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Connecting the Dots: A Mixed-Methods Analysis of Social Networks and Community-Institution Relationships in the Kuiseb River Valley

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Abstract

Community-institution relationships are important both for the effective operation of institutions and wellbeing of communities. To determine if relationships between communities and institutions can promote progress and build resilience, we examined the ways in which Topnaar community members' connections to different institutions affect their perceptions of and willingness to act in conjunction with these institutions. Our study also aimed to identify potential barriers to connectivity. Using social network, statistical, and qualitative analysis, we found that connections between communities and institutions significantly impact perceptions and collective action. Additionally, distinct subgroups exist within the network, impeding mutual understanding and coordinated action. Low network cohesiveness may stem from individuals' tendency to interact with similar others, as well as the social distance between communities and institutions. Through our analysis, we discovered that the existence of a tie is not enough. Rather, it is more important for these relationships to facilitate knowledge exchange and a two-way flow of benefits. A strong social network can foster intergroup understanding, which establishes a foundation for the coordinated action necessary to achieve conservation and development goals.

Introduction

In the era of the Anthropocene, rural communities are most vulnerable to climate change as they are trapped between their dependence on increasingly scarce natural resources and international pressures to protect the same resources (Morton 2007, Van-vliet, 2010). Climate change is a "wicked problem," one with non-linear patterns of change, frequent surprises, and no stopping rule or test for a solution; consequently, it does not lend itself to conventional management practices (Ludwig 2001, Young 2017). Rather, reducing vulnerability depends on the capacity of a system to be adaptable to change. Additionally, because climate change is not just a technical problem but also a social one, it cannot be separated from social justice issues and subsequently depends upon the involvement of all stakeholders – researchers, government institutions, and local communities (Ludwig 2001). Moreover, such social justice issues - namely in the equitable development of local indigenous communities, especially in light of colonial and neo-colonial legacies of oppression - are an end in themselves. Top-down approaches with command-and-control policies fail to provide effective solutions to dynamic and uncertain issues such as climate change and social inequality. Therefore, adaptive governance approaches that facilitate learning and involvement of local actors are necessary for managing systems in the presence of complexity and uncertainty (Chaffin et al. 2014).

Institutions cannot function in isolation, and long-term co-management depends upon coordinated efforts; therefore, social networks are highly relevant because they foster commitment to common rules, facilitate information exchange, and increase willingness to engage in monitoring, sanctioning, and conflict resolution. (Gupta et al. 2010, Bodin & Crona 2009). The existence of bridging ties between different stakeholder groups is essential to establishing a common understanding (Crona & Bodin 2006). Strong intergroup relations, characterized by meaningful connections and positive perceptions, also create potential for collective action, which is key to adaptive co-management (Crona & Bodin 2006, Granovetter 1973). Therefore, connectivity and perception serve as two important intermediaries to collective action, especially in the context of institutions and communities working together.

Two related barriers to connectivity and collective action are homophily and psychological distance. Homophily is the preference for interacting with others who are similar in terms of gender, age, social status, education, and occupation, due to ease of communication and similarity in experiences (McPherson et al. 2001, Erikson 1988). Homophily leads to small, tightly integrated subgroups within a network, which limits access to and receptivity of outside sources of ideas (Ruef 2002, McPherson et al 2001, Erickson 1988). According to Construal-Level Theory, those who are socially or physically distant from an institution have high-level, abstract construals and thus will have a less positive perception (Trope et al. 2011). In order to overcome these barriers, there must be persistent and continuous interaction between the various institutions and local communities, as well as the development of new relational ties. Over time, these interactions will strengthen the social network, and foster collective action across subgroups.

We assessed the importance of social networks in the Namib Naukluft Park, where the local Topnaar community faces multiple constraints on its livelihood such as residence in a national park, frequent droughts, limited material means, and inadequate access to information and transportation. For the rural Topnaar communities facing these constraints, strong ties to the Gobabeb Research and Training Center, the Ministry of Environment and Tourism (MET), the Ministry of Agriculture (MOA), and the Topnaar Traditional Authority (TTA) are essential to improving livelihoods. This is because the social network affects the likelihood that the actors in this system will reach a common understanding of the issues at hand, which affects their ability to organize around regulations and needs (Crona & Bodin 2006). The existence of a connection alone, however, may not be enough to improve governance. It is equally important that the ties are used for knowledge transfer, information sharing, consensus building, and equitable power relationships to encourage increased collaboration (Bodin and Crona 2009). Therefore, strong connectivity is crucial to effective collective action.

We hypothesized that a community's connectivity to an institution, characterized by both quantity and quality of ties, affects the community's perceptions of that institution, with individuals who are more connected to institutions having more positive perceptions than less-connected actors. Subsequently, actors who have greater connections to and positive perceptions of an institution will be more willing participate in collective action, specifically adaptive co-management. We also hypothesized that homophily and social distance affect connectivity, forming subgroups within a network which affect perceptions of institutions and opportunities for collective action. Bridging ties that bring together these different stakeholder groups are necessary in order to overcome these barriers and work collectively towards common goals. Institutions must acknowledge the importance of connectivity in building perceptions and fostering action in social networks in order to build resilience, strengthen adaptive co-management, and usher progress for indigenous communities.

Methods

Data Collection

In answering our hypotheses to understand the relationship between connections, perceptions, and action between communities and institutions, the Kuiseb River Valley is of interest because of its geographically well-contained community-institution network formed by the Topnaar Community, Gobabeb Research and Training Center, Ministry of Agriculture, and the Ministry of Environment and Tourism. We used community, staff, and expert interviews to gain qualitative and quantitative information on individuals' connections, their perceptions of institutions and communities, and their action in the Kuiseb community-institution network.

Before developing our study's focus on connectivity, perceptions, and interactions between institutions and communities, we began at a larger scale trying to understand community-institution relations and how they affect the wellbeing and success of both. In a preliminary focus group discussion during a community livestock workshop at Gobabeb on October 31st, 2018, we noted that community members spoke extensively of their exchanges, from monetary to interpersonal, with Gobabeb characterizing their perceptions of the institution. Based on this initial finding, we developed a survey strategy to understand how communities characterize their connections with institutions, and in turn how this social network of various connections affect their perceptions.

To understand the social network and the relationship between connections, perceptions, and actions, we designed a qualitative and quantitative survey approach. We interviewed four main categories of stakeholders:

Table 1 Overview of Interviews Conducted

Community Members	23
Gobabeb Staff	5
Gobabeb Management and Researchers	4 (3 and 1)
Traditional Authority	2

Although we initially sought to interview management and staff of all three institutions, the three contacted members of MET management, one contacted member of MOA management, and one contacted member of MOA staff were not available for interview. Therefore, Gobabeb was the only institution for whom we could interview to understand the institutional perspective on community-institution relations.

Our approach to interviewing the community included interpersonal interviews at several field sites along the Kuiseb River from November 1st through November 6th. Different constraints and purposes affected our sample selection, as detailed below:

Network Analysis: In order to capture an accurate picture of the social network, we interviewed communities all across the Kuiseb River Valley. This also allowed us to understand how distance affects connectivity, as we interviewed in communities more than 80 km apart- Ururas and Natab.

Community-Institution Relations: To understand how different members of the Topnaar community at large view different institutions, we interviewed a diverse sample of individuals with different sex, age, education, residence, and occupation. We also interviewed communities close to and far away from institutions, for example Soutriver which is less than 5 km from Gobabeb and Natab which is less than 10 km from Homeb, the residence of the Topnaar Chief.

Constraints: Our two translators Dennis Khorisab and Caroline, from Natab and Aramstrat respectively, scheduled interviews with those who they knew in some communities, especially those near their hometowns. Additionally, individuals would sometimes decline interviews, affecting our sample selection and size. Moreover, we interviewed between 9:00 a.m. and 5:00 p.m. which conflicted with the work schedules of community members who would often be out herding livestock or at jobs during the day.

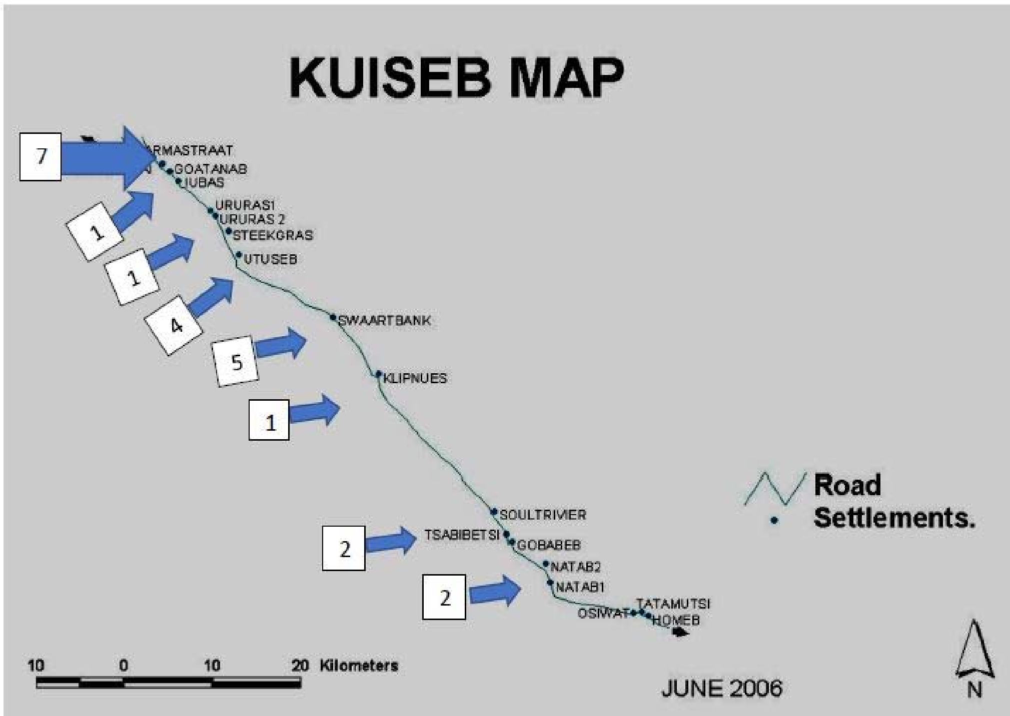


Figure 1: Map of Kuiseb River Valley and communities visited for interviews.

Table 2 Village Distribution of Interview Respondents

Village	No. of Interviews	Village	No. of Interviews
Aramstrat	7	Ururis	1
Gaodanab	1	Utuseb	4
Klipneus	1	Soutriver	2
Natab	2	Swartbank	5

With the assistance of two translators, one of whom is a member of the TTA, we interviewed 23 community members (see Table 2). Below is demographic information for the interviews conducted:

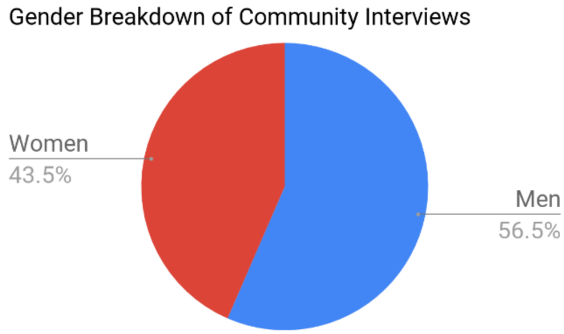


Figure 2: 10 interviewed community members were women, while 13 were men.

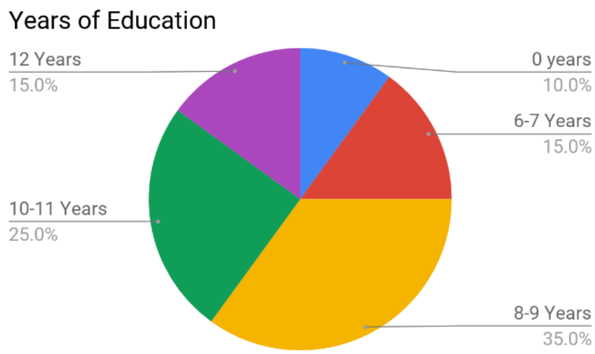


Figure 3: Sampled community members follow an approximately normal distribution of education across the range 0-12 years.

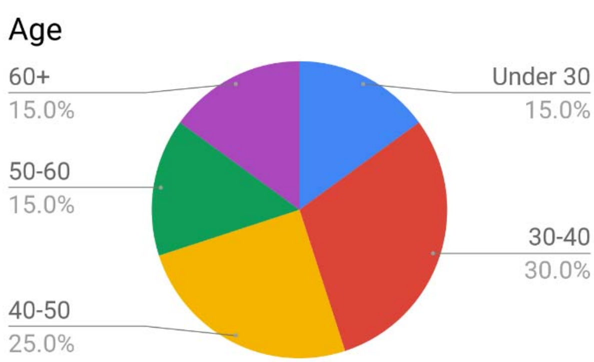


Figure 4: Sampled community members follow an approximately normal distribution of age.

In interviews with community members, our goal was to understand their connections across the Topnaar community and to institutions, and how they perceived four institutions: Gobabeb Research and Training Centre, the Ministry of Agriculture (MoA), the Ministry of Environment and Tourism (MET), and the Topnaar Traditional Authority (TTA).

To understand community members' connectivity, we asked questions to understand the number and types of connections community members had along the Kuiseb River Valley, and then who and how they knew different members of institutions. Specifically, we assessed the types of relationships by understanding frequency of interactions, nature of interactions, and knowledge and benefit-sharing through those interactions. To assess community members' perceptions of institutions, we asked questions to understand how they experience benefits and difficulties due to institutions, and what areas of improvement in their relationships with institutions they identify. Finally, to understand individuals' willingness to reach out to institutions, we asked about prior experiences seeking help from institutions, success in those attempts, and future willingness to seek out help from institutions.

In addition to community interviews, we interviewed members of Gobabeb to understand how institutions perceive the community and what individuals are at the source of institution-community connectivity. Therefore, we interviewed the three main sectors of Gobabeb staff: management, researchers, and the maintenance team. During our interviews with the three members of the management team, in order to understand the institution's mission and interactions with the community at a larger scale, we collected information about their role, their connections within and outside of Gobabeb, and their perceptions of the Gobabeb-community relationship. Similarly, spoke with one researcher about their role, who they interact with, how they involve the community in their research, and ways that research can be leveraged to strengthen relations with communities. Finally, we spoke to five maintenance staff about their role and connections within Gobabeb, especially to understand how their presence at the intersection of the Topnaar community and Gobabeb affects institution-community connectivity.

Finally, in order to understand the role of the TTA in the social network, especially in how they affect, and potentially facilitate, community-institution relations, we interviewed two members of the TTA: Chief Seth Kootjie and one junior counselor. We asked both about their role in the community, in what communities they worked with most, their perceptions of institution-community relations, and opportunities for improvement.

Data Processing

Before analyzing the data, we compiled survey data from each community member into categorical indicators for connectivity, perceptions, and willingness to interact with three of the institutions - Gobabeb, MoA, and MET. We processed this data for later quantitative analysis through linear regression and for use in the social network analysis, specifically to construct a social network topography.

For connectivity, we assessed both the quantity and strength of an individual's connections to an institution. Quantity of connections was a direct response to a survey item. To assess the strength of each connection, we aggregated a connectivity score ranging from zero to five - zero indicating weak connectivity and five indicating strong connectivity- using survey responses explaining the frequency, content, and nature of communication through that connection (Appendix B). To create one composite connectivity score, we multiplied the quantity of connections an individual possessed by the connectivity score with that institution.
We also created a five-point perception score, which uses the ratio of positive to negative opinions expressed during the interview to assess respondents' perceptions of an institution (Appendix C). Using the survey responses related to past experiences with seeking help, we developed a binary indicator to assess a respondent's willingness to reach out to an institution.

Data Analysis

Statistical Analysis

To evaluate the relationships between connectivity, perceptions, and willingness to interact with institutions, we used STATA to create several linear regression models. After developing the aforementioned indicators for connectivity, perceptions, and willingness to reach out to institutions, we employed linear regression to evaluate the relationships between community members' connectivity to institutions, their perceptions of those institutions, and their willingness to work with those institutions. Before analysis, we conducted a balance test to identify demographic or geographic factors which have a statistically significant effect on relationships between connectivity, perceptions, and agency. This is important for two reasons:

1. Demographic factors which affect connectivity are relevant when considering barriers to communication and integration of subgroups in the social network. Therefore, we present relevant analyses of demographic factors' effects on connectivity, perceptions, and action in our results.
2. In analyzing the relationship between connectivity, perceptions, and action, we controlled for demographic factors to isolate the relationships absent the bias of demographic factors' effect on different demographic factors.

Our regression analysis followed three key steps:

First, we evaluated the effect of connectivity to an institution, in terms of the quantity and quality of an individual's connections to that institution, on the individual's perceptions of that institution. Regressions took the basic structure below, where connectivity is the aforementioned connectivity composite score, perception is the perception five-point score, and u_0 is the error term. We used the second model to evaluate the differential effects of quantity and quality of connectivity on perceptions.

a) perception = B0 + B1*connectivity + u0
b) perception = B0 + B1*connectivity number +B2*connectivity quality + u0

Second, we evaluated the effect of an individual's perceptions of and connectivity to an institution on their willingness to seek help from that institution. While the first two models allowed us to understand the isolated relationship of connectivity and perception, respectively, to willingness to seek help, the final model allowed us to understand their individual explanatory power in a controlled model, for example helping us understand the effect of perceptions on willingness to seek help controlling for connectivity. Regressions took the following basic structures:

a) willingness = B0+B1*connectivity + u0
b) willingness = B0+B1*perception + u0
c) willingness = B0+B1*connectivity + B2*perception + u0

Third, we evaluated the impact of sex, age, education level, English language ability, and geographical distance from institutions on connectivity, perceptions, and willingness to reach out to institutions through regression models building on those used in the balance test.

Social Network Analysis

The complexity of social networks makes it difficult to understand relationships based solely on direct links. Thus, it can be useful to study social groups using tools from social network analysis (SNA) in order to understand the consequences of indirect interactions and the influence of network topology (Borgatti et al. 2009, Wey et al. 2008). Using the connections identified by respondents during the interviews, we first created an edge list, a data structure which represents all the connecting ties between different nodes in a system**.** In our case, this edge list contained all the connections among and between communities and institutions. The edge list also contained connectivity scores which were used during the analysis to assign weights to the ties based on the quality of the connection. Using R (V 3.2.0), we then conducted analyses to find the degree centrality and betweenness centrality of each individual. Individual measures such as centrality describe a specific individual's position in the network and the potential effect that they have on others (Wey et al. 2008). Calculating the degree centrality allowed us to identify focal individuals in the network who have many connections and may therefore have more influence on those around them (Wey et al. 2008). Using the betweenness centrality, we determined whether key actors serve as bridges that connect different nodes. Finally, to describe the overall structure of the network, we constructed a visual network topography. Modeling the network and generating a group-level measure allowed us to evaluate network cohesion, or the degree to which the network is interconnected rather than divided into discrete subgroups. This has important implications for who interacts with who and subsequently, the ways in which information and benefits flow between different groups (such as communities and institutions) in the network.

Qualitative Analysis

Finally, we conducted a qualitative analysis of our interview data to support our quantitative findings. First, we used our hypotheses to identify questions that we wanted to investigate further in the interviews. We then created seven different codes to address these questions: 1) institutions provide help, 2) expressions of dissatisfaction, 3) desire for more interaction, 4) reasons for disconnect from the institutions, 5) psychological reasons for connections, 6) expressions of underlying fears of institutions, and 7) expressions of empathy. Within each of these codes, we also created multiple subcodes to pinpoint specific patterns in the interview data (see Appendix E). Using this coding list, we compiled a variety of perspectives about each institution. After coding each interview, we divided our results into three categories: general perceptions of and expectations for each institution, connectivity versus disconnection, and expressions of empathy and discontent. Findings under codes 1-3 fell under the first category. The second section examined the contrast between the results under codes 4 and 5. Finally, we discussed the quotes under codes 6 and 7 in the third section.

Results

In the following results, we find that the Kuiseb River Valley institution-community network is separated into distinct subgroups with relatively few ties bridging subgroups, and more specifically, institutions and communities. We find that connectivity, both in the quantity and quality of connections, improves perceptions of institutions, especially in the case of Gobabeb and the MOA. Strong connectivity and positive perceptions, in turn, improve community members' willingness to reach out to institutions. Qualitative analysis shows that distrust and a lack of knowledge and benefit sharing serve as key barriers to connectivity, perceptions, and joint action.

Social Network Analysis

The following results include our visual construction of the social network topology of the lower Kuiseb Valley, and subsequent analysis based on the structure of the social network topology.

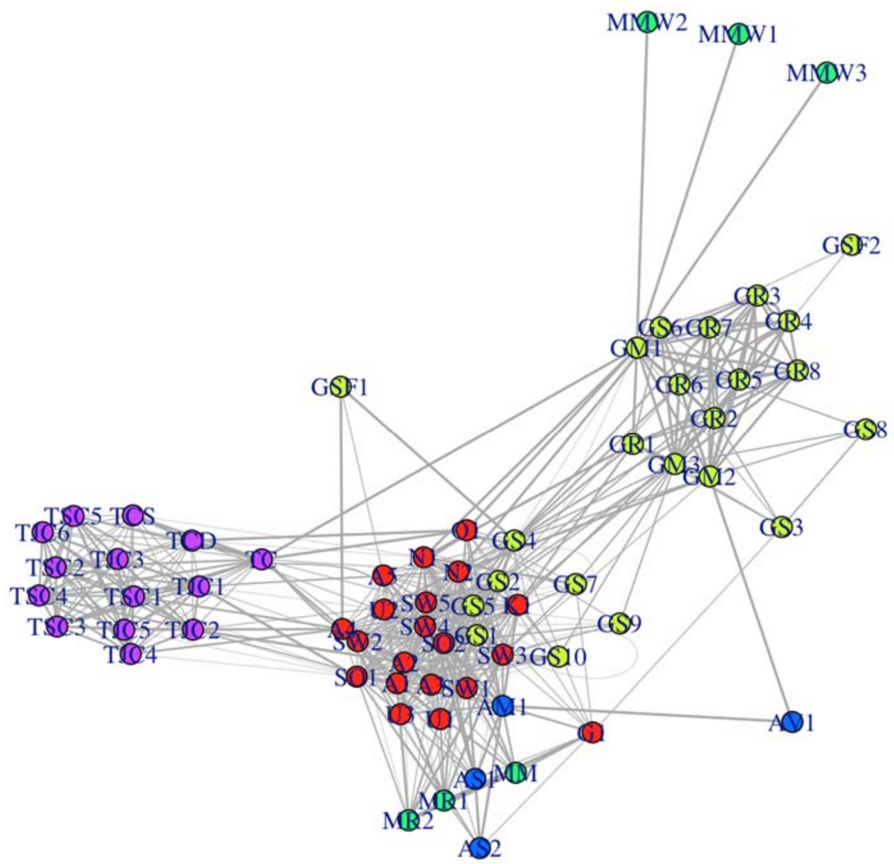


Figure 5: Social Network Topology of Communities and Institutions.
In this network, each circle (node) represents an individual interviewed or referred to by a interviewee. Purple circles correspond to the Traditional Authority, red to community members, green to MET employees, blue to MoA employees, and yellow to Gobabeb employees. An undirected line (edge) connects the nodes representing two individuals with a connection. The weight of the edge - how thick the line is - corresponds to the quality of the connection, i.e. the assessed connection quality score. See Appendix D for an explanation of codes used in the above topography.

The above topography highlights the formation of distinct subgroups, indicated by the separate clustering of different nodes via dense connections. These subgroups include the TTA, Topnaar Community with Gobabeb Topnaar staff, and Gobabeb management and researchers. Moreover, there exist far more bonding ties within these subgroups than bridging ties between different subgroups. Some key nodes serve to connect different clusters in the topology. For example, the Topnaar staff of Gobabeb bridge the Topnaar community with the greater Gobabeb staff, while Topnaar Chief bridges the TTA with the Topnaar community and the Gobabeb staff.

Table 3 Centrality of Key Actors in the Kuiseb Valley Social Network

	Degree Centrality	Betweenness Centrality
Chief (TC)	22	246.45
Gobabeb Executive Director (GM1)	22	402.43
Gobabeb Research Director (GM2)	16	63.42
Gobabeb Coordinator (GM3)	21	114.30
Ministry of Agriculture Extension Officer (AM1)	22	57.02
Ministry of Environment & Tourism Ranger (MR1)	12	5.33

The above table elaborates on the importance of various nodes in the system based on different assessments of centrality. Degree centrality measures the number of ties that the node has, while betweenness centrality measures the influence of a node over connectivity and information-sharing between every pair of other nodes in the network. Based on the results, the Topnaar Chief, Gobabeb Executive Director, and Ministry of Agriculture Extension Officer have the greatest degree, or number of ties. In the cases of the two Gobabeb employees, this is in part due to almost twenty ties they each have within Gobabeb to researchers and staff. However, the Ministry of Agriculture Extension Officer high degree results from ties to the Topnaar community, as evidenced by AM1's closeness to the Topnaar community cluster in Figure 1.

The above table also reflects the large influence of specific nodes on connecting different actors and subgroups, as indicated by betweenness centrality. Namely, the Topnaar Chief, Gobabeb Executive Director, and Gobabeb Coordinator have the largest betweenness centrality, which accords with their positioning in the network topography closer to the center of the network, serving as the connection between their subgroups and others.

Table 4 Summary of Connectivity, Perception, and Willingness to Reach out Indicators

Institution	Indicator	Average	Standard Deviation
Gobabeb	Connection Quantity (#)	4.68	2.85
	Connectivity Quality Score (1-5)	2.53	1.68
	Perception Score (1-5)	2.85	1.66

	Willingness to Reach Out (%)	43	53
MOA	Connection Quantity (#)	1.90	1.33
	Connectivity Quality Score (1-5)	2.80	1.40
	Perception Score (1-5)	3.30	1.17
	Willingness to Reach Out (%)	75	45
MET	Connection Quantity (#)	1.60	1.10
	Connectivity Quality Score (1-5)	2.40	1.70
	Perception Score (1-5)	2.32	1.67
	Willingness to Reach Out (%)	61	50

The above table presents average number of connections, connectivity quality score, perception score, and willingness to reach out of community members to the three institutions. Community members have the most connections to Gobabeb, likely due to many reporting that they know the entirety of the Topnaar staff. However, community members have the highest connectivity quality score with the MOA. Accordingly, they also have the greatest perception score of the MOA, at 3.30 on a 1-5 scale. Community members are also most willing to reach out to the MOA, with 75% reporting they would be willing, compared to Gobabeb, to whom the smallest percentage, 43%, report being willing to reach out to Gobabeb for help. For more detailed description of the score scales, see Appendices B and C.

Linear Regression to Evaluate Demographic Factors which Affect Connectivity, Perceptions, and Willingness to Act

In regard to our second hypothesis that demographic factors affect connectivity between different actors in social networks, specifically in increasing the likelihood that similar others engage with each other, below findings explore the effects of different demographic factors on connections, perceptions, and interactions with different institutions. Below findings inform what demographic factors are used as control variables in later regression models.

Physical Distance, Connectivity, Perception, and Action

Results of regressions of connectivity, perceptions, and willingness to reach out to each of the three institutions on individuals' physical distance from the institutions are not statistically significant. Coefficients across institutions are extremely small and statistically insignificant, reflecting that distance does not significantly affect community members' connections to and perceptions of institutions, and in turn their willingness to reach out to those institutions for help. We will expand on the relationship between physical distance and its apparent lack of effect on connectivity, perceptions, and action in our discussion. However, this finding informs future regressions, allowing us for to omit controls for physical distance from regression models.

Table 5 Education and Connectivity to Gobabeb

	(1)	(2)	(3)
	Connectivity Composite Score	Connectivity Quantity	Connectivity Quality Score
Years of Education	2.073**	0.554**	0.281**
	(0.840)	(0.229)	(0.131)
Observations	19	19	19
R-squared	0.264	0.294	0.333
Controls?	Age and Gender		
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table presents results of regressions of connectivity to Gobabeb on community members' education level. In the first model, the statistically significant coefficient on education indicates that community members with greater education have greater connectivity, as a composite score of quantity and quality, to Gobabeb. The second and third models indicate that years of education significantly affect both the quantity and quality of community members' connections to Gobabeb. Specifically, one year of education yields an increase of 0.5 connections to individuals in Gobabeb ($p<0.05$) and a 0.3, or 6pp, increase in one's connection quality to Gobabeb ($p<0.05$). We will elaborate on mechanisms through which greater education improves connectivity to the research center in our discussion. However, given the significant impact of education on connectivity, we will include education as a control in future regressions.

Table 6 Gender and Willingness to Reach out to MET for Help

	Willingness to Reach Out
Male	0.705**
	(0.276)
Controls?	Age, Education, and Village
Observations	18
R-squared	0.739

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The above table shows results of regressions of willingness to reach out to the MET on gender. While being male does not significantly affect connectivity to or perceptions of the MET, it has a statistically significant and positive impact on willingness to reach out to the MET with problems or for help. Specifically, controlling for age, education, and village of residence, males are 70 percentage points ($p<0.05$) more likely than female counterparts to be willing to seek help from the MET.

Table 7 Age and Connectivity to the MOA

Variables	(1)	(2)
	Connectivity	Perception with Connectivity Control
Age	-0.214**	0.0474**
	(0.0849)	(0.0183)
Connectivity Composite Score		0.195***
		(0.0437)
Observations	20	20
R-squared	0.261	0.541
Standard errors in parentheses		
*** p<0.01, ** p<0.05, * p<0.1		

The above table presents results of regressions of connectivity to the MOA on age. The statistically significant coefficient in the first model indicates that youth have greater connectivity to the MOA. Specifically, being one year older decreases community members' connectivity scores to the MOA by 0.2 points, or about 5pp ($p<0.05$). The second model finds that, controlling for connectivity, older individuals have better perceptions of the MOA; specifically, one year of age increases one's perception score by about 0.05 pp ($p<0.05$). However, this result is very small. This indicates that a 20 year age difference will only result in an about 0.16 point, or 4pp ($p<0.05$), increase in perception score. Because age has a significant effect on connectivity, and to a lesser extent perceptions, we will include it as a control in future regressions. We will also further discuss the varying effects of age on connectivity to and perceptions of the MOA in our discussion.

Linear Regression and Models to Evaluate Relationships Between Connectivity, Perception, and Willingness to Act

Statistical Analysis

As previously discussed, all regression models below include three demographic factors as controls: age, years of education, and gender. The following results outline the relationships between connectivity and perceptions, and their varying effect on community members' willingness to reach out to the following three institutions for help: Gobabeb Research and Training Center, Ministry of Agriculture (MOA), and Ministry of Environment and Tourism (MET).

Connectivities and Perceptions

The following results pertain to our first hypothesis, and assess the relationship between connectivity to institutions and perceptions of those institutions, specifically in regard to the differential effects of community members' quantity and quality of connections on their perceptions of institutions. As the following regression tables omit coefficients for findings and control variables, and some models, expanded regression tables are available in Appendices G-L.

Table 8 Results of Regressions of Perceptions of Institutions on Connections to Institutions

VARIABLES	Gobabeb		MOA		MET	
	(1) Regression on Connectivity Composite Score	(2) Regression on Connectivity Components	(3) Regression on Connectivity Composite Score	(4) Regression on Connectivity Components	(5) Regression on Connectivity Composite Score	(6) Regression on Connectivity Components
Connectivity Composite Score	0.115***		0.196***		-0.0942	
	(0.0225)		(0.0471)		(0.0774)	
Quantity of Connections		-0.0147		0.507**		-0.246
		(0.0809)		(0.216)		(0.581)
Quality of Connections		1.123***		0.425**		-0.0543
		(0.141)		(0.157)		(0.368)
Observations	19	19	20	20	19	19
R-squared	0.685	0.893	0.545	0.570	0.200	0.156
Standard errors in parentheses						
*** p<0.01, ** p<0.05, * p<0.1						

The above regression table shows pairs of regression models for each of the three institutions. The first model in each pair shows the relationship between community members' connectivity composite score and perceptions of the institution. The second model shows the relationship between community members' individual components of connectivity and their perceptions of institutions. This model helps determine which of the two connectivity components, quantity or quality, is a more important indicator of perceptions of institutions.

Statistically significant coefficients on connectivity composite score in models 1 and 3 indicate that connectivity to Gobabeb and MOA significantly affect perceptions, while the insignificant finding in model 5 suggests that connectivity does not affect perceptions of the MET. For example, the model 1 coefficient on connectivity composite score indicates that a one-point increase in connectivity composite score yields an approximately 0.1-point increase ($p<0.01$) in perceptions of Gobabeb. Given the scale is out of 5, this represents a 2 percentage-point (pp) increase.

In model 2, the coefficients on quantity and quality of connectivity suggest that the quality of one's connections to Gobabeb has a greater impact on perceptions than does the quantity of one's connections to Gobabeb. After including the control for connectivity quality, the coefficient on quantity of connections is not significant. Meanwhile, after adding the control for connectivity quantity, the coefficient on quality of connectivity is significant, suggesting that a one-point increase in connectivity quality score yields a 1.1-point, or 22pp, ($p<0.01$) increase in perceptions of Gobabeb.

In contrast with the findings of model 2, the coefficients on both quality and quantity of connections to the MOA in model 4 are both positive and significant ($p<0.05$). This suggests that controlling for each other, both quantity and quality of connections to the MOA are significant indicators of perceptions.

The differential effects of quantity and quality on perceptions of the MOA and Gobabeb may potentially be due to multicollinearity, which suggests that explanatory variables which are heavily correlated to each other, in this case connectivity number and quality, can dampen the power of each individual indicator in the multivariate model to explain variation in the dependent variable, in this case perceptions. In the case of the MOA, connectivity number and quality are not statistically significantly correlated (see Appendix F). However, in the case of Gobabeb, the quantity and quality of connections are highly correlated, as a one-point increase in connectivity quality score leads to a 1.16-point increase in number of connections ($p<0.01$), indicating an almost directly linear, one-for-one relationship (see Appendix F). Therefore, the drop in explanatory power seen in model 2 may in part be a result of the multicollinearity of the quantity and quality of community connections to Gobabeb. See Appendix F for both the results of mentioned regressions, and further discussion on possible explanations for this multicollinearity and its impacts.

Finally, statistically insignificant findings in models 5 and 6 suggest that there does not exist a relationship between connectivity to and perceptions of the MET like there is in the case of the MOA and Gobabeb. We will expand on the differential relationships between connectivity and perception across institutions in our discussion.

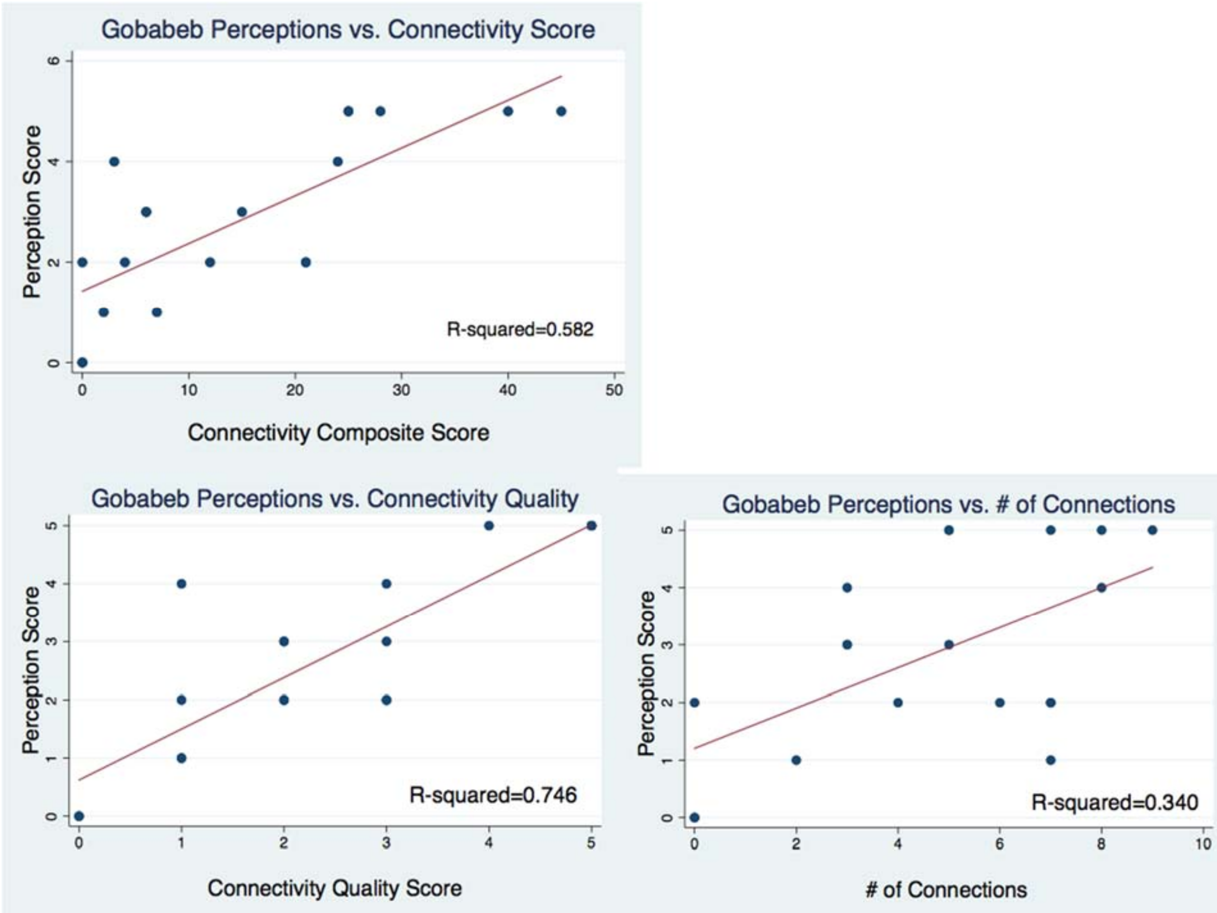
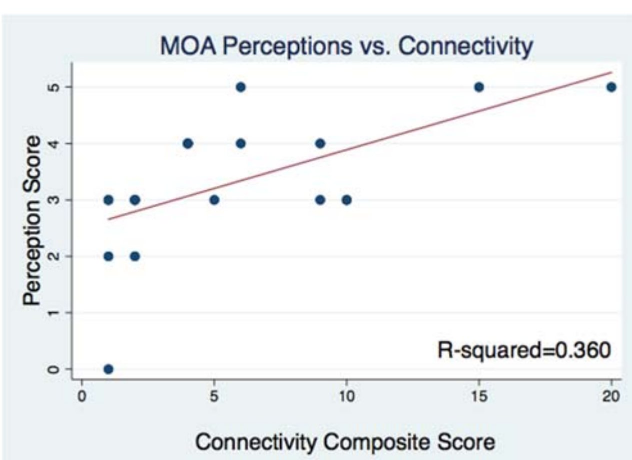


Figure 6 Gobabeb Perceptions and Connectivity Linear Models.

The above three graphs represent the linear relationship between community members' connectivity to and perceptions of Gobabeb. All three graphs show that perceptions increase with connectivity and more specifically, connection quality and quantity. The difference in R-Squared terms, namely in the much larger R-squared of the linear model of perceptions and connectivity quality, reflects that connectivity quality better explains perceptions of Gobabeb than does connectivity quantity. This supports findings of the second model in Table 8, which suggests that connection quality is a more meaningful indicator of perceptions than is connection quantity.



