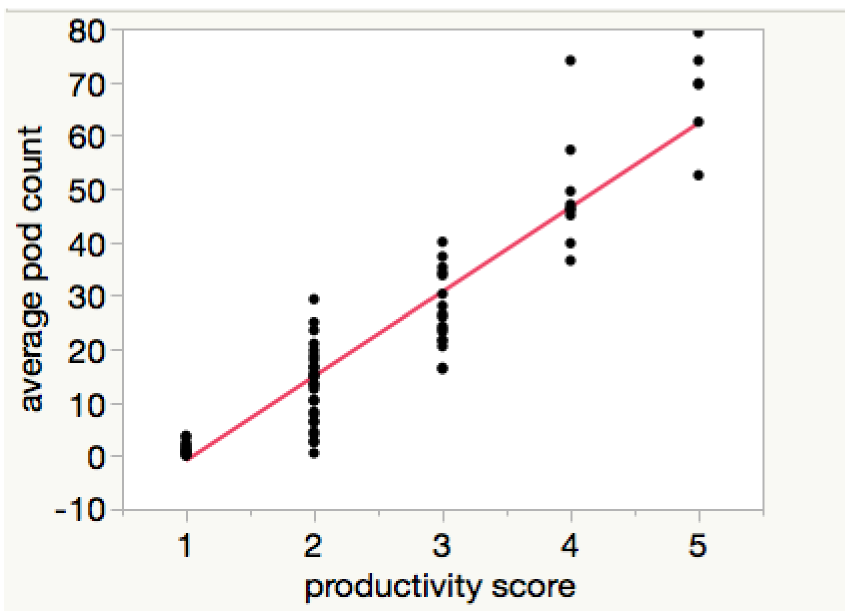


**Figure 10:** A strong positive relationship between productivity scores and average pod counts (R square = 0.89, N = 115, p <.0001). This relationship can be described by the equation y = 15.80165x – 16.73567.

While the positive linear relationship between productivity score and pod count was strong, the positive linear relationship between pod count and trunk circumference remained significant but explained less of observed variation in pod count (see Figure 6).

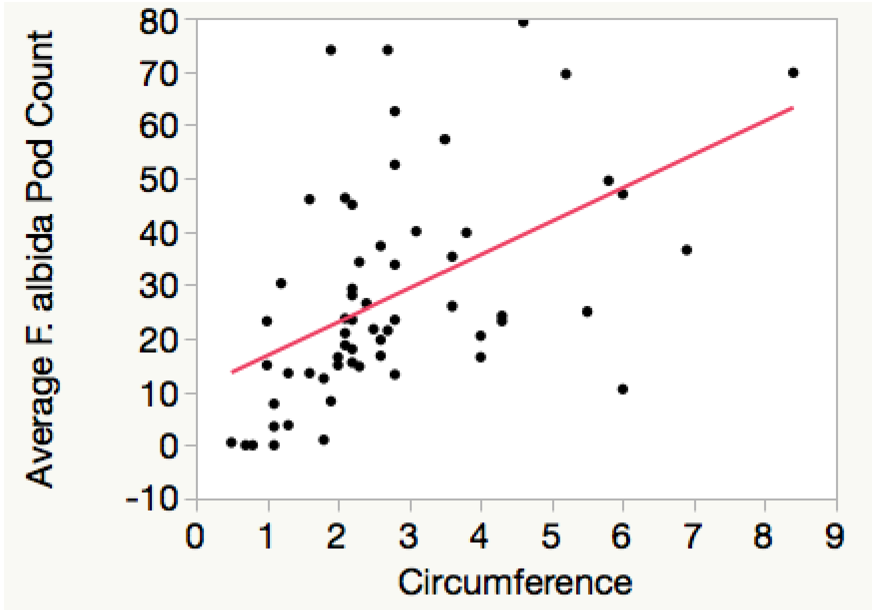


**Figure 11.** A weak positive relationship between pod count and trunk circumference described by the equation y = 0.03467x + 1.86223 (R square = 0.25, N = 116, p <.0001). Circumference was measured in meters.