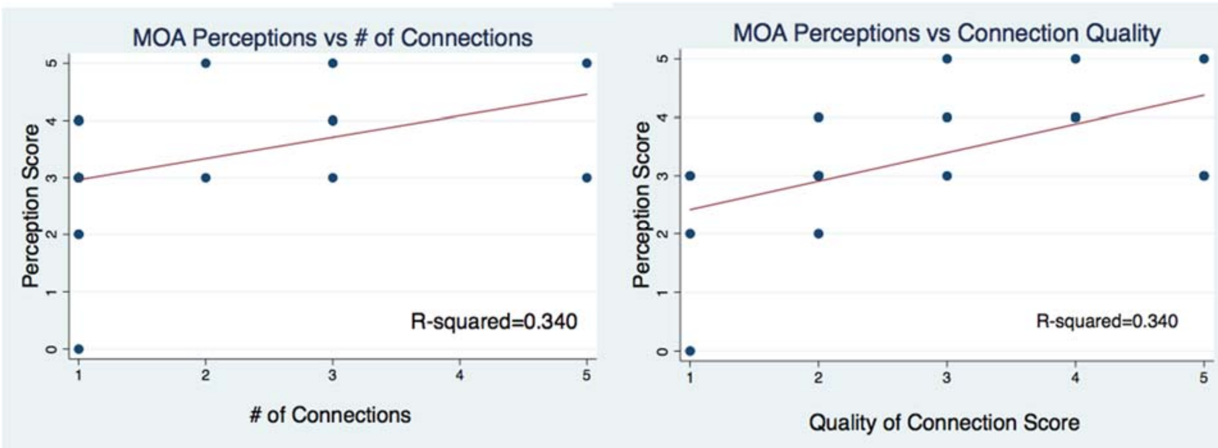


Figure 7 MOA Perceptions and Connectivity Linear Models.
The above three graphs show that perceptions and connectivity, specifically connection quantity and quality, have a positive relationship. Moreover, the similar R-squared term of the bottom two graphs represents that connectivity quantity and quality explain similar proportions of the variation in perception scores. This supports the finding in model 4 of Table 8, which suggests that both connection quantity and quality are significant and almost equivalent predictors of perception score.

Connectivity and Perceptions' Effect on Willingness to Reach out to Institutions

The following results evaluate the effect of community members' connections to and perceptions of institutions on their willingness to reach out to those institutions in times of need or with problems. See regression at Appendix G-L.

Table 9 Perceptions, Connections, and Willingness to Reach Out

	Gobabeb			MOA			MET		
Variables	(1) Bivariate on Perception	(2) Bivariate on Connection	(3) Multivariate	(4) Bivariate on Perception	(5) Bivariate on Connection	(6) Multivariate	(7) Bivariate on Perception	(8) Bivariate on Connection	(9) Multivariate
Perception Score	0.206**		0.0730	0.126		-0.0400	0.0277		0.0258
	(0.0766)		(0.120)	(0.0954)		(0.140)	(0.0677)		(0.0803)
Connectivity Score		0.0278***	0.0202		0.0490*	0.0571		-0.00352	-0.00105
		(0.00876)	(0.0154)		(0.0227)	(0.0369)		(0.0173)	(0.0215)
Observations	16	15	15	16	16	16	17	18	17
R-squared	0.434	0.550	0.568	0.191	0.342	0.347	0.558	0.569	0.559

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Each trio of regression models in this table evaluates the relationship between community members' connectivity to institutions, their perception of those institutions, and their willingness to reach out to the institution. The first model evaluates the relationship between perceptions and willingness to reach out. The second model analyzes the relationship between connectivity - specifically, connectivity composite score - and willingness to reach out. Finally, the third model uses a multivariate approach to assess the individual effect of perceptions and connectivities on willingness to reach out, while controlling for each other - perceptions and connectivities, respectively. This in turn allows us to determine whether perceptions or connections is a more significant indicator of willingness to reach out to institutions.

Models 1 and 2 suggest that both perceptions and connections affect willingness to reach out to Gobabeb, as a one-point increase in a community member's perception score yields a 21% increase in their willing to reach out to Gobabeb ($p<0.05$) and a one-point increase in the community member's connectivity composite score yields a statistically significant 3% increase in their willingness to reach out to Gobabeb ($p<0.01$). While perception's effect is almost ten times greater than connectivity, this is in part due to the nature of the indicators: the range of the perception score is 1-5 while the range of the connectivity composite score is 1-45, almost a parallel ten-fold increase. Therefore, the difference in magnitude of the coefficients is not simply a reflection of differential effects, but differential indicators.

While connections and perceptions do not significantly affect willingness to reach out to the MET, connectivity to the MOA does significantly affect willingness to reach out to the MOA. A one-point increase in a community member's connectivity composite score yields a 5% increase in their willingness to reach out to the MOA ($p<0.1$). However, perception of the MOA does not affect individuals' willingness to reach out. We will discuss this discrepancy between perception and connection's effects on willingness to reach out to the MOA in our discussion.

For both the MOA and Gobabeb, once multivariate models 3 and 6 include both perceptions and connections as explanatory variables, coefficients are no longer significant. This again points to potential multicollinearity between connectivity and perceptions, which diminishes their individual explanatory power when controlling for each other. This is supported by earlier findings in Table 8 showing that connectivity and perceptions of both Gobabeb and the MOA are strongly connected. While the multivariate analysis does not show that connectivity and perception individually affect willingness to reach out while controlling for each other, the fact that this is likely due to multicollinearity supports the validity of the connectivity and perception effects found in models 1, 2, and 5.

Qualitative Results

Given that our quantitative results show that connectivities, perceptions, and action are interrelated, our qualitative results explore the mechanisms through which these relationships occur. First, the below graph identifies ways in which community members experience support and benefit from institutions, sources of their dissatisfaction with institutions, and their hopes for future improvement through and alongside institutions.

Perceptions and expectations of the institutions

Table 10 Numbers indicate the number of community members who made statements during conversations about the above topic areas in relation to the institutions of focus.

	Gobabeb	MET	MoA	TA
Forms of Support	Employment (1) Trainings (needle training) (6) Education (8) (grade 7 program and communicating research findings) Transport (3) Livelihood support (4) Research (5) (cattle and !Nara)	Workshops (2) Predation support (9) Protect wildlife (3) Provide meat (1)	Workshops (2) Livestock health support (5) Accessibility (6) Gardening support (1)	Serve as intermediary (2)
Sources of Dissatisfaction	Lack of transport (2) No community development (2) Lack of benefit sharing (4) Lack of community involvement (2)	Lack of support for predation (8) Inability to retaliate (2) Park regulations (4) Lack of Nara protection (2) Lack of extension officer (1)	Slow/lack of response (3)	Bureaucracy (1) Lack of response (4) Lack of information sharing (1)
Future Interactions	Education/trainings (9) Employment opportunities (6) Community involvement (5) Transport (5) Information sharing (7) Advocate for and help develop community (4)	Employment opportunities (1) Workshops/trainings (3) Extension officer (2) Predator (4) Compensation (6)	Information sharing (2) Visit communities more (6) More trainings (3)	

Conversations with community members revealed both positive and negative perceptions of institutions - mainly through experiences of benefit, sources of dissatisfaction, and recommendations for improvement. Positive comments generally centered around tangible benefits such as workshops, which we labelled as forms of support, or ways in which community members feel aided and supported by institutions. Sources of dissatisfaction include the lack of benefit dissemination and knowledge sharing, limited support, and stringent rules. The most common recommendations for growth in future institution-community interactions include concrete benefit and knowledge-sharing such as workshops, employment opportunities, and research knowledge sharing.

Connectivity versus disconnection

Expressions of homophily in community-institutional relationships do not always translate into positive interactions. Most of the community members that we interviewed said that they knew “everyone” living in the other Topnaar communities along the Kuiseb River. This demonstrates that individuals are interacting with each other at multiple levels, but it does not specify how this connectivity might influence institutional relationships - their relationships with and perceptions about institutions. For instance, C7 of Utuseb spoke about how easy it is to reach the community members in the MoA and the TTA, stating that he could contact these individuals, “any time night or day hours.” Several of the community members mentioned that the individual who works in the MoA informs them of all the happenings relevant to their town and gardening/livestock needs. The quality of this closeness demonstrates the importance of community members working in institutions and serving as bridges between communities and institutions. C9 also expressed her closeness to two individuals working within the MET, due to her own personal involvement in their monitoring of the area: “if I see something, like other cars around and something not nice, I report it. Happens once or twice a month. The offices are in the field and I work there in the field.” However, in contrast with C7, C11 expressed that those individuals who are also family members and working within the MET do not discuss how to solve problems relevant to the role of the MET. In other words, closeness between two nodes does not always equate to improved information sharing, problem resolution, and better institutional relationships. Also, family ties do not always equate to greater ability to solve problems, as shown by C6: “My uncle is the chief. The deputy chief is also my uncle. The counselors are related. The counselors are doing nothing – they aren’t making changes." Similar comments were made by C12 and C9 (C9’s concerns were that she could not bring her complaints to her direct family member - rather, she brings them to another TA nearby).

There were several different expressions of disconnection stemming from the community in relationship to the MET, MoA, TTA and Gobabeb. For the MET, community members expressed apathetic statements that the MET office was located too far from their locations and pointed out that they had little knowledge of signs of action originating from the MET in their communities. Four individuals expressed that there was an overall lack of communication and interaction from the TTA, and one mentioned that the TTA worked primarily with elites. Those who had no connection to the MOA typically had no livestock or little contact with the MOA. Gobabeb was perceived to have ‘changed’ over time in their approaches to contacting the community, sharing information, and transmitting results from their research. Several individuals noted that community relations with Gobabeb worsened over the last decade, with Gobabeb now “less visible.” As stated by one respondent (C18), “all [Gobabeb] does is research, research, research, students, research, research.” Five people made similar statements about the lack of knowledge about what Gobabeb does for the community, and one other individual expressed some nuance to this perception, stating that Gobabeb only shares knowledge with the TTA.

Distrust and empathy between institutions and community

Limited knowledge and connectivity between subgroups, specifically between communities and institutions, can create distrust. The following table presents institutional and community responses in interviews expressing distrust of the “other.”

Table 11 Expressions of discontent and empathy

Community members’ expressions of distrust towards institutions	**Institutions’ expressions of distrust towards communities**
C16/Swartbank: “The thing is, I cannot come alone to Gobabeb to ask for help … don’t want to come alone, but if somebody says they will come to ask for help, then I will go”	GM3/Gobabeb: “They are difficult people to work with. They are untrustworthy and unreliable. Things disappear, money disappears. I cannot promote any of them.”
C18/Swartbank: “Who here is from Gobabeb? Because I don’t like Gobabeb people.”	GM1/Gobabeb: “They absconded because they had to sleep in tents, even though we had explained and translated everything beforehand. I was enraged - this is not the first time it has happened. So I called the project off.”
Community members’ expressions of empathy towards institutions	**Institutions’ expressions of empathy towards communities**
C5/Soutriver: "The workers at Gobabeb say that there is no money, so they don’t want to employ much.”	GM1/Gobabeb: “Good neighbors try to help one another out in times of emergency and real need. ” GM1/Gobabeb: “If tourism thing works out, it might potentially employ more women.”
C7/Utuseb: "Gobabeb is willing to assist us. The only problem is finance. For them to drive here, collect the teachers, take them to Gobabeb where there are a lot of computers, and bring them back is a lot of money. They are constrained by their budget."	GM2/Gobabeb: “There are a lot of things on the list that we should be doing for the community.”
	GR1: “I give them advice when it comes to farming and help transport kids to Walvis Bay. Why not pick them up if I have enough space.”

The top portion of the table presents statements demonstrating an underlying current of distrust for the ‘other’ on the part of either the institutions or the community. Because we were not able to reach members of the MOA or MET, or interview members of the TTA in depth, institutional comments come primarily from Gobabeb. In turn, we only included comments of discontent and empathy by community members about Gobabeb in the above table. The second half of the table presents statements that expressed empathy for the ‘other’ in the Gobabeb-Topnaar community relationship.

Individuals on both sides were distrustful of each other. In the Topnaar community, some interviewees expressed discomfort at the thought of interacting with Gobabeb staff. Likewise, Gobabeb management highlighted previous experiences with community members which indicating a negative perception of the Topnaar people as unreliable.

Although the discussions often adopted an “us-versus-them” framework, in which interviewees focused on dissatisfaction with and ideas to improve the flow of benefits between Gobabeb and communities, there were instances when individuals from both the Topnaar community and the institutions expressed empathy for the ‘other.’ Expressions of empathy from community members stemmed from their acknowledgement of Gobabeb’s limited financial capabilities (see Table 11). Even though these community members wanted to see more support from the institution, they also realized that these institutions have limitations. However, only 3 of 20 interviewed community members mentioned such financial constraints. Similarly, members of Gobabeb management acknowledged the needs and constraints of their Topnaar neighbors, in turn demonstrating a desire to do what they could to support their neighbors, from providing livelihood support to creating new initiatives.

Discussion

Connectivity and Perceptions

In the literature, connectivity has a significant impact on community members’ perceptions of institutions. Research has shown that individuals are most influenced by the people with whom they engage in frequent interactions with (Cooley 1909, Festinger et al. 1950, Homans 1950, Kadushin 1966, Bodin & Crona 2006). Frequent interaction increases connectedness of the network, a structural feature which enables information flow (Weimann 1982, Gould & Ferndanded 1989, Warriner & Moul 1992, Abrahamson & Rosenkopf 1997, Reagans & McEvily 2003). Furthermore, as the Construal-Level Theory states, increased connectedness simultaneously reduces social distance and improves perceptions. Exchange of information helps to improve perceptions and develop mutual understanding amongst stakeholders, which are key components of successful management. Based on the SNA, the regressions, and the qualitative analysis, the following discussion explains whether such a mutual understanding exists between the communities and institutions in the Kuiseb River Valley.

We found that individuals who have stronger connections to Gobabeb and the Ministry of Agriculture have better perceptions of the institutions. Better perceptions result from transfer of knowledge through frequent, meaningful interactions (Hansen 1999, Reagans & McEvily 2003). This supports our finding that those with greater access to jobs, trainings, workshops, and livelihood support provided by Gobabeb & the MOA have stronger ties to, and subsequently better perceptions of, these institutions. For example, C5/Soutriver said that the sewing training she received from Gobabeb “changed [her] life.” Similarly, C6/Soutriver praised the MOA for providing workshops on livestock health and trainings for injections: “I was farming for nothing, just sitting with my livestock. I learnt how to make a lot of money.” As these quotes demonstrate, information exchange can provide an avenue for building relationships. This, in turn, increases the potential for successful collaboration and positive outcomes in the future (Ostrom 2011). These individuals represent the nodes most closely connected, both through bridging ties and spatial adjacency, in our social network topography to institutions like Gobabeb.

Unlike Gobabeb and the MOA, connections to the MET did not positively influence perceptions with any statistical significance. Ostrom (2011) argues that people need to have agreed upon goals in order for successful collaboration to take root. In this case, the MET's purpose is to maintain the park and conserve biodiversity. In contrast, the community members are motivated by livelihood needs. Conflicts often arise between these vested interests, as livelihoods are heavily dependent upon livestock, which often fall prey to the wildlife that parks are designed to protect. For example, C6/Soutriver explained the negatives of living in a park in which you cannot access resources like firewood and "can't do anything because the MET can take you to jail if you kill [predators]." Because park regulations forbid hunting and livestock loss compensation, the MET officials are unable to help the community members whose livestock are killed by predators. Additionally, even when people knew rangers, they were not more likely to receive a response. Thus, individuals with many or strong ties have the same perceptions as those with few or weak ones. As C3/Utuseb emphasized: "The MET responds very slowly to our cries, especially to dangerous animals who kill our livestock. Sometimes they don't even respond. I haven't heard of any time they succeeded in anything." Thus, although many community members have ties to the warden and to the two MET rangers who operate in this region, these connections do not lead to better perceptions of the MET, as they do not yield any solutions to the issue of predation. The limited capacity of the MET officials explains why neither connections nor perceptions had a significant effect on willingness to reach out to the institution for help, as reaching out rarely creates change.

Another reason why connections fail to improve perceptions in this case is because there are fewer ties between the community and the MET, as evidenced in community members' average connection to the MET being the lowest among the three institutions (Table 4). This stems from the MET's inaccessibility. While every interviewee knew where the MOA office was, the majority of interviewed community members did not know where the closest MET office is. Many interviewees also mentioned that they only speak to the MET rangers once a year for two-three weeks during the hunting season, unless they report a problem with predation. Meanwhile, MOA officers frequently visit the communities to check on livestock, so there are more opportunities to establish a stronger connection. Accordingly, the MOA creates far more connections with the community, and far stronger connections - as evidenced by the MOA's average connectivity score of 2.8, the highest among the three institutions. One way to rectify MET's community connectivity is to establish an MET office near the communities and send officials to the villages to check-in every month or so. In fact, two community members mentioned the establishment of an MET extension office similar to that of the MOA as a critical opportunity for improvement in MET-community interactions. Not only would this improve connections and by extension, perceptions, it would also demonstrate to communities that their concerns are being heard. The strengthened social network would set the stage for increased community involvement in future policy development and management.

While both community members' connectivity to Gobabeb and the MOA significantly affects their perceptions of those institutions, the significance of the components of connectivity - namely the quality and quantity of community ties to institution- varies in their effect on perceptions of Gobabeb and the MOA. For Gobabeb, the quality of connections is more important than the quantity of connections in fostering positive perceptions, as evidenced by model 2 of Table 8. The statistical insignificance of quantity of connections in affecting perceptions after controlling for connection quality, likely stems from the lack of impact that Topnaar staff, the source of much of the community's quantity of connection to Gobabeb, have in sharing knowledge or stirring positive perceptions of Gobabeb. Although most of the community members cited the Topnaar maintenance staff as their connection to Gobabeb, the existence of these ties did not increase the community's understanding of Gobabeb's role or help to create an avenue for information sharing, as information-sharing between Topnaar staff and the community was rarely related to Gobabeb's conservation focus or ecological research.

Unlike Gobabeb, both the quantity and quality of connections that community members have to the MOA significantly influence their perception of this institution. This may be for a number of reasons. Quality is important as the MOA focuses on livestock, a key component of many interviewed community members' livelihoods, and provides services which create tangible benefits and share knowledge which the community values and understands. Additionally, the high betweenness centrality of MOA personnel that operate in this region suggests that they effectively serve as a bridge between the institution and communities. Differences in connection quantity, determined by connection to the three employees of the office in Utuseb but especially by its extension officer, therefore also has a significant impact on perception. In other words, community members are able to easily access concrete information and support that MOA offers through these few individuals, which establishes the importance of both the quantity and quality of connections.

Since the MOA regularly visits all of the villages, communication links are distributed more evenly, ensuring that everyone benefits. This high connectivity had a statistically significant effect on community members' willingness to reach out. However, while greater connectivity did lead to more positive perceptions of the MOA, perceptions were not a significant indicator of willingness to reach out. This may be because the MOA provides communities with necessary support for their livestock, making proximity to these services far more influential than perceptions. Thus, accessibility and integration of these institutions into local communities improves the opportunity for communities and institutions to effectively work together. Knowledge-sharing between institutions, such as Gobabeb and the MOA, can promulgate communication and community interaction strategies which facilitate joint action.

Connectivity, Perceptions, and Collective Action

For Gobabeb, both connectivity and perception significantly affect community members' willingness to reach out to the institution. While connectivity and perception do not maintain this significant effect after controlling each other, they remain crucial to community members' willingness to work with Gobabeb, as this drop in significance is likely a product of multicollinearity. Moreover, qualitative analysis highlighted community perceptions of Gobabeb as inaccessible and invisible, precluding connectivity and worsening perception. Therefore, when community members do not feel connected to Gobabeb, or see it as a positive influence, they are reluctant to reach out to it for help, evidenced in only 43% of individuals indicating that they would be willing to reach out to Gobabeb for help. While part of this is due to Gobabeb's mission as a research center, not a development organization, and some community members' understanding of that, it also has implications for joint action between Gobabeb and the Topnaar community. Willingness to reach out to an institution in the face of a problem is a necessary precursor to joint action between the Topnaar community and institutions to improve the wellbeing and operational success of each. Given that regression results show that connectivity and perceptions affect willingness to reach out to Gobabeb, and by extension joint action with Gobabeb, and that connectivity to and perceptions of Gobabeb are not strong (see Table 8) improving connectivity and perceptions is necessary for joint action between institutions and communities, which is key to network resilience and the effective management of systems.

As previously mentioned, the Gobabeb maintenance staff have the potential to serve as a bridge between Gobabeb and the community, as evidenced by their crucial position bridging the Topnaar community and Gobabeb researchers and management in our social network topography. However, they do not currently use their position to initiate the spread of information through their ties to the villages (Krishna 2002). This could be due to poor information sharing within Gobabeb, as some workers could not identify Gobabeb's research-centric mission, or to the positionality of Topnaar staff as technical team, rather than part of the "mission" of Gobabeb - which reduces their incentive and feelings of ability to share the center's mission. In other words, the existence of these ties is not enough to forge a meaningful connection between community and institution that promotes mutual understanding. Without this connection, there is a spatial and psychological distance between community members and Gobabeb staff. Since most community members do not have a concrete understanding of what Gobabeb does, they develop abstract high-level construals, which are often biased because they hear only one side of the story. This results in negative perceptions as well as a reluctance to engage. Similarly, because the Gobabeb's management team's connectivity to the Topnaar community is fairly limited, centered around a few connections in addition to the Topnaar technical team, they also develop high-level construals through which they generalize perceptions of the Topnaar community and become removed from the concrete problems facing the Topnaar community. Discrepancies in perceptions of each other preclude joint understanding, and in turn joint action.

By contrast, individuals who overcome this distance to develop high-quality relationships with Gobabeb management have far better perceptions of Gobabeb, and willingness to act in unison with Gobabeb. These relationships increase levels of trust, facilitate information flow, prioritize the co-production of knowledge, and strengthen benefit-sharing (Berkes 2017, Ostrom 2009). For instance, one community member who developed a strong relationship with the Gobabeb management is now involved in creating nets for the study of tree-pods. Regression analysis suggests that such strong connectivities create strong perceptions, while social network analysis suggests that these connectivities can bridge ties between subgroups and break down division. In turn, these connectivities to and perceptions of Gobabeb can strengthen community members' willingness to reach out to Gobabeb for help, and by extension act in unison with the institution.

In recent years, community-based participatory research (CBPR) has been presented as a promising collaborative approach to create ties and joint action between research institutions and communities as it encourages active and equal partnerships between community members and academic investigators (O'Fallon & Deary 2002, Minkler 2005). The involvement of a few community members in research translates to a few high-quality connections, which has beneficial effects above and beyond the cumulative effect of these individual ties (Renzulli et al. 2000). Furthermore, because the strength of ties is crucial to perceptions of Gobabeb, even moreso than is the quantity of connections, inclusion of community members in research can foster strong ties and therefore vastly improve community perceptions of Gobabeb. In turn, Topnaar community members who learn through participatory researchers can serve as nodes of betweenness centrality, connecting community members with Gobabeb and its research through weak ties. Weak ties are ties bridging strongly connected subgroups which are, according to the strength-of-weak ties thesis, crucial in spreading information between tight-knit subgroups like Gobabeb and the

Topnaar community (Burt 1992). A handful of Topnaar community researchers, who would possess weak ties to community members across the villages and Gobabeb research staff, can help Gobabeb disseminate information and significantly improve community understanding and perception of Gobabeb's mission and work. Moreover, not only will these ties affect perceptions and eventually joint action, but community-based participatory research is a direct example of joint action between communities and institutions, laying the foundation for further unified action.

Barriers and Opportunities for Greater Connectivity

Given that connectivity has a significant impact on perceptions of institutions and community members' willingness to seek help, which is a precursor for collaboration, a more interconnected network has greater potential for joint action. However, different demographic factors have significant effects on connectivity and willingness to interact with institutions. According to construal-level theory, the more distant an object is from an individual, the more abstract the thought of it will be due to the psychological distance. Based on this theory, we hypothesized that individuals living further from institutions would have less connectivity to those institutions, and in turn worse perceptions and coordinated action. However, distance from institutions did not produce statistically significant effects on connectivity, perceptions, or willingness to reach out to institutions. This finding can be explained by our social network analysis. Although transport is difficult, connectivity between community members is quite strong, as almost all community members answered that they "know everyone" along the Kuiseb river. This strong connectivity between members of the Topnaar community across a large region mitigates the differences in knowledge and perception that we might expect from spatial differences, as strong network density among Topnaar communities fosters knowledge and perception sharing.

Because of the tendency to interact with similar others, a phenomenon known as homophily, demographic differences often preclude connectivity, creating subgroup divisions in connectivity and joint action across lines of sex and age. Regression results show that men are more willing to reach out to the MET for help, a potential offshoot of men's greater ownership of livestock. However, this could also result from homophily, as all three Topnaar MET staff are men, making them more accessible to Topnaar men. Because connectivity affects willingness to reach out to institutions for help generally, sex can preclude women especially from accessing the resources of institutions and acting in unison with institutions. Similarly, youth have significantly greater connectivity to the MOA, in part a result of the relative youth of staff at the MOA extension office, making it easier for similarly young others to engage with the office, as exemplified by C12/Aramstrat and C4/Gaodanab who were ages 22 and 34, respectively, who mentioned speaking with Joel often and learned about livestock health and solved livestock issues frequently through him. Such demographic barriers affect connectivity, and in turn perceptions of and joint action with institutions. In order to ensure equitable benefit sharing and community interaction, the MET and MOA must acknowledge the demographic barriers affecting connectivity and action.

Subgroup division resulting from homophily is clearly demonstrated in the social network topology (Figure x), which shows that the upper-level staff at Gobabeb (management and research teams) and the Topnaar communities form two distinct subgroups. Both subgroups, especially the Topnaar community subgroup, are very dense. This means that the bonding ties within the subgroups are stronger than the relational ties between subgroups. The connections which do exist between the two subgroups occur through the Topnaar staff. This demonstrates that the majority of the community members are only interacting with other community members.

Much like the community, the upper-level staff of Gobabeb also displayed tendencies to interact with similar others. Gobabeb, standing as a research center of high academic prestige, serves as an example for homophily, as it maintains connections primarily with community members similar to it - those with greater education. As models in Table 5 suggest, those with greater education are more likely to be connected to Gobabeb, both through stronger relationships and more of them. In turn, this indicates that less educated individuals have fewer connections to Gobabeb. This homophily leaves the Topnaar community, which experiences high education dropout rates, unconnected and uneducated, even in the presence of an academic institution: while 8 community members cite education and trainings as main benefits of Gobabeb, 9 community members also suggest education and trainings as a key area of improvement, and opportunity for the development of the Topnaar community in partnership with Gobabeb. Moreover, one community member exclaimed, "[Gobabeb is] not really visible. They must be around in the community. They have everything there, the community does not. They must create education opportunities or something for the community. Kids end up dropping out while there is a research center right here!"

All of this goes to show that there is a disconnect between community members and non-community-member staff at Gobabeb. In other words, homophily limits the cohesiveness of the broader community-institution network, as evidenced by high-subgroup formation in the network topology. Low density of relational ties between groups can have negative effects on the capacity for collaboration among subgroups (Bodin & Crona 2009). Not only does it become more difficult to facilitate coordinated action, such as community capacity-building projects, but weak relational ties between subgroups also have implications for key social processes such as information sharing. As regression results show, information sharing, the core of connectivity quality, is critical to improving perceptions, as mutual understanding is a key component of trust.

One effect of homophily is the distrust that both groups harbor toward each other, which is in part also a result of subsequent low cohesion in the network. Because Gobabeb management have not had pleasant encounters with community members, they view Topnaar people as a whole as unreliable and untrustworthy (see Table 11). Similarly, some community members were apathetic and even hostile towards Gobabeb, because they "do nothing for the community." This discontent may dissuade both community members and Gobabeb staff from coordinating subgroup activities. Our qualitative analysis unearthed one potential pathway for mending this relationship: education. Collectively, community members cited education as the greatest benefit of Gobabeb's presence. Similarly, education was also the most frequent response for what community members wanted to see more of from Gobabeb. Many of these responses centered around the grade 7 program, but several also mentioned that they enjoyed hearing from Gobabeb researchers who visited communities to share their findings. This is further supported by the fact that information-sharing was the second most common answer for desired future interactions with Gobabeb. These responses demonstrate that community members are interested in the work that Gobabeb does and are hopeful for future collaboration and information sharing.

Recommendations for Future Action

Information sharing is not simply an opportunity for growth; rather it is a necessary duty for all researchers in the Kuiseb River Valley - both Gobabeb and Dartmouth. Several community members highlighted the one-way flow of benefits: C3/Ururas asserted that, "research must bring difference. Otherwise, your research is only doing you benefit. We need more information sharing. We want those things. We believe and we pray." Although Gobabeb is not a development organization, information-sharing is a necessary component in community-centered research. Without this exchange of knowledge, research serves only to extract information to the benefit of researchers. As our experience shows, this drastically reduces the willingness of community members to participate in the research that these institutions conduct. The first step to making this relationship more equitable is reforming the research culture to continue engaging the community after the data collection phase. This will help mitigate, rather than perpetuate, knowledge inequalities in the region. Dartmouth can improve sharing of research findings with the Topnaar communities is by facilitating yearly presentations of these research project results in the community, as it did this year during the community livestock workshops. Active efforts must be made to improve accessibility of these presentations, such as offering transportation.

One venue for increased information-sharing that Gobabeb, the MOA, and the MET can capitalize on is a radio station, such as the widely listened to Damara Nama station. Interviews with both community members and members of the TTA suggest that radio communication is an effective method of disseminating information and engaging community members. Moreover, education and community involvement in research align with Gobabeb's mission of dry land training and research. As previously discussed, community-based participatory research can build community-institution connectivity, increase knowledge of Gobabeb's mission, improve perceptions of its work, and provide the foundation for future join action. Building upon already-established education and outreach programs can similarly improve connectivity and perceptions, and lay the foundation for future collaboration between communities and institutions.

Further research is needed to expand on our analysis of the social network in the Kuiseb River Valley. Our community interviews covered approximately 6-10% of the households in the Topnaar community. However, according to verbal estimates by members of Gobabeb management and the TTA, a larger sample of the Topnaar community and interviews with members of the MOA and MET are needed to gain a more complete picture of the social network. Moreover, future research into the Kuiseb River Valley social network can further explore the role of the TTA, and perceptions of the TTA, as our collaboration with a translator who worked for the TTA sometimes precluded that line of study due to the dynamics that go along with asking a community member about the traditional authority in the presence of the traditional authority. However, the traditional authority is a unique governance presence, and operates at the intersection of local institutions and the Topnaar community; therefore, it is of importance in futher research on social networks and collective action. Additionally, we explored a specific form of collective action between communities and institutions: community members reaching out to institutions for help. Other indicators of joint action, such as participation in community-based research or participation in rulemaking, are also relevant to the discussion of connectivity as a foundation for future joint action between communities and institutions.

Finally, future research in the Dartmouth-Gobabeb-Topnaar partnership must break the cycle of the one-way flow of benefits, and put specific emphasis on community-based research that creates value for the Topnaar community. Our findings demonstrated that connectivities are only positive for the community insofar as they share knowledge and create benefits for the community. We must implement this finding in our own action in this system. We therefore recommend that further research explore the feasibility and effectiveness of concrete methods of community engagement, such as use of the Damara Nama radio or inclusion of community members in research. Additionally, we urge Dartmouth to end the cycle of knowledge and benefit extraction by actively working to create spaces for community engagement in the research projects. We recommend that Dartmouth require every research group to include a community-engagement componen, from a day of fieldwork with learners in the JB Brandt Primary school to a community-based research project which includes a development focus (e.g. an educational outreach program).

In the broader academic context, the findings of this study fill gaps in the literature surrounding the impacts of connectivity and perceptions on community-institution relations. However, at the scale of the community, our research only has value insofar as it creates value for the Topnaar community. Construal level theory states that our great physical and cultural distance from the Topnaar community increases the likelihood of our abstraction of Topnaar problems; therefore, our focus on answering larger academic questions is understandable. However, that does not make our action admissible. Future researchers on this program must acknowledge our positionality, multi-dimensional distance from the Topnaar community, and the history of our role in the Kuiseb River Valley to end the one-way flow of research benefits and create equitable benefits through our presence in the region. Through this flow of benefits, our ties to this system can foster joint action, create equitable benefit and knowledge sharing, and foster development at the community level.

Connectivity between individuals and institutions affects their perceptions of those institutions, and in turn their willingness to act alongside those institutions. In order for institutions to operate productively, and for the Topnaar community to maintain resilience in the face of broader social-ecological changes, strong connectivity between institutions and communities is needed. This will improve intergroup perceptions, deconstruct subgroup divisions, and foster intergroup understanding and collective action. An important aspect of these connections is their strength: the potential for benefit-sharing, knowledge exchange, and mutual learning through the relationship. A strong network, established through interactions with Gobabeb, MET, and MOA, is integral to supporting the marginalized communities that reside in the Namib Naukluft Park. This will become more important as anthropogenic climate change continues to change the environment. As global environmental problems do not occur in isolation and are highly interconnected, collaboration across different scales, coupled with adaptive approaches that incorporate learning, are crucial to conservation. Moreover, institutions and communities must connect, foster joint understanding, and act in unison in order to use resources to stimulate human development. Connectivity and joint action are the key to effective conservation and improvement of the wellbeing of indigenous communities.

Acknowledgements

We first and foremost thank the community. It is still yet to be seen if we break or continue the cycle of information extraction from the Topnaar community, but hope that what we've learned and shared can change things for the better. We are so thankful to all who welcomed us into their homes and took time out of their day to sit down with us and share. We aspire to a day on which we need not thank the community, as on that day they will stand as our partners in knowledge creation. However, that day is not today. We hope our work has set us on the path to that day. In partnership with Gobabeb and Dartmouth going forward, we hope to move forward along that path.

We would also like to thank Julie Snorek, for guiding us spiritually, intellectually, and emotionally. She led both our group and the other community group with poise and kindness through tension, rebellion, and celebration. We thank both her and Eric Shiningayama for their trusty driving, as they each gave us a unique opportunity to come together as a team and lift a car out of the sand with our collective spirit. We thank Dennis for his speedy translations and refreshing fashion sense. Beer *is* always the answer. We thank Caroline for her help not only with translating, but also for sitting with us on thorns as we ate fruit and cookies -- not a packed lunch. We thank the management and staff of Gobabeb for speaking with us openly and hosting us so kindly. We hope that our findings are received as a call for action, rather than a condemnation of the past.

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Appendices

Appendix A: One-Pager

Community-Institution Relationships in the Lower Kuiseb River Valley

Vignesh Chockalingam, Alyssa Gao, Rironderuapi Kavari & Meghna Ray

Questions:

1. How do connections between the Topnaar community and Gobabeb, the Ministry of Agriculture (MOA), and Ministry of Environment and Tourism (MET) affect how they see and interact with those institutions?

2. How can we improve communication and connection to better help the community?

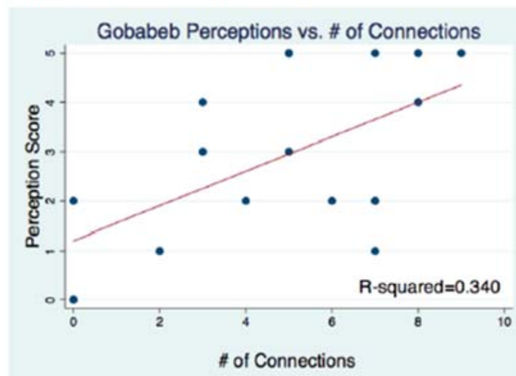
Approach

Interviewed:

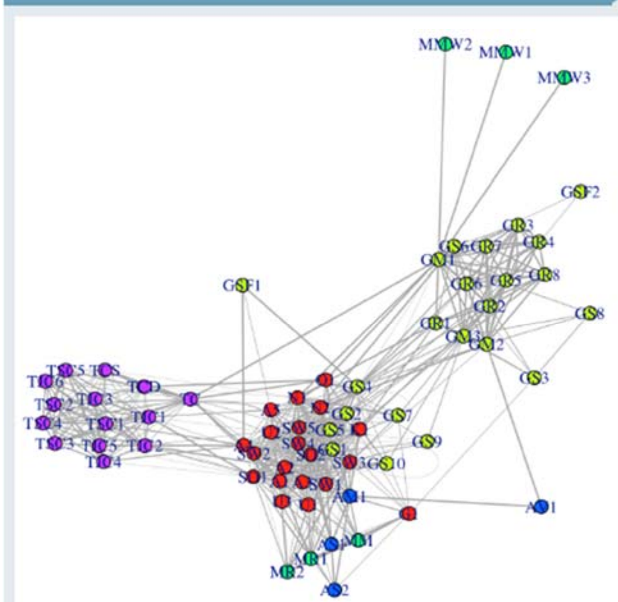
- 23 Topnaar community members
- 2 Topnaar Traditional Authority
- 11 Gobabeb management/maintenance staff

Results

- Topnaar community members are most connected to the MOA
- Topnaar community members feel least connected to the MET
- More connections to Gobabeb and the MOA improve perceptions of them
- Quality of connections was more important than quantity



What does the Kuiseb River Valley Social Network Look Like?



Key:
Purple - Topnaar Traditional Authority Topnaar
Red - Community
Yellow - Gobabeb staff
Green - MET
Blue - MOA

- Separate groups
- Less ties between different groups than within groups
- Who do you think are the circles (people) connecting the different groups?

Recommendations

- Ask Gobabeb to use Damara Nama Radio to communicate events and opportunities
- Reach out to Gobabeb, MOA, and MET through your connections

Appendix B: Connectivity Questions and Connectivity Assessment

Connectivity survey questions used to assess connectivity quality score
1. Do you know anyone who works there? a. How many? b. What do they do there? c. How are you related to them?
2. How often do you talk to them? Why/about what do you talk to them?

Using survey responses explaining the frequency, content, and nature of communication through that connection.

Connectivity assessment

Connectivity Score	Characterize	Description
0	Nonexistent	Doesn't interact with anyone from the institution
1	Very Weak	Doesn't interact with individuals from the institution often
2	Weak	Interacts with individuals from the institution sometimes, but doesn't talk about the institution at all
3	Okay	Interacts with individual often, but only talks about the institution rarely and doesn't learn about the institution's greater work through the relationship
4	Strong	Interacts with individuals from the institution to talk about the institution's work
5	Very Strong	Has a close or familial relationship with someone who works at the institution, talks to them often, and learns about the institution through that individual

To assess the strength of each connection, connectivity quality score ranges from zero to five - zero indicating weak connectivity and five indicating strong connectivity.

Appendix C: Perception Questions and Perception score used to assess the perception of the communities toward the institutions

Perception Questions
1. What do you think the institution (Gobabeb, MET, MOA, TTA) does?
2. What does the institution do that is good?
3. What does the institution do that is bad?
4. How do you think the Institution could do better working with your community?

The above survey questions were used to assess the below perception score.

Perception score

Perception Score	Characterize	Description
0	Nonexistent	Complete lack of knowledge
1	Very Bad	Strong negative opinions of the institution
2	Bad	Primarily negative opinions of the institution
3	Okay	Balance of positive and negative opinions of the institution
4	Good	Primarily positive opinions of the institution
5	Very Good	No critique of institution and names examples of its positive aspects and perceived benefits

The five-point perception score uses the ratio of positive to negative opinions expressed during the interview to assess respondents' perceptions of an institution.

Appendix D: Abbreviations

Gobabeb Research and Training centre		**Ministry of Agriculture (MOA)**		**Ministry of Environment and Tourism (MET)**		**Topnaar Traditional Authority**	
Management	GM	Managemen t	AM	Management	MM	Chief	TC
Researcher	GR	Veterinarian	AV	Ranger	MR	Deputy chief	TCD
Maintenance Staff	GS	Staff	AS	Staff	MS	Secretary	TCS
Former Staff	GSF			Windhoek Management	MM W	Junior Councilor	TJC
						Senior Councilor	TSC

Abbreviations used in the social network and throughout the study

Appendix E: Qualitative Analysis Coding Trees

	Code 1: Institutions provide help	Code 2: Expressions of dissatisfaction	Code 3: Desire for more interaction	Code 4: Reasons for disconnect from the institution s	Code 5: Psychologic al reasons for connections (homophily)	Code 6: Expressions of underlying fears of institutions	Code 7: Expressions of empathy for the institutions
Subcode 1	Trainings and workshops	Perceptions of rules	Training and workshops	Apathetic statements			
Subcode 2	Visits by members of institutions	Lack of support	Communication	Lack of knowledge			
Subcode 3	Tools: transportation, vaccinations, ear tags, etc.	Other	Transportation	Lack of access			
Subcode 4	Predation support		Predation support	Other			
Subcode 5	Other		Employment				

The above table shows the categories through which our qualitative analysis identified patterns in interview data.

Appendix F: Relationship between Connectivity Number and Quality

VARIABLES	(1)	(2)	(3)
	MOA Connection Number	Gobabeb Connection Number	MET Connection Number
MOA Connectivity Score	0.204		
	(0.219)		
Gobabeb Connectivity Score		1.166***	
		(0.299)	
MET Connectivity Score			0.442***
			(0.111)
Constant	1.328*	1.739*	0.540
	(0.683)	(0.900)	(0.323)
Observations	20	19	20
R-squared	0.046	0.472	0.469
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table shows results of regressions of community members' number of connections to an institution on their quality of connections to the institution. In the case of Gobabeb and the MET, there is a strong positive correlation. Specifically, with Gobabeb there is an almost one-to-one relationship. In contrast, with the MOA, there is not a statistically significant relationship between connection quantity and quality. This has two main implications:

1. Connection quantity and quality being highly correlated may reflect experimental bias in assessing connectivity scores, as it does not necessarily follow that connectivity quality should be correlated with connectivity quantity. This in part makes sense, as all individuals with zero connections also immediately were given a connectivity score of 0 according to our assessment process. However, it should not be the case that an individual's many connections imply that all those connections are strong.
2. Despite the fact that generally connection quality and quantity should not be correlated with each other, there are reasons for which they may justifiably be correlated in this case. In interviews with community members, many community members had the same responses when asked who they know at Gobabeb and the MET, and how: many knew the

7 Topnaar staff at Gobabeb and the 2 park rangers and 1 warden for the MET. Moreover, these connections were always family, friends, or “Topnaars”, whom they talked to once in a while, reflecting similar types of connectivity across interviewed community members. Therefore, if community members have a similar number of connections and similar types of connections by knowing the same people through the same mechanisms, it follows that their quantity and quality of connections would be correlated.

Appendix G: Gobabeb Perceptions vs. Connectivity Regression Results

	(1)	(2)	(3)
VARIABLES	Without Controls	With Controls	Quantity and Quality Instead of Composite Score
Connectivity Composite Score	0.0949***	0.115***	
	(0.0195)	(0.0225)	
Years of Education		-0.145	-0.165**
		(0.110)	(0.0688)
Male		1.186*	1.137***
		(0.596)	(0.356)
Quantity of Connections			-0.0147
			(0.0809)
Quality of Connections			1.123***
			(0.141)
Constant	1.423***	1.525	-0.136
	(0.391)	(1.600)	(1.001)
Controls	N	Y	Y
Observations	19	19	19
R-squared	0.582	0.685	0.893
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table presents expanded results of those presented in Table 8.

Appendix H: Gobabeb Willingness to Reach Out, Perceptions, and Connections Regression

Variables	(1) Willingness and Perceptions	(2) Willingness and Connectivity	(3) Multivariate
Perception Score	0.206**		0.0730
	(0.0766)		(0.120)
Connectivity Score		0.0278***	0.0202
		(0.00876)	(0.0154)
Male	0.269	0.535*	0.510
	(0.294)	(0.286)	(0.298)
Constant	0.517	0.413	0.399
	(0.712)	(0.659)	(0.681)
Controls?	Y	Y	Y
Observations	16	15	15
R-squared	0.434	0.550	0.568
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table expands on results found in Table 9.

Appendix I: Agriculture Perceptions vs. Connectivity Regression Results

	(1)	(2)	(3)
VARIABLES	Without Controls	With Controls	Quantity and Quality Instead of Composite Score
Connectivity Composite Score	0.137***	0.196***	
	(0.0431)	(0.0471)	
Age		0.0498**	0.0394
		(0.0232)	(0.0269)
Quantity of Connections			0.507**
			(0.216)
Quality of Connections			0.425**
			(0.157)
Constant	2.519***	0.0136	-0.380
	(0.327)	(1.549)	(1.852)
Controls?	N	Y	Y
Observations	20	20	20
R-squared	0.360	0.545	0.570
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table presents expanded results of those presented in Table 8.

Appendix J: Agriculture Willingness to Reach Out, Perceptions, and Connectivity Regression Results

	(1)	(2)	(3)
Variables	Willingness and Perceptions	Willingness and Connectivity	Multivariate
Perception Score	0.126		-0.0400
	(0.0954)		(0.140)
Connectivity Score		0.0490*	0.0571
		(0.0227)	(0.0369)
Constant	0.0662	-0.490	-0.521
	(0.790)	(0.793)	(0.836)
Controls?	Y	Y	Y
Observations	16	16	16
R-squared	0.191	0.342	0.347
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table expands on results found in Table 9.

Appendix K: MET Perceptions and Connectivity Regression Results

	(1)	(2)	(3)
VARIABLES	MET Perceptions without Controls	With Controls	Using Quantity and Quality Instead of Composite Score
Connectivity Composite Score	-0.0794	-0.0942	
	(0.0747)	(0.0774)	
Quantity of Connections			-0.246
			(0.581)
Quality of Connections			-0.0543
			(0.368)
Constant	2.704***	1.835	2.086
	(0.528)	(2.668)	(3.004)
Controls?	N	Y	Y
Observations	19	19	19
R-squared	0.062	0.200	0.156
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table presents expanded results of those presented in Table 8.

Appendix L: MET Willingness to Reach Out, Perceptions, and Connectivity Regression

	(1)	(2)	(3)
VARIABLES	MET Perceptions without Controls	With Controls	Using Quantity and Quality Instead of Composite Score
Connectivity Composite Score	-0.0794	-0.0942	
	(0.0747)	(0.0774)	
Quantity of Connections			-0.246
			(0.581)
Quality of Connections			-0.0543
			(0.368)
Constant	2.704***	1.835	2.086
	(0.528)	(2.668)	(3.004)
Controls?	N	Y	Y
Observations	19	19	19
R-squared	0.062	0.200	0.156
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table presents expanded results of those presented in Table 8.

Appendix M: Distance from Institutions and Connectivities, Perceptions, and Action

Variables	(1) Willingness and Perceptions	(2) Willingness and Connectivity	(3) Multivariate
Perception Score	0.0277		0.0258
	(0.0677)		(0.0803)
Connectivity Score		-0.00352	-0.00105
		(0.0173)	(0.0215)
Male	0.559**	0.552**	0.558**
	(0.212)	(0.207)	(0.224)
Constant	0.132	0.142	0.145
	(0.698)	(0.618)	(0.772)
Controls?	Y	Y	Y
Observations	17	18	17
R-squared	0.558	0.569	0.559
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

The above table expands on results found in Table 9.

Table 7: Distance from Institutions and Connectivities, Perceptions, and Action

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Gobabeb			MOA			MET		
Variables	Connectivity	Perception	Willingness to Reach out	Connectivity	Perception	Willingness to Reach out	Connectivity	Perception	Willingness to Reach out
Distance from Gobabeb in (km)	0.0595	0.00525	0.00152						
	(0.0517)	(0.00637)	(0.00201)						
Distance from MOA (km)				-0.00822	-0.000121	0.00202			
				(0.0227)	(0.00521)	(0.00197)			
Distance from MET (km)							0.00322	-0.0152	0.00343
							(0.0310)	(0.0170)	(0.00292)
Observations	19	20	16	20	20	16	20	19	18
R-squared	0.072	0.036	0.039	0.007	0.000	0.070	0.001	0.045	0.079
Standard errors in parentheses									
*** p<0.01, ** p<0.05, * p<0.1									

The above table shows results of regressions of connectivity, perceptions, and willingness to reach out to each of the three institutions on individuals' physical distance from the institution. Results are not statistically significant, and mostly unexpected, as positive coefficients on 2/3 of indicators reflect that increased distance from an institution improves connectivity and perceptions. The exception is the MOA, for which being closer to the MOA office in Utuseb increases one's connectivity and perception. However, these results are extremely close to 0, and statistically insignificant.

Habitat Selection by livestock in the Lower Kuiseb River Valley

November 11, 2017

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Abstract

Heterogeneity in resource distribution is a critical determinant of herbivore feeding behavior with implications for the productivity and health of domestic livestock. The Topnaar community in Namibia are dependent on livestock for their livelihood, yet there is little information about the movements and distribution of livestock among the three major habitats where they forage in this region. We sought to find out how livestock are distributed, and what factors are influencing movement patterns. Our group had several hypotheses: first, livestock would avoid areas with a high concentration of predators; second, livestock will be less active during the hottest times of day; third, livestock will travel further distances in the wet season compared to the dry season; fourth, livestock will not be as concentrated in the river in years with more rainfall; finally, an unusual late rainfall event will have increased the carrying capacity of the landscape compared to the previous year. In order to analyze animal movement and distribution, we gathered data about how livestock were distributed down the river, gravel plains, and inter-dunes by counting the animals in each of these habitats and collecting telemetry data from collars on cattle. We also gathered data about the external factors influencing livestock movement by collecting data on pods from *F. albida* and *A. erioloba* trees, grass samples from different habitats, and examined photos from camera traps to estimate the number of predators in the area. There was no correlation between predators and livestock number or distribution. Using the telemetry data, we found that there was no correlation between the distance traveled and season, but cattle spent more time in the river during the dry season, relative to the gravel plains and inter-dunes. Adding grass into the analysis of carrying capacity nearly doubles the estimated carrying capacity of the system, suggesting that even sparsely distributed grass resources have important implications for livestock foraging. In conclusion, we found that habitat selection by livestock was more influenced by seasonal fluctuation in food and water resources than predation or temperature.

Introduction

Animal movement is complex and can be attributed to countless factors like food, water, predation, climate, mating, and others. We do not yet fully understand what factors are most influential on movement patterns and behavior across species. Perhaps the most important factor influencing movement among ungulates is the availability of vegetation resources for consumption. Optimal foraging strategies of different species generally maximize energy gain or focus on the minimization of time devoted to foraging (Belovsky, 1986).

Habitat selection is one critical aspect of animal movement; animals' response in space and time to perceived risk and reward (Mayor et al., 2009). The risk of predation can vary across time and space, thus forcing forging animals to change their migratory and density patterns (Mayor et al., 2009). The "Landscape of Fear" framework argues that predators have two different effects on prey: lethal effect and risk effect (Moll et al., 2017). The risk effect is more influential on animal distribution and behavior since the animals are minimizing the risk of predation by practicing antipredator behaviors which are triggered by risky locations and risky times (Moll et al., 2017).

Certain species may choose to forage high quality vegetation and others may find that energy is best maximized with large quantities of lower quantity food. Although energy gain in ungulates can theoretically be maximized at relatively low biomass densities of food, time and digestibility constraints may cause herbivores to seek patches of greater biomass density (Bergman et al., 2001). For livestock in regions where vegetation biomass may be minimal and dispersed, they may be forced to travel greater distances to find patches that support their food intake requirements.

The forage maturation hypothesis predicts that herbivores will seek out resources of intermediate age in order to avoid patches of low biomass or those that are fully mature and thus of low quality. For example, the migration patterns of elk increase access to higher quality forage, suggesting that large-scale habitat selection and movement is associated with the timing and distribution of food resources (Hebblewhite et al., 2008). A study by Owen-Smith (2010) using GPS Telemetry also showed a relationship between large-scale patterns of animal movement to season, time and availability of food resources. Animals in specific regions may be more impacted by seasonal changes due to drought and rainfall that influence food abundance than others in ways that may cause drastic changes to movement and distribution patterns.

Livestock must limit their activity during the hottest part of the day since the ambient temperature is close to their body temperature, which may also influence movement. According to Collier and Gebremedhin (2014), an animal that is stressed will seek shade, increase water intake, and change their orientation in the sun. Moreover, cattle will change their feeding patterns in response to fluctuations in temperature to maintain a constant level food and nutrients. Their responses also depend on how much energy they are putting into foraging or regulating body temperature (Prescott et al., 1993). For example, during the hot temperatures, a cow will seek shade and expend a great deal of energy and water trying to cool itself down, so it will need to consume more food and water to maintain a constant level of nutrients which are being used up quickly. In order to accommodate this bodily response, the cow may spend the hottest time of day in the river where it has access to food, water, and shade then forage more intensively when the temperature drops. Temperature plays a significant role in influencing livestock movement and behavior since they must regulate their body temperature to be compatible with the ambient air temperature while maintaining a constant nutrient intake.

In the hyper-arid region of western and coastal Namibia, conditions for livestock husbandry present many challenges to productivity. Rainfall in western and coastal regions is less than 20 mm, so the region is almost totally dependent on ephemeral rivers and groundwater (Sweet 1998). The Gobabeb region of western Namibia in the lower Kuiseb River offers an ideal study site for several reasons. First, the Topnaar people that live along the river in dispersed settlements are dependent on livestock more so than many areas in Namibia for economic, sociocultural and survival reasons. Second, the style of livestock management that is characteristic of the region allows for livestock to range far more freely than cattle confined to fenced pastures or led by herders. Livestock then, because they are left to free-range the landscape, may exhibit behavior more reflective of environmental and ecosystem level influences. Additionally, these livestock are not reliant on ephemeral grasses in the gravel plains and inter-dunes as they have adapted to the harsh environment by taking advantage of the vegetation in the river. They have adapted to feed on the *A. erioloba* and *F. albida* pods throughout the year to supplement or completely comprise their diet despite being natural grass grazers. Having changed their feeding behaviors to adapt to the Lower Kuiseb River region, it is possible that cattle may have adjusted other behaviors or display other unusual movement patterns. Third, this site comprises three distinct habitats with different resource availabilities: the riverbed, gravel plains, and inter-dunes The site thus offers the opportunity to study the movement patterns and habitat selection of desert inhabiting livestock across 3 distinct habitats in the region. Each of these habitats may offer different services throughout the year, and cause livestock to utilize them to different degrees.

Based on the condition of the Lower Kuiseb and the unique behaviors of livestock in the region, we have explored 5 hypotheses that may give insight into the patterns of livestock habitat selection and utilization:
Hypothesis 1: Livestock will avoid areas of high predator concentration

Hypothesis 2: Livestock will be less active and in the river during the hottest parts of the day - will only go to gravel plains and inter-dunes to feed in the mornings, evenings, and night (heat and shade)

Hypothesis 3: Livestock will travel farther distances in the wet season as opposed to the dry season because food and water are more abundant during winter the *A.erioloba and F.albida* trees produces food in the river- so they will travel less

Hypothesis 4: Because of the increased amount of rainfall in 2018, livestock will not be as concentrated in the river as they were in 2017

Hypothesis 5: Given the ranging behavior of livestock, ephemeral grass resources in the inter-dunes/gravel plains have the potential to substantially increase carrying capacity.

To examine these claims, we collected data on resource availability and predator abundance across the Lower Kuiseb River. We also analyzed livestock telemetry data and conducted animal counts along the 3 habitats to understand livestock distribution. Finally, we compared our data to past studies conducted by Dartmouth students in the region and found intriguing differences between the years.

Methodology

Food

SSHIT Method (modified)

To assess the food abundance and animal distribution in the river, we used a modified version of the SSHIT (Sampling spatial heterogeneity in transects) Method to measure animal distribution and vegetation abundance in approximately 20 km of the lower Kuiseb river. The 20 km section of the river was divided in 10 transects with 2 km intervals between transects like Kovvuri et al. (2016). We used GPS coordinates from Kovvuri et al. (2016) to define our study sites and marked the locations of our transects. Unlike the original SSHIT method, we chose to leave out canopy cover, vegetation cover, and tree size measurements because we were most concerned with food abundance and its relationship to livestock distribution and not vegetation distribution. At each transect, we conducted pod counts to analyze resource distribution. We also conducted dung counts of cattle and donkeys to assess animal distribution in the river, and that it relates to food abundance. At each point, we sampled 2 transects on either side of the riverbed where we divided the river into right bank, left bank, inner bank, and outer bank for potential differences in tree pod production. We walked 50 meters downstream from our starting on the inner and outer bank counting whole *A. erioloba*, *F. albida* pods, donkey dung, and cattle dung on the ground within a meter on both sides. Because of thick vegetation, the outer bank transect began where there was a large enough clearing, so the distance between the inner and outer transects varied somewhat at each site.

We counted the number of dung individually instead of piles; moreover, donkey dung was counted by pairing halves of the dung to count as one full piece of dung. We counted both old pods, new pods, and focused only on full pods. Additionally, we randomly identified one *A. erioloba* tree and one *F. albida* tree along the transect (usually in the middle or end) to count the pods still on the tree. Pod counts of the tree occurred on 2 sides of the tree for 30 seconds.

Grass sampling survey

To estimate the amount of grass available, we sampled random areas of grass fields in the inter-dunes and gravel plains. In doing so, we hoped to gain an understanding of the makeup of grass populations near the Kuiseb River. It is important to note that we sampled few areas, but we covered the major grass-bearing habitats. We relied on the local knowledge of our Gobabeb mentor to find areas of grass fields in the inter-dunes and gravel plains along the river near our transects to conduct measurements. He selected areas that were easily accessible from the river with grass cover. We walked 10 meters into the grass field from our starting location and randomly threw the quadrat at the 10 meter mark. We counted the number of grass tufts, both dead and living, identified the species of grass present in each quadrat. To measure grass biomass we harvested all vegetation in one quadrat at the site. Afterwards, we dried and weighed the grass. From these measurements we could approximate the makeup of the grass population at each site as well as a rough estimate of the abundance of grass in the general study area. We repeated this process 5 times at each location. At each site, we marked the location with GPS coordinates.

Animal Distribution and Movement

Animal Distribution along Three Habitats

In order to find out where animals were distributed, we conducted animal surveys in the three habitats in the research area. As we surveyed the habitats, we recorded the number of animals at the location, the time each individual was seen, the herd size, and the body condition (cattle only). To account for the possible difference in animal activity at the different times in the day, we surveyed the different halves of the river twice at opposite times: downstream in the morning and afternoon, and upstream in the afternoon and morning.

For the river, we traveled 42.1 kilometers in the river by vehicle, counting all animals we saw. For cattle, we differentiated between male and female, age class, and body conditions. In the river habitat, we also marked the GPS locations of ephemeral pools during our animal count surveys. During and after our animal count surveys of the river, we climbed the inter-dunes and looked any cattle on the inter-dunes or gravel plains using binoculars, and we did not stay for more than 15 minutes. The inter-dunes locations were surveyed from high vantage points along the river. Afterwards, we moved onto the gravel plains. To survey the gravel plains, we drove from our ending points along the river to the main road back to Gobabeb. We performed this survey each time we finished the river survey, so each gravel plains survey was conducted during from 14:00 to 16:00.

Animal Movement

Using GPS enabled tracking collars on selected livestock, we were able to utilize longitudinal spatial data on individual cattle and donkeys in the Topnaar community. The collars tracked and collect livestock location, temperature, and activity every ten minutes. The data was collected from the collars using an automatic transceiver, which downloads data when the collared cattle are in range of the transceiver set-up near a waterhole, and a manual transceiver, which downloads data once you find the cattle and it gets in range. In total we collected data from 6 cattle and 2 donkeys.

Animal Behavior

We conducted focal follows to observe movement and behavior of donkeys and to understand what they are doing at various times day. The focal follows allowed us to focus on individuals while minimizing the disturbance our presence on the whole herd. Each observer chose, at most, three donkeys on an *ad* *libitum* basis. Therefore, we are acknowledging this bias in our methods. The focal follows lasted for an hour and we recorded observations every five minutes. During the five minute intervals, we counted the vigilance of our selected donkeys by counting the times they surveyed the landscape and looked up with pointed ears. In total, we conducted three separate focal follow events on nine individual donkeys. We used the track function on the GPS to record the migration of the donkeys while we followed them.

Predation

According to community members, the Kuiseb River has high concentrations of predators while the Salt River wash in the gravel plains does not. So, Gobabeb researchers placed camera traps in areas of high and low predation to determine whether these perceptions of predator concentrations were well-founded. 19 camera traps were set up along the downstream half of the river in ten locations, two cameras at each location on opposite sides of the river, except for cameras GB01, GB11, and GB12 which were located away from the river or individually. Half of the cameras also had scented lures (Canine Call Lure by Russ Carman) to attract predators which was the basis for the paired design. Due to rainfall and river flow, one camera was lost, so our data examines photos from the 18 surviving cameras. The cameras are active every day for 24 hours and measure time, date, and temperature. They take a series of pictures when movement is detected in front of them. The cameras caught images from October 19, 2018, when they were first placed, to November 1, 2018, when we first downloaded data. We collected camera trap photographs twice during our research period. The second was collected on November 6. We counted the number of animals caught on the photos and categorized the animals by species so that we could get a count for the types of animals that inhabit or utilize the areas around the camera traps. At the end of our first collection, we adjusted some of the cameras, so that branches were out of vision of the camera traps to prevent them from triggering the camera. While some of the cameras were adjusted, none have been completely removed from the area.

Carrying Capacity

Given the ranging behavior of livestock, ephemeral grass resources in the inter-dunes/gravel plains have the potential to substantially increase carrying capacity. For their 65 km study area, Cervenka et al. (2017) estimated the associated carrying capacity of the Kuiseb River valley to be 1575 standard animal units per year. This estimate was based solely on the number of *Acacia* and *Faidherbia* pods available. To extend this estimate to include edible vegetation for grazing herbivores (grasses (*Stipagrostis* spp., *Centrepodia* spp.) and *Zygophyllum simplex*) in the inter-dune and gravel plains habitats, we used *QGIS* to calculate areas accessible to livestock along the 65 km study area of Cervenka et al. (2017). Areas were selected based on estimates of the distances that cattle walk from the riverbed into these environments from GPS collar data. We then multiplied average biomass per unit area for inter-dune and gravel plains habitats (from quadrat data) by area to estimate additional edible biomass and added these values to the equation for carrying capacity, following Cervenka et al. (2017):

$$C = (AN + Fn + V_{interdune} + V_{gravel\ plains}) / (U(12))$$

Statistical Analysis

We used JMP and R to analyze our data and last year's data to understand the relationships between the factors we were examining in our hypotheses. For our statistical analysis, we used linear regressions to assess the relationships between continuous variables. We also used a matched paired T-test to compare the averages between samples. For analyses of GPS data we used linear mixed effects models with random intercepts to control for repeated observations within individuals.

Results

Predator impact

The camera trap photographs were collected between October 19 and November 6, 2018. To avoid counting duplicate animals in each individual picture, we only counted animals once if they were shown in more than one picture. Our camera traps caught a total of 56 predators, the largest being brown hyenas and the smallest being a small-spotted genet. The most common predator caught by the camera traps was the black-backed jackal (see Table 1in appendix for full breakdown).

Animal Activity

We define "active" as the frequency with which animals were seen in the camera trap photos. Activity, in this case, does not correspond to the physical activity of the animals, but to their presence in the river during the course of a day. Examining the activity graph, animals were least active during the the hottest daytime temperatures (see Figure 1). They were also least active during the coolest parts of the day and night. Both livestock and small stock were most active between 18 C and 27 C.

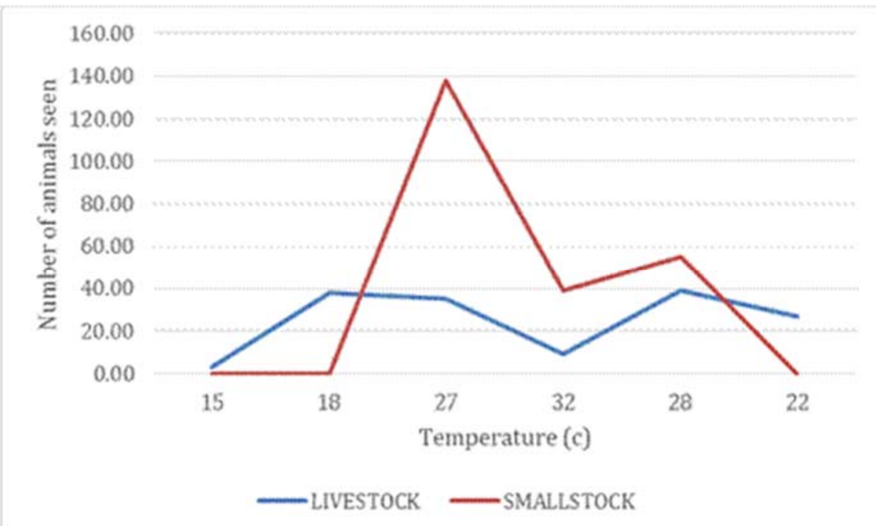

Figure 1. Temperature over the course of 24 hours vs number of animals seen in camera traps.

According to the camera trap data, Figure 2 shows that livestock are active throughout the day and night with the least active times ranging from between 00:00 to 4:00 and 12:00 to 16:00. Small stock were most active during the day between 8:00 and 20:00; however, this can be attributed to fact that goats and sheep are brought back to the corrals at night and cannot continue ranging the region. Domestic animals in general are most active during the day, but both livestock and small stock appear to less active between 12:00 and 16:00 as both trend lines take dips during that time period. As expected, predators were more active at night with the peak being at 20:00 to 24:00, but the number of predators was significantly lower than the number of livestock seen on the camera trap photos. According to Table. 2 (Appendix 1), a majority of predators consists of jackal and brown hyena which are normally nocturnal animals, as are the smaller predators in the region.

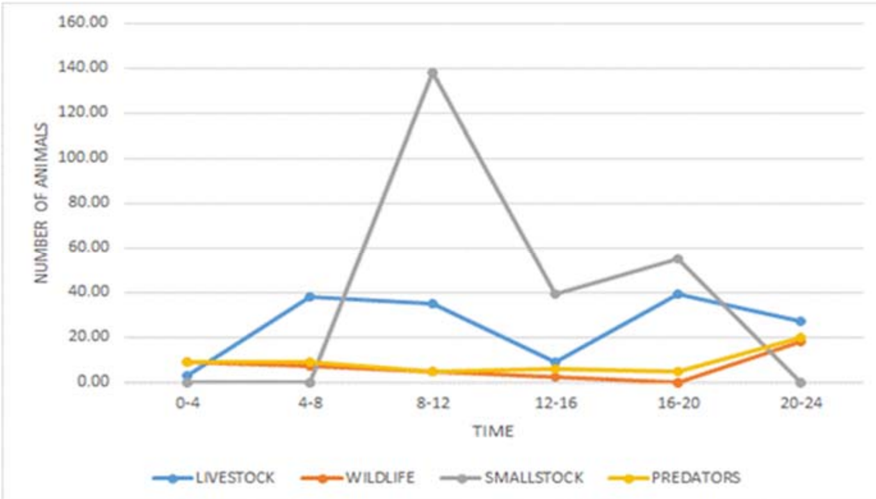

Figure 2. Change in animal numbers seen by camera traps over the course of 24 hours.

Using the locations of the predator heat map used by Bang et al. (2017), we divided livestock and predator sightings according to low and high predator areas perceived by the community. The high predation area corresponded to the riverbed and the low predation area corresponded to a salt river wash in the gravel plains. We found that more than double the average amount of animals per camera were seen in the river, compared to the salt river (see Figure 3). Small stock were the majority in both cases, but all 3 averages significantly were greater in the region of high reported predator presence (small stock: $t_{df=10.6}$= -2.6, P = 0.03, livestock: $t_{df=10.0}$=-2.2, P = 0.05, predators: $t_{df=10.1}$=-2.3, P=0.02). The numbers proportionally consistent across the habitats.

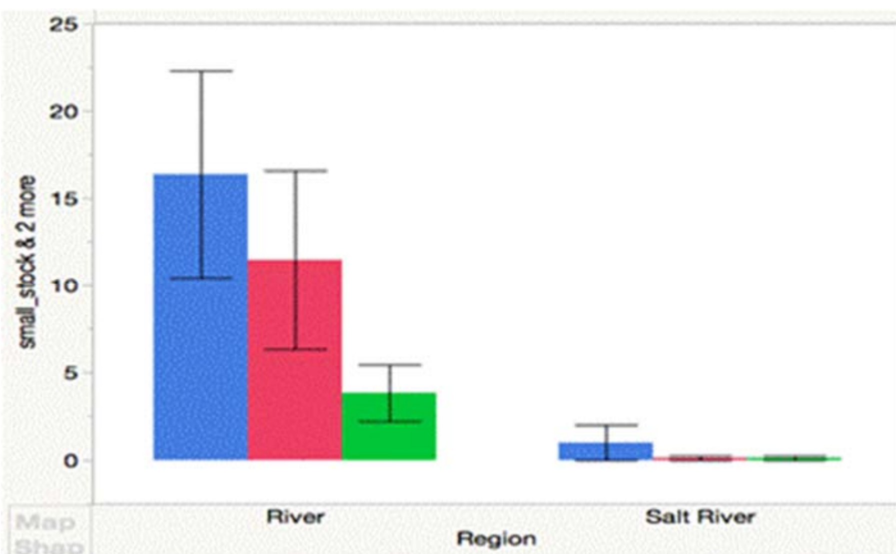

Figure 3. Region divided by river (perceived high predator area) and salt river (perceived low predator area) vs. small stock (blue), livestock (red) and predators (green) seen during animal count drives.

A linear regression of total livestock by total predators (see Figure 4) observed during animal counts revealed that there is no statistically significant correlation between predator and small stock densities (ß±se = 0.27±0.91, $t_{df=17}$ = .29, P = 0.78). The number of predators observed explains very little variance in the number of livestock observed (R^2 = 0.005).

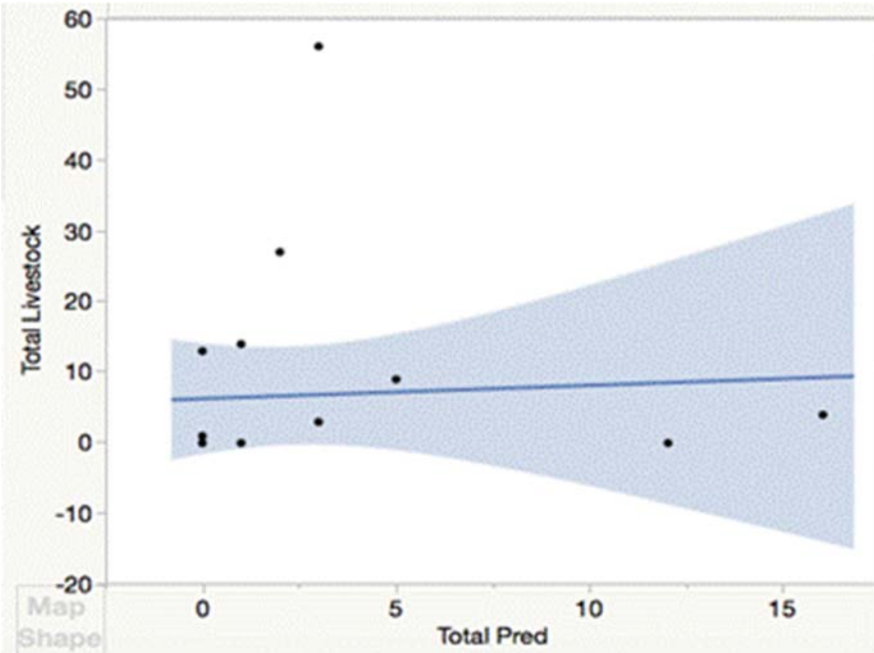

Figure 4. Total predators seen on the camera traps vs total number of livestock seen on the camera traps. Each point of the graph represents 1 camera trap.

Lures were placed in areas of perceived high and low predator concentrations; however, the presence of lures did not increase the number of observed predators (paired t-test: $t_{df=14.9} = -1.0$, $P = 0.31$). (see Figure 5)

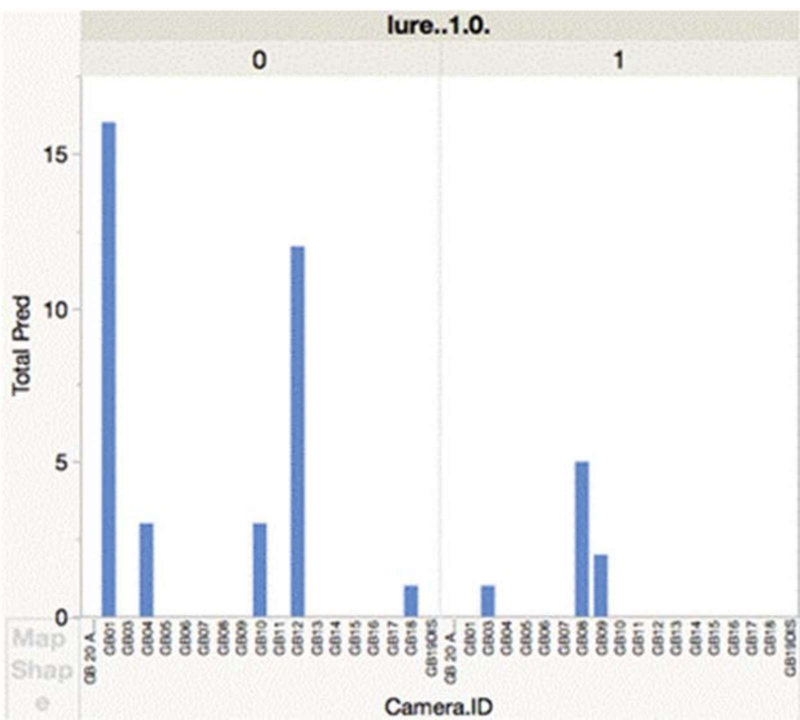

Figure 5. Total predators observed at camera traps with lures (1) vs. camera traps without lures (0)

Animal Movement and Distribution

Animal Count Results

We counted a total of 194 livestock and 27 wildlife during our 2 full animal count survey drives upstream and downstream (see Table 3 in Appendix 1 for breakdown by species). The location and distribution of livestock is presented in Figure 6, showing clear heterogeneity in their space use. We saw significantly less livestock in the gravel plains and inter-dunes; only a combined total of 39. Conversely, we observed more wildlife in these areas more than in the river. While some animals may have been counted more than once, we attempted to circumvent this by driving down the entire 40-kilometer study site once on the first day. We also attempted to account for the effect of temperature and time of day by driving the upstream half in the afternoon on a separate day and the downstream half in the morning on a separate day. Analyzing the animal count data, the highest percentage of animals were found in the riverbed.

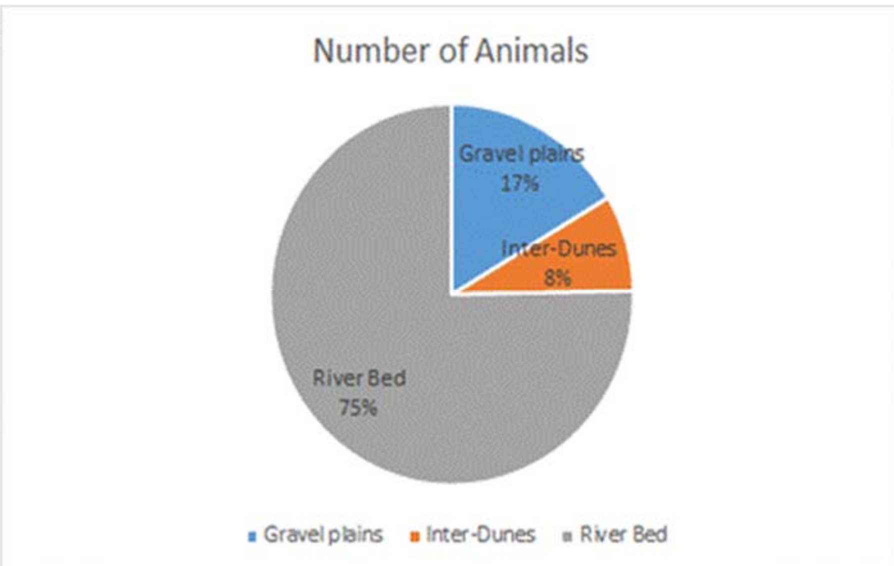

Figure 6. Breakdown of total animals found in habitats surveyed during animal count drives.

Comparing 2017 AC and 2018 AC by river

Our results show that per river transect, Cervenka et. al 2017 observed more animals than we did in our animal survey of the river (paired t-test: $t_{df=8}$= 1.88, p-value= 0.09; Fig. 7).

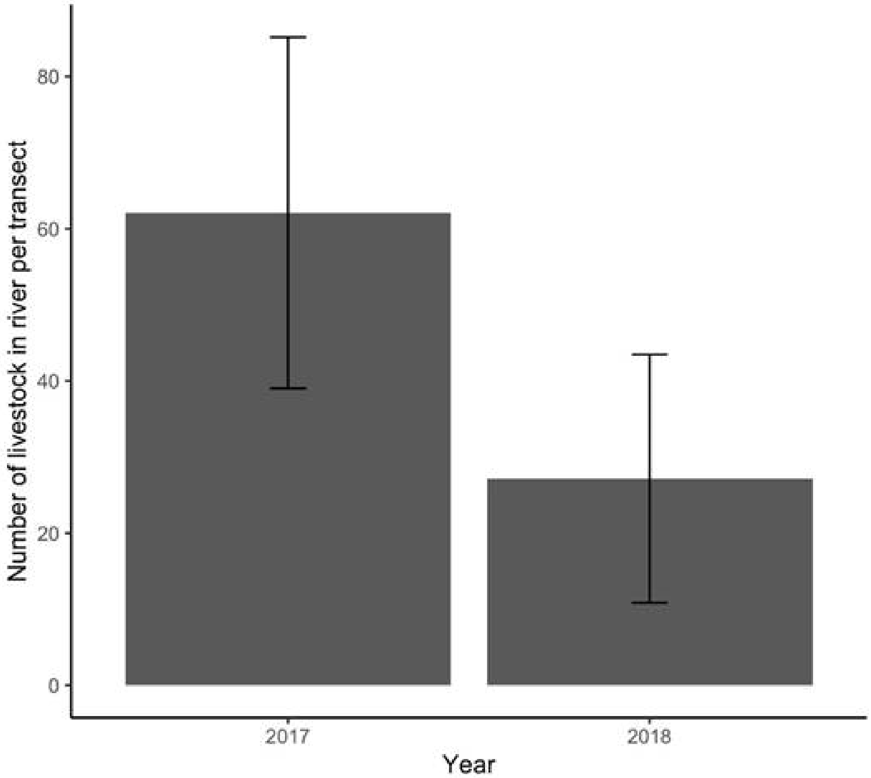

Figure 7. Average number of livestock per study transect comparison between 2017 and 2018.

SSHIT Method findings

Using dung as an indicator of livestock presence, our analysis shows that in the inner banks the number of pods (primarily *F. albida*) correlated positively with livestock presence (ß±se = 19.6±7.8, $t_{df=18}$=2.5, P = 0.02, R^2=0.26; Fig. 8). For transects along the outer banks the number of pods (mainly *A. erioloba*) did not significantly predict livestock presence as measured by dung counts (ß±se = -5.5±8.7, $t_{df=18}$ = -0.6, P = 0.53, R^2 = 0.02). There were more pods along outer transects compared to inner transects (paired t-test: $t_{df=14.9}$= -1.0, P = 0.31; Fig. 8), most likely due to the current season and relative phenology of *F. albida* compared to *A. erioloba* (Morgan 2017).