There was a moderate positive correlation between the canopy area ($m^2$) and average pod count for each focal *F. albida* tree during the study period A separate analysis of *A. erioloba* trees revealed no significant relationship between canopy and pod count during this time of year which is out of season for their pod production phenology.

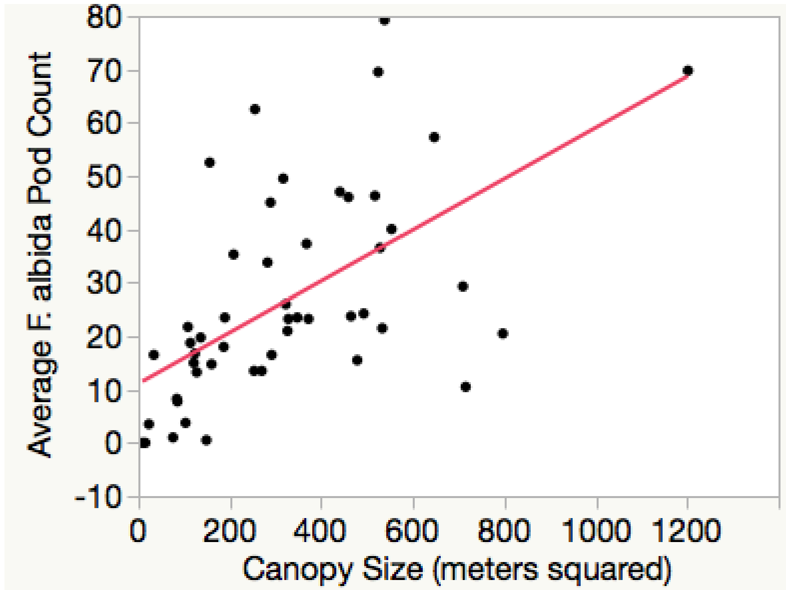


**Figure 12.** A moderate positive correlation between canopy area and pod count described by the equation y = .04795x + 11.10930 (R square = 0.35, N = 50, p <.0001).

Mean number of pods in F. albida trees increased with distance travelled upstream (Figure 13; R square = 0.54, N = 12, p = 0.0070).

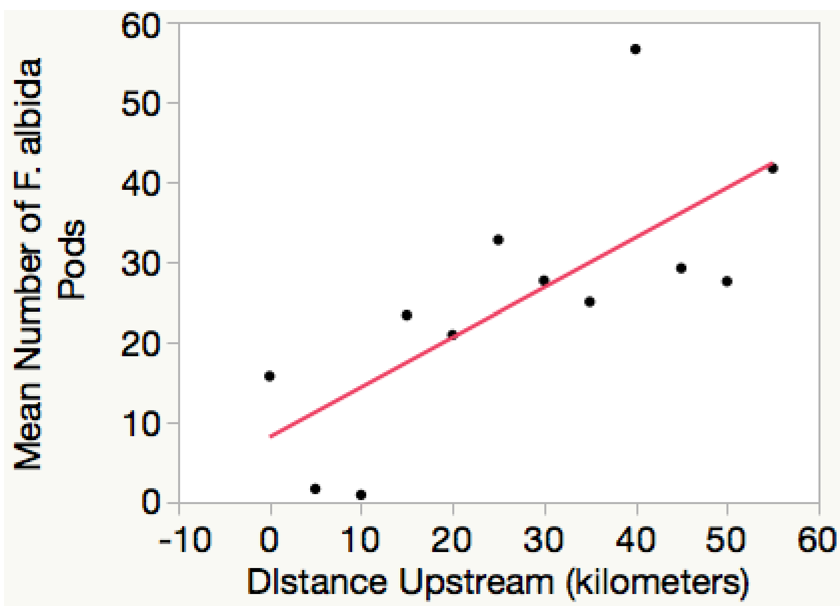


**Figure 13.** A moderately strong positive correlation between kilometers upstream from the start site and the average number of F. albida pods counted in the trees. Each pod represents one transect (Alpha-Lima).

***Relationships Between Livestock and Pod-Producing Trees***

*Relative Abundance*

We found a moderately strong, positive relationship between the relative abundance of the two pod producing tree species and cattle distribution (R square = .54, N = 12, p = .0064). In areas with high densities of *A. erioloba* and *F. albida*, there was a significantly higher cattle presence.

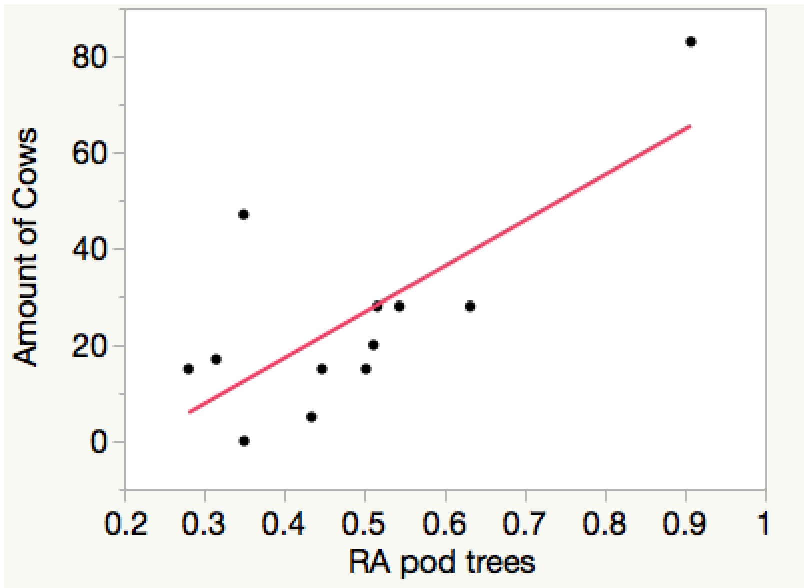


**Figure 14.** Relationship between relative abundance (RA) of *A. erioloba* and *F. albida* and the amount of cattle in and around each transect. Each point represent one transect (Alpha-Lima). This relationship can be described by the equation y = 95.05570x - 20.79301.

We found no significant relationships between cattle abundance and *A. erioloba* density, *F. albida* density, *A. erioloba* relative abundance, and *F. albida* relative abundance.

*SSHIT Method Findings*

We found no relationship between the number of dung piles and tree pods counted on the ground through linear regression. The p-value = 0.4682, meaning that we accept the null hypothesis that the two variables are not correlated.

*Herbivory plots*

Transects Alpha, Bravo, Charlie, Delta and Echo had the most amount of fallen pods, both initially and after 48 hours, while transects Foxtrot, Golf, Hotel, India, Kilo, and Lima had very few pods. While the herbivory plots resulted in a wide range of data, we found no statistically significant relationships between any of the variables seen in Table 5 after conducting both t-tests and linear regression. Within these plots, we found no correlation between livestock activity and the amount of pods on the ground.

**Table 5**. Number of pods, dung, and tracks found in 3x3 meter^2 boxes swept in the sand and checked after two days under an F. albida tree in each transect. Data from transects Hotel, India, and Juliet are incomplete due to time restraints.

| Transect | Initial pod count | Second pod count | Cow dung | Donkey dung | Cow tracks | Donkey tracks |
|---|---|---|---|---|---|---|
| Alpha | 90 | 52 | 0 | 0 | no | no |
| Bravo | 29 | 12 | 0 | 0 | no | no |
| Charlie | 177 | 99 | 3 | 0 | yes | no |
| Delta | 96 | 41 | 2 | 0 | yes | no |
| Echo | 60 | 82 | 0 | 0 | yes | no |
| Foxtrot | 2 | 3 | 1 | 0 | yes | no |
| Golf | 2 | 3 | 1 | 0 | no | no |
| Hotel | 2 | n/a | n/a | n/a | n/a | n/a |
| India | 2 | n/a | n/a | n/a | n/a | n/a |
| Juliet | n/a | n/a | n/a | n/a | n/a | n/a |
| Kilo | 4 | 1 | 2 | 2 | no | no |
| Lima | 5 | 0 | 2 | 2 | yes | yes |