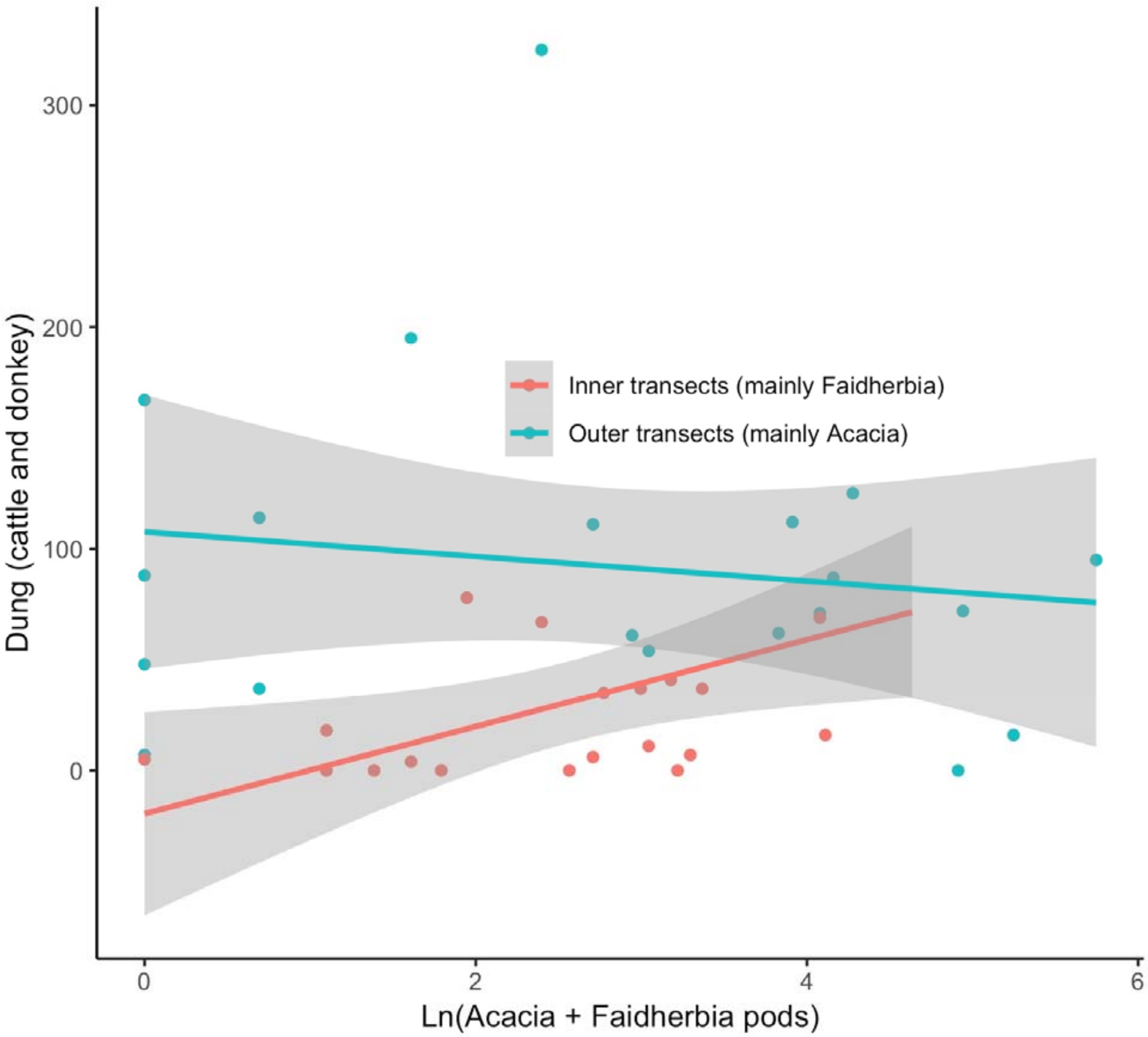

Figure 8. Natural log of *A.erioloba* and *F.albida* pods counted in the inner and outer river banks vs. cattle and donkey dung counted in the inner and outer river banks.

Telemetry Data Findings

We expected that livestock would travel further distances and spend less time in the river during the wet season because grass is more abundant in the gravel plains and inter-dunes. Figure 9 shows that cattle spent most of their time in the river during April through May. These months are considered the wet season, while time in the river declined significantly in the dry season. Interestingly, the relationship between time spent in the river and date differed for cattle from different sites (see Figure

A1 in Appendix 2).

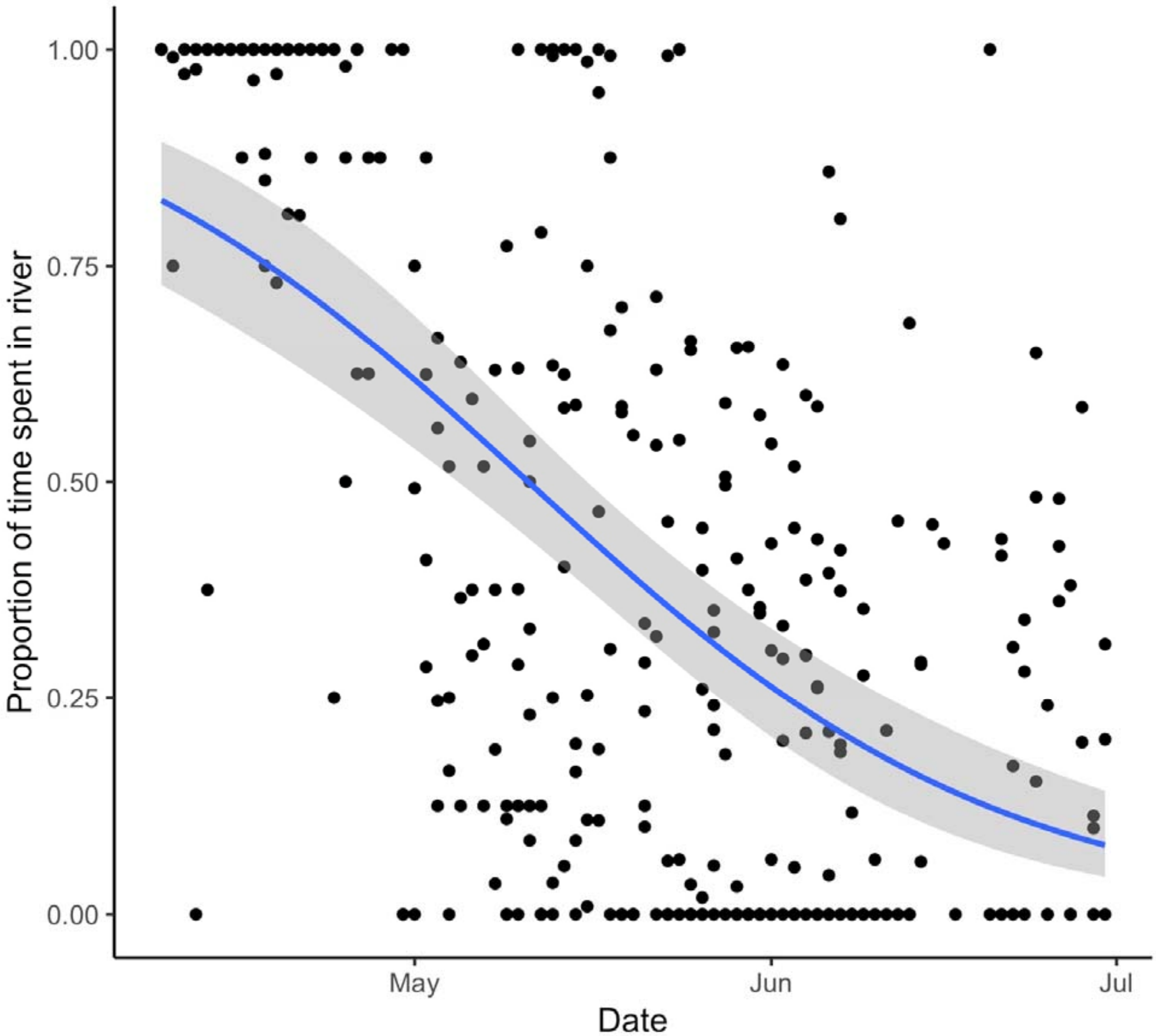

Figure 9. The proportion of daily time cattle spent in the river as a function of date. Time spent in the river decreased with increasing date in this interval (linear mixed effects model of logit-transformed proportion of time spent in river as a function of date, with a random intercept for individual: ß±se = -0.06±0.005, P < 0.001). Each datapoint represents one cattle-day and is based on the proportion of GPS fixes in the riverbed compared to other habitats.

Examining the distance and movement from the telemetry data, the distance that cattle traveled ranged between ~5 and 15 km per day. Daily travel distance increased significantly with increasing time spent in the river (ß±se = 3717±721, P < 0.001). But there was also a significant interaction between time spent in the river and site ($F_{df=2,307}$=20.3, $P < 0.001$), showing that only cattle from Homeb and Natab traveled farther distances when spending more time in the river (see Figure 10).

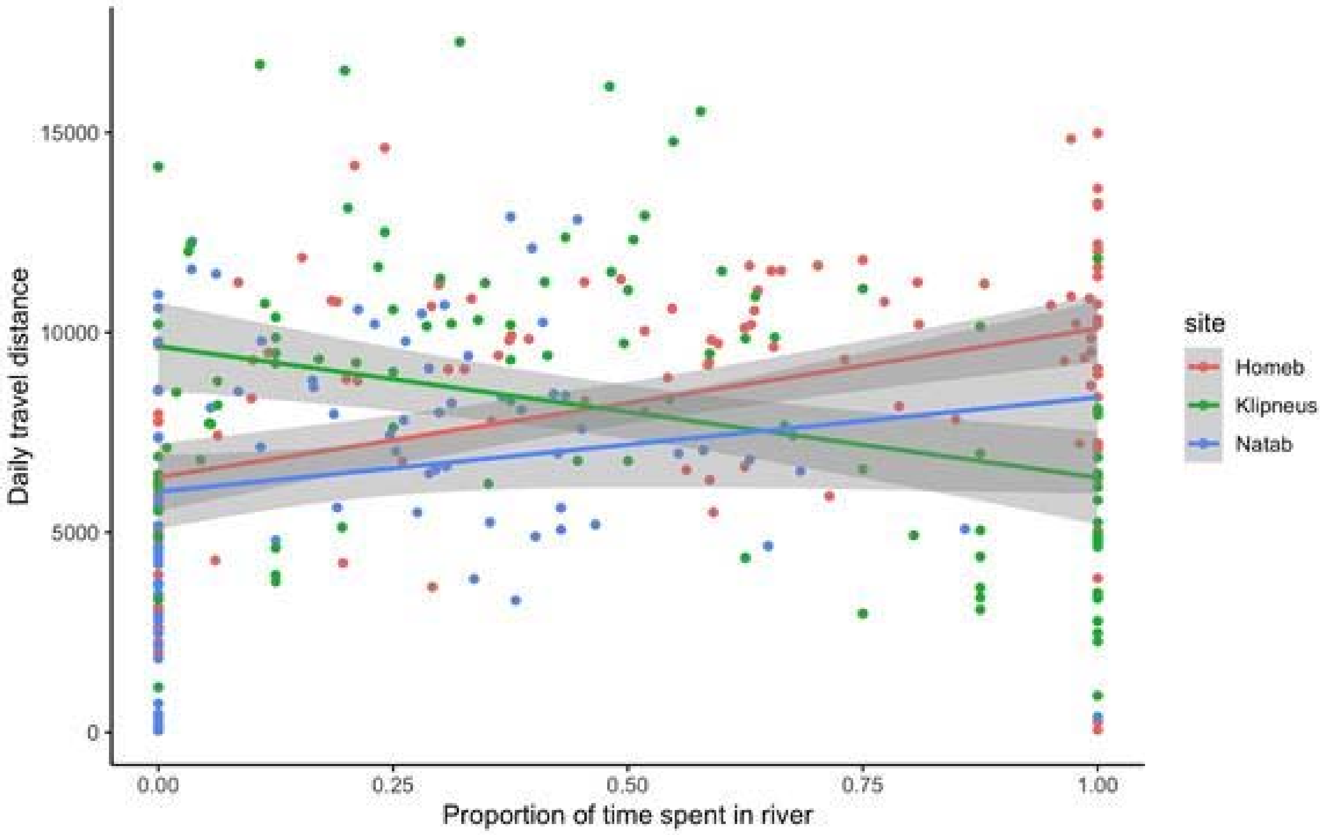

Figure 10. Daily distance traveled as a function of the proportion of time spent in the river. Individual points represent a single day for an individual cow

The average distance cattle traveled is relatively similar during the wet and dry seasons (linear mixed effects model: ß±se = -149.6±389.3, $t_{df=309}$= -0.4, $P < 0.70$, Fig. 11), reflecting the pattern in Figure 10; however, Klipneus cattle travel slightly further during the wet season, walking approximately 3 km more than in the dry season. The maximum and median distance of the cattle stay mostly similar between both seasons, which may indicate that rainfall does not predict the distance of daily travel between cattle.

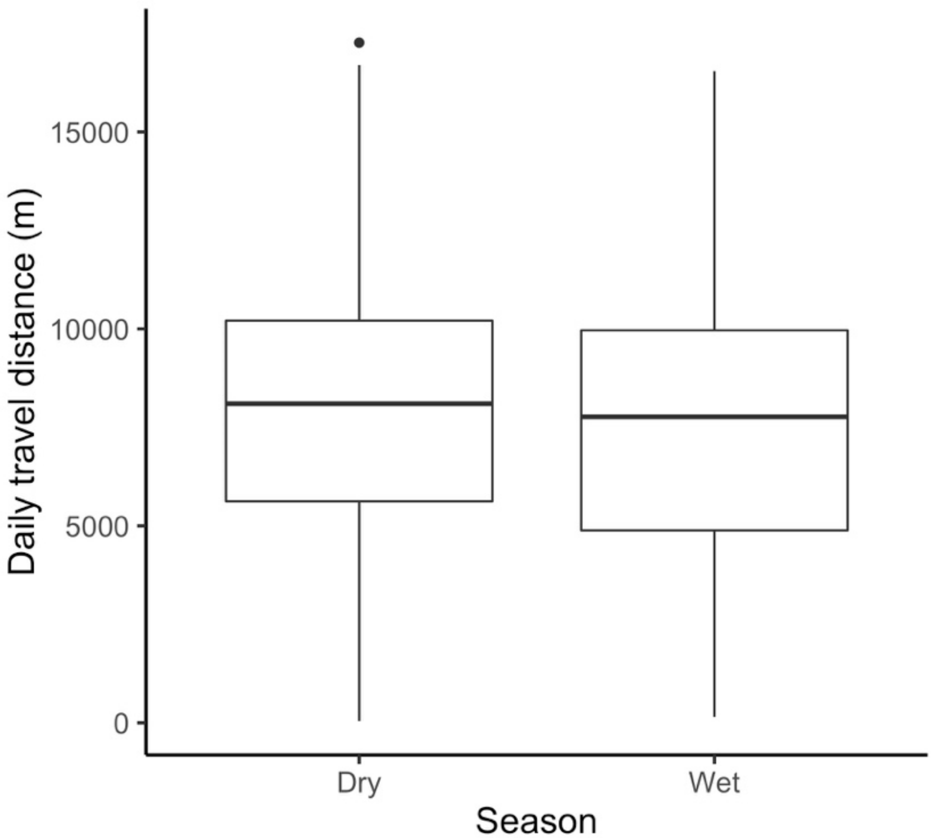

Figure 11. Daily travel distance as a function of season and home site for cattle.

Carrying capacity comparison 2017 vs. 2018

Total estimates of standing biomass yielded values of 4882 and 1595 tonnes for the gravel plains and interdune habitats, respectively. Estimates correspond to the 65 km study region of Cervenka et al. (2017), who estimated the carrying capacity of the Kuiseb River valley to be 1575 standard animal units per year (Cervenka et al. 2017). Modifying the equation for carrying capacity to include the values of vegetation in other habitats yields the following:

$$C = 3{,}095 \text{ standard animal units/year}$$

Thus, the inclusion of edible vegetation in the inter-dunes and gravel plains nearly doubles the estimated carrying capacity of the system (see Appendix 3 for full equation).

Discussion

Hypothesis: Livestock will avoid areas of high predator concentration

We hypothesized that livestock would avoid areas with high concentrations of predators since, according to the Landscape of Fear framework states that potential prey animals should exhibit antipredatory behavior (Moll et. al 2017). According to the framework, animals should avoid risky locations and risky times to minimize danger. Although camera traps documented more animals in the Kuiseb River throughout the day and night, there was no difference in the proportions of livestock, including small stock, and predators seen in either location. During our animal count drive, we noticed that vegetation significantly reduced downstream. We believe that the lack of resources may explain the stark difference in average total animals seen in the river and salt river regions. Our hypothesis tied closely with the Landscape of Fear framework which discusses changes in ungulate behavior to avoid areas with high numbers of predators as well as being more aware during times of predator activity (Moll et al. 2017). Our results do not seem to correspond with the ungulate behaviors predicted by Moll et al. (2016). As Figure 3 shows, the presence of predators in the river bed, a perceived high predator area, do not impact livestock and small stock numbers. This may be due to livestock not feeling threatened by the presence of predators since jackals were the most common predator and are only likely to present a threat for non-adult goats and other small stock. We did not see any large predators like leopards or cheetahs that may more strongly influence livestock behavior.

In another attempt to find a relationship between livestock distribution and predator influence on it, we used our camera trap data to create a graph of total predators versus livestock. Each point on the graph represented a camera trap and the total number of predators and livestock seen on that camera. Our results showed that there is no correlation between livestock numbers and predator numbers caught on the camera traps. The random distribution of the points on the graph reveal that the animals are not clustered in any particular region nor influenced by the presence of potential threats. Additionally, a majority of the predators caught on camera that could potentially harm livestock were jackals. However, as some locals pointed out, jackals are no threat to larger ungulates. Brown hyenas were also spotted but they eat mostly insects and scavenge, and thus are no threat to livestock.

To further estimate the presence of predators in high predator area, as perceived by local community members, a few of the camera traps were set up with scented lures next to them to draw the in surrounding individuals. We found that there was no correlation between the camera traps with lures and without lures. In fact, the data shows that more predators were observed near camera traps without lures than near camera traps with lures (Fig. 5). While the lure cameras did draw some interesting animals, the polecat and genet, the predator numbers were contrary to our prediction. Once again, we believe that this may be due to the fact that there are not any large predators that could kill large ungulates like cattle, or, at least, we did not see any large predators on the camera trap photos. However, we did see leopard prints further upstream, but we did not observe any livestock distributed in those areas. So, this could be a result of livestock avoiding the areas upstream since they are aware of the leopard's presence in the area. We did not study this area in great detail, so it may be interesting to assess the area further.

Hypothesis 2: Livestock will be less active and in the river during the hottest parts of the day - will only go to gravel plains and inter-dunes to feed in the mornings, evenings, and night

Examining the data on livestock activity (frequency of appearance on camera photos) and temperature from our camera traps, our hypothesis that livestock will be more active during the cooler temperatures and less active during the hottest temperatures throughout the day was supported. This result is intuitive since the heat makes it difficult for animals to remain active searching for food outside of the river, especially with the intense solar radiation (Collier and Gebremedhin, 2014). Our results show that temperatures between 18C and 27C are the most conducive to livestock activity. Both livestock and small stock experience declines in activity during temperatures around 32C, the hottest part of the day (12:00-16:00). It is possible then, to hypothesize that these animals may need to retreat to shaded areas to escape the temperatures. While the graph does not present information regarding daily movement patterns, we speculate that the need to find cooler areas may influence migration and habitat choice. In which case the river provides an ideal habitat during extreme weather events considering the amount of shade provided by trees.

The temperature results correspond to activity (frequency of appearance on camera photos) throughout the day. Livestock and small stock had the same results as found in the temperature graph, which was expected since time and temperature have a direct relationship. What is particularly significant about this graph is that predators, and wildlife, are least active during the daytime hours and most active during the late night and early morning. While many livestock owners claim that livestock loss due to predators is a significant issue, the results here show that it is unlikely that livestock and especially small stock would come into contact with harmful predators while out during the day. On the contrary, jackal predation at night is more likely to be a problem, especially if small stock are not kept in well-sealed enclosures.

We also note that cattle are much more free ranging than small stock, and as a result, it is valid to conclude that the reason they were seen less often on the camera trap footage at night is simply because they are absent from the area at night. Goats may display similar patterns to cattle during the night if left alone, but we cannot sufficiently conclude their natural activity would decline at night. In regard to perceived predator threats, studies in the future should continue to track predator presence in the region.

Hypothesis 3: Livestock will travel farther distances in the wet season as opposed to the dry season because food and water are more abundant so they are not constrained to one place

During the wet season, we hypothesized that livestock time spent in the river would decrease, since there would be grass available in the other habitats. Based on this hypothesis, we also expected the daily distance traveled to increase as the proportion of time spent in the river decreased. According to weather data in the region, the rainy season lasts from March to May. Figure 9 shows that the time spent in the river is at its highest point during May, which contradicts our expectations that livestock would spend less time in the river. We suspect that this has to do with the lag time between when it rains and when grass actually begins to grow on the gravel plains and inter-dunes. Increased telemetry data in tandem with high-resolution phenology data on grasses would better elucidate the relationship between habitat selection by livestock and season in this system.

Looking at the season and distance, we expected to see the livestock move further in the wet season compared to the dry season, since there will be more food available for livestock. Yet, the results of our analysis showed that the distance traveled by livestock did not significantly differ between seasons, on average, between each of the settlements (Fig.11). However, the data showed that the cattle in Klipneus moved further in the wet season than in the dry season. These contradictory results may be attributed to the same factors: water and food. Ephemeral pools along the river may allow them to have access to additional water sources outside of the human-provided watering holes. On the other hand, water maybe the factor limiting livestock distance, since water is not available outside of the communities and the river during the dry seasons. Furthermore, the cattle from Klipneus may be travelling farther, because there are not any pods or grass near Klipneus which forces cattle to walk even further along the river. On the other hand, the cattle in Natab and Homeb are dispersing out from the river and walking into the gravel plains and inter-dunes. They are the same distance from water at most points outside of the river and have relatively more abundant numbers of pods, grass, and water further upstream. Unfortunately, we did not observe this interaction since we were not focused on the Klipneus population; however, our Gobabeb mentor also attributes the further movement to the presence of ephemeral pools along the river. We concluded that livestock movement is not driven by food but by water availability. They travel the same long distances no matter the time in the year, but they extend their range of feeding when there are ephemeral pools present in the river to support their movement.

The proportion of time spent in the river and the daily distance traveled shows that there was a weak correlation or no correlation between the two variables. The lack of correlation indicates that livestock do not restrict themselves to the river habitat and may select other habitats for different resources that the river may not provide. A notable outcome of the results is that the cattle travel great distances, up to more 15km per day, again regardless of the time spent in the river as, some cattle who spends almost all their time in the river, Natab and Klipneus cattle, still travel 5km to 15km per day. Such large distances traveled may suggest that food resources, like *A. erioloba*, *F. albida* pods and grasses, are widely dispersed throughout the river and across the whole landscape of habitats.

Hypothesis 4: Because of the increased amount of rainfall in 2018, livestock will not be as concentrated in the river as they were in 2017

According to Cervenka et al.'s 2017 report, they recorded seeing 290 cattle, 97 donkeys, and 277 goats in the river along a 65 km stretch during their animal count surveys. During our animal count surveys, we spotted 60 cattle, 123 goats, and 30 donkeys altogether including animals on the inter-dunes and gravel plains. So, after accounting for differences in the number of transects, we observed significantly less livestock in the river which aligns with our hypothesis. We are particularly intrigued by this finding as we sighted significantly less animals in the river than past groups. The large difference in animal sightings could be a result of the grass in the gravel plains and inter-dunes being a more significant source of food in 2018 compared to 2017 which may have drawn livestock away from the river. Yet, we did not observe many cattle in the gravel plains and inter-dunes, so we are still unsure about the source of large differences, which could include a general decrease in livestock in local communities due to losses or selling. In addition, the telemetry data that revealed no difference in the amount of time livestock spent in the river regardless of the time of year and season, so there is some currently unknown factor driving livestock towards other habitats. The impact of an external factor not related to time of year and seasonal variation in rainfall could explain the difference. Another possibility could be that the data collected from the cattle collars is not representative of the changes in migration patterns over the span of a whole year.

Hypothesis 5: Given the ranging behavior of livestock, ephemeral grass resources in the inter-dunes/gravel plains have the potential to substantially increase carrying capacity.

Given the change in vegetation, we sought to understand the potential impact of grasses on the environment and livestock. Cervenka et. al calculated that the region had a carry capacity of 1575 standard animal units per year in 2017 (Cervenka et al. 2017). As we predicted, grasses do seem to improve carrying capacity. Our calculations revealed that carrying capacity nearly doubles to 3,095 standard animal units per year in 2018 by the addition of grass biomass to previous estimate. Thus, the inclusion of edible vegetation in the inter-dunes and gravel plains may have a significant impact on animal life in the Lower Kuiseb region. As a hyper-arid environment, conditions are not optimal for many species of animals and vegetation, and thus, livestock husbandry should be difficult in such regions. If the environment can support robust forgers like cattle and potentially support significantly more, this may spark promise and optimism for livestock owners looking to expand herd numbers. Additionally, given the abundance of edible vegetation, the health of cattle and small stock have the opportunity to improve. Most of the cattle and small stock in the region boast already healthy body conditions.

While the abundance of food may indicate better conditions for animals, one factor may severely limit population growth among species: water availability. As a hyper-arid region and as weather patterns and seasonal temperature averages climb, food abundances like that of this year are not guaranteed as rainfall is rare in Namibia and especially rare in Gobabeb. In our results, we found that the resources in the river do not influence or change migratory patterns of cattle. What seems to be telling of the migration pattern is that the river does play a crucial role to livestock, in the form of a food and water source. Given that Belovsky argues that some species may seek to maximize energy intake, we believe that food, although dispersed widely, is high in nutrient content, thus there is no significant enough tradeoff from continuous movement across the landscape for forging (Belovsky 1986). Ephemeral pools of water line the river so, cattle are not tied to settlements for water allowing them range far in order to forge the widely dispersed food sources. Pools may also act as tethers that keep livestock close to the river. While our grass sampling of the area was not a central feature of the study, the findings have major implications across ecological, environmental, and social systems that rely on the services provided by vegetation. Future studies should also research the impacts of water in the systems as another predictor of carrying capacity as ours and Cervenka et al. (2017) examined vegetation.

Conclusion

Overall, we conclude that livestock movement and distribution along the Lower Kuiseb River is influenced by food and water distribution. The findings showed that predator presence has no impact on livestock distribution in reported low and high predation areas. Our short-term data collection suggests that while predator abundance is higher in highly sighted predator areas, livestock numbers are also high. Livestock then are not changing their spatial habits most likely due the fact that the most abundant predator, the jackal, is not a threat. It is possible that our short-term data collection is not representative of the total predators that do utilize the region. Given the importance of livestock to the Topnaar people, if longer term camera trap studies were conducted and find similar results, the people may not need to worry as much about the potential threat of predators. Additionally, we found that they may be confounding factors to the experiment we conducted that was based on local reports. The Salt River region cannot support animal livelihood because of the lack of water and vegetation, so it is reasonable that few livestock or predators were found. We also recommend that studies on high and low predation area be conducted within areas of the riverbed to eliminate any confounding factors. Doing so would be more valuable to local settlements that want to protect their livestock.

Of our results, one of the least explored was the impact of grasses on the ecological landscape. Our survey of grasses in the inter-dunes and gravel plain regions was done at a very low resolution. Considering that cattle move very far into the gravel plains and inter-dune habitats, as shown by telemetry data, it would be useful to have a high-resolution survey to explore their impact on livestock. Its significantly large impact on carrying capacity in the ecosystem could further motivate studies on resources in the region. For example, given the impact of grasses, Topnaar livestock owners may look to make water more accessible at more points in the river to increase the foraging range of livestock. However, such additions may not be feasible given the complex environmental and political systems of the Lower Kuiseb.

With livestock and farming making up 3% of Namibia's economy but accounting for 75% of the population's livelihood, many Namibians are dependent on the land to raise their livestock as a source of food and income. The Topnaar will be most affected since their livelihoods are based on their livestock. Despite the harsh arid climate, limited food and water resources, and predator threats, livestock are able to thrive in the Lower Kuiseb River region.

Acknowledgements

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To our fellow FSP group, I firmly believe that common struggles and trials forge the strongest bonds, and the work we've achieved up until this point is a testament to that. Thank you so much for struggling along with us!

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Appendices

Appendix 1: Tables

Table 1: Breakdown of animals caught on camera traps

Animal	NUMBER OF ANIMAL
Brown hyena	9
Cape fox	2
Cattle	126
Donkey	19
Goat	208
Hare	20
Jackal	44
Polecat	1
Sheep	21
Small spotted genet	1
Springbok	16
Steenbok	1

Table 2: Number of Livestock and Wildlife by habitat seen during animal count drives

Habitat type	Livestock	Wildlife
Riverbed	194	27
Gravel Plains	18	45
Inter-dunes	21	27

Table 3: Breakdown of all animals seen during animal count drives

Animal	Number observed all three habitats
Cattle	60
Goats	123

Springbok	55
Donkey	30
Sheep	20
Guinea fowl	12
Jackal	3
Steenbok	2

Table 4: Grass counts from grass surveys by species

Species	Quantity
Centrepodia glauca	255
Stipagrostis ciliata	409
Stipagrostis obtusa	737
Stipograstis gonatostachys	21
Zygophyllum simplex	81

Appendix 2: Graphs

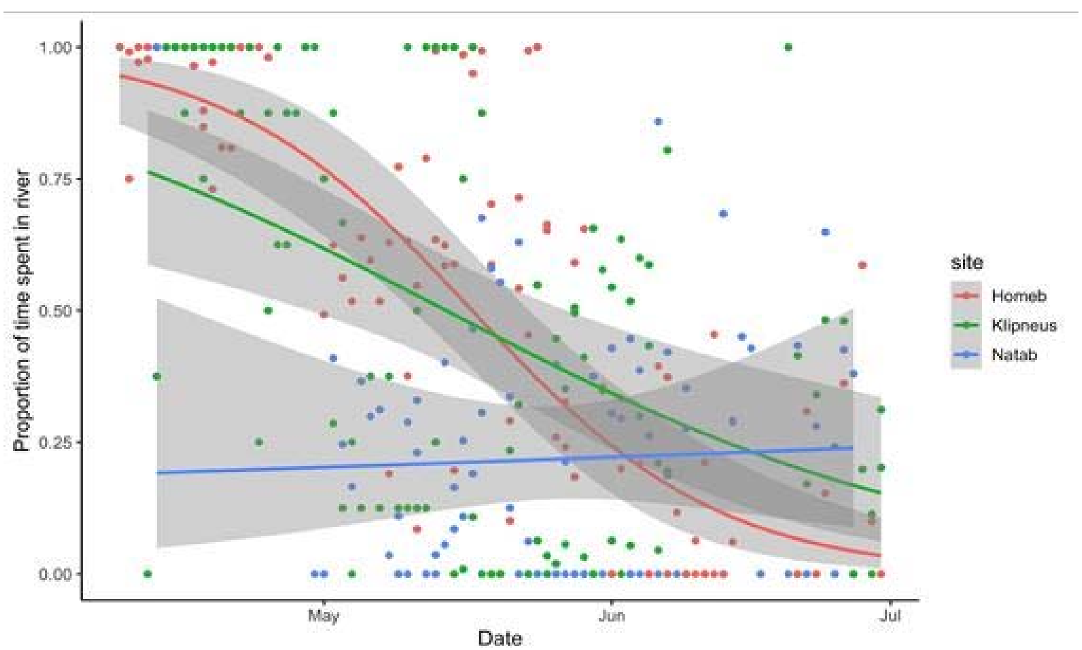

Figure A1: The proportion of daily time cattle spent in the river as a function of date and site. Time spent in the river decreased with increasing date in this interval (linear mixed effects model of logit-transformed proportion of time spent in river as a function of date, with a random intercept for individual

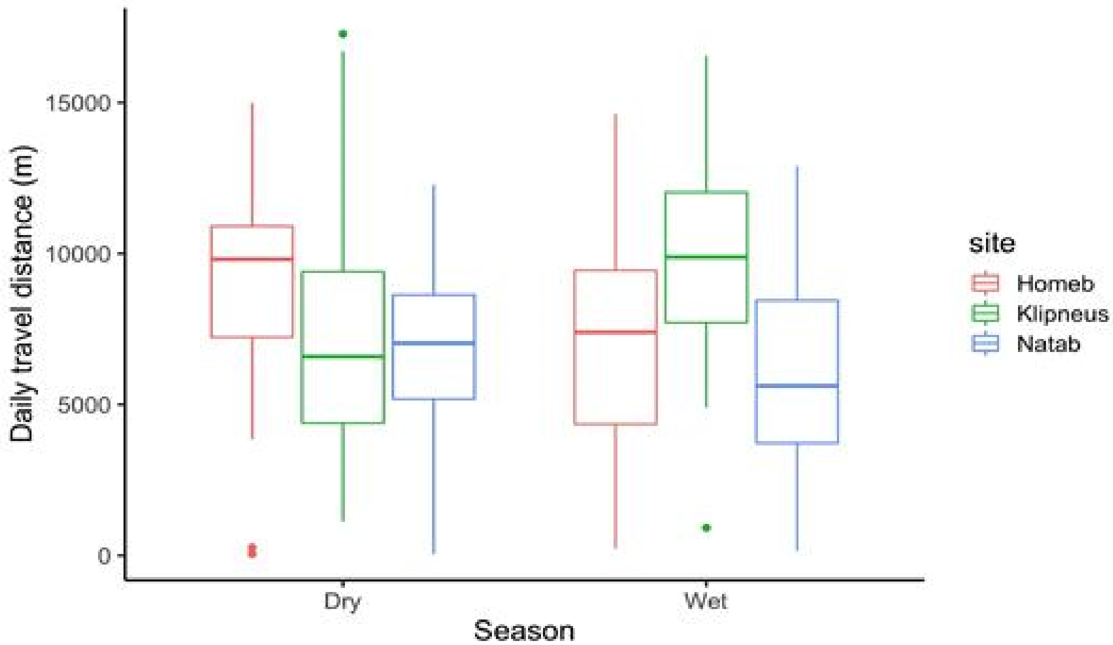

Figure A2: Daily travel distance as a function of season and home site for cattle.

Appendix 3: Carry Capacity Equation

C = (AN + Fn + V) / (U(12))
C = ((135 kg)(29,010) + (120)(23,273) + 4,882,479 + 1,595,145) / ((355 kg)(12))

C = 3,095 standard animal units/year

Selling the Kids: Investigating the Potential Formalization of the Livestock Market in the Topnaar Community

November 12, 2018

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Abstract

As observed in a 2016 study by Dartmouth College, livestock plays an important role in the livelihoods of Topnaar people. This study seeks to investigate the current market for livestock and the potential for market formalization of this market, with specific attention to a local auction. We administered a structured survey at a livestock workshop, conducted interviews with livestock owners in the Kuiseb and buyers in Walvis Bay, and had phone interviews with auction participants. We found that sellers' access to buyers decreases as the distance from Walvis Bay increases. Both livestock sellers in the Kuiseb region and buyers in Walvis Bay expressed interest in a local auction in Utuseb. However, sellers do not currently comply with the necessary regulations. Utilizing a cost-benefit analysis, we compared the current market system and the proposed auction in Utuseb. This analysis revealed that livestock owners farther away from Walvis Bay may benefit more from access to a local auction than those in closer proximity. Yet, barriers such as a lack of information sharing, the financial cost of compliance, and lack of access to transportation could hinder the process of formalization. Despite this, there are benefits to the broad process of formalization that are not contingent on the introduction of a local auction, which have the potential to enhance livelihood stability for the Topnaar community.

Introduction

Rural communities are increasingly exposed to disturbances that affect their livelihood strategies (Mortimore and Adams 2001; Tol et al. 2004). The concept of sustainable rural livelihoods suggests that people adapt livelihood strategies to overcome challenges such as poverty and environmental change, thus increasing their resilience against these shocks and disturbances (Folke 2006; Scoones 1998). Livelihood strategies for rural communities include either intensifying or expanding their agricultural production, diversifying modes of income, or moving to a town or city with more opportunities (Scoones 1998). Should communities opt to intensify their agricultural production, formalization can support this (Galal 2005).

Formalization is defined as "converting extralegal entities and activities to the legal sector" (Galal 2005: 1An Egyptian case study investigated potential welfare gain to entrepreneurs from formalization; the study found that formalization has positive net gains to entrepreneurs, workers, consumers, and the government and contributes to poverty alleviation and economic growth (ibid). Additionally, formalization of extra-legal activities can facilitate transition from a subsistence-based economy to a market-based economy by increasing productivity, expanding firms, and realigning prices (ibid). Furthermore, formalization may contribute to the sustainable livelihoods of rural communities by increasing the security of investments and incentivizing sustainable practices of agricultural intensification (Carswell 1997).

However, barriers such as distance and transportation costs tend to disincentivize rural communities from participating in a formal market-based economy. According to Kano et al., "distance creates a large price gap between the consuming and the producing regions" (2012: 410). Specifically, distance can particularly impact prices through an increase in transportation costs (Kouyaté et al, 2016). Similarly, "marketing costs, and thus market access, are in turn closely related to distance to markets and the nature of the infrastructure and systems operating between the supply and demand zones" (Baltenweck and Staal 2007:537). Utilization of locally-based, formal markets can decrease the distance between the supply and the buyer, enhancing formal market access for distant rural communities.

Although previous literature explored the potential net gains from an extra-legal entity transitioning to a formal system, few studies specifically explore the costs and benefits of market formalization (Galal, 2005). Additionally, few studies analyze the barriers rural communities face in transitioning to a formal livestock market. This case study addresses this gap in the literature by examining the extralegal livestock market in the Kuiseb region, the costs and benefits for livestock owners of transitioning to a formal market, and the specific barriers that the Topnaar community faces for market formalization.

Local context

The Topnaar community is situated along the Kuiseb river, located in the Erongo region of Namibia. The population is estimated to be between 332 and 700 people (DRFN and TCN 2004). The community's primary livelihood sources consist of seasonal harvesting of the !nara fruit, tourism, livestock, government pensions (for the elderly), and migrant labor (Herrick, Caspeta, and Van Loon 2016). The nearest city center is the Walvis Bay municipality, located approximately 40 km away from the closest Topnaar village of Utuseb.

This community has been impacted by changing social and economic pressures, such as lack of employment opportunities within the community and consequential youth migration to urban areas (Herrick, Caspeta, and Van Loon 2016; Shomeya nd; Werner 2003). The Topnaar Traditional Authority has identified ways to diversify their livelihood strategies in the face of these pressures. Such diversifications include the recent acquisition of a tourism concession and attempts to intensify agricultural and livestock production. In light of the importance of livestock to Topnaar livelihoods, the Topnaar Traditional Authority, along with the Regional Council, began developing a commercial livestock auction *kraal* in Utuseb approximately five years ago, a project that has stalled due to budgetary constraints.

This study seeks to understand the current system[1] for buying and selling livestock in the Kuiseb and to assess the extent to which the formal market system is utilized. This study is based on the broad hypothesis that formalization has the potential to enhance income for Topnaar livestock owners. We predict that distance will have a negative effect on the number of buyers that Topnaar livestock sellers receive at their homes. Additionally, we hypothesize that both Topnaar sellers and Walvis Bay buyers perceive benefits to a formalized livestock market. Lastly, we hypothesize that barriers exist that prevent Topnaar sellers from accessing the formal market.

Methods

Research Design

In order to understand the supply and demand associated with the livestock in the Topnaar community, we visited sites within the Kuiseb area and in Walvis Bay.

Using data from the 2018 Gobabeb livestock census, we identified study sites with the greatest number of livestock owners for a larger sample size. We focused on villages both upstream (from Homeb to Swartbank) and downstream (Swartbank to Ururas) based on perceived differences in land use and livestock numbers between the two, as expressed during a focus group discussion.

We examined the current livestock market for the Topnaar community using three different methods: focus group discussions, a survey of livestock owners at a livestock workshop, and an individual interview questionnaire. Our focus group discussion with six Topnaar community members at the first

[1] Throughout the paper, the expressions "current system" and "informal system" and used interchangeably to refer to the current extralegal livestock market in the Kuiseb region.

livestock workshop at Gobabeb helped establish baseline data about the livestock market. These answers helped us create a standardized survey, which we administered at the second livestock workshop, enabling us to gather a large amount of data on how Topnaar community members buy and sell their livestock. All of this information was then qualitatively supplemented with fourteen individual interviews, which allowed us to explore possible reasonings behind some of the survey question answers and to identify unexplored gaps in our understanding of the Topnaar livestock market. We also had phone interviews with three auction participants, informal interviews with two government officials, and met with Chief Seth Kooitjie.

We decided to focus on Walvis Bay buyers because numerous survey respondents identified that their buyers came from Walvis Bay. We conducted informal interviews with a total of six butcheries and *kapanas* (street-side meat grilling stands) to obtain information because of the sensitivity of the subject given the illegal nature of the market.

Data Collection Methods

We conducted in-depth interviews with fourteen livestock owners from five different villages along the Kuiseb River based on interviewee availability and at the advice of our translators. Furthermore, we used the “popcorn method,” where we asked interviewees to recommend other livestock owners we should talk to.