***Estimated Carrying Capacity***

Morgan 2017 found the number of *A. erioloba* and *F. albida* trees in the study area to be 29,010 and 23,273 respectively. Annual pod yield for *A. erioloba* and *F. albida* was determined to be 135 kg/year and 120 kg/year maximum from previous studies (Bernard 2002) and kilograms of dry matter consumed per month for one animal unit month was determined to be 355 kilograms (Meehan et al. 2016). Using this knowledge we were able to make the following calculation for carrying capacity:

$$C = (AN + Fn) / (U(12))$$

$$C = ((135\text{ kg})(29{,}010) + (120)(23{,}273)) / ((355\text{ kg})(12))$$

$$C = 1{,}574.91 \text{ standard animal units/year}$$

## Discussion

*Abundance and health of cattle*

The difference between our mark and recapture estimate of 316 cattle and our complete enumeration value of 130 could be due to several factors. First, we most likely did not see every cow in the Lower Kuiseb River during our total-transect census drive. In areas with high tree density, it was difficult to see past the banks of the river. Firsthand accounts also informed us that many cows were too weak to leave the settlements, so it was unlikely that we would ever see them. Additionally, the mark and recapture method has inherent error, as it is a tool for approximate estimation. The recapture rate was 41.9%, and according to Hilborn et al. 1975, if the recapture rate is less than 50% then the actual population size is usually 10-20% smaller than the estimate. Even without adjusting for this error, both census estimates are still significantly lower than the original hypothesis that we would find 400 cattle in the riverbed. This could be attributed to the recent drought, a lack of food, or the possibility that Joel's estimate was inaccurate. Additionally, Joel's estimation was conducted after research within Topnaar community settlements, rather than in the riverbed, and likely took into account cattle outside of our study area.

In order for cows to be considered healthy on the BCS scale, they must have a body index score of at least 2.5 (Bewley et al. 2008). The average body score was 2.7, suggesting that most cows are on the line between healthy and unhealthy. These findings are bolstered by the interviews conducted in communities by Bang et al. 2017. The researchers reported that they saw cattle too weak to stand, and one woman even claimed that she lost over 100 cattle in a single year. These relatively low body scores and supporting reports of unhealthy cattle in communities could be due to decreased vegetation as a result of drought in the last few years. Because we did not see the cows in the settlements, we were not able to account for the cows that were too weak to walk in the river bed. Thus, average cattle health may be even poorer than we estimated because we did not factor in these cows.

The finding that cattle numbers decrease as distance upstream increases is contrary to our initial hypothesis that we would find more cattle upstream due to increased pod density and water availability. This could be attributed to the fact that the riverbed widens and the tree density decreases downstream, which allows more space for cattle to roam, and gave us the ability to see more of them without vegetation blocking our view. There also may have been more cattle downstream and clustered around the Kharabes settlement because this was the only settlement where we did not see herds of goats. Perhaps more cows were found further downstream because they did not have to compete with other livestock for pods, or because people in Kharabes own more cattle and fewer goats than other settlements.

In addition to the cattle and goat populations, we also sighted more wildlife towards the ends of the study site away from settlements. Livestock and wildlife compete for similar resources such as tree pods and water, so our data supports the idea that wildlife is being edged out and forced away from human settlements by this inter-species competition.

*Abundance and productivity of Acacia erioloba and Faidherbia albida*

The higher pod density counts found with the *F. albida* trees is not surprising, given that *F. albida* trees were in their productive season when the data was collected, as they produce the most pods in September and October. In contrast, *A. erioloba* trees are the most productive between December and March (Morgan 2017). Hence, *F. albida* likely provide the most abundant food source for cattle at this time of year, but may provide fewer pods during the rest of the year.

We found that there is a strong correlation between the pod productivity scores and the average pod density counts for each tree. This supports the validity of using the cardboard square method as a means of measuring pod productivity. In future experiments, we recommend using this method to assess the viability of an *A. erioloba* or *F. albida* to produce pods.

Our hypothesis that tree pod production would increase further upstream was supported by the data. During seasonal floods, water flows from the Khomas Hochland Mountains from the East downriver to Walvis Bay on the Atlantic Ocean (Morin et al. 2009). As the water flows down the river, it soaks into the ground and is taken up by vegetation. This phenomenon is called transmission loss because water becomes increasingly more scarce downstream (Dahan et al. 2008). Perhaps the trees upstream produce more pods on average because they have had greater access to water, and this water is concentrated in a more defined channel, as seen on the cattle and goat heat maps.

*Relationships between livestock and pod producing trees*

Interestingly, there is a greater abundance of cattle downstream, even though there is a significantly lower density of pod producing trees downstream. This unexpected result could be due to a variety of reasons. It is possible that due to the greater density of trees upstream, a substantial number of cattle were hidden from view by tree thickets, which could have skewed our census data. However, this is unlikely because cows' mobility would then be reduced. Cows may also prefer open spaces, and correspondingly move downstream where the river is much wider and spread out. The absence of goats downstream may imply that cattle do not have to compete with goats to forage and thus more cattle can occupy these areas. Another possible explanation is that the majority of cattle are owned by Topnaar people who live in downstream settlements like Kharabes. Restricted by water sources inside their owners' home settlements, cattle may not travel long distances upstream to areas of higher pod densities even if there is more food there. However, we did find that 80% of cows we recorded were upstream from the closest settlement. Since higher densities of *F. albida* trees with higher densities of pods are upstream, it is reasonable to infer that cows move upstream to utilize food resources in these areas.

The SSHIT method findings yielded no statistically significant correlations between any of the variables that it tested for. Contrary to its employment by Freehafer et al. 2016, this method was not an accurate predictor of the total number of pods found in each transect. This discrepancy may be because of our sample size of ten transects across a 20 km stretch of the Kuiseb was too small and therefore insufficient for detecting any trends. Alternatively, the fact that cows do not strictly defecate where they eat could inhibit the effectiveness of this method. Furthermore, this method has multiple sources of error. First, the four researchers conducting pop and dung counts may different counting preferences; some may be more generous with they consider as falling within the 50x2 transect, while others may be stricter. Second, the transects in which we conducted counts were not perfectly linear due to the obstruction of impassable foliage or geologic structures. Dung counts are also easily skewed because it is often difficult to differentiate between individual piles of dung. Most importantly, the SSHIT method does not take the activity of goats into account because it is not feasible to accurately quantify their dung. However, goat activity is important to measure because they share tree pods as a food source with cattle, and may even compete for them. Hence, the SSHIT method does not account for the interaction of goats and the Kuiseb ecosystem.

The findings from herbivory plots were useful because they suggest that trees with higher pod densities drop also drop more pods, which this study assumes. These findings also support the data from pod density counts and subjective productivity scores of *F. albida*, confirming that there is indeed greater pod density upstream. The herbivory plot results may be due to the greater number of cows downstream because they collectively eat more pods at a faster rate. This would be exacerbated by the lower density of *F. albida* downstream because less forage is produced.

*Livestock Carrying Capacity*

Based on our census estimates and our estimation of carrying capacity in standard animal units per year, we conclude that the ecosystem's carrying capacity is not currently at risk of being breached. By converting the goats, sheep and donkey to standard animal units using conversion rates found in the literature (.15 for goats, .2 for sheep and .4 for donkey) and adding them together with cattle we reached a total demand of 398.75 standard animal units per year (Meehan et al. 2016). Even when considering all cattle along the Kuiseb river as in a 2014 census, when 540 cattle and 2,367 goats were counted standard animal units per year only reaches 895--just 57% of carrying capacity (Morgan 2017). However, our model is a rough estimate of carrying capacity and several assumptions were made and several significant variables were left out.