Few interviewees could speak English fluently, and therefore some or all of our questions were translated. Through our translators, we asked interviewees to identify the number of potential buyers that came each year; we then gathered data on which village they resided in to understand how distance from Walvis Bay could affect the number of potential buyers. We also asked interviewees for the highest and lowest price they had sold their goats for in the past to understand how the price was affected by distance. To investigate the Topnaar community’s potential for a formalized auction, we gauged local interest and current compliance to regulation required for entry into the formal market. We asked Topnaar livestock owners if they were interested in a local auction using our survey and in our individual interviews, and assessed compliance by asking whether their goats have ear tags and/or are vaccinated.

We also assessed potential demand for Topnaar livestock in Walvis Bay through informal interviews with meat buyers over the course of two days. On our first visit to Walvis Bay, we relied on the knowledge of a state veterinarian based in the Walvis Bay municipality to locate a butchery and some *kapanas*. On our second visit, we visited *kapanas* and butcheries identified by Topnaar community member interviewees as having bought meat from the Topnaar community. We also visited the open market of Ekutu and drove through the town looking for butcheries, *kapanas*, and advertisements of relevant sellers. Over the course of these two days, we interviewed three butcheries and three informal sellers about their interest in a local auction and their knowledge of Topnaar meat.

Using our data, literature, and government resources we created a cost-benefit analysis of a commercial livestock auction in Utuseb.

Data Analysis

We used Excel to develop a qualitative coding tree for the analysis of our interview data. We coded interview responses into categories based on our hypotheses.

For our quantitative analysis, we analyzed data provided by interview and survey responses in JMP Pro 10.13.1.. We ran a linear regression to examine if there was a statistically significant relationship between seller distance from Walvis Bay and number of buyers arriving to their homes looking to buy livestock. We ran another linear regression to determine if there was a significant relationship between distance from Walvis Bay and sell price of livestock.

We created a cost-benefit analysis equation for the current and proposed livestock market systems. The cost-benefit analysis of the current livestock market assumes that buyers go directly to Topnaar livestock owners' houses to buy livestock. Because distance impacts the number of yearly buyers, cost-benefit analysis results are separated by village (Figure 1). We modeled this analysis on livestock owners who sell goats because we had a more robust sample size for goat owners (see Results). See Appendix II for full methods for calculating each variable in the cost-benefit analysis.

Equations for cost benefit analysis

Estimated annual profit (EAP) for the current informal system (see Table 1)

$$EAP = \underbrace{(P \times GS)}_{\text{Total benefit}} - \underbrace{(OC \times GO)}_{\text{Total cost}}$$

The estimated annual profit (EAP) of livestock owners in this village is calculated by subtracting the total cost from the total benefit, or gross income. The total cost is the operations costs (OC) per goat multiplied by the average number of goats owned by livestock owners in the region (GO). The total benefit is the number of goats sold in a year (GS) multiplied by the price of the goats (P).

EAP = Estimated annual profit for a livestock owner
P = Average price of goat in specific village
GS = Average number of goats sold in one year in specific village
OC = Annual operations cost per goat
GO = Average number of goats owned by livestock owners in Kuiseb region

Sample calculation for the village of Aramstraat:
$EAP = (N\$1225 \times 3\ goats) - (N\$30 \times 9\ goats)$ = N$3405

EAP for Utuseb auction

$$EAP = \underbrace{\big((GO \times PS) \times MP\big)}_{\text{Total benefit}} - \underbrace{\left(\frac{\$1.06}{Km} D + ((OC + TC + VC) \times GO)\right)}_{\text{Total cost}}$$

EAP = Estimated annual profit for a livestock owner
GO = Average number of goats owned by livestock owners in Kuiseb region
PS = % of herd selling at auction
MP = Market price of goat
D = Distance of village from Utuseb
OC = Operations cost per goat
TC = Ear tagging cost per goat
VC = Vaccination cost per goat

Sample Calculation for the village of Aramstraat:

$$EAP = \left((9\ goats \times .6) \times N\$\ 680\right) - \left(\frac{\$1.06}{Km} 10km + \left((N\$30 + N\$2.50 + N\$12) \times 9\ goats\right)\right) = N\$\ 3260.91$$

Results

Problems with the current state of market access

Current market dynamics

The Topnaar community sells livestock in both formal and informal markets. Goats were the most commonly owned livestock. Eleven out of the fourteen livestock owners interviewed own or recently owned goats; seven own cattle. Similarly, twenty-two of the thirty-two livestock owners surveyed own goats, while only eleven own cattle.

The majority of livestock buyers (79%, Figure 1) come from Walvis Bay, the closest municipality to the Kuiseb River region. Twelve out of the fourteen interviewees mentioned that people from Walvis Bay arrive at their homes inquiring about buying livestock. Five out of fourteen interviewees mentioned that they travel to Walvis Bay to sell.

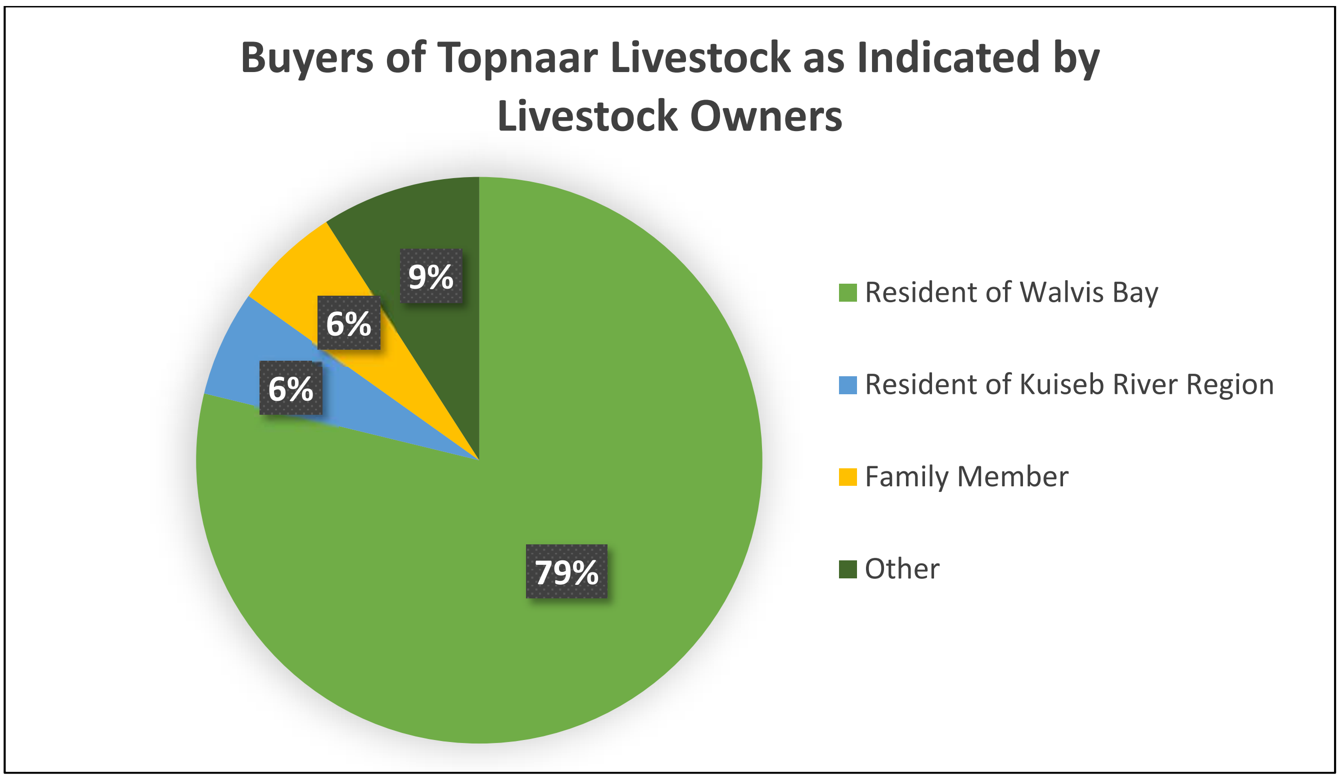


Figure 1: Buyers of livestock as described by surveyed livestock workshop attendees.

Finding transportation to Walvis Bay is difficult for many Topnaar livestock sellers as it is both expensive and infrequent. Four interviewees mentioned difficulties with transportation. Interviewee 10311 specifically mentioned that "transportation is a big challenge." According to participants in a focus group discussion at Gobabeb, one can hire a car to Walvis Bay for N$700-N$800. Other interviewees stated that they must wait until passing cars head to Walvis Bay to pick them up (as hitch-hikers) due to the high fee to hire a car (1162, 1141). For example, interviewee 1141 stated that their only opportunity to transport their slaughtered meat to Walvis Bay was at the end of the month, and that s/he depends on the elders who collect their pensions in Walvis Bay for a ride.

Distance between buyers and sellers

Interviewees perceived that distance impacts market access. Specifically, interviewees located in Natab, located 90km from Walvis Bay and upstream from the other communities in the Kuiseb River region, noted a strong discrepancy between upstream and downstream livestock selling opportunities. For instance, interviewee 1141 stated that Utuseb and villages closer to Walvis Bay (downstream) receive more buyers; "if [the buyers] don't get what they want down there [downstream], they will come up here [upstream]." Interviewee 1142 reiterated this, mentioning that buyers only come to his or her village if they don't find what they are looking for downstream, closer to Walvis Bay.

Below is a map of study sites with the average lowest and highest prices that interviewees have sold their goats for and the average number of buyers that arrive each year (Figure 2).

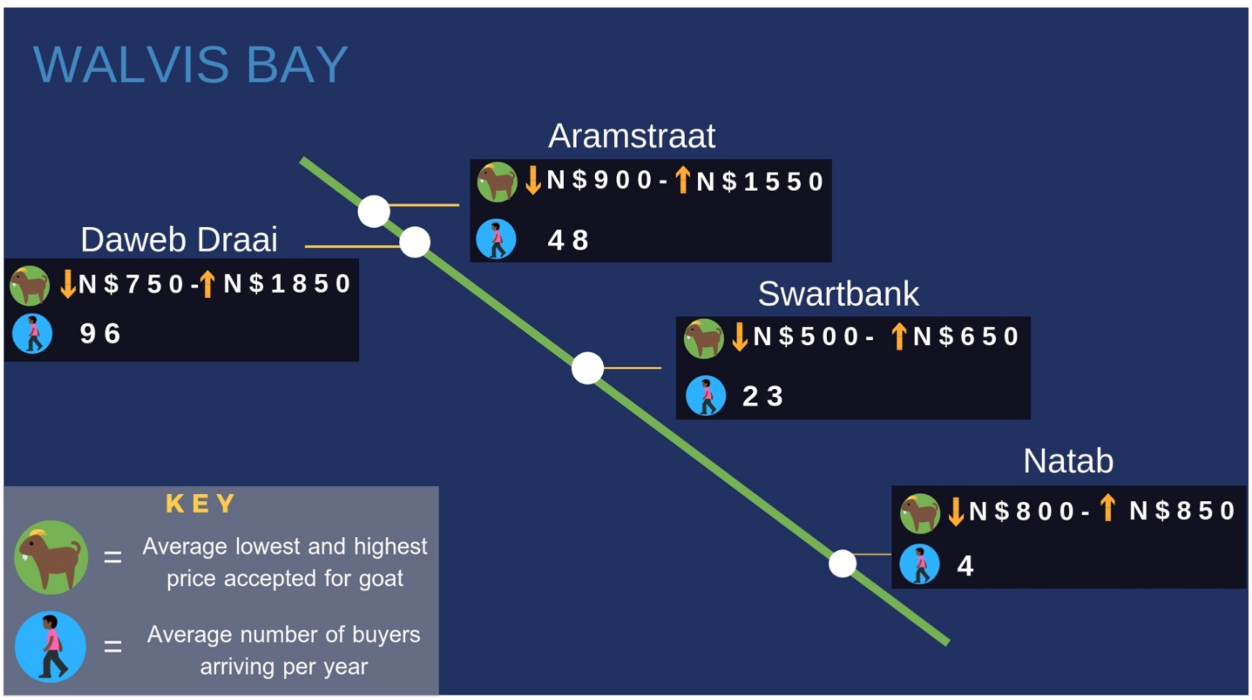


Figure 2: Kuiseb study sites and average prices received for goats and number of buyers arriving (not to scale).

As distance from Walvis Bay increases, the number of buyers that arrive at Topnaar homes per year decreases. This relationship is marginally statistically significant (Figure 3).

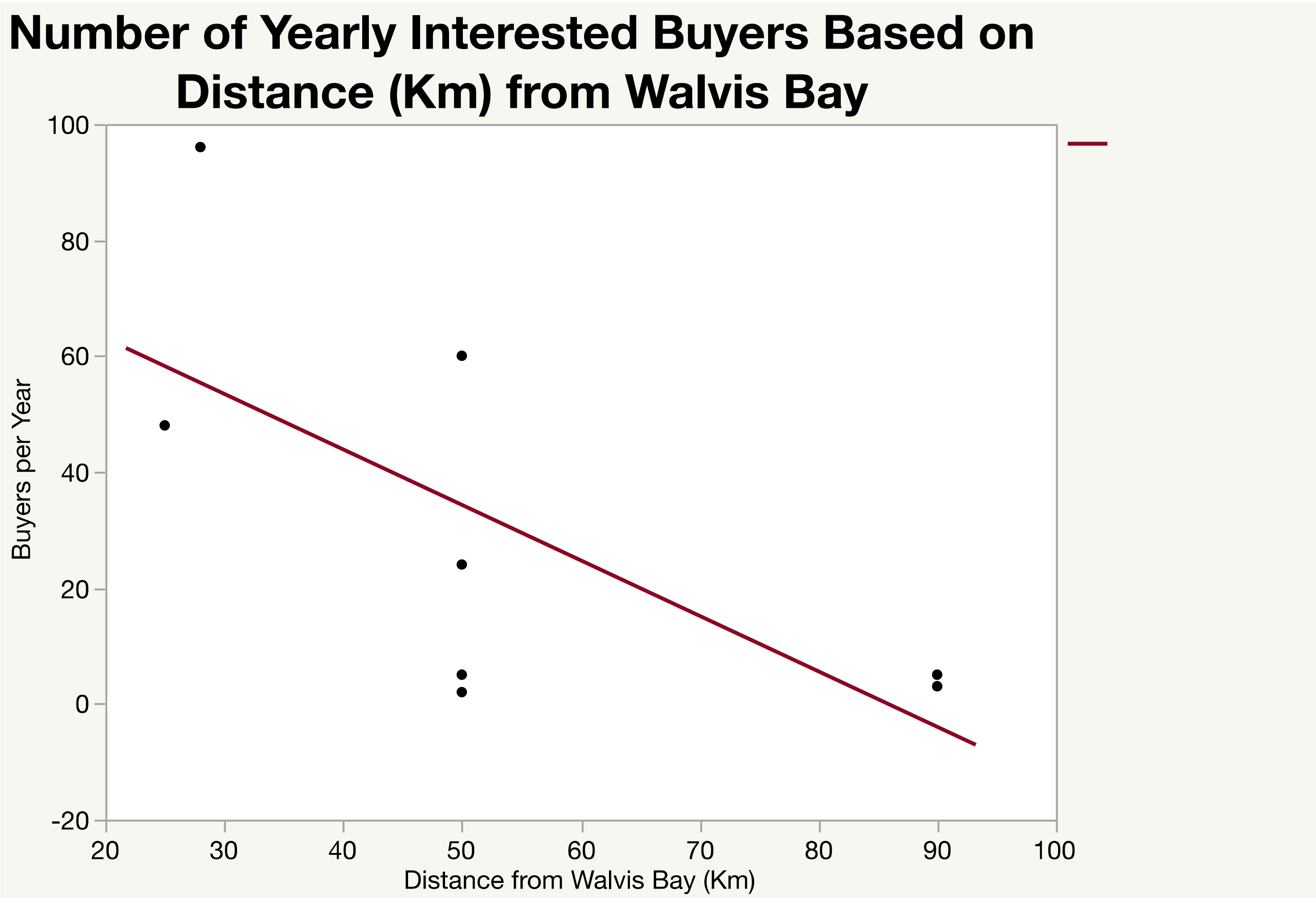
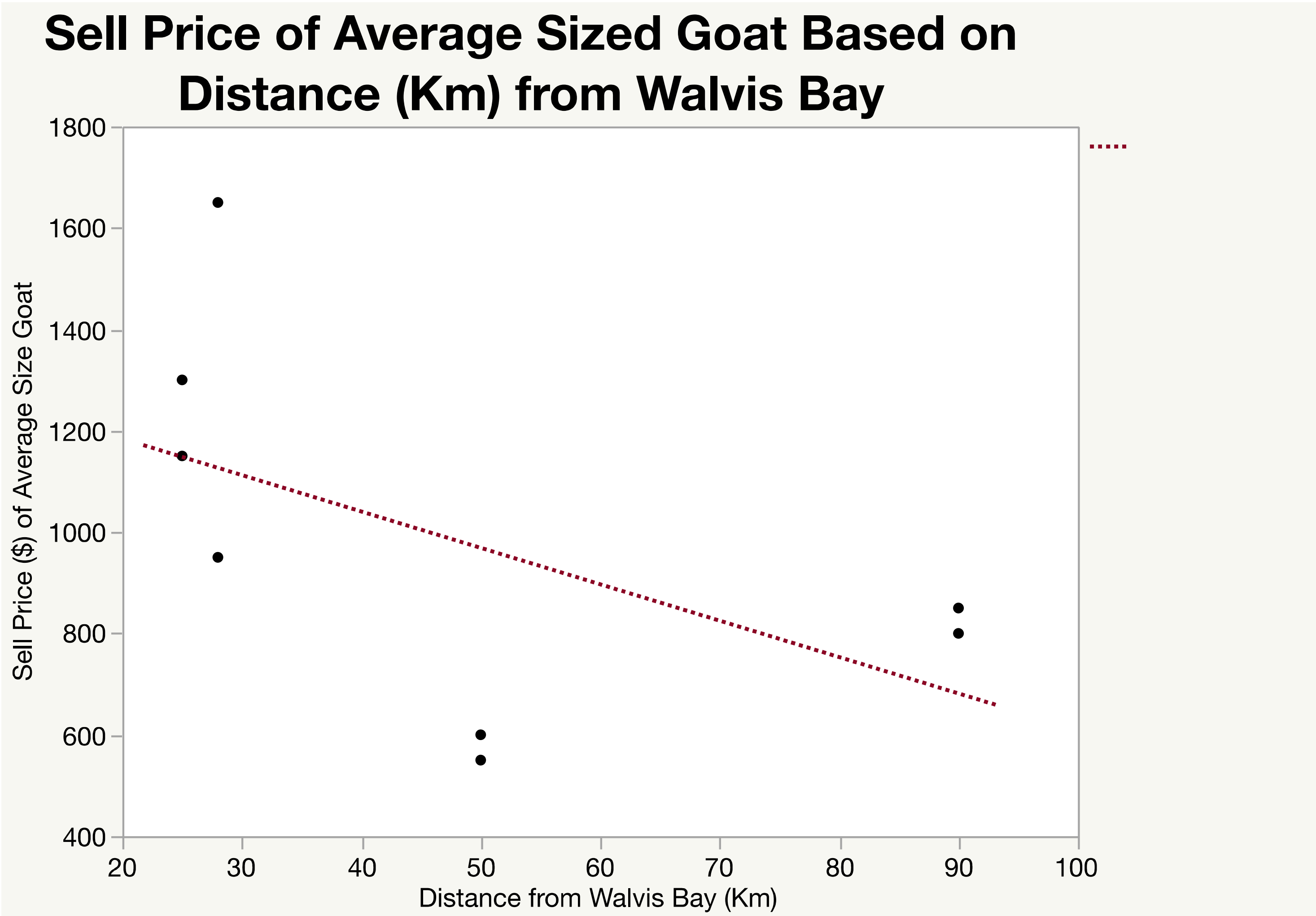


Figure 3: A moderate negative relationship exists between distance from Walvis Bay and the number of buyers per year that sellers receive (R square = 0.456). Each data point represents one interviewee. (Estimate $\pm$ SE = -0.957 $\pm$ 0.426, t_7 = -2.24, p = 0.066).

There is a negative trend between the sell price for an average size goat and distance from Walvis Bay (Figure 4). However, the relationship is not statistically significant.



4: The dotted line represents a negative trend between sell price of an average goat and distance from Walvis Bay (R square = 0.289, Estimate $\pm$ SE = -7.177 $\pm$ 4.590, t_7 = -1.56, p = 0.168).

Buyer arrival to Kuiseb River region

All six participants in the focus group affirmed that there have been times when they have wanted to sell livestock but could not find a buyer. Interviewees 1141 and 1161 further corroborated this, mentioning that it is difficult for them to find buyers.

Not only is it difficult to find buyers, but their arrival can also be inconvenient. A focus group participant further underscored this: “sometimes people just come, even when your livestock are out in the field” and that “even if you want to sell you can’t go get [the animals].”

Qualitative data shows inconclusive levels of predictability of buyer arrival. Three interviewees noted that there were certain times when buyer arrival increases, either at the end of the month or during the holiday season (1131, 1132, 1141). Furthermore, we spoke with one person who makes a living from connecting Topnaar livestock sellers and buyers from Walvis Bay. Connecting buyers and sellers could enhance the predictability of buyer arrival and help sellers plan for a sale.

Local perceptions about Topnaar livestock market formalization

To understand whether the proposed formalization of the livestock market is supported by the Topnaar community, we asked interviewees about their interest in a local auction (Figure 5).

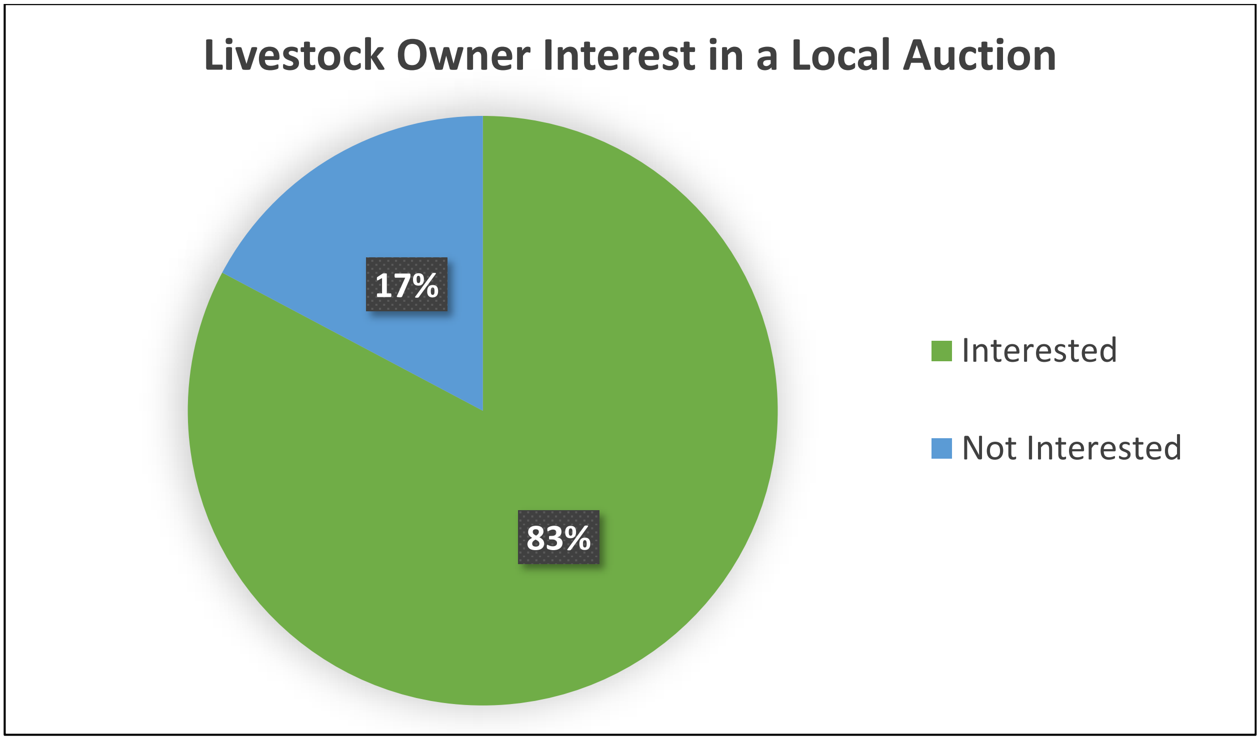


Figure 5: Results from livestock workshop survey. Three survey responses were blank, and are not included in the above chart.

Interviewees described reasons for their interest in entering a formal livestock market, citing higher profits, increased agency over the sale, and various indirect benefits of formalization as reasons for this interest. Four interviewees expressed that they perceived that a formal market could increase their profits. With specific mention to the proposed local auction, interviewee 1141 said, "you might be able to get a better price [at a local auction]." A participant in the focus group at the livestock workshop at Gobabeb also expressed that auctions are more profitable and could be a better way to make money.

One interviewee also expressed that a local auction, in particular, could enhance their agency over the sale of the animal, and that they could bring the animal back home if the price offered at the auction is not acceptable (1131).

Others mentioned perceived indirect benefits associated with the formalization of the livestock market. Interviewee 1164 mentioned that ear tagging—an aspect of the formalization process—could prevent against stock theft: "You know that [the animal] is yours and no one takes them." Interviewee 1165 explained that in the event of stock theft, ear tags could enable owners to report the loss: "It's good to have ear tags because... If someone steals and sells to Walvis [Bay] you can report them."

The qualitative analysis of interview data also provided possible reasons why 17% of survey respondents were not interested in a local auction. For instance, current sellers express ambivalence towards complying with ear tagging and vaccination legislation and pushback against a transition to a more formal system. Ten people expressed that current buyers are not concerned with ear tags or vaccinations (interviews, focus group participant). Interviewee 10311 stated, "generally people don't care about regulations for selling." Furthermore, three interviewees specifically mentioned that their buyers only care about buying the meat (1131, 1141, focus group participant).

Two interviewees mentioned potential conflicts between the traditional and commercial systems. Statements about the opposition to a more commercialized livestock system included: "This is the problem, starting over from the traditional way and going to the government way" and "doing this the commercial way is something new for the traditional Topnaar" (1161, 1131).

Local perceptions of barriers to formalization

Information asymmetry

Despite the wide use of auctions to sell livestock throughout the country, five interviewees lacked information on the specifics of an auction. Interviewee 1154 stated, "we don't know about auctions." Additionally, six interviewees stated that they lacked information about ear tagging, vaccination, and branding legislation. In fact, interviewee 1161 claimed that they had never known about the laws and regulations surrounding livestock until the workshop in Utuseb, which was held the same week that this study was conducted.

The majority of survey respondents who owned goats did not comply with legislation on ear tagging, which is required for participation in auctions (Figure 6).

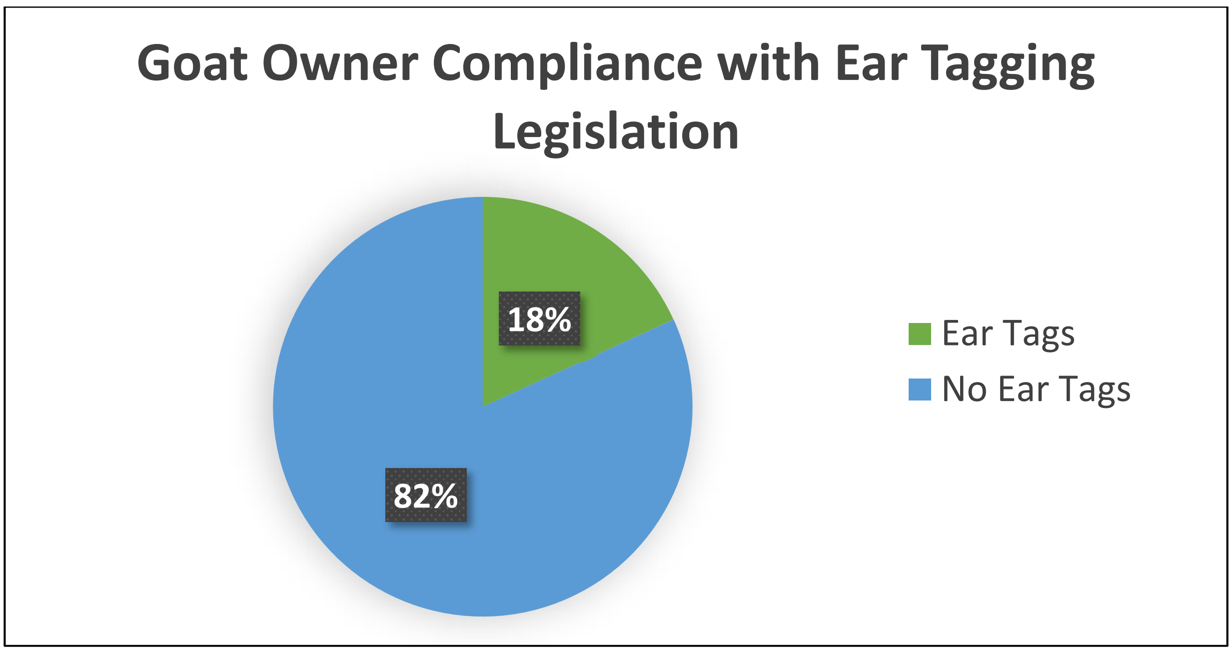


Figure 6: Eleven out of thirteen goat owners at the livestock workshop responded about compliance with legislation.

Perceived financial cost of entering the formal market

The costs of compliance with legislation are another perceived barrier. Interviewee 10313 said that "regulations [ear tagging, vaccinating, branding] drive up costs for farmers." One interviewee specifically mentioned that they do not vaccinate their animals because they have more pressing expenses, such as cement to build their house and parts for their car (1131).

Apathy towards legislation

There was minimal evidence of non-compliance due to apathy towards legislation. Interviewee 1111 stated that cost was a barrier to compliance with vaccination policies, but that s/he had never tried to buy vaccines. Another interviewee was aware of the legislation but stated that his goats do not have ear tags (1134).

Perceptions of potential buyers of Topnaar livestock

We established that there is a demand for more localized livestock market access. All six meat sellers in Walvis Bay expressed interest in an auction in Utuseb. Seller #6 expressed strong interest in an auction: "I'll be there first… if they've got everything I'd buy everything." The close proximity of such an auction was among the key perceived benefits in having a local auction in Utuseb. Currently, two sellers obtain their meat from farms 300 km away. Thus, a local auction would reduce transportation costs significantly. Other perceived benefits included fairer prices, and the ability to see the quality of the meat that they purchase.

However, only one seller was aware of the existence of livestock in the nearby Topnaar community, and two sellers stated that they were surprised that livestock were able to survive in the harsh Namib Desert. Furthermore, some buyers expressed concern about compliance with national laws. One butchery manager asked, "are they marked according to Namibia law?" Two sellers brought up the issue of the lack of access to an *abattoir* (legal slaughterhouse facility). The closest *abattoir* is in Swakopmund, and, as one seller explained, it is difficult to access by those in Walvis Bay because it only uses meat sourced by its owner.

Cost-benefit analysis of proposed auction in Utuseb compared to current informal system

Table 1 Estimated annual profit for goat sellers in the current market

Village	Estimated Annual Benefit (Gross Income) (N$)	Estimated Annual Cost (N$)	Estimated Annual Profit (N$)
Aramstraat	3675.00	270.00	3405.00
Daweb Draai	3900.00	270.00	3630.00
Swartbank	3450.00	270.00	3180.00
Natab	825.00	270.00	555.00

This analysis does not include unquantifiable or potential costs. For example, it does not include the fines, confiscations, or loss taken from the death of livestock due to non-compliance with ear tagging and vaccination policies.

Table 2 Estimated annual profit for goat sellers at Utuseb auction

Village	Estimated Annual Benefit (Gross Income) (N$)	Estimated Annual Cost (N$)	Estimated Annual Profit (N$)
Aramstraat	3672.00	411.10	3260.90
Daweb Draai	3672.00	407.92	3264.08
Swartbank	3672.00	413.22	3258.78
Natab	3672.00	453.50	3218.50

This analysis assumes that sellers are driving to Utuseb, To account for other modes of transportation, we can assume that carpooling would decrease the overall cost, and therefore increase the annual profit, while hiring a car from Walvis Bay would increase overall cost, and decrease annual profit. This analysis also assumes that sellers have enough stock to sell 60% of their herd without risking the health of the herd, and that the auction is held annually.

Difference in EAP between current system and Utuseb auction

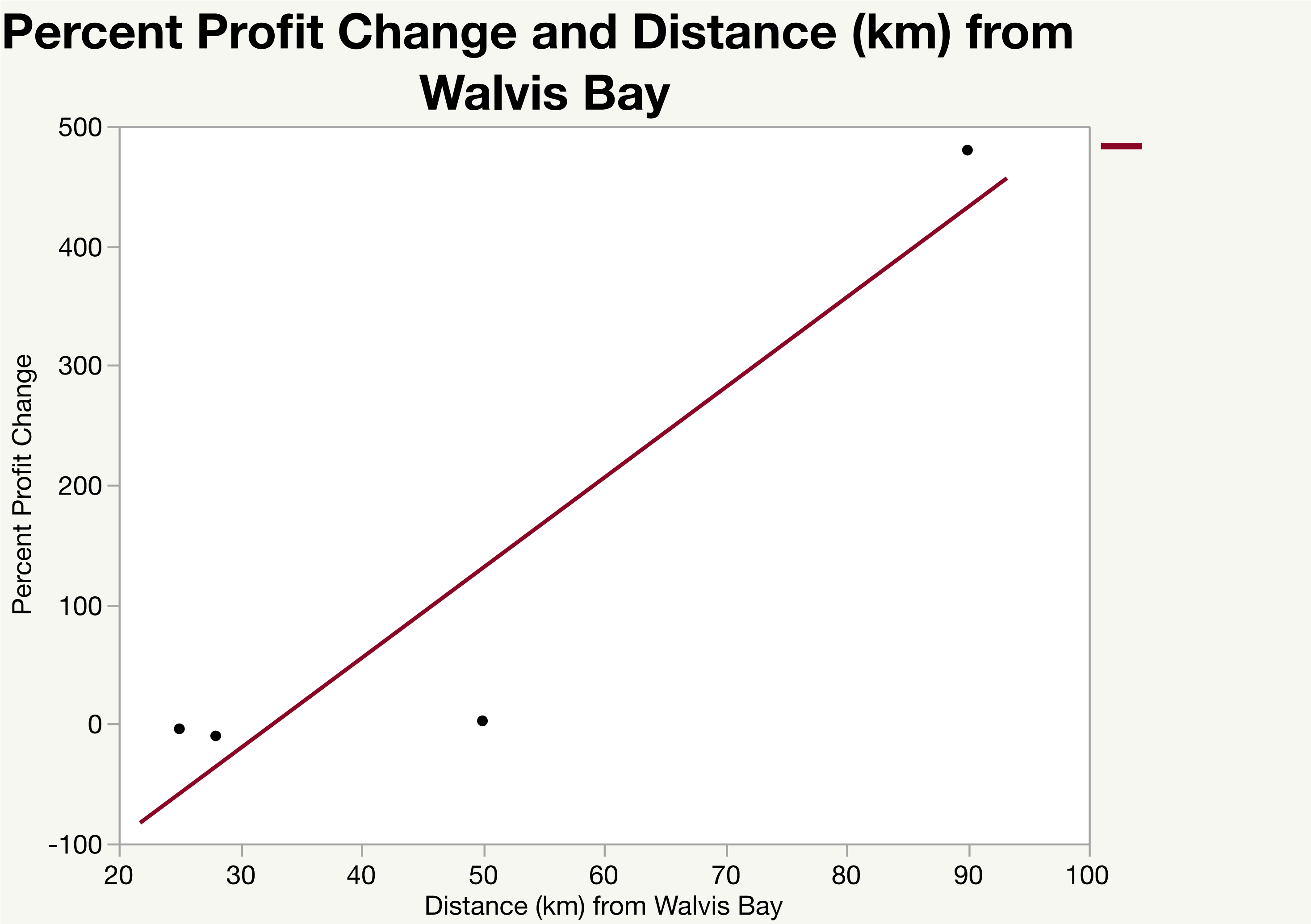
Some livestock owners may financially benefit from transitioning from the current system to an annual local auction (Table 3). This analysis assumes complete abandonment of the current system, yet participation in the current system and the formal system are not mutually exclusive. Livestock owners could attend an annual auction and continue selling their livestock to buyers coming from Walvis Bay. Mitigating these flaws would only increase annual financial earnings; therefore, the cost benefit analysis for formalization underestimates estimated annual yearly profit.

Table 3 Difference in EAP between current system and Utuseb auction

Village	EAP in the Current System (N$)	EAP for Utuseb Auction (N$)	Percent (%) Difference in EAP
Aramstraat	3405.00	3260.90	- 4.23
Daweb Draai	3630.00	3264.08	-10.08
Swartbank	3180.00	3258.78	2.48
Natab	555.00	3218.50	479.81

Financial benefits of transitioning to the formal market increase as distance from Walvis bay increases (Figure 7). Specifically, a local auction could increase annual profit for livestock owners in Swartbank and Natab (Table 3). Villages closer to Walvis Bay, however, have similar EAPs for both the current system and hypothetical auction in Utuseb; in this analysis they do not benefit from a local auction.

As livestock owners get increasingly farther from Walvis Bay, their percentage change in profit increases. This relationship is statistically significant (Figure 7).



7: A positive relationship exists between distance from Walvis Bay and percentage profit change from the current informal livestock market system to the formal market (R square = 0.874, Estimate $\pm$ SE = 7.524 $\pm$ 2.029, t_3 = 3.72, p 0.0653). Each data point represents an average livestock owner in the Kuiseb River region.

Discussion

There is a supply of livestock in the Kuiseb region and a demand for Topnaar livestock in Walvis Bay. However, there is disconnect between this supply and demand. High transportation costs and lack of compliance to regulations hinder some Topnaar livestock owners from accessing buyers in Walvis Bay. In the current system, sellers who live farther away from Walvis Bay are disadvantaged due to lack of access to buyers. This has implications for the sustainability of their livelihoods, as there is an inequitable distribution of risk among Topnaar livestock sellers. Livestock owners farther from Walvis Bay have difficulty withdrawing money from the "bank" that is their livestock (Turner 2009). In light of frequent shocks that impact rural livelihoods, necessity of access to monetary benefits from assets is essential. Thus, this study has explored the potential benefits of a rural-based livestock market, such as an auction.

Benefits of formalization

Formalization increases market access, which leads to greater sustainability of rural livelihoods. In particular, the introduction of an auction in the Topnaar community could increase annual profits of livestock owners located farther from Walvis Bay. Livestock owners from the farthest villages will benefit from the auction because it would create an opportunity for equitable market access, provided that livestock owners can access transportation from their village. In turn, it would be easier for these livestock owners to safeguard against financial shocks.

However, there is potential for an auction to create benefits for all Topnaar sellers, as it could enhance the predictability of buyers. In the current system, buyers arrive infrequently and occasionally at inconvenient times; interviewees cited surges in buyer activity at the end of the month and during the holiday season. It is possible that an auction could help regulate this unpredictability and fluctuation, allowing sellers to predict the number of livestock they can sell at a specific time. An auction could enhance the sustainability of their livelihoods, as it would enable livestock owners to budget and plan for future disturbances to their livelihoods, thereby increasing their resilience.

Additionally, there are numerous benefits to formalization that are not contingent on engaging in a local auction. Notably, livestock sellers could engage with more buyers in the formal market, as all six sellers were intrigued by the presence of livestock in such close proximity to Walvis Bay. Furthermore, this increased access to buyers in the formal market could potentially result in an increase in number of livestock sold and annual profits.

Furthermore, compliance with legislation has other positive externalities for livestock owners. For example, vaccinating goats reduces annual goat mortality (Islam et al, 2012). In turn, the increased overall herd health and increase in numbers could offset the cost of vaccination. Additionally, several interviewees emphasized that ear tagging and branding livestock could reduce stock theft.

Barriers to formalization

Although there are benefits to entering the formal system and complying with legislation, there are significant barriers to doing so. Notably, the upfront financial cost to compliance, coupled with the fact that many livestock owners do not see benefits from complying with this legislation, could prevent livestock owners from engaging in the formal market.