When we calculated carrying capacity, we assumed every single tree had the maximum yield possible for its species. Given that our average subjective rating for every transect was 2.77 out of 5 this was most likely not a realistic assumption. If we were to weigh the yields we used off of this subjective rating average, roughly 55%, carrying capacity would be much closer to being breached. In the future we suggest a more thorough study be done to determine a more accurate average pod yield per tree as well as determining seasonal variability. Placing a net under trees to collect pods over a longer period of time could potentially provide the information necessary to inform a more accurate carrying capacity.

The formula we used to calculate carrying capacity is an overly simplistic frame that does not incorporate several important variables. Some variables were omitted because our current understanding of the system did not allow us to know to what degree these variables should properly be taken into account. It is our hope that over time other groups and other studies can analyze and incorporate additional elements to create a more dynamic and precise equation. One factor that we hope future groups can assess is a harvest efficiency determinant. In other examples of carrying capacity equations, this coefficient reflected the amount of biomass that would realistically be used by cattle (Meehan et al. 2016). Through our own experiences conducting the SSHIT method and the herbivory plots, we realized that not all pods are eaten. Many pods get lost inside of bushes or buried in the soil, recycling into the system without being consumed. By conducting more thorough herbivory plots and by coming up with experiments to determine an accurate ratio of fallen to eaten pods, this factor could also be implemented into the equation to further limit carrying capacity.

During our cattle census drives, we observed cattle utilizing plants besides the *A. erioloba* and *F. albida* trees. We witnessed cows actively eating Ostrich grass and found bushes that had been heavily consumed by cattle. Further studies could explore the nutritional content of ostrich grass, or other species eaten by cattle, and the role they play in cattle diets. By incorporating as many plant species as possible into a carrying capacity formula, we can gain a better insight into the population sizes this region is able to sustain.

The formula we used calculated carrying capacity for the study region as a whole, yet due to the extreme spatial heterogeneity of the landscape and the potential reduction of mobility due to water restrictions, this may not be the most accurate way of expressing the concept. Several studies have been done exploring the relationship between carrying capacity and distances from watering sites. A 2015 study by Cowley et al. found that the majority of feeding occurred within 3 km of water even in poorly watered paddocks. They used this result to conclude that a 3 km radius from water should be used to calculate carrying capacity and stocking rates instead of a 5 km radius (Cowley & Walsh 2015). Furthermore, other sources indicate that forage located 1.6 kilometers away from water sources is only 50% utilized and resources located over 3.2 kilometers away from water are hardly utilized at all (George & Lile). Although we know this does not perfectly fit the study region, as the mean cattle distance from water was 3.4 kilometers away, we did find evidence of increased cattle activity closer to water since all herbivory plots closest to settlements had cattle tracks. Furthermore, although the majority of cattle were not found upriver where there's a larger number of pod producing trees, 80% of cattle were found upriver of their nearest water source. This could demonstrate that cattle utilize the most productive areas of land that are near to water resources. It is therefore possible that even if carrying capacity for the study area as a whole remains unbroken, localized carrying capacities around water could be breached. In the future we hope to develop carrying capacity estimates for specific watering areas, and if they are broken study the effects of this breach. If localized carrying capacities are found to be a relevant metric, we theorize that increasing the spread of watering areas throughout the study area could raise carrying capacity.

Lastly, in order to establish a more accurate carrying capacity estimate, tree productivity measurements should be conducted at different times of the year to understand how many pods *A. erioloba* trees produce during their peak season. Carrying capacity is essential for linking human socioeconomic activities and ecosystem balances, and determining animals' limiting factors and their movements is an important step towards understanding this relationship. Although our simplified estimate of carrying capacity in the region indicated livestock populations were well inside of their bounds, anecdotal evidence of recent die-offs may indicate that this is not the case. Introducing more detailed elements into our equation of carrying capacity may help provide greater insight into the population dynamics of the Kuiseb River.

## Conclusion

Overall, we conclude that livestock are spatially restricted by several limiting factors in the Kuiseb river region, the most relevant being water. Water availability also affects tree pod production, density, and relative abundance. To improve water accessibility and thus cow health, more water should be made available at different parts of the river so that cows are not restricted by their one settlement. While this is a simple suggestion to make from a purely ecological framework, water accessibility in the Kuiseb River has intricate environmental and political complications. Water is extremely scarce, and while some settlements on the river have free access to boreholes, other settlements must pay for their usage (Bang et al. 2017). Balancing human and animal water needs will be an increasing challenge in the future as tension between the settlements and water companies rises, and as climate change increases extreme weather events such as droughts.

Understanding a region's carrying capacity is essential for linking human socioeconomic activities and ecosystem balances. Livestock have powerful economic significance in the Topnaar villages and in most other pastoral communities around the world. Community members invest their money in livestock, primarily due to cultural norms, but also because of their lack of other options (Olbrich et al. 2016). Banks are far away, and there are few other livelihoods for the Topnaar to pursue. Investing in livestock is unique in the sense that this capital is living and, therefore, can die. In order to sustainably grow and maintain human, livestock, and wildlife populations, carrying capacity should be considered in pastoral communities because it has important consequences for financial security and food security.

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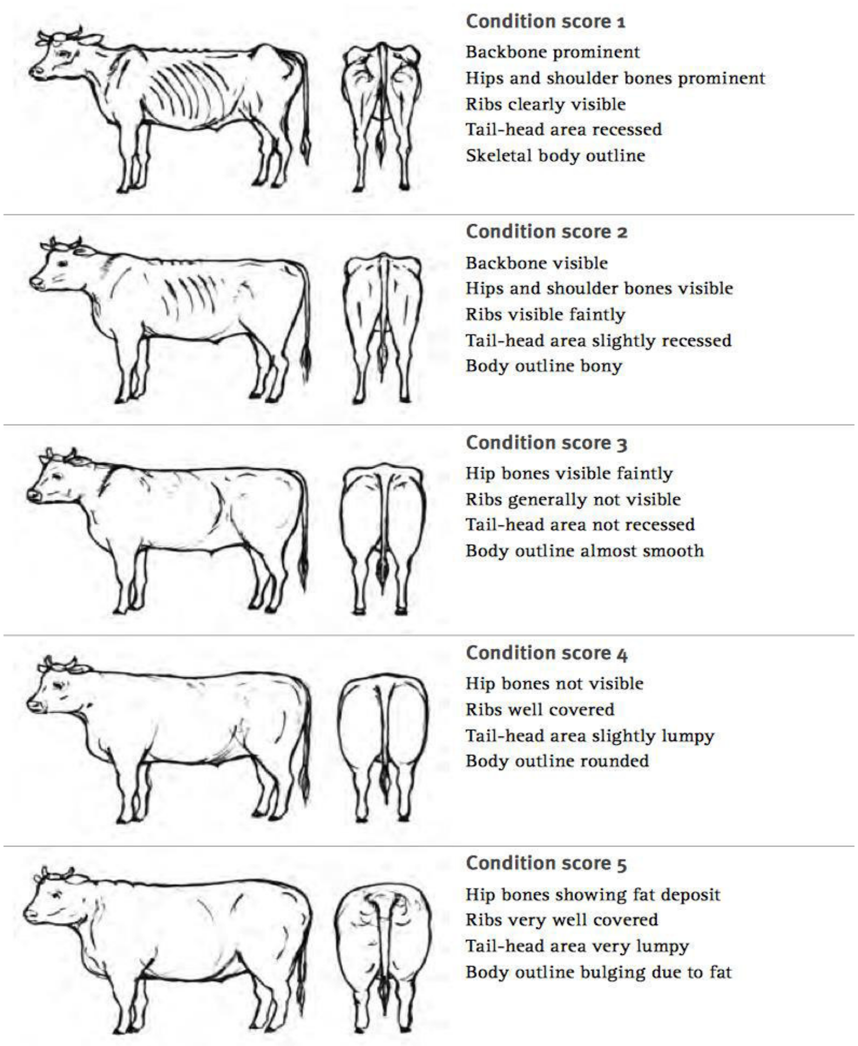
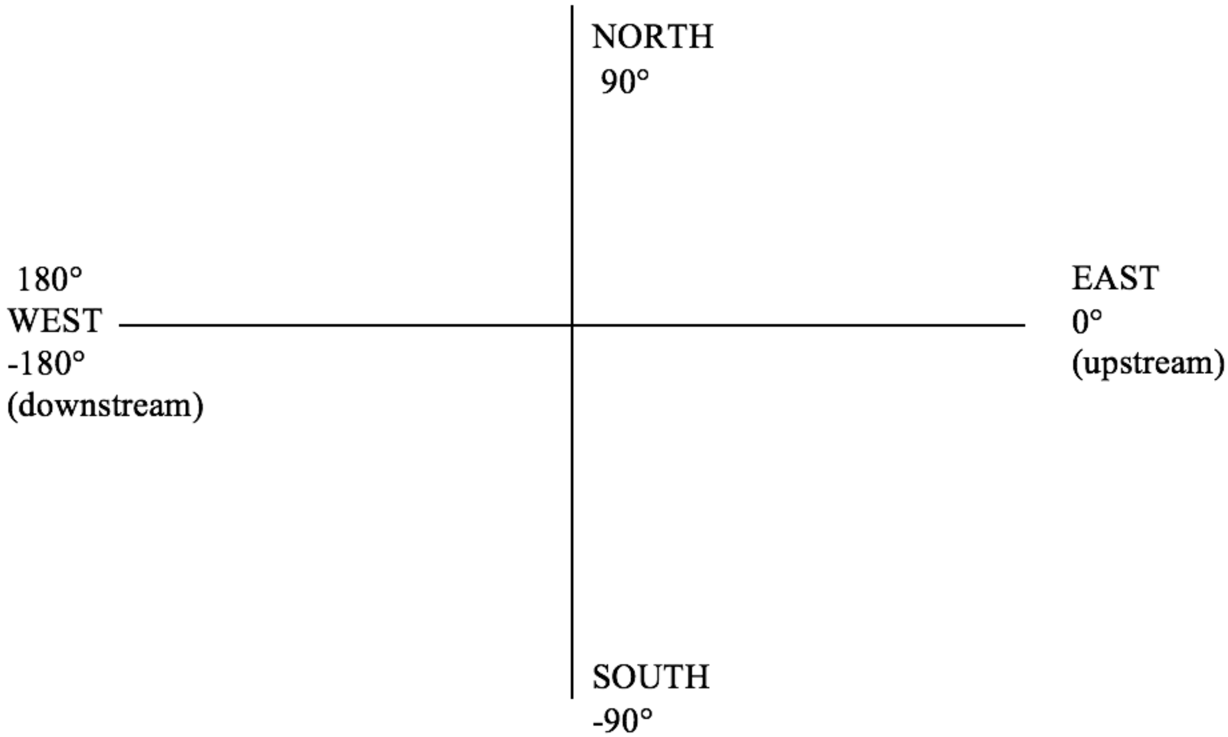
# Appendices

## Appendix 1: Cattle Body Condition Score Index




**Legend**: This scoring index was used to assess the health of cattle we sighted along the riverbed (Grotz et al. 2015).

**Appendix 2: Compass rose used to assess upstream/downstream angle from village**




**Legend:** The origin of the compass rose represents the nearest settlement to a cow. If the cow is found in the first or fourth quadrant between -90° and 90°, then it is East and therefore upstream from the settlement. If it is found between -180° and 180°  then it is West and therefore downstream of the settlement. This method assumes that the river is linear.