Low government enforcement and buyer ambivalence toward ear tagging, branding, and vaccination legislation creates a system where non-compliance is the most cost-effective. Additionally, many livestock owners are unaware of the benefits of compliance. Therefore, it is it is unlikely that they will personally absorb the cost of ear tags, brands, and vaccinations. Even the one-time costs of the application fee (N$129), enough ear tags for their stock, a branding iron for cattle owners (N$800-900), and transportation to Walvis Bay to submit the application could create a significant enough barrier to prevent livestock owners from complying (presentation at livestock workshop 10/31).

Another possible challenge for compliance is the lack of information sharing between the government, Traditional Authority, and the Topnaar community. Without disseminating information about regulations and potential costs for non-compliance, the Topnaar community cannot comply even if they were interested in doing so, barring them from potentially accessing the many services and benefits of the formal system provided by the government. Lack of communication of these costs also exposes Topnaar livestock owners to potential confiscation of livestock, fines, even imprisonment.

Significantly, there is no *abattoir* in Walvis Bay, which makes legal, sanitary slaughter of livestock impossible. Even if farmers were to comply with legislation and prepare for entry into a formal market, the lack of an *abattoir* is a significant barrier. However, it is possible that if the process of formalization were undertaken by the Topnaar community, the government would recognize the need for an *abattoir*.

Despite these barriers, however, the community desires engagement in a local auction. Due to increasing pressure on rural livelihoods, it is crucial that community members adapt their livelihood strategies (Mortimore and Adams 2001; Tol et al. 2004). Formalization can enhance sustainability of rural livelihoods, as it encourages engagement with the broader formal market and can provide economic opportunities (Carswell 1997). However, it is important to consider whether this process of formalization can stay within the bounds of environmental sustainability. Formalization could promote the increase in the number of livestock in the Kuiseb River region, which has implications for the fragile desert environment. Therefore, efforts to formalize the Topnaar livestock market should focus on intensifying agriculture sustainably, and consider diversifying livelihoods to mitigate potential environmental degradation.

Recommendations

For livestock owners:

- Establish a farmers' association or cooperative to increase information sharing. Talking about sell price, collaborating on transportation to formal markets, and management practice advice could improve livestock profits. Since this has been tried in the past, the community will need to alter their modes of communication'
- Tag and brand your livestock. There is a demand for Topnaar livestock in Walvis Bay, especially if it is tagged and branded. Most buyers emphasized that they would only be interested in Topnaar meat if livestock were tagged and branded. Cost-benefit analysis shows you can benefit financially from entering the formal market, but you must have tagged and vaccinated your livestock in order to participate.
- Attend available livestock workshops and farmers days to learn about new legislation and find out how to tag and brand your livestock
- Carpool to local auctions. Carpooling can minimize transportation costs and maximize profit.
- Improve marketing. There is a demand for your livestock in Walvis Bay but most buyers are unaware of the Topnaar supply. Only one seller was aware of the Topnaar community, and two sellers stated that they were surprised that livestock survives in the Namib Desert. Yet, all six sellers demonstrated interest in an auction in Utuseb.

For government officials:

- As we saw that distance improved market access, we recommend that a market, such as the Utuseb *kraal,* be opened closer to the Topnaar community that would bring all livestock sellers together to negotiate prices. Chief Kooitjie emphasized interest in continuation of the project and 83% of Topnaar people said they would be interested in a local auction. Additionally, this kraal would reduce necessity for illegal sale on the informal market and could create incentives for compliance with regulations.
- Facilitate more livestock workshops and farmers education programs in the Kuiseb region. After the livestock workshops on 10/31 and 11/1 in Gobebeb and Utuseb farmers expressed a desire to brand and tag their animals.
- Emphasize the benefits of branding and tagging animals to livestock owners at livestock workshops. Livestock owners were more interested in branding and tagging animals if they were aware of how it could benefit them (i.e. could report losses from predators for compensation, reduce mortality and stock theft).
- Assist in creation of *abattoir* in Walvis Bay. Lots of illegal slaughtering is occurring on farms due to the privatization and selling of the previous *abattoir* in Walvis Bay.

To guide future Dartmouth research:

Additionally, we have identified areas for future research in conjunction with the Topnaar community. During our two days at the livestock workshops, we presented findings from the 2017 students and received feedback on future research that the community would find beneficial. The following research ideas were identified through these conversations.

- Understanding water usage dynamics between downstream and upstream communities. How does water usage upstream affect those that are downstream? What are the social dynamics between Walvis Bay and Swakopmund's and the Topnaar regarding water consumption? It could also be interesting to investigate how mining companies utilize water and how this plays into the overall social-ecological system.
- Building on the upstream and downstream dynamic amongst communities, we heard from downstream communities that upstream communities had more cattle because their land is better for grazing cattle. Furthermore, the downstream communities said their land could only support small stock because there is less water. Land-use dynamics and social dynamics between communities could influence grazing patterns and livestock choices for individuals.
- Human-wildlife conflict was brought up numerous times by community members during the livestock workshops. Community members pointed out that cheetahs and leopards were killing their animals in the kraal, and it is illegal for them to kill these predators due to the regulations of living within a national park. They expressed interest in research that could inform strategies that they could use deal with predators killing animals and also follow the regulations of living in a national park. This could be framed within the history of the national park, with an emphasis on how policy has affected livestock management.
- Researching the use of dogs in herding would be useful to inform future livestock management practices. The 2017 research showed that herding, specifically with a dog, was the most effective way to decrease predation. However, during the livestock workshop community members pointed out that dogs were difficult to deal with, though no one refuted the finding. Investigating the number of community members that use dogs for herding, the number that have dogs as pets, and community perceptions about dogs as a prevention method against predation could help influence future prevention of predators.

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We extend our sincere thanks to Simasiku for his knowledge and guidance. We are fortunate to have met someone who was so willing to help us take our project in new directions, even if that meant quite literally traversing Walvis Bay to visit *kapanas* and butcheries.

Finally, we are so thankful to the Topnaar community participants in this study for kindly welcoming us into their homes, for giving us their time, and for sharing their thoughtful responses. We hope that this research can begin or reignite meaningful conversations within communities, as well as between other actors such as the municipality, Regional Council, and Traditional Authority, in discussing the future of the Topnaar community's livestock market.

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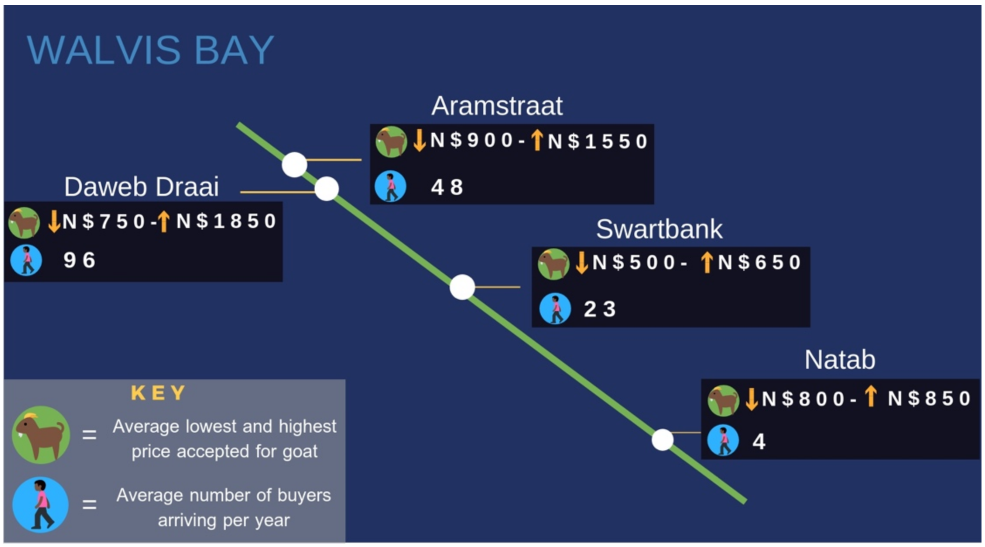
Appendices

Appendix I

Non-technical summary of principal findings

Our project

Our research looked at the current livestock market and the benefits of selling livestock that follow government laws. We interviewed fourteen livestock owners and six meat sellers in Walvis Bay.



Current market for livestock

Community members in villages farther from Walvis Bay have less buyers coming to their houses (see left figure). Livestock owners in villages like Natab, for example, get an average of 4 buyers a year, while livestock owners in Aramstraat get an average of 48 buyers a year. Livestock owners also do not always have access to buyers or their livestock when they want to sell because they can't predict when buyers will come. This can make it difficult in times when money is needed and makes planning for future saving and investments more difficult.

Room for growth

We wanted to see if the local auction in Utuseb proposed by Chief Kooitjie would benefit the community. We found that sellers from villages farther from Walvis Bay would be positively affected by having an auction if livestock owners work together and split the cost of transporting their livestock to the auction. However, many livestock owners did not seem to know what exactly an auction is like or how it will benefit them. A workshop or other information-sharing gathering could be beneficial.

We also interviewed six meat sellers in Walvis Bay. All six were interested in buying Topnaar meat. However, five of six did not know that the Topnaar community sold livestock. More marketing and advertising of the availability of Topnaar livestock could increase the number of buyers coming to the Topnaar community, as all six said they would be interested in attending a local auction in Utuseb.

Most buyers said that they would only be interested in Topnaar meat if livestock were tagged and branded. Topnaar livestock owners could sell to more buyers if they follow these government laws.

Appendix II

Methods for calculating cost benefit analysis

Methods for identifying each variable in EAP equation in the current informal system

Variable	Method
P: Average price of goat in specific village	Interviewees identified the cheapest and most expensive prices they have sold their goats for. We took the average of the cheapest and most expensive goat prices in each village to establish an average sale price for each specific village.
GS: Average number of goats sold in one year in specific village	Utilized responses from the survey question: "How many times did you sell your livestock in the last year?" We assumed that sellers sold only one goat per sale based on interview data.
OC: Annual operations cost per goat	Published data shows that cost of facilities and equipment is about N$30 per goat (Queeley and McKenzie-Jakes nd.)
GO: Average number of goats owned by livestock owners in Kuiseb region	Utilized data from the 2018 Livestock Census reported by Gobabeb to find average goats owned per person in the 5 villages in the Kuiseb region where we collected data. Excluding 2 outliers, an average person in these 5 villages owns 9 goats. Calculation: (18 + 15 + 5 + 4 + 1 + 4 + 23 + 9 + 14 + 3 + 1 + 2 + 15) / 13 = 8.769 = ~9 goats per owner

Calculated variables per village in current market system

Village	P	GS	OC	GO
Aramstraat	1225	3	30	9
Daweb Draai	1300	3	30	9
Swartbank	575	6	30	9
Natab	825	1	30	9

Methods for identifying each variable in EAP equation for proposed Utuseb auction

Variable	Method

GO: Average number of goats owned by livestock owners in Kuiseb region	See Appendix I
PS: % of herd selling at auction	Phone interviews with sellers at commercial auctions, livestock owners should keep 40% of their heard annually to repopulate.
MP: Market price of goat	The current market value of a medium sized goat is N$680.00 (Agra Meat Prices, 2018)
D: Distance of village from Utuseb	Distance of villages from Utuseb was provided by an interviewed Traditional Authority member.
OC: Operations cost per goat	See Appendix I
TC: Ear tagging cost per goat	Cost per set of ear tags = N$ 2.50 for each goat (Schlechter, D, 2014).
VC: Vaccination cost per goat	Annual vaccinations cost N$12 per goat (Queeley and McKenzie-Jakes).
Cost per km	See *Cost per kilometer calculation*

Calculated variables per village for proposed Utuseb auction

Village	**GO**	**PS (%)**	**Distance from Utuseb (km)**	**OC (N$)**	**TC (N$)**	**VC (N$)**
Aramstraat	9	60	10	30	2.50	12
Daweb Draai	9	60	7	30	2.50	12
Swartbank	9	60	12	30	2.50	12
Natab	9	60	50	30	2.50	12

Cost per Kilometer Calculation

In order to complete the equation cost per kilometer from Uteseb calculation was necessary:

Gas in Namibia = N$10.68 per Litre (Namibian Broadcasting Corporation, 2018)
Average km per gallon in a vehicle = 37.981 km/gallon (Plumer, 2013).

$$\frac{\$10.68}{Litre} \times \frac{3.785\ \text{Litres}}{Gallon} = \frac{\$40.43}{Gallon}$$

$$\frac{\$40.23}{Gallon} \times \frac{1\ \text{Gallon}}{37.981\ Km} = \frac{\$1.06}{Km}$$

Appendix III

A method for identifying meat sellers

Figure 8: “Donkey meat $50 each,” an adventurous day in Walvis Bay identifying meat sellers

Factors Influencing !Nara Health and Distribution in the Lower Kuiseb River: A Pilot Study

November 12, 2018

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Abstract

Understanding the biotic and abiotic factors that influence species health, and therefore its distribution, is crucial for understanding how that species will be affected by changing external pressures such as climate change or human and animal disturbances. However, the complex nature of ecological interactions impedes development of a comprehensive species distribution model, so it can be beneficial to begin such studies by determining a species' bioclimate envelope. This study seeks to begin building this baseline characterization for the !nara plant by randomly sampling populations in the lower Kuiseb River region and analyzing the impacts of different water sources, as well as trends in herbivory and human harvesting. Our analysis demonstrates that groundwater is the overall most important variable for both individual health and general distribution, though fog is also significant. We also discovered strong trends of increasing herbivory away from the coast and clustered around villages. Our studies were generally more exploratory than definitive and therefore offer promising opportunities for further study into !nara distribution. Overall, !nara's dependence on groundwater and fog water indicates that future declines in these resources will likely limit its ability to grow throughout the Kuiseb region, which could have drastic ramifications for local people and ecosystems.

Introduction

The concept of the fundamental ecological niche has been steadily developed since the early 20th century. A species' niche is often defined as "those environmental conditions within which a species can survive and grow" (Pearson & Dawson, 2003). Hutchinson (1957), an early seminal author in population ecology, formalized this definition into a "a set of points in an abstract n-dimensional N space," or a conceptual volume bounded by the ecological variables that limit or define where a species can survive. A species' fundamental niche refers to such a space that is defined only by abiotic limitations—for example, temperature, soil type, rainfall—or the set of all possible ecological conditions the species could survive in, ignoring its interactions with other animals or plants (Pearson & Dawson, 2003; Hutchinson, 1957). Its realized niche, on the other hand, incorporates biotic interactions such as competition, dispersal, predation and symbiosis (Pearson & Dawson, 2003; Austin *et al.*, 1990). Though more descriptive than the fundamental niche, the realized niche is significantly more difficult to define given the complexity of species interactions. Therefore, defining a "bioclimate envelope" is a good place to start when attempting to understand a population's distribution (Pearson & Dawson, 2003). This distribution model incorporates only the climatic variables that affect a species' fundamental niche, ignoring biotic interactions and other environmental factors like soil or topography. It is substantially easier to develop than a more complete model, especially when little is known about the species in question (Pearson & Dawson, 2003).

Climate change is affecting species distributions by shifting niche spaces and altering resource availability. The strain this places on populations is exacerbated by human-induced activities, such as harvesting, exploitation, and the introduction of non-native species (Keddy, 2017). Despite the overwhelming evidence for climatic changes and the disturbances they cause, determining the long-term impacts of these shifts on species health and distribution is difficult (Parmesan & Yohe, 2003; McCarty, 2002; Thomas *et al.*, 2004; Walther *et al.*, 2002; Thuiller *et al.*, 2008). For species that have not yet been intensively studied, these projections are near impossible, as predicting how a changing climate will affect a given species requires at a minimum an understanding of how the current climate facilitates and inhibits its survival. To gain this understanding, one can look at both individual health and general distribution. Factors that improve individual health will subsequently shape where, and how densely, that plant grows. Similarly, a concentrated population could suggest the presence of factors that are beneficial for plant health. Therefore, defining the important variables that influence a species' distribution, based on analyses of individual health and observations of population density, are essential for building a baseline on which to predict how that population will respond to the changing world.

The !nara plant (*Acanthosicyos horridus*), a leafless, spiny cucurbit which grows in Namib Desert from northern South Africa into southern Angola, is an example of a 'mystery species' about which little is known. Only a handful of studies have attempted to map its distribution, though researchers generally agree that the plant is limited to areas with easy access to the water table (Müller, 2004; Dongol *et al*., 2014; Wommack *et al*., 2013; Berry, 2003; Henschel *et al*., 2004; Victor, 2013). Even details about fundamental characteristics like its taproot length, water sources, size, and age are uncertain and contested in the literature (Klopatek & Stock, 1992; Henschel *et al*., 2004; Hebeler, 2000). The !nara holds immense cultural significance for the Topnaar people, an indigenous Nama group that have lived along the Kuiseb River for many centuries (Henschel *et al*., 2004). Historically, it was both a primary food and water source, as well as an important cultural figure that distinguished the Topnaar from other Nama ethnic groups. With the rise of modern influences, their livelihoods have diversified; however, the !nara is still a vitally important source of income and food in Topnaar communities along the river (Ito, 2005; Shilomboleni, 1998).

Given the plant's limited range and how little is scientifically known about it, it is currently unclear how changes in climate will affect the !nara. Additionally, there is evidence indicating that human activities in the area are extracting groundwater at an increasing and unsustainable rate, limiting what is believed to be one of the most important controls on !nara's distribution (Victor, 2013). A reduction in !nara productivity or population size due to either changing climatic conditions or reduced groundwater could prove dangerous for Topnaar livelihoods and general well-being in this area, as well as have potentially catastrophic ecological impacts if the plant is—as some suspect—a keystone species of the Namib Desert (Ito, 2005; Klopatek & Stock, 1992). Therefore, developing an understanding of the !nara's fundamental and realized niches and characterizing its overall distribution is vital for the social-ecological system of the lower Kuiseb.

We therefore aimed to develop an understanding of some of the anthropogenic and climatic factors that influence !nara population health and distribution. We investigated the effects that access to different moisture sources (fog and groundwater) may have on !nara population health, and how this may influence both current and future distribution patterns given the Namib's hyper-arid climate, and the potential for climate change to exacerbate its precipitation and fog scarcity (Soderberg, 2010). Additionally, we examined the impact that human activities, such as livestock farming, water extraction, and harvesting, are having on !nara populations, and how this pattern is spatially distributed.

Guiding Questions

Based on our review of the existing literature and previous studies, we developed the following guiding questions for our research: *How is !nara health impacted by human and environmental factors? How do these impacts affect !nara distribution?*

Hypotheses

We suspected that within the lower Kuiseb area, !nara population distribution is limited by groundwater access and to some degree by fog patterns. Less access to groundwater will be related to poorer plant health and decreased population density. Less access to fog water will be similarly related to lower plant health indices and sparser populations. We also hypothesized that distance from nearby villages will correlate with decreasing herbivory levels and increasing fruit count, due to expected reductions in livestock and harvesting pressures in more remote areas. In this study, we also compared several descriptive population metrics to ascertain larger trends, such as differences between the delta and interdune zones. For these comparisons, we anticipated that delta populations would be overall healthier and denser than interdune fields, as they have better access to groundwater and fog water.

Methods

Study species: !Nara

!Nara is a desert-adapted plant which grows in interdune areas, as well as within and along the ephemeral rivers of the Namib (Hebeler, 2000; Henschel *et al.*, 2004; Cole *et al.*, 2014). Over time, windblown sand collects at the base of the interdune bushes and creates large hummocks, which are typically between 1-8 meters in height and can cover areas up to 1500 m^2 (Cole *et al.,* 2014). As !nara photosynthesize through their stems, bushes in the interdunes must keep growing upward to maintain access to sunlight and moisture from fog and rain (Henschel *et al.*, 2004). Gerber's (2017) that !nara also absorb some water through the stems indicate that fog may be a significant water source supplementing !nara's perceived dependence on groundwater.

!Nara are dioecious; male plants produce flowers almost year-round while female plants produce flowers and spiky fruits, most commonly starting in the summer months and ending in June (Henschel *et al.*, 2004; H. Areseb, personal communication, 11/5/2018). Though !nara bushes are capable of producing hundreds of these melons, the species has a very low recruitment rate (Müller, 2004). Local people harvest these melons twice a year, utilizing its pulp and seeds for various products. The seeds are particularly economically important; they are roasted and sold in quantities as high as 3-4 tons per year (Henschel & Moser, 2004; H. Areseb, personal communication, 11/5/2018). To protect the !nara-dependant Topnaar economy from external exploitation, however, seeds are not sold raw and until recently, harvesting permissions were only granted to the Topnaar (H. Areseb, personal communication, 11/5/2018).

Study area: Lower Kuiseb River

The lower Kuiseb Valley within the Namib desert contains the highest known concentrations of !nara (Henschel *et al.*, 2004). The largest fields are generally found within the delta region, though interdune valleys can also contain significant populations. This region of the Namib is characterized by three ecosystems: the gravel plains, the sand sea, and the riparian "linear oasis" that runs in between them (Bates *et al.*, 2008). These distinct ecosystems support markedly different types of vegetation, primarily due to their disparate water supplies. !Nara is one of few plants that can occupy both the interdune regions of the Sand Sea and the more water-rich riverine area and delta.

The area is hyper-arid; between Gobabeb and the delta, precipitation ranges from less than 5mm per year at the coast to less than 25mm per year further inland (Eckhardt *et al*., 2013). However, the coastal region does receive up to 100 days of fog per year (Soderberg, 2010). Some inland regions also receive a significant amount of fog, though the occurrence frequency tapers off dramatically with distance from the coast (Haensler *et al*., 2011). The fog results from the stratus cloud that forms over the upwelling Benguela current occurring off Namibia's western coast, and acts as a key water source for various plants within 60km of the coast (Eckhardt *et al*., 2013). Rising global temperatures, however, could increase the height at which fog develops and potentially remove it as a water source from lower-elevation populations. As a result, vegetation near the coast that relies heavily on fog could lose access to one of their key water sources in the coming decades. If !nara is more dependent on fog than previous studies have indicated, this change could limit its distribution further.

The Namib is also home to a variety of herbivores, jackals, and various insects. !Nara is a nutritious and key food source for these animals, as well as the Topnaar's donkey and cattle populations (Klopatek & Stock, 1994). These species all impact !nara and the surrounding ecosystem through intense herbivory, grazing, and trampling (Keddy, 2017; 212). Wildlife graze throughout the interdunes and riparian areas, while water-dependent livestock tend to remain closer to their human-made water sources in the villages, return every evening to drink (Gabriel, 1993). Donkeys are generally believed to have the most intense impact on !nara, as they are frequently sighted around !nara and remove both stem tips and fruit (Henschel *et al.*, 2004). However, relatively few studies have sought to quantitatively examine this claim, or more concretely measure herbivory's overall impact on !nara. Gobabeb's current exclosure experiment attempts to address this knowledge gap with the support of various Dartmouth student groups, and based on preliminary data and other case studies on plant-animal interactions, they have hypothesized that despite the positive impacts of animal presence—providing dung as compost and dispersing seeds—herbivory, especially by large livestock, harms !nara overall.

Data Collection

To address our guiding questions, we assessed !nara populations in the interdune valleys and delta region along the stretch of the Kuiseb river west of Gobabeb, examining both differences between and variations within these populations. We used the river gradient as a proxy for variance in fog occurrence and collected data on population densities and sex ratios, as well as randomly sampled plant-specific measurements. For populations in interdune valleys, we focused on differences in herbivory, human harvesting and plant access to groundwater as distance from river and height above water table increased.

Though both plant health metrics and population densities can inform an understanding of species distribution, we chose to focus our investigations on health indicators. These indicators are often simpler to measure in a short time; it is easier to gain an in-depth understanding of a singular plant than an entire population. Our analysis also focused more on plant health because of the economic implications of !nara productivity for the Topnaar people. However, we supplemented this information with density estimates based on our population transects and a distribution map (See Analysis Methods; Appendix 4).

Transect Determination

We identified 9 !nara populations to sample along the Kuiseb River between Gobabeb and the delta. Of these, 4 of them stretched at least 1km into an interdune valley, while 2 of them were concentrated closer to the river and 3 of them were located in the delta itself. All populations were located within or south of the riverbed. We disregarded populations in the northern gravel plains, because in this area !nara plants are rare and generally outliers. We chose the populations to be both evenly spaced down the river and near enough to the main road to be relatively accessible to vehicles. In each, we determined 1-2 transect(s) (depending on the size of the population) that traversed the field's major axis and provided some lateral variation. Along each of these transects, we took detailed measurements on a !nara plant every 100-200m (depending on the length of the transect) and marked the sex of each !nara plant within 10m on either side of our transect line between measured hummocks. We noted juvenile plants in a separate category when we came across them.

At each plant we measured, we recorded the following data:

Hummock Characteristics

For each hummock, we categorized the approximate *hummock height* into: 0-2m, 2-4m, 4-6m, >6m. We estimated this height standing at the base of the hummock (the point of inflection between the hummock slope and the surrounding ground) using our measuring pipes as a guide when necessary. We also recorded the length of the hummock's *major-axis diameter*, rounded up to the nearest 5m, and recorded sex, noting if there was evidence of both male and female plants within one hummock. Note: As hummocks can often be difficult to define, especially in denser areas, we demarcated the line between hummocks as a dip of at least a quarter of the overall hummock height.

Health Metrics

At each hummock, we measured certain characteristics of the visible vegetative matter, referred to hereafter as bushes, and took GPS coordinates. We determined four recording sites, one on each side of the plant in the cardinal directions. At each recording site, we measured *bush height*—recording height in cm one-quarter of the way into the bush—and counted the number of medium to large (bigger than a tennis ball) fruits (*fruit count*). We also noted if these fruits were predominantly on one side of the hummock. As !nara health is not currently well characterized or understood, we used a combination of two methods to assess the health of each plant's biomass. Primarily, we adopted the cardboard method piloted by Dartmouth students in 2014 to determine a Cover Density Estimate (CDE) (Dongol *et al*., 2014). At each recording site we used an approximately 30cm by 50cm cardboard rectangle with a grid of 20 evenly spaced holes to assess the overall density of sand vs. living !nara matter vs. dead !nara matter. One researcher started at the hummock base, and backed away until the top of the cardboard piece was lined up with the top of the hummock, and the bottom with the inflection point between the mound and the rest of the sand. From this vantage point, he or she looked through each hole one at a time to determine if it displayed predominantly green (live) !nara matter, brown (dried/dead) !nara matter, or sand. Any other vegetation was categorized as sand. These ratios comprise the plant's overall CDE. For the *proportion of live matter*, we removed sand to look at plant composition in isolation:

$$\frac{\#\ live\ matter\ holes}{\#\ live\ holes\ +\ \#\ dead\ matter\ holes}$$

A similar ratio of sand to overall !nara matter (live and dead) was used to determine hummock composition. For our other plant health metric, we pressed the 50cm by 50cm Plexiglass herbivorometer against the plant at each recording site, counting the quantities of dried and green stems touching or within 1cm of the square.

We averaged the data for bush height, hummock composition and the two biomass measurements from all four sides to obtain one representative data point for each metric and create an overall average characterization of each plant.

Herbivory

To analyze herbivory at each plant we sampled, we counted and categorized the dung on the hummock and within 1m of its base; this protocol was taken from the ongoing !nara exclosure experiments at Gobabeb so that their data may be better contextualized by our findings. The *dung counts* were recorded for both pellets and piles for livestock animals, though in our analysis we used the pile metric for consistency across species. We found dung from donkey, cow, oryx, jackal, and assorted smaller animals including springbok and goat. We grouped these smaller animals into a single category because their dung is difficult to distinguish, and we focused primarily on assessing large livestock and total herbivory metrics. Because of this, eliminating distinctions between smaller species simplified our data collection without compromising our analysis. We also used these dung counts to assess whether counting dung surrounding the hummock is an accurate proxy for herbivory. When we used the Plexiglass square to obtain the ratio of dried to green stems, we also counted how many stems had been grazed to assess herbivory impact on the hummock's bushes (*eaten stems/herbivory*). We again only counted stems that were touching or within 1cm of the glass and applied this method at each of the four recording sites.

Human Impact

To determine the intensity of human harvesting or damage on !nara populations, we measured the distance to the nearest settlement(s) for each !nara field using Google Earth, and supplemented this metric with information from Herman Areseb, a local !nara expert, about the timing of the harvesting seasons in different locations along the Kuiseb. We used this distance as a variable in our herbivory and fruit count analyses.

Fog Water

From the literature, we extracted background information on the area's annual rainfall and fog gradients, as well as a graph of paleochannels underlying the Kuiseb. We interpolated fog data of the past five years from the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) weather stations between Gobabeb and the delta, including the Coastal MET, Gobabeb MET, and Aussinanis Stations (Gobabeb Research and Training Centre, 2018). We used this data to validate the river as a climate gradient proxy, and as a variable in several analyses.

Groundwater

We determined the height above the water table by subtracting the lowest altitude of our site within the river from the altitude of each hummock's GPS point. Though water is not evenly distributed, even within homogenous-looking landscapes, the groundwater under the Kuiseb is very shallow throughout, and therefore does not vary by a significant number of meters (Keddy, 2017; F. Becker, personal communication, 11/8/2018). Though we did not have access to enough borehole data to obtain concrete measurements near each !nara field, we believe our estimates are accurate enough to demonstrate a potential relationship.

Standardization of Fruit and Dung

For some of our data, we needed to standardize values to account for variations in hummock size. To standardize the fruit measure, we divided the number of large fruit by the Relative Vegetation Index (RVI), where:

RVI = average bush height (m) x major-axis diameter (m) x proportion live matter

We also standardized the amount of dung per hummock by dividing the amount of dung by the circumference of the hummock. While this does assume that the hummock is perfectly circular with a radius of half the major-axis diameter, which is not necessarily true, it was our best way of standardizing the dung.

Analysis Methods

To conduct our statistical analysis, we first found a series of distances using Google Earth: for interdune !nara hummocks, we used GPS coordinates to determine their distances from the river and heights above water table, and for overall !nara populations we calculated distance from the coast based on a chosen central point in the population. We also used the averaged plant-specific data— namely, height, health, and herbivory—to create "representative plants" for each transect by averaging this data again for all plants along it. We compared these "representative plant" characteristics across transects to determine impacts along the river gradient, while for plants in the interdune valleys we compared hummock-specific data.

Using Excel, we created graphs testing the impact of each of the measured distances —as well as height above water table—on various plant indicators, including herbivory levels, sex ratio, and dung counts. We analyzed the statistical significance of these correlations using a linear trendline and r^2 values. Standardized fruit counts, proportion of live plant matter from the cover density estimate (CDE), and proportion of live, undamaged stems measured by the herbivorometer were analyzed to quantify individual plant health. We used standardized livestock, wildlife, and total dung counts as supplements to the herbivory damage captured by the herbivorometer. We used the software R to run linear regressions, Fisher Exact tests, and Wilcoxon Rank tests to determine if the relationships in these graphs are statistically significant.

We approximated the density of each of the !nara populations we examined by using !nara counts from our sex ratio data and calculating the area in which we counted them:

Transect width (20m) x transect length (measured in QGIS based on our GPS data)

The densities calculated using this method will overestimate !nara frequency because we counted !nara plants that barely fell within the bounds of our transect as equal to !nara that fell completely within the transect—which means the effective transect width may vary from 20 meters to 60 meters for a very large hummock on the edge of the transect—but this effect will exist across all site densities and therefore the relative densities are still valuable for comparison among !nara population sites. We used Excel analysis to determine the impact of both height above water table (within a transect) and distance from coast (across all transects) on population density. Finally, we ran a correlation matrix in R with all population-level and individual-level variables, to inspect relevant trends and compare potentially auto-correlated variables.

Results

We collected in-depth data on 122 individual hummocks and recorded the sex of 497 others for a total of 619 hummocks. 285 of our recorded hummocks were female, 286 were male, and 48 were unknown (juvenile or lacked buds). Occasionally we encountered hummocks that contained both male and female bushes, and counted these as separate male and female individuals. We otherwise treated hummocks as single plants, as determining separate plants is challenging and subjective without genetic analysis.

Impacts of Fog Water Access on Hummock Characteristics

Our data showed a weak nonsignificant relationship between the density of !nara fields and fog water availability. As annual fog precipitation increased, so did the density of !nara fields ($r^2 = 0.1745$; df = 7; $p = 0.2632$).

We also observed that an increase in the availability of fog in a field correlated with an increase in the juvenile plant count. This relationship was statistically nonsignificant ($r^2 = 0.2606$; df = 7; $p = 0.1603$), but our sample size was relatively small. Further research is needed to determine if this correlation can be generalized.

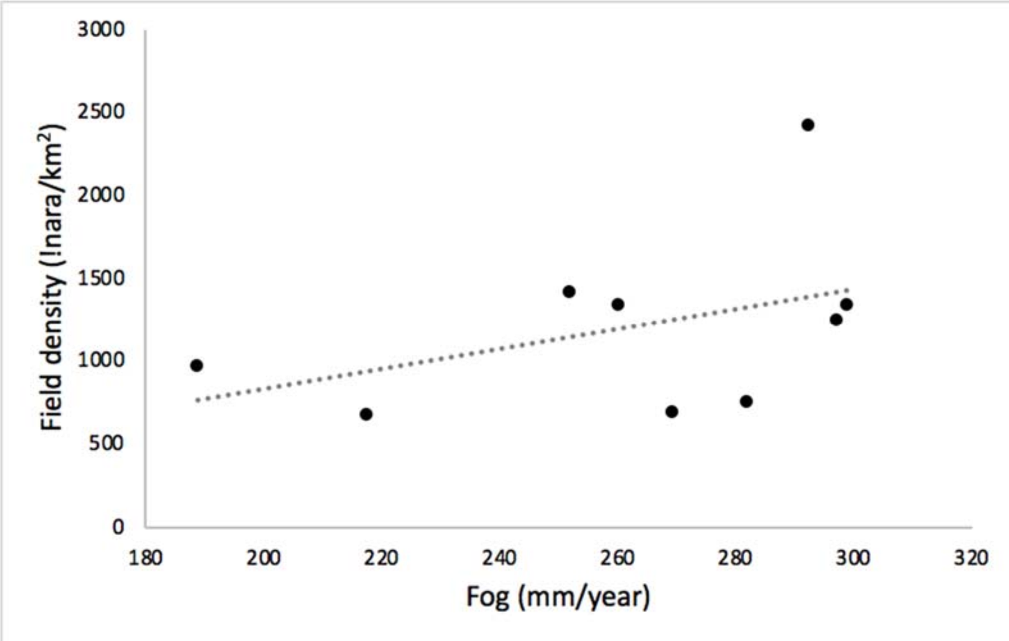

Figure 1 Positive weak nonsignificant relationship between fog (mm/year) and field density (!nara/km^2), ($r^2 = 0.1745$, df = 7, and $p = 0.2632$).

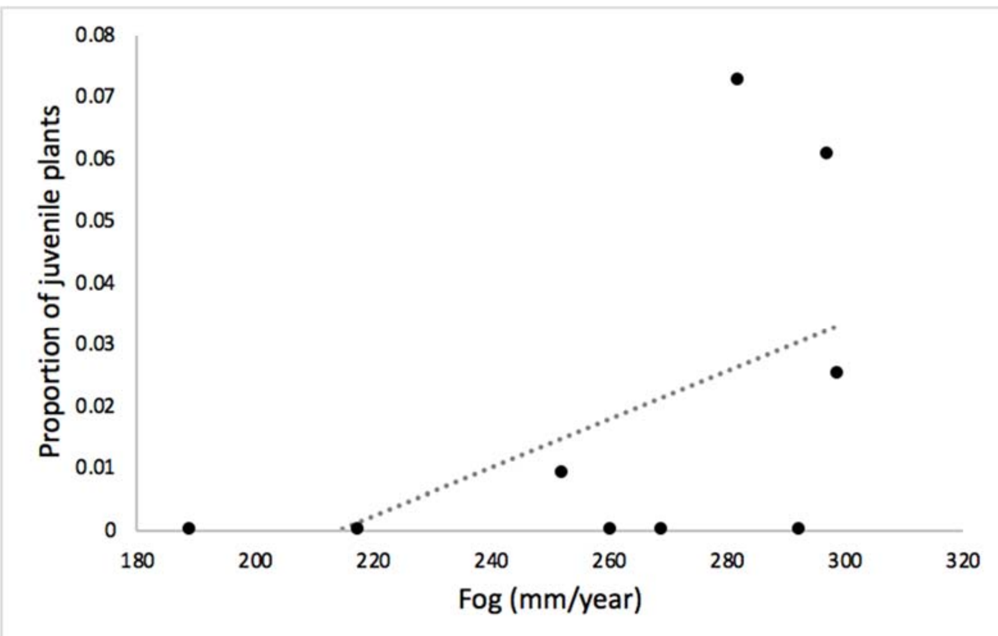

Figure 2 Nonsignificant relationship between fog (mm/year) and proportion of juvenile plants, ($r^2 = 0.2606$, df = 7, and $p = 0.1603$).

We found that there was a very strong and significant correlation ($r^2 = 0.9268$, df = 7, $p < 0.0001$) between distance from the coast and annual fog precipitation, suggesting that our use of distance from the coast as a proxy for fog impacts is justified for other analyses.

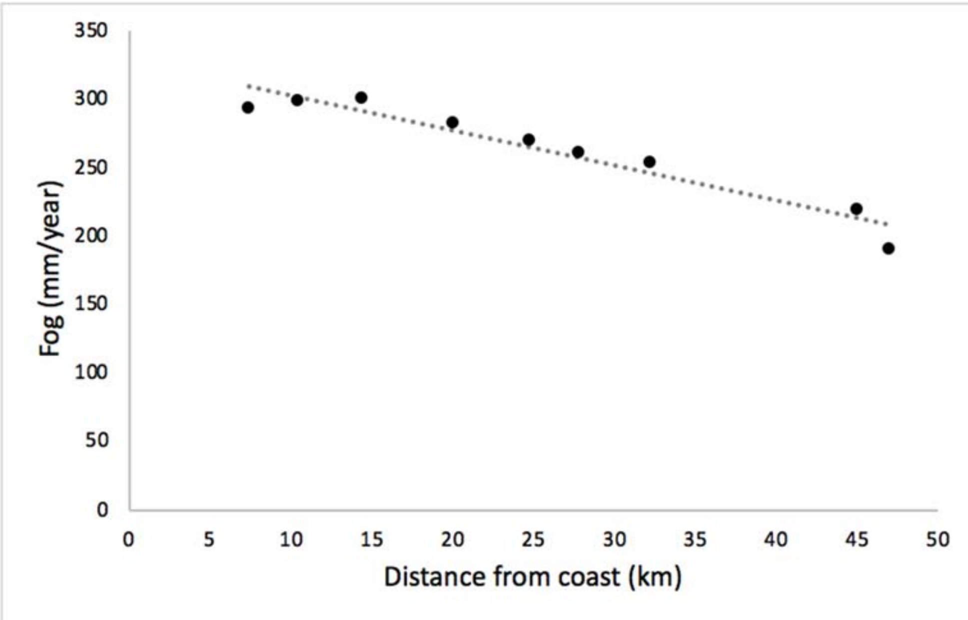

Figure 3 Relationship between distance from coast (km) and fog (mm/year), defending our use of distance from coast as a proxy for fog ($r^2 = 0.9268$, df = 7, and $p < 0.0001$).

Distance from the coast had varying impacts on our measurements of plant health and productivity. Although the correlation was weak and nonsignificant, we found a slight trend of decreasing numbers of large fruit (standardized with respect to hummock size) further from the coast ($r^2 = 0.1018$, df = 7, p = 0.4026); again, further studies with larger sample sizes are necessary to determine the relationship's statistical significance.

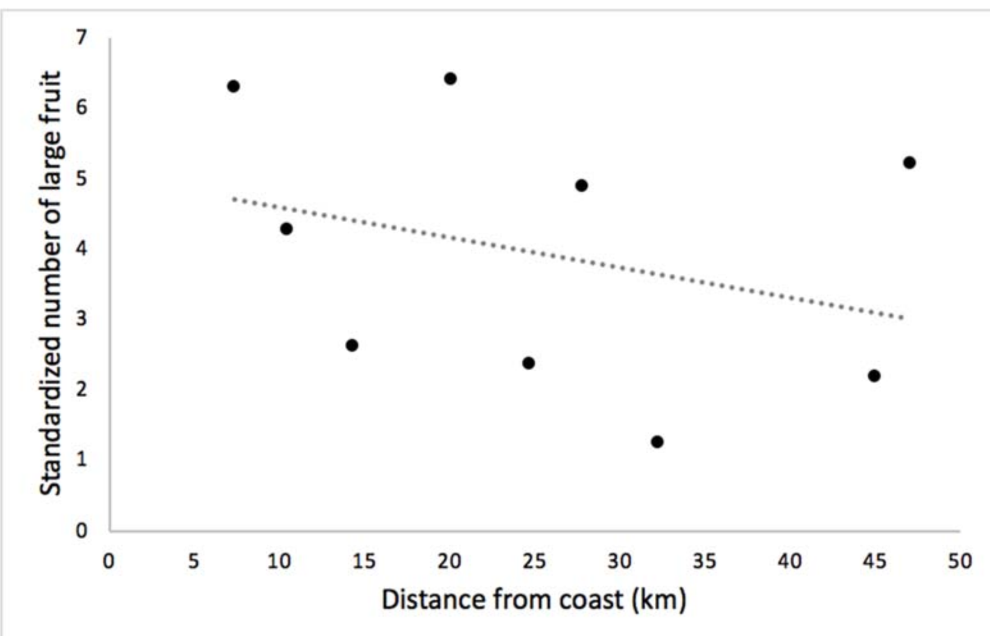

Figure 4 Slight negative trend of the standardized number of large fruit per site population vs. the distance from the coast (km), ($r^2 = 0.1018$, df = 7, and p = 0.4026).

Our analysis also found positive correlations between distance to coast and proportion of living plant matter ($r^2 = 0.2709$, df = 7, p = 0.1508), and between distance and average number of live stems ($r^2 = 0.5185$, df = 7, p = 0.02869). Though the trend in percentage of living plant matter over varying distance from the coast is not statistically significant, we hypothesize that more data points would make this correlation significant, based on the strength of our r^2 value. Therefore, increasing distance from the coast suggests potential increases in both biomass health metrics.

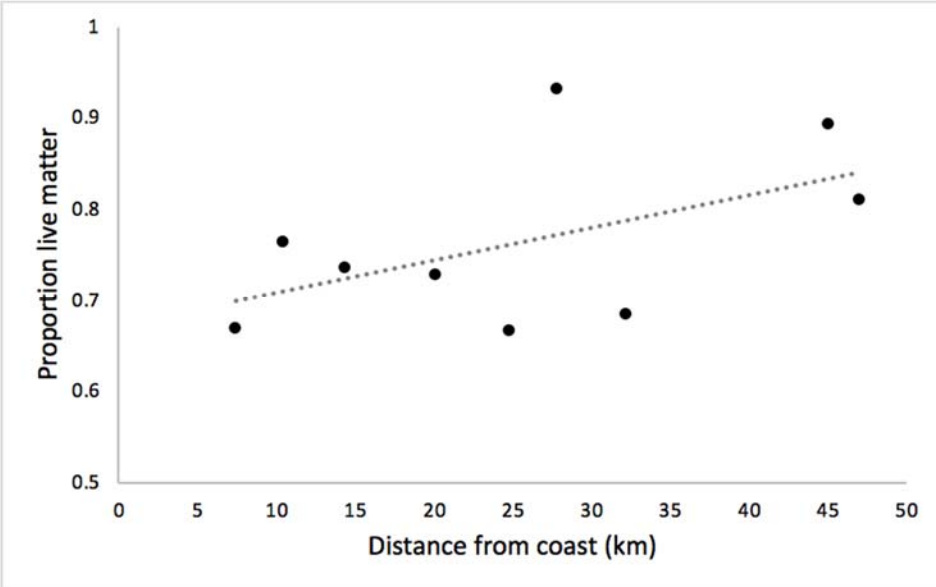

Figure 5 Positive correlation between the proportion of live matter in a hummock averaged per site population (0 = completely dead, 1 = completely alive) and distance from the coast (km), ($r^2 = 0.2709$, df = 7, and $p = 0.1508$).

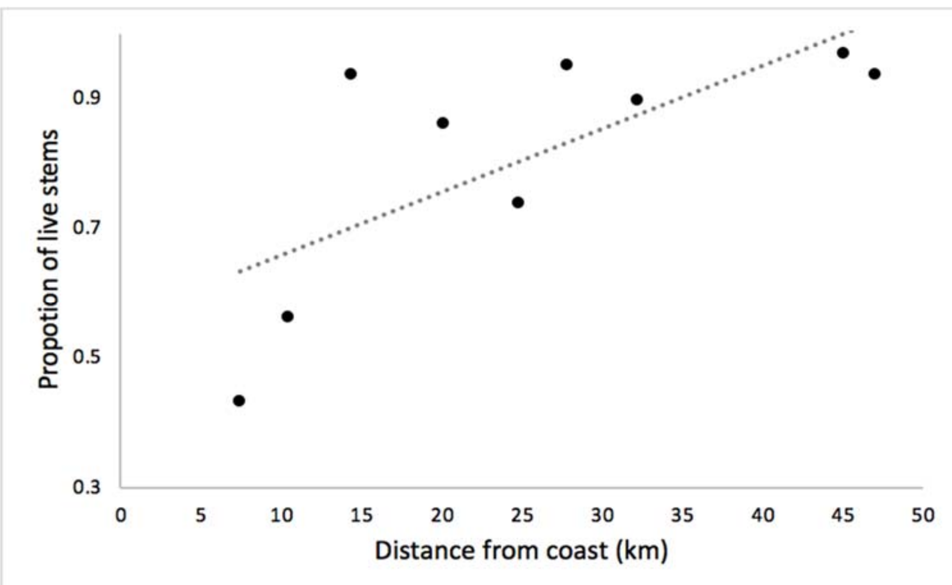

Figure 6 Relationship between the proportion of stems measured with the herbivorometer that were alive and the distance from the coast (km), ($r^2= 0.5185$, df = 7, and $p = 0.02869$).

Impacts of Groundwater Access on Hummock Characteristics

We found a significant downward trend in the density of !nara distribution as the height above the water table increased ($r^2 = 0.718$, df = 7, and $p <0.01$**).** However, height above the water table had no conclusive impact on any of our other metrics when all datapoints were included (Table 1).

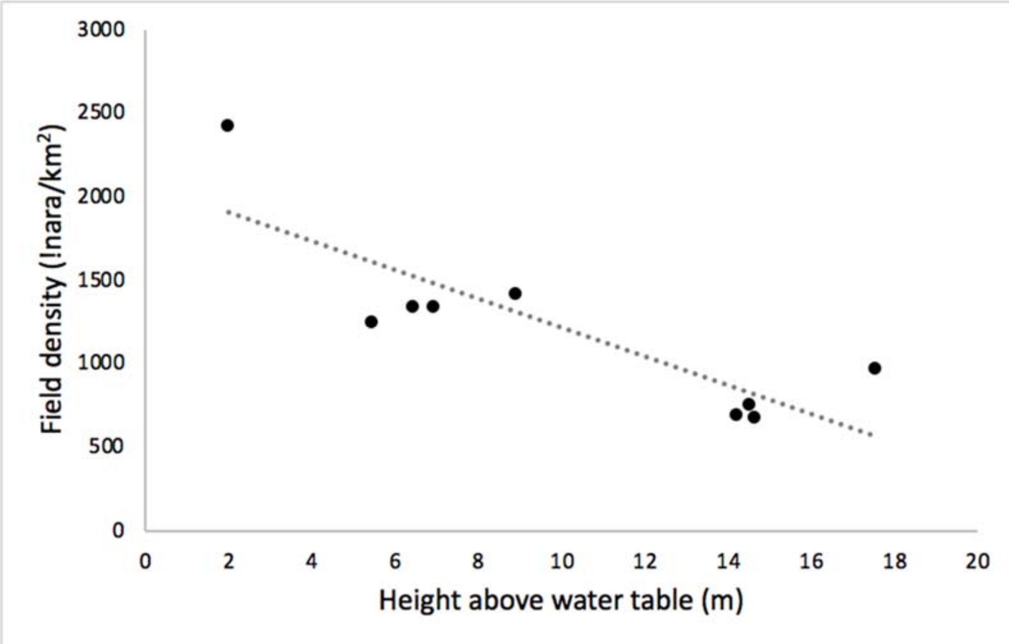

Figure 7 Strong negative relationship between field density and the height above the water table (m), ($r^2 = 0.718$, df = 7, and $p < 0.01$).

Table 1 R^2 Values of Height Above Water Table Correlations (all data included)

Impact On:	**R^2 Value**
Proportion Live Matter	0.00007
Proportion Live Stems	0.0341
Standardized Number of Large Fruit	0.0308
Major-axis Diameter	0.0086
Bush Height	0.0021

When coastal data was excluded, however, there was a slightly stronger, albeit still very weak, relationship between height above water table and standardized number of large fruit in the interdunes.

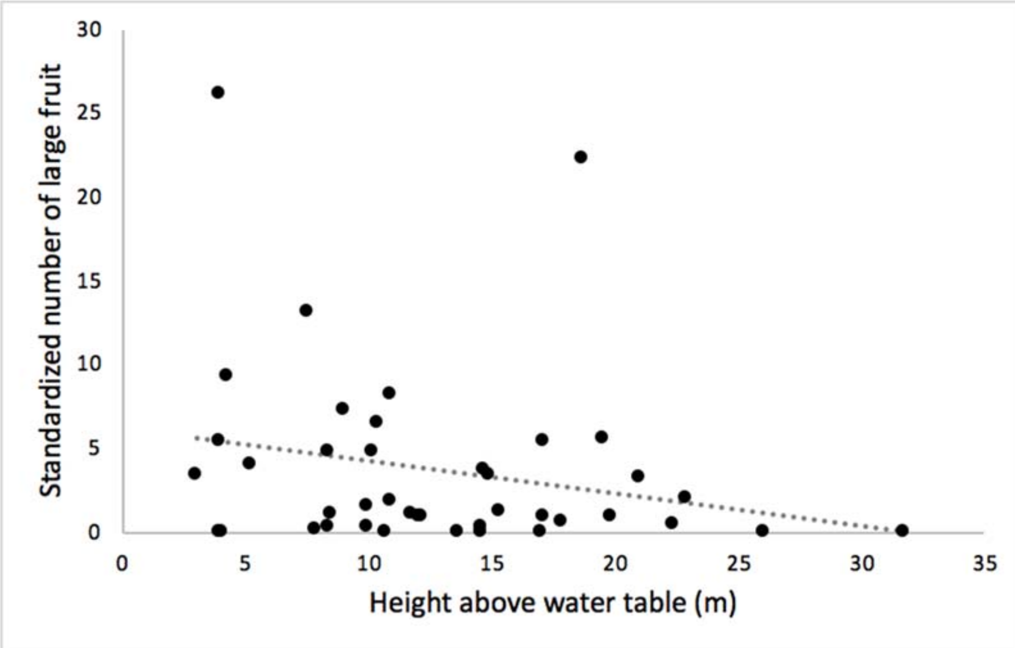

Figure 8 Negative relationship between the standardized number of large fruit and the height above the water table (m) for interdune populations ($r^2 = 0.0507$, df = 39, and p = 0.1569).

When we excluded the delta data, average bush height and proportion of live stems also showed significant correlations. Linear regressions demonstrated that the proportion of live stems trends downward slightly with increasing height above water table, in a nearly significant correlation ($r^2 = 0.052$, df = 66, p = 0.0617), and that average bush height also marginally decreases further from the water table in a statistically significant trend ($r^2 = 0.0609$, df = 66, p = 0.043).

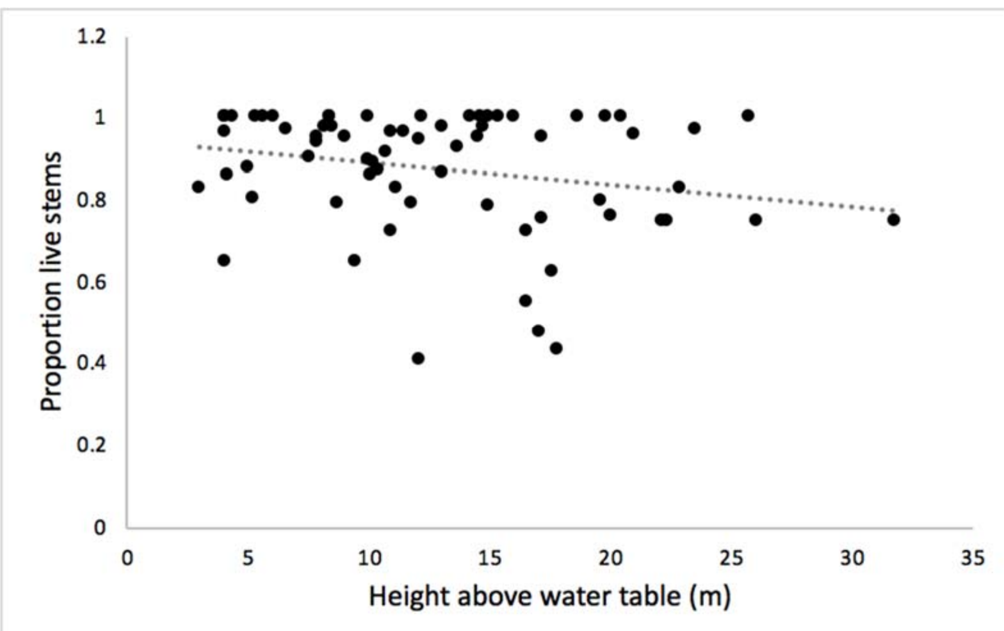

Figure 9 Negative relationship between proportion of live stems measured by the herbivorometer and the height above the water table (m), ($r^2 = 0.052$, df = 66, and p = 0.0617).

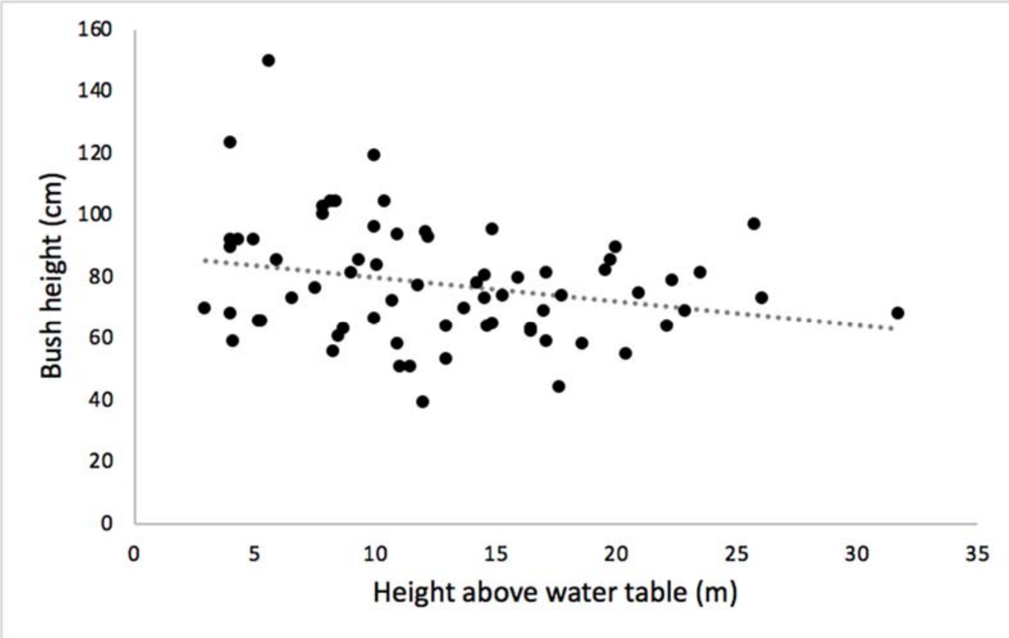

Figure 10 Negative relationship between average bush height of a hummock and the height above the water table (m), (r^2 = 0.0609, df = 66, and p = 0.043).

Impacts of Settlement, Coast, and River Proximity on Herbivory and Fruit Count

Distance from Settlements

Overall, proximity to the nearest human settlement was demonstrably related to herbivory and number of large plants, suggesting that strength of human and herbivore impact does vary with plant accessibility.

Distance from the nearest settlement was particularly strongly correlated with decreasing herbivory levels (r^2 = 0.6171, df = 7, p = 0.0121).

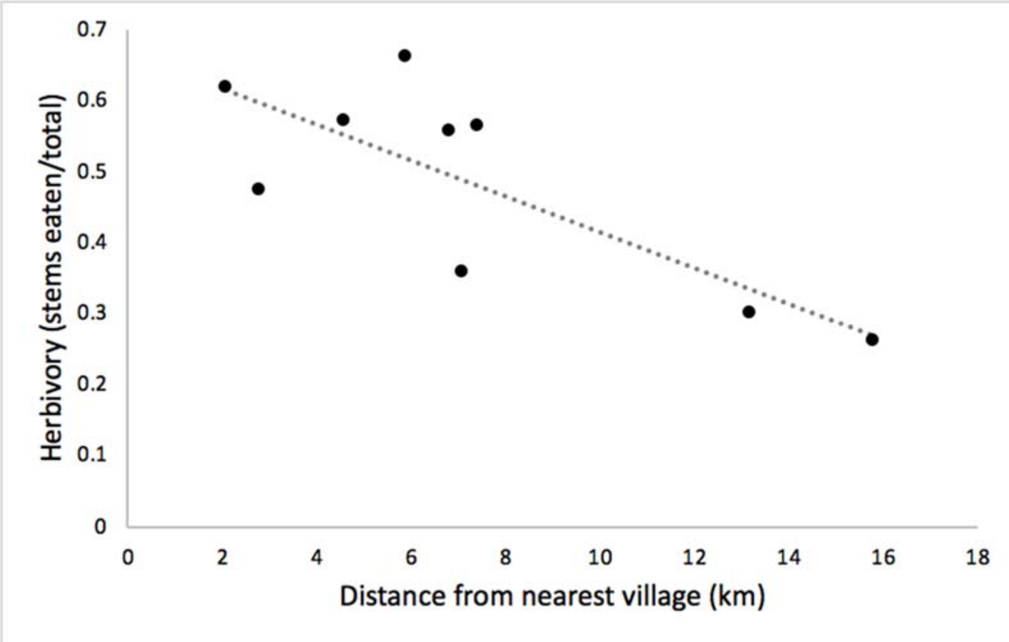

Figure 11 Negative relationship between average herbivory of hummock per site (0 = no herbivory damage, 1 = all stems grazed) and the distance from the nearest village (km), ($r^2 = 0.6171$, df = 7, and p = 0.0121).

It was also weakly and nonsignificantly correlated with the standardized number of large fruits ($r^2 = 0.1428$, df = 77, p = 0.316). When one data point was removed as a potential outlier, this correlation strengthened and became significant ($r^2 = 0.5524$, df = 6, p = 0.0346).

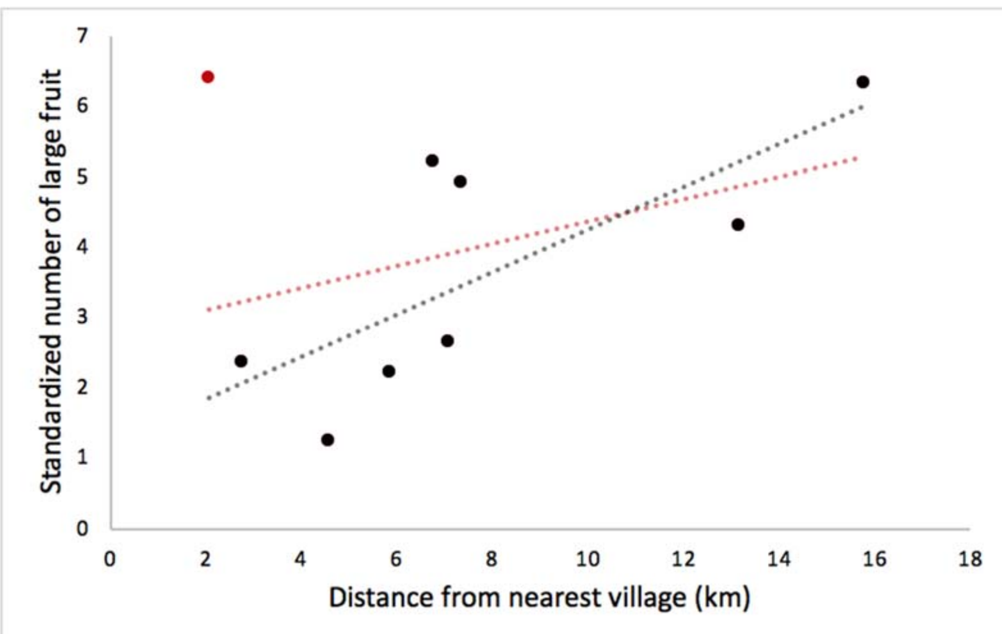

Figure 12 Relationship between the standardized number of large fruits averaged per site and the distance from the nearest village (km). The red data point and linear trendline represent the data with an outlier ($r^2 = 0.1428$, df = 77, and p = 0.316) while the black trendline represents the relationship without the outlier ($r^2 = 0.5524$, df= 6, and p = 0.0346).

Distance from River

Distance from the river did not seem to have a significant impact on any of the variables we tested. How far away !nara population sites were from the Kuiseb did not impact the average amount of livestock dung ($r^2 = 0.017$), wildlife dung ($r^2 = 0.065$) or total dung ($r^2 = 0.0005$) on or within 1m of the hummock. Average herbivory also did not change based on distance from the river ($r^2 = 0.0418$). This analysis focused on interdune populations, and coastal data (plants in the delta) was therefore excluded. Including coastal data would have skewed the regressions by creating a disproportionate amount of points with a distance from the river of essentially zero. Production of fruit was also not impacted by a population's distance from the river ($r^2 = 0.0079$). Because our r^2 values for these relationships are so small, we did not run further regression analyses.

Herbivory and Dung

The following figure demonstrates the correlation between eaten stems and standardized piles of dung. There was a slight increase in the standardized dung piles as the proportion of eaten stems increased, but it was a statistically weak relationship.

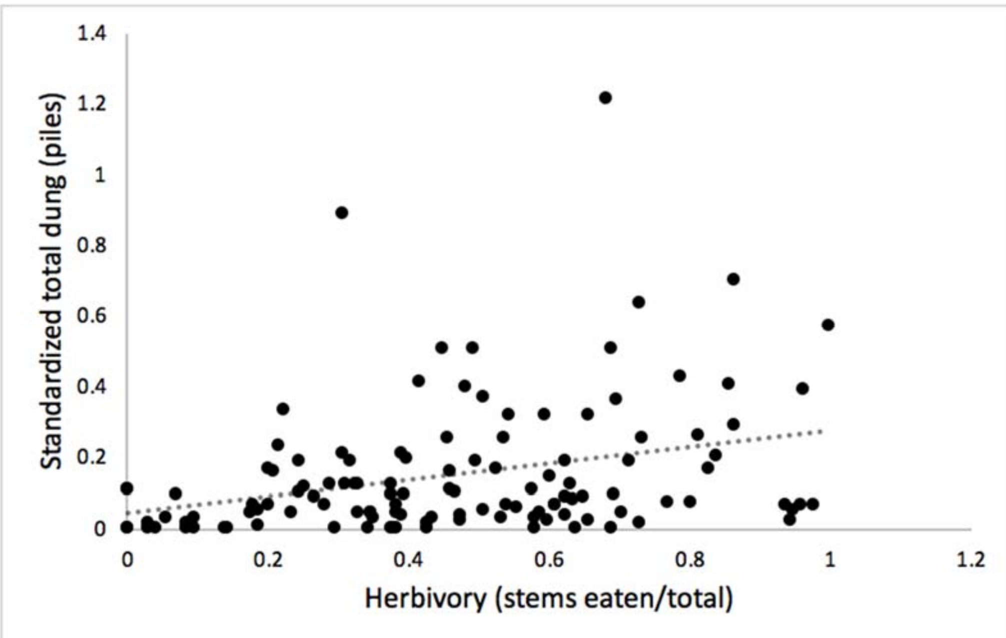

Figure 13 Relationship between stems eaten and standardized total dung ($r^2 = 0.0972$, df = 118, and $p < 0.01$).

Herbivory Composition

Our data shows that donkeys are the primary herbivorous consumers of !nara, as the percentage of donkey dung that we found around the hummocks was equal to the percentage of dung from all other animals combined. We found that wildlife generated 30% of the counted dung, while other livestock, such as cattle and smallstock, comprised the smallest proportion of the total dung piles.

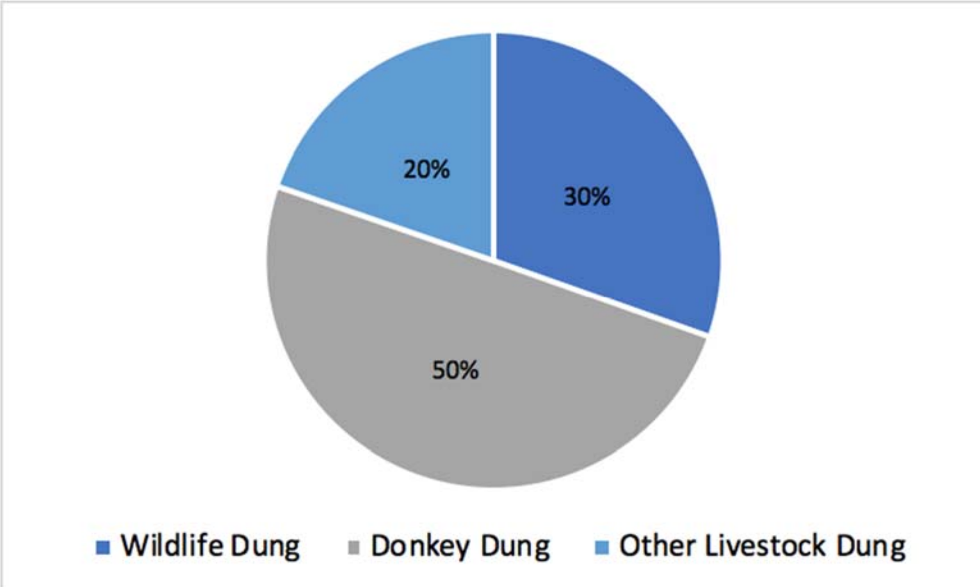

Figure 14 Chart demonstration the composition of dung found around !nara hummocks by wildlife, donkey, and other livestock dung.

Descriptive Comparisons Between Delta and Interdunes

We found a slight difference in sex ratio between !nara in the delta and interdunes, with more male plants found in the interdunes and more females in the delta (Appendix 5.7). However, based on a Fisher's Exact Test, this difference is not statistically significant ($p = 0.3232$). Additionally, there were no substantial differences between major-axis diameter and hummock height (Appendix 5.5, Appendix 5.6). This indicates that the difference in climate conditions (namely groundwater and fog water access) between the two zones may not have a large impact on plant size or structure.

Delta !nara, however, have significantly lower proportions of live stems than plants in the interdunes ($t = -3.761$, $df = 71.66$, $p < 0.001$). They also exhibit significantly shorter average bush heights ($t = -1.746$, $df = 116.93$, $p = 0.042$). The field density in the delta, on the other hand, was substantially higher than the density of fields in the interdunes ($w = 15$, $p = 0.083$).

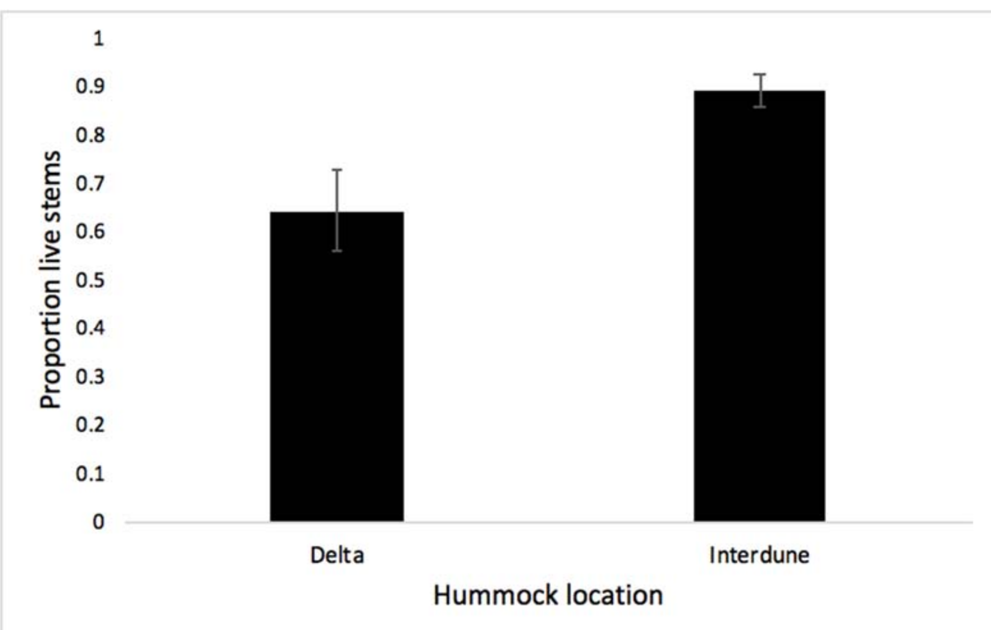

Figure 15 Comparison of live stem proportion in interdunes and live stem proportions in delta area (t = -3.761, df = 71.66, and p <0.001). Error bars indicate 95% confidence intervals.

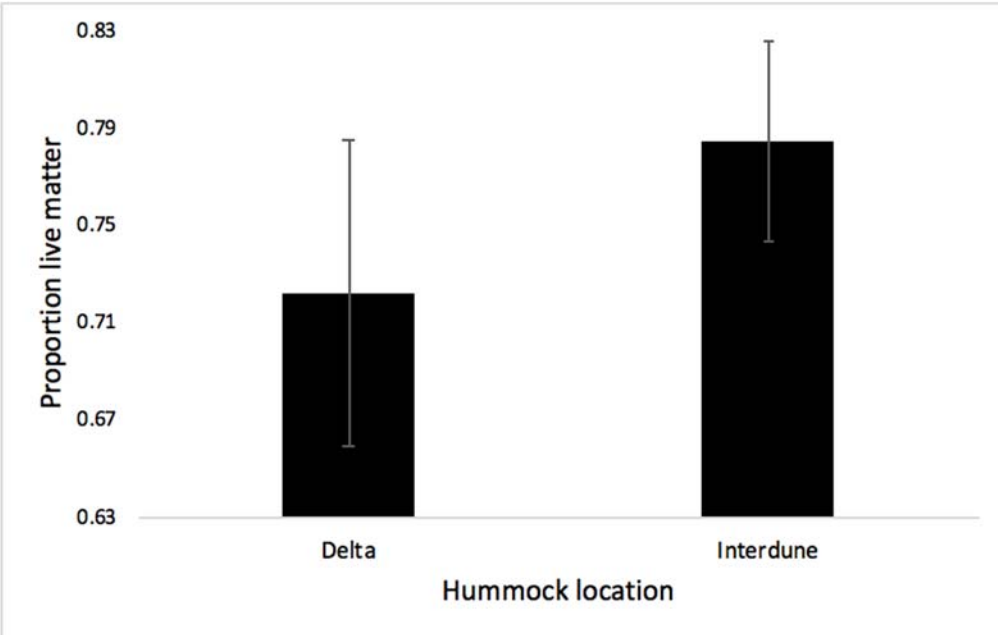

Figure 16 Comparison of live matter proportion in interdunes and delta zones. Error bars indicate 95% confidence intervals.

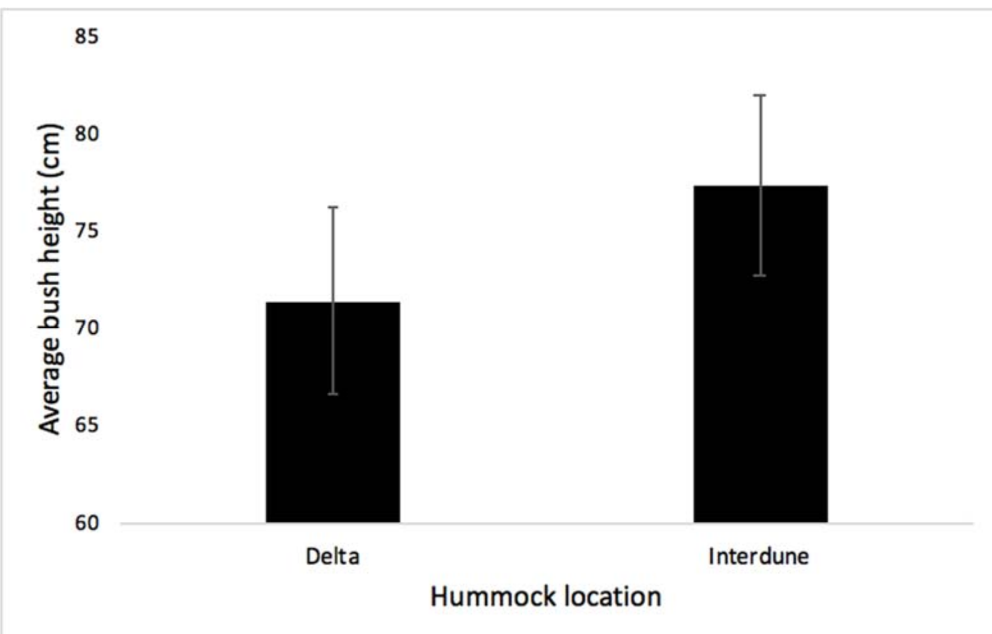

Figure 17 Comparison of average bush height in delta and interdune populations (t = -1.746, df = 116.93, and p = 0.042). Error bars indicate 95% confidence intervals.

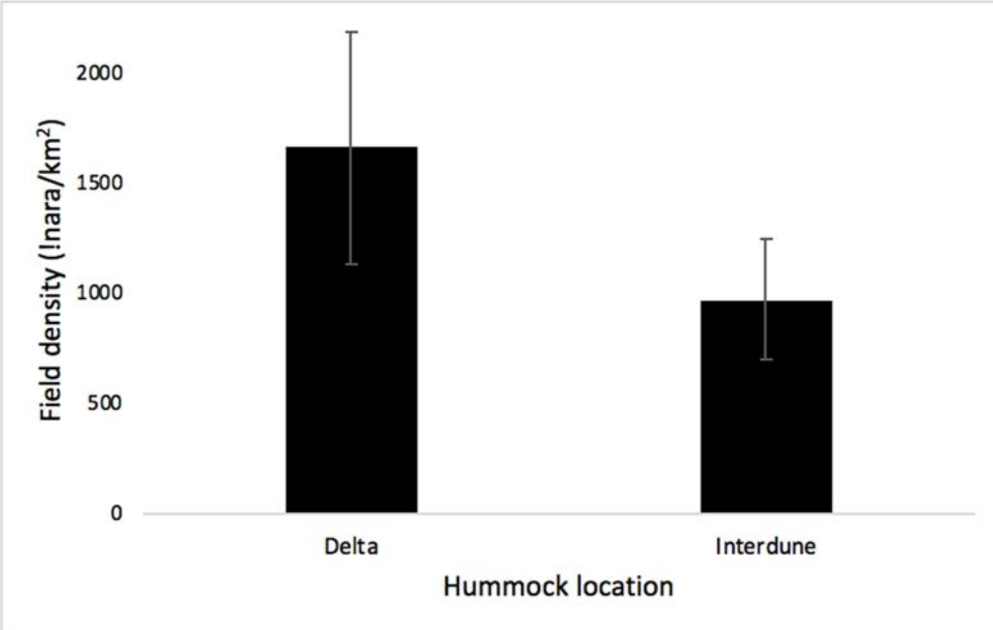

Figure 18 Comparison of average field density in delta and interdune populations (w = 15 and p = 0.083). Error bars indicate 95% confidence intervals.

We also discovered a significant difference in hummock composition between the two sites, confirming that hummocks in the interdunes have far greater proportions of sand to total surface area than those in the delta ($t = 7.6116$, $df = 119.23$, $p < 0.001$, Appendix 5.4).

Discussion

Synthesizing the relationships found in our data revealed that water source availability and village proximity have impacts on !nara health and herbivory intensity, respectively. We also noted that delta and interdune populations tend to behave differently, and therefore separated these populations for some analyses.

Water Source Impacts

Our data demonstrate the importance of water to !nara health, and suggest that different sources may be important for different plant functions. There is a strong positive relationship between the fog gradient data and number of observed juveniles (Figure 2), as well as a weak positive relationship between fog and field density (Figure 1). This suggests that large amounts of fog precipitation at the coast may translate to increased germination, recruitment and establishment rates, resulting in the large concentrations of !naras at the coast (Figure 18). Though the literature generally agrees that !nara require sufficient precipitation to germinate—and the coast experiences little rainfall—the fog in the delta is heavy enough that it often causes a light drizzle, enough to register on rainfall precipitation measuring instruments such as tipping buckets (Gobabeb Research and Training Centre, 2018). It is therefore most likely enough to engender seed germination. Field density is also strongly negatively correlated to height above the water table (Figure 7), indicating that while fog water may be more important for germination, better groundwater access can also facilitate establishment and survival rates.

Groundwater access appears to positively influence plant health in several metrics, particularly in the interdune populations. Height above the water table in these populations exhibited negative relationships with proportion of live stems (Figure 9) and average bush height (Figure 10). By contrast, fog water (represented in these cases by distance from coast; Figure 3) did not appear to positively influence plant health metrics as expected, but rather had negative correlations with proportion live stems and proportion live matter (Append ref; Figure 5; Figure 6). Our categorical comparisons between delta and interdune populations also reveal lower health metrics in the delta populations (Figure 15; Figure 16; Figure 17), despite their substantially higher access to fog water. This likely indicates that other factors have more drastic impacts on plant health.

We argue that increasing human use of groundwater, as described by Victor (2013), is primarily responsible for deteriorating plant health in the delta. The water table in this area is already sensitive to water depletion, due to the low levels of rainfall, and therefore even small increases in abstraction likely have dramatic impacts (Eckhardt *et al.*, 2013). These impacts are already evident in the slightly lower health metrics of delta plants, both through our collected measurements and more anecdotal observations that fields in this region seemed to have more entirely dead or mainly dead !nara hummocks. Given !nara's longevity, we propose that historically higher groundwater and fog water levels enabled past establishment of large and healthy populations in this region, which are now suffering in response to a lower water table than they are adapted to. Evidence suggests that !nara have existed for as long as the Namib dunes themselves, and though they have not been concretely aged, existing populations may be up to 100 years old (Cole *et al.*, 2013; Henschel *et al.*, 2004). Therefore, they likely adapt more slowly to changing climatic conditions than species with shorter generation spans. As a result, reliance on decreasing groundwater may make !nara highly vulnerable in coming years. Climate change induced reductions in fog occurrence would exacerbate this vulnerability and likely reduce already low recruitment rates.

We also observed a decrease in fruit correlated with increasing distance from coast and increasing height above water table (Figure 4; Figure 8). While these correlations are relatively weak, a reduction in fruit production because of reductions in water availability (both of ground and fog water) would be particularly detrimental for the local Topnaar, and is therefore important to consider in depth. From our interview with Mr. Areseb, we learned that most Topnaar go to coastal !nara populations to harvest, and our data collection occurred just before the starting of the harvesting season. These two factors suggest it is unlikely that human harvesting is to blame for lower fruit counts. Rather, we propose that the decrease is again due to lower relative groundwater access, as water is also specifically important for fruit production. Considering these complexities holistically explains why delta plants have lower health metrics but higher fruit counts. We argue that this is not an indication of inconsistency within our data, but rather that !nara plants with limited water may prioritize reproduction over other functions. For interdune plants, the relationship is simpler: they produce fewer fruit as a result of lower groundwater and fog water access. Similarly, Mr. Areseb mentioned that fruits from plants in the interdunes generally have higher ratios of seeds to flesh when compared to plants from the delta and plants in the river. This could be another example of resource prioritization for !nara, as the seeds are the key reproductive agent within the fruit.

Though our relationships for water impacts are at times only borderline significant, we believe the trends they demonstrate are compelling enough to add weight to the existing claims about groundwater's importance for !nara growth, and inspire future research about how fog water is utilized. However, we also want to caution future researchers against placing too much emphasis on groundwater as a singular limiting or enabling distribution factor. A past attempt to examine groundwater's impact on !nara noted that in some areas with a high and easily accessible water table, hypothetically ideal groundwater access, no !nara were growing (Müller, 2004). We argue, therefore, that groundwater is an important factor in !nara growth, but not the only abiotic characteristic that defines its distribution.

While a number of the variables along the inland-to-coast gradient are auto-correlated (e.g. distance to village, herbivory intensity; Appendix 6), and therefore difficult to draw conclusions from, we argue that our health and density metrics demonstrate that access to these two water sources are crucial for !nara phenology.

Herbivory and Harvesting

Our data demonstrate that animal and human impacts—specifically, herbivory and fruit harvesting—are most intense near human settlements.

There is a significant increase in herbivory as distance from the nearest village decreases (Figure 11). We argue that this demonstrates that proximity and accessibility are important for cattle grazing. This finding aligns with Gabriel's (1993) claim that in these harsh environments cattle do not have large grazing areas because they return to their enclosures every night, increasing the amount of grazing in nearby areas, and significantly reducing grazing rates as distance from a village's surrounding area increases.

Our findings for the relationship between the average number of fruits per !nara plant and proximity to villages were inconclusive when all data was included (red line in Figure 12). However, we found a significant positive trend (i.e. average fruit count increasing as distance from nearest village increases) when we excluded a likely outlier (red point in Figure 12; black line in Figure 12). We suspect this point is indeed an outlier because the plant it represents is located near Edoseb, one of the largest Topnaar settlements along the river, and this area has large quantities of plants closer to the settlement itself. As a result, Edoseb harvesters do not range as far to harvest !nara as individuals from other settlements, and therefore this plant was harvested abnormally less than others located similar distances from other settlements. Its fruit count is unusually high, and can therefore be removed from the analysis. Our data therefore indicate that overall, plants near villages are more intensely harvested than more remote individuals.

Our data also demonstrate that dung count, while still an informative metric, is not a good proxy for herbivory (Figure 13). The two variables are not unrelated, but the weak r^2 values indicate high levels of noise in the data, and that dung counts may better characterize the type of animals around hummocks than how much they are grazing. Therefore, we recommend that dung counts are used to inform understanding of interactions between !nara and other species, rather than quantify herbivory. It is worth noting that although we measured dung in the same area defined by the Gobabeb exclosure experiment, we counted all dung regardless of age, while the exclosure experiment removes dung periodically so only new dung is counted; it is possible that this difference in methods could change the relationship between dung counts and herbivory metrics. Dung age is less relevant in determining what types of species visit hummocks, and our findings support the claim that donkeys visit !nara most frequently (Figure 14; Henschel et al, 2004). Additionally, donkey dung constituted such an overwhelming proportion of our total dung count that in this case it does suggest that donkeys also graze on !nara most intensely. However, further research would be needed to validate this claim in light of Figure 13.

Auto-Correlated Variables

Several of our variables have significant correlations (Appendix 6) that do not actually represent relationships. These auto-correlated trends include: field density and distance from village (Appendix

5.3), herbivory and distance from coast (Appendix 5.2), and distance from river and height above water table (Appendix 5.1).

The increase in field density as distance from villages increases and the intensifying herbivory as distance from the coast increases are both likely due to the fact that there are no villages near the coast. Variations in water or other gradient factors likely do not have a significant impact on these auto-correlated trends. We do not think there is an anthropogenic cause for the decrease in density of fields in proximity to villages, though further research could explore this component of human impact.

While we originally attempted to use distance from river as a proxy for height above water table, we later eliminated these comparisons. The two metrics are only weakly correlated; moreover, groundwater does not necessarily follow surface topography. Paleochannels may not necessarily be located directly under the Kuiseb riverbed, and elevation above the groundwater may not increase linearly with distance into the interdunes. Therefore, despite the correlation, we contend that groundwater accessibility should be more carefully measured in the future.

Conclusion and Future Recommendations

Overall, our research indicates that water sources and herbivory impact !nara health and distribution, though the strengths of these impacts and how they interact with each other are unclear. Further research is necessary to determine what variables are indicative of !nara plant health, as the ones we used for this study (proportion of live vegetative mass, live stems, bush height, and standardized fruit count) may not necessarily be the most characteristic metrics. While we successfully determined some of herbivory's geographic distribution, this knowledge gap prevented us from examining how this activity impacts the plant. Our data also suggests that !nara may rely more on groundwater than fog water, and that different water sources may be used for different functions, though to what extent remains unclear.

Our analyses of !nara population health and distribution indicate some preliminary factors that define the plant's bioclimate envelope, and suggest potential avenues for developing this model. Specifically, we recommend future research explores other abiotic factors that may influence !nara distribution, including soil type, temperature, and access to sunlight. Resources and climatic factors frequently fluctuate, which limits experiments that are as short-term as ours; we cannot concretely assert that our relationships were not influenced by temporary variations (Keddy, 2017). Incorporating consideration of these abiotic variables into longitudinal studies would therefore be beneficial for building a foundational model. We also believe it would be beneficial to examine how !nara interacts with other plant species, especially if these interactions are related to competition or symbiosis within a niche. Finally, we noted some evidence of diseases affecting !nara along our transects. Though these occurrences were rare, given !nara's important economic and cultural value we contend that developing an understanding of any viruses before they become widespread is vitally important to protecting local livelihoods.

We hope that our examination of !nara health and distribution can provide a foundation for deeper understanding of the plant, and therefore bolster its resilience to future climate change and anthropogenic disturbances.

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Appendices

Appendix 1

Non-technical summary of principal findings

For our research, we traveled to 9 different sites with lots of !nara. At each site, we walked for a distance of 1-2km and took detailed measurements of multiple !nara bushes. We measured the height of the bush from four directions, as well as how many stems had been eaten by animals and how much of the bush was green, not dried or dead. We also estimated hummock mound heights and length as well as counted how many fruits were on the plant if it was female.

We found that !nara fields closer to villages had more damage from grazing than !nara fields further away from villages. We also think that the herbivore that eats !nara most are donkeys because we found their dung the most on and around hummocks. Additionally, we found that !nara by the coast produced more fruit than !nara in the interdunes. The harvesting of !nara by the coast does not seem to have a significant negative impact on those plants.

Interestingly, we found that there was more dead plant matter on plants by the coast. This was surprising to us because !nara near the coast have the most access to groundwater and fog water. Further research is needed, but we think this could suggest that too much groundwater is being extracted in this area. If plants near the coast continue to look unhealthy, it could be because they can no longer reach the groundwater and are dying because they cannot drink.

With our dung counts, we found that the amount of dung decreased as the distance from the nearest village increased. This suggests that livestock graze on !nara more than wildlife do. Finally, we also found that the amount of fruit on !nara bushes increases as distance from the nearest village also increased. We think the consumption of !nara by people and livestock explains this relationship, but since we did not see any other negative impacts that seemed to come from people, we do not think harvesting is harming !nara.

Appendix 2

Protocol: Materials and Methods

Materials:

- sand ladders (4)
- vehicle capable of driving through sand dunes
- GPS units (2)
- height poles (2)
- herbivorometers (2)
- notebooks (4)
- pens (4)
- water bottles and hats (5 of each)
- all group members (5)
- sunscreen (much)
- positive attitudes (at least 3, but 5 if possible)
- compasses (2)
- satellite phone (from Doug)
- piece of cardboard with 20 holes for cardboard method to find CDE (2)
- boxed lunches (5 or more)

Field data collection:

1. Determining the transects—using Google Earth, find the length of the longest axis through the field. Map two transects that run separate but parallel to each other and the long axis of the field.

2. At the field, go to the coordinate that indicates the beginning of one of the transects. Walk the entire length of the transect, stopping every 200 or 400 steps (depending on transect length).

3. While walking between stops, keep tally of male, female, juvenile, and dead and/or flowerless !nara plants passed within a 10m radius of the transect to estimate density.

4. Every 200 steps, identify the nearest !nara hummock to the transect, and collect the following data:

    a. GPS coordinates of the hummock

    b. Plant sex

    c. Number of fruits larger than a tennis ball (with a subcount of how many fruits are growing in the 4 cardinal directions of the hummock)

    d. Herbivory measure: press the herbivorometer against the plant roughly halfway up and count the number of stems touching it (or within 1cm). Note how many stems have been eaten out of the total. Repeat this process on all 4 sides of the plant (N, E, S, W), and how many stems are dry.

e. Average plant height: using the height pole measure the height of a stem approximately halfway up the plant. Like herbivory, repeat for the other three sides (so there are measurements for N, E, S, W).

f. Dung count: record the amount of dung and what animal it came from for all pieces either on the hummock or within a 1m radius of the base of the hummock. For livestock, record both the number of piles and the number of pellets in each pile.

g. Cover density estimate: hold up the piece of cardboard with 20 holes from a distance such that the top holes line up with the top of the hummock and the bottom holes line up with the base. Count and record how many holes show green live plant, how many show dry dead plant, and how many show sand. Repeat for all four Cardinal directions. Average the four sides together to get a Cover Density Estimate.

5. Repeat these steps until you reach the end of the transect.

Appendix 3

Approximation of Total !Nara Fruit between Gobabeb and the Kuiseb Delta

Using imagery from Bing Satellite in QGIS, we approximated !nara densities for delta populations and interdune populations separately. Five delta sites and six interdune sites were selected for this investigation. We counted all of the !nara within a plot of just over one third of a square kilometer in area at each of these sites, and then averaged the densities calculated with these figures. This is a crude approximation method because densities were highly variable, with delta densities ranging from 340 !nara/km^2 to 778 !nara/km^2 and interdune densities ranging from 78 !nara/km^2 to 366 !nara/km^2. Additionally, determining what qualifies as a !nara from the satellite imagery is quite subjective because there are places were hummocks border each other and oftentimes it is not easy to distinguish between !nara and other vegetation. Using estimates of land area containing !nara populations for the delta and interdune stretches between Gobabeb and Rooibank obtained from Google Earth, we estimated the total delta !nara population to be 7,271 !nara and the total interdune population to be 3,840 !nara. We then used sex ratio data and average fruit counts to approximate the number of females in each area and the total fruit count for the region: 1,878 interdune females cumulatively bearing 51,118 fruits and 3,723 delta females cumulatively bearing 133,001 fruits, for a grand total of 184,119 !nara melons in the region. This is a very coarse approximation method, but we believe this is the first attempt to quantify the !nara fruit productivity of the region and could be a good starting point for future estimates. When we spoke to Mr. Areseb, we had hoped to obtain a figure for the portion of !nara which is utilized so as to calculate a total yearly !nara harvest, but he did not think any guess he could make would be accurate enough to be useful—this gap in information could be another good area for further investigation.

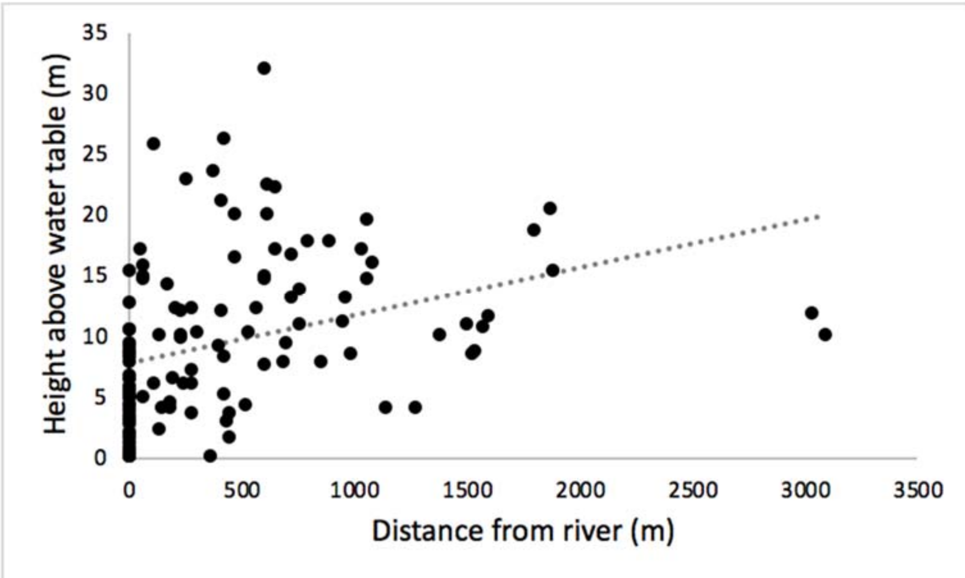
Appendix 4

Map of Major !Nara Populations between Gobabeb and the Kuiseb Delta

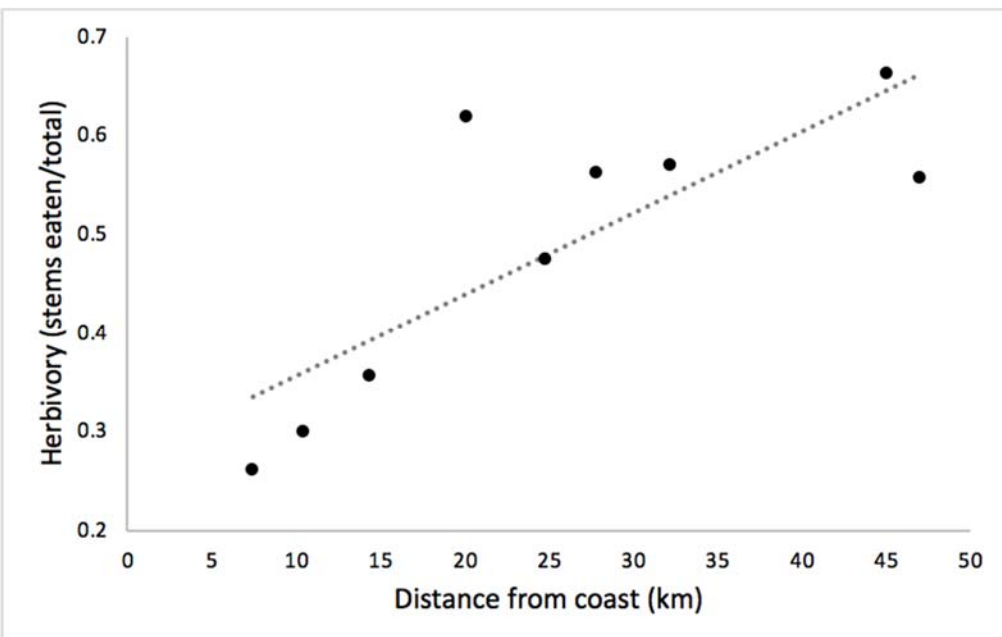
Appendix 4.1 Major !nara populations between Gobabeb and Kuiseb Delta (Source: Google Earth Pro).

Appendix 5

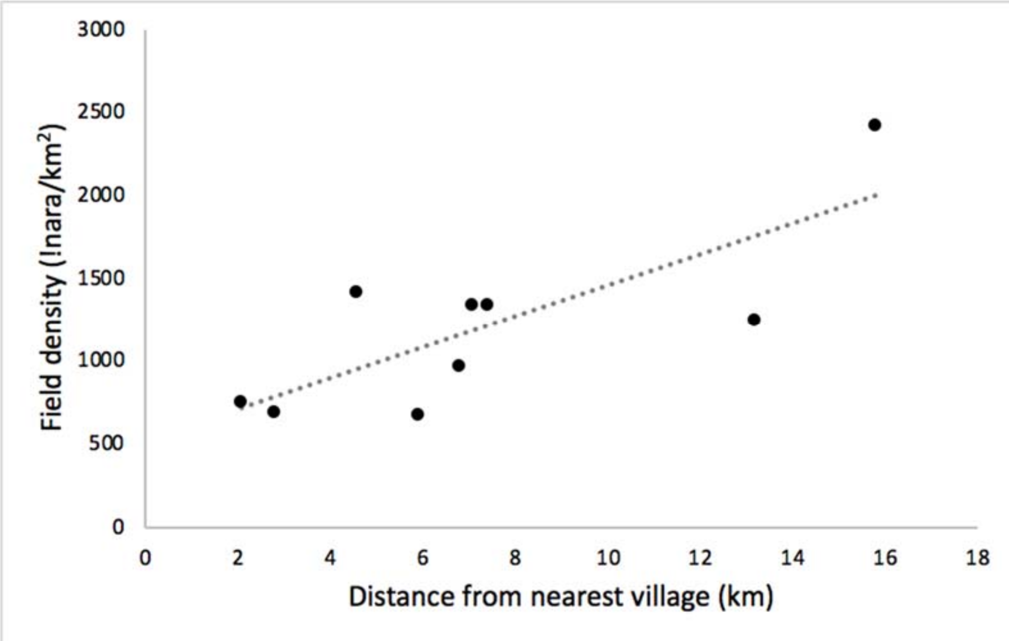
Additional Graphs



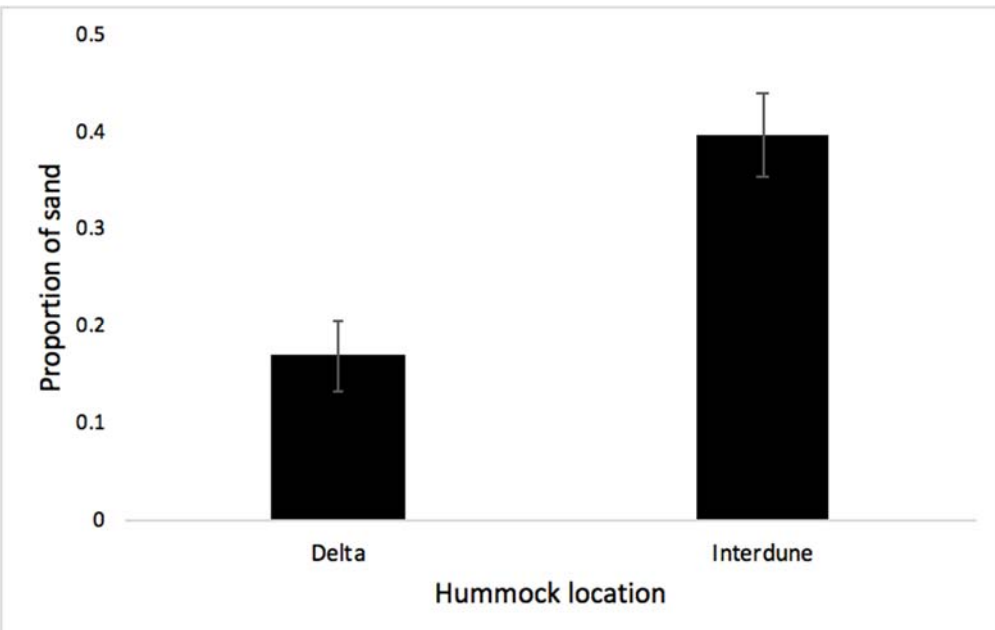
Appendix 5.1 Relationship between distance from river (m) and height above water table (m), ($r^2 = 0.1231$, df = 120, and $p < 0.0001$).



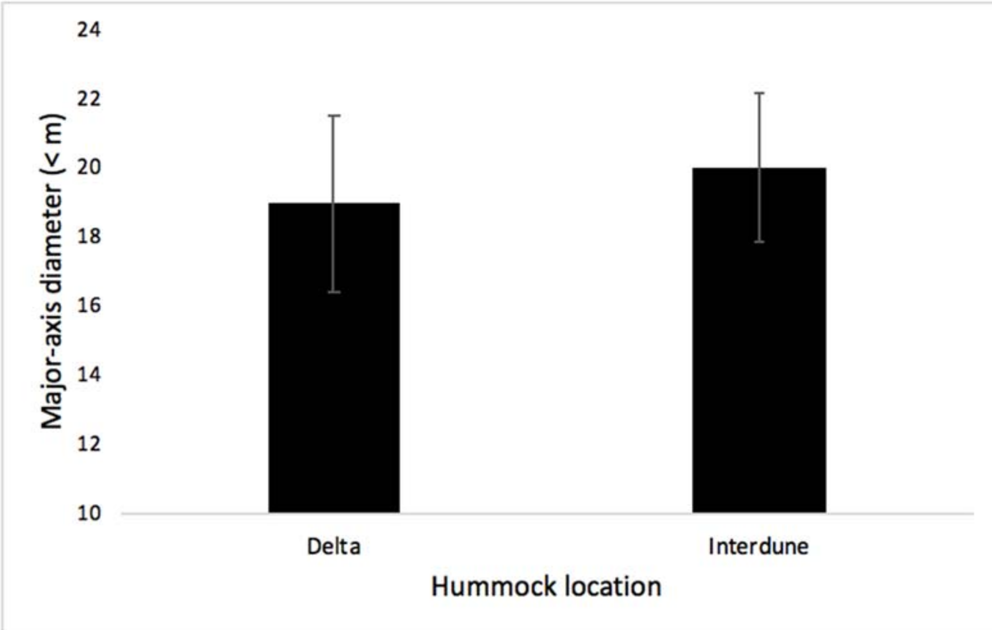
Appendix 5.2 Positive relationship between distance from coast (km) and herbivory (0 = no herbivory damage, 1 = all stems grazed), ($r^2 = 0.6522$, df = 7, and $p < 0.01$). This relationship is potentially due to the lower concentration of settlements in the delta area.



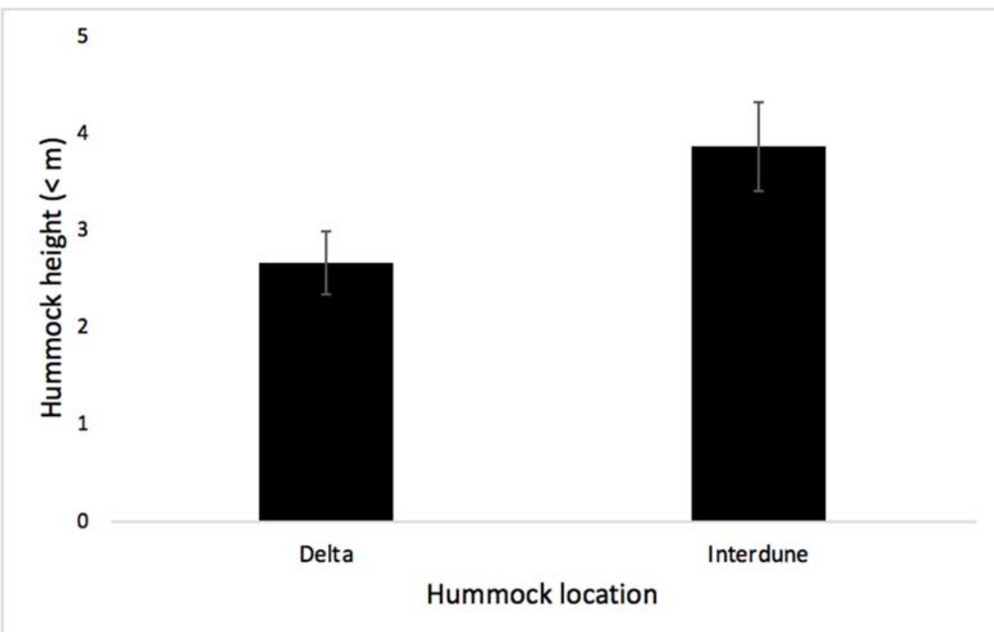
Appendix 5.3 Strong positive relationship between field density and the distance from the nearest village (km), ($r^2 = 0.6159$, df = 7, and p = 0.01224).



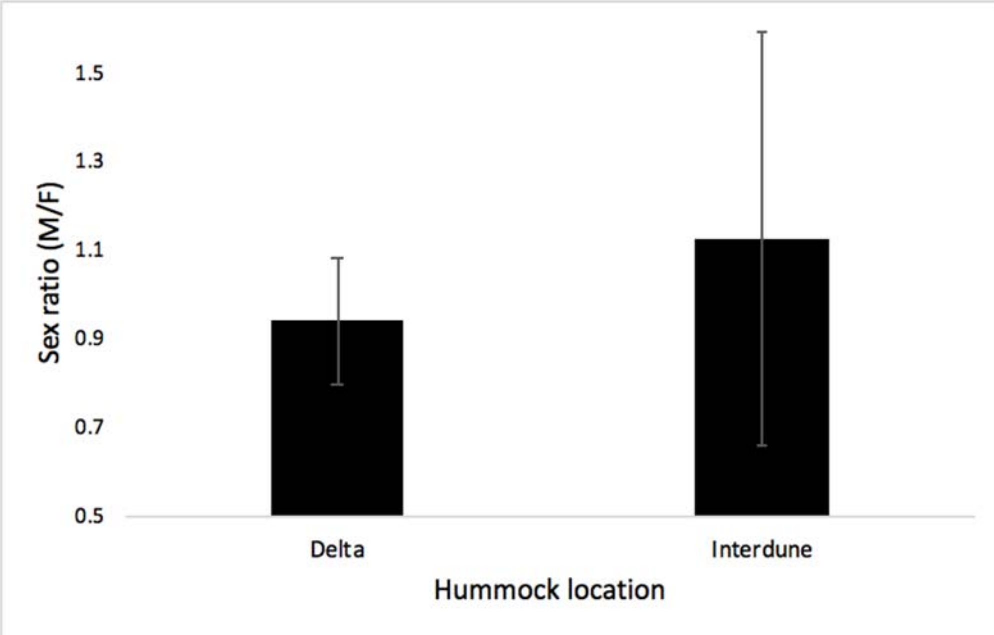
Appendix 5.4 Comparison between amount of sand on hummock averaged for interdune !nara (0 = no sand coverage, 1 = completely covered in sand) and coastal !nara (t = 7.6116, df = 119.23, p = <0.001). Error bars indicate 95% confidence intervals.



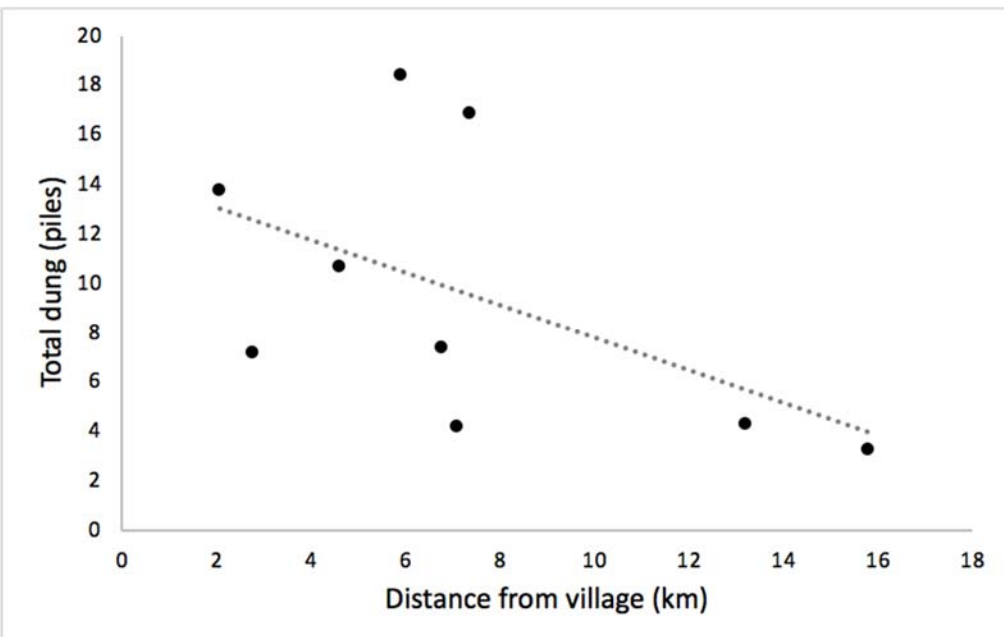
Appendix 5.5 Difference in average major-axis diameter of hummocks in the delta vs. in the interdune valleys. This difference (around 1m) is too small to draw any conclusions from, as we estimated diameter in intervals of 5m. Error bars indicate 95% confidence intervals.



Appendix 5.6 Difference in average height of hummocks in the delta vs. in the interdune valleys. This difference (around 1.5m) is too small to draw any conclusions from, as we estimated height in intervals of 2m. Error bars indicate 95% confidence intervals.



Appendix 5.7 The sex ratio of male/female plants of sites in the delta vs. sites in the interdunes ($p = 0.3232$). The ratio leans towards female in the delta populations and male in the interdune populations. Error bars indicate 95% confidence intervals.



Appendix 5.8 Negative relationship between distance from village (km) and total dung (piles), ($r^2 = 0.2911$, df = 7, and $p = 0.1338$).

Appendix 6

Correlation Matrices

6.1 All population r^2 values

- Green: $r^2 > 0.5$
- Yellow: $0.5 > r^2 > 0.25$

All populations r^2 values	Altitude	Field density	Distance along gradient	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	1	0.29736823	0.947709259	0.853902	0.585688483	0.264906715	0.548153	0.113310047	0.48362177	0.719608	0.098713	0.223339541	0.230749
Field density	0.297368	1	0.172717542	0.15174	0.666993304	0.092609093	0.328579	0.093647667	0.25415664	0.420426	0.383833	0.492170734	0.065064
Distance along gradient	0.947709	0.17271754	1	0.933746	0.517998922	0.226181258	0.353647	0.049039415	0.32235346	0.60888	0.112655	0.11484086	0.285356
Fog	0.853902	0.15174001	0.93374574	1	0.521103934	0.230533021	0.310864	0.021340733	0.26294364	0.450795	0.167242	0.038988891	0.252741
Height above water table	0.585689	0.66699334	0.517998894	0.521104	1	0.038885194	0.343613	0.015411742	0.13931377	0.578546	0.30326	0.457800184	0.000412
Proportion of live matter	0.264907	0.09260908	0.226181282	0.230533	0.038885194	1	0.295948	0.003709721	0.40386864	0.227912	0.018643	9.11379E-05	0.039125
Live stems	0.548153	0.32857865	0.353647276	0.310863	0.343612936	0.295947795	1	0.150915596	0.76965406	0.631085	0.006504	0.399408482	0.016523
Standardized large fruit	0.11331	0.09364769	0.049039394	0.021341	0.015411743	0.003709721	0.150916	1	0.35489578	0.043206	3.13E-06	0.06598426	0.111794
Bush height	0.483622	0.25415664	0.322353462	0.262944	0.139313786	0.403868626	0.769654	0.354895789	1	0.500978	0.033928	0.194254991	0.028403
Herbivory	0.719608	0.42042593	0.608879795	0.450795	0.578546466	0.22791181	0.631085	0.043206296	0.50097843	1	0.088038	0.623522012	0.005837
Diameter	0.098713	0.38383303	0.112654612	0.167242	0.303260192	0.018642658	0.006504	3.12521E-06	0.03392772	0.088038	1	0.030842712	0.165947
Hummock height	0.22334	0.49217072	0.114840874	0.038989	0.457800185	9.11379E-05	0.399408	0.06598426	0.19425501	0.623522	0.030843	1	0.069071
Juveniles	0.230749	0.06506382	0.285355858	0.252741	0.000412481	0.039124585	0.016523	0.111794133	0.02840317	0.005837	0.165947	0.069070852	1

6.2 All population p values

- Green: $p < 0.05$

All populations p values	Altitude	Field density	Distance along gradient	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	0.00E+00	0.128890763	9.72E-06	3.69E-04	0.016249059	0.15624843	0.022529	0.3757475	0.03752642	0.003847	0.410285	0.19891598	0.190596
Field density	1.29E-01	0	2.66E-01	3.00E-01	0.007220885	0.42592216	0.106634	0.4232072	0.16639103	0.058902	0.07517	0.03518661	0.507719
Distance along gradient	9.72E-06	0.265945809	0.00E+00	2.24E-05	0.028802803	0.19568513	0.091217	0.56690048	0.11078768	0.013101	0.377219	0.37233698	0.138475
Fog	3.69E-04	0.300058851	2.24E-05	0.00E+00	0.028100747	0.19083324	0.118819	0.70764057	0.15805768	0.047675	0.274438	0.61058714	0.16777
Height above water table	1.62E-02	0.007220885	2.88E-02	2.81E-02	0	0.61107183	0.097145	0.75032144	0.32246064	0.017325	0.124406	0.04534561	0.95864
Proportion of live matter	1.56E-01	0.425922162	1.96E-01	1.91E-01	0.611071831	0	0.129993	0.87630324	0.06586397	0.193742	0.726132	0.98055327	0.609954
Live stems	2.25E-02	0.106634065	9.12E-02	1.19E-01	0.097145026	0.12999281	0	0.30149112	0.00188592	0.010541	0.836597	0.06784937	0.741714
Standardized large fruit	3.76E-01	0.423207202	5.67E-01	7.08E-01	0.750321437	0.87630324	0.301491	0	0.09050093	0.5915	0.996399	0.50462751	0.379162
Bush height	3.75E-02	0.166391027	1.11E-01	1.58E-01	0.322460635	0.06586397	0.001886	0.09050093	0	0.032897	0.635209	0.23506586	0.664691
Herbivory	3.85E-03	0.058901509	1.31E-02	4.77E-02	0.017325479	0.19374195	0.010541	0.59150013	0.03289709	0	0.438151	0.01136633	0.845117
Diameter	4.10E-01	0.075170098	3.77E-01	2.74E-01	0.124405888	0.72613192	0.836597	0.99639862	0.63520935	0.438151	0	0.65129637	0.276486
Hummock height	1.99E-01	0.035186609	3.72E-01	6.11E-01	0.045345606	0.98055327	0.067849	0.50462751	0.23506586	0.011366	0.651296	0	0.494468
Juveniles	1.91E-01	0.507719361	1.38E-01	1.68E-01	0.958639774	0.60995406	0.741714	0.37916225	0.66469143	0.845117	0.276486	0.49446819	0

6.3 Interdune population r^2 values

- Green: $r^2 > 0.5$
- Yellow: $0.5 > r^2 > 0.25$

Interdune populations r^2 values	Altitude	Field density	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	1	0.00477725	0.906545	0.070260377	0.235252743	0.37146	0.086503692	0.3485546	0.037655	0.133444	0.694351475	0.528718
Field density	0.004777	1	0.001278	0.613836366	0.014113084	0.129488	0.016519298	0.1777827	0.019817	0.205227	0.147471552	0.062165
Fog	0.906545	0.001277699	1	0.2277054	0.162977243	0.32992	0.004991582	0.1657899	0.043473	0.349537	0.573479208	0.291091
Height above water table	0.07026	0.613836366	0.227705	1	0.035737823	0.029318	0.054570614	0.1729414	0.005557	0.733866	0.004683891	0.0236
Proportion live matter	0.235253	0.014113072	0.162977	0.035737823	1	0.633181	0.073158981	0.3770486	0.230109	0.039379	0.337929222	0.101133
Live stems	0.37146	0.129488287	0.32992	0.029317812	0.633180822	1	0.019600997	0.6796123	0.506143	0.017758	0.281844128	0.033536
Standardized large fruit	0.086504	0.016519298	0.004992	0.054570614	0.073158998	0.019601	1	0.1687173	0.019247	0.036309	0.012085051	0.330959
Bush height	0.348555	0.177782625	0.16579	0.172941369	0.37704856	0.679612	0.168717312	1	0.373866	0.016849	0.204205648	0.174779
Herbivory	0.037655	0.019817145	0.043473	0.005557442	0.2301095	0.506143	0.019247334	0.3738663	1	0.108297	0.023818885	0.122324
Diameter	0.133444	0.205227447	0.349537	0.73386555	0.039379029	0.017758	0.036309047	0.0168494	0.108297	1	0.001822621	0.063308
Hummock height	0.694351	0.147471552	0.573479	0.004683891	0.337929222	0.281844	0.012085051	0.2042057	0.023819	0.001823	1	0.691207
Juveniles	0.528718	0.062165329	0.291091	0.023599971	0.101132904	0.033536	0.330958941	0.1747788	0.122324	0.063308	0.691207054	1

6.4 Interdune population p values

- Green: $p < 0.05$

Interdune populations p values	Altitude	Field density	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	0	0.89648862	0.003383	0.61171173	0.32950921	0.198985	0.5715484	0.21731302	0.71258	0.476423	0.03937742	0.101528
Field density	0.896489	0	0.946405	0.06524772	0.82264063	0.483531	0.8082705	0.40501623	0.790235	0.366956	0.45228566	0.633755
Fog	0.003383	0.94640546	0	0.33855148	0.42734073	0.233171	0.8941996	0.42299299	0.69178	0.216501	0.0812172	0.269234
Height above water table	0.611712	0.06524772	0.338551	0	0.71981127	0.745673	0.6559686	0.41216659	0.888385	0.029347	0.89750184	0.771379
Proportion live matter	0.329509	0.82264063	0.427341	0.71981127	0	0.05833	0.6041752	0.1946978	0.335646	0.706245	0.22624677	0.53906
Live stems	0.198985	0.48353062	0.233171	0.74567329	0.05832953	0	0.7913668	0.04355242	0.112889	0.801295	0.27847919	0.728377
Standardized large fruit	0.571548	0.80827046	0.8942	0.65596863	0.60417523	0.791367	0	0.4185223	0.793233	0.717635	0.83576623	0.232263
Bush height	0.217313	0.40501623	0.422993	0.41216659	0.1946978	0.043552	0.4185223	0	0.19713	0.806386	0.36830258	0.409436
Herbivory	0.71258	0.79023479	0.69178	0.88838477	0.3356455	0.112889	0.793233	0.19713039	0	0.524192	0.77033751	0.496769
Diameter	0.476423	0.36695556	0.216501	0.02934716	0.70624495	0.801295	0.7176353	0.80638595	0.524192	0	0.93600064	0.630548
Hummock height	0.039377	0.45228566	0.081217	0.89750184	0.22624677	0.278479	0.8357662	0.36830258	0.770338	0.936001	0	0.040248
Juveniles	0.101528	0.6337552	0.269234	0.77137851	0.5390598	0.728377	0.2322633	0.40943612	0.496769	0.630548	0.0402479	0

6.5 Delta population r^2 values

- Green: $r^2 > 0.5$

- Yellow: $0.5 > r^2 > 0.25$

Delta populations r^2 values	Altitude	Field density	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	1	0.00477725	0.906545	0.070260377	0.235252743	0.37146	0.086503692	0.3485546	0.037655	0.133444	0.694351475	0.528718
Field density	0.004777	1	0.001278	0.613836366	0.014113084	0.129488	0.016519298	0.1777827	0.019817	0.205227	0.147471552	0.062165
Fog	0.906545	0.0012777	1	0.2277054	0.162977243	0.32992	0.004991582	0.1657899	0.043473	0.349537	0.573479208	0.291091
Height above water table	0.07026	0.61383637	0.227705	1	0.035737823	0.029318	0.054570614	0.1729414	0.005557	0.733866	0.004683891	0.0236
Proportion of live matter	0.235253	0.01411307	0.162977	0.035737823	1	0.633181	0.073158981	0.3770486	0.230109	0.039379	0.337929222	0.101133
Live stems	0.37146	0.12948829	0.32992	0.029317812	0.633180822	1	0.019600997	0.6796123	0.506143	0.017758	0.281844128	0.033536
Standardized large fruit	0.086504	0.0165193	0.004992	0.054570614	0.073158998	0.019601	1	0.1687173	0.019247	0.036309	0.012085051	0.330959
Bush height	0.348555	0.17778263	0.16579	0.172941369	0.37704856	0.679612	0.168717312	1	0.373866	0.016849	0.204205648	0.174779
Herbivory	0.037655	0.01981714	0.043473	0.005557442	0.2301095	0.506143	0.019247334	0.3738663	1	0.108297	0.023818885	0.122324
Diameter	0.133444	0.20522745	0.349537	0.73386555	0.039379029	0.017758	0.036309047	0.0168494	0.108297	1	0.001822621	0.063308
Hummock height	0.694351	0.14747155	0.573479	0.004683891	0.337929222	0.281844	0.012085051	0.2042057	0.023819	0.001823	1	0.691207
Juveniles	0.528718	0.06216533	0.291091	0.023599971	0.101132904	0.033536	0.330958941	0.1747788	0.122324	0.063308	0.691207054	1

6.6 Delta population p values

- Green: $p < 0.05$

Delta populations p values	Altitude	Field density	Fog	Height above water table	Proportion live matter	Live stems	Standardized large fruit	Bush height	Herbivory	Diameter	Hummock height	Juveniles
Altitude	0	0.89648862	0.003383	0.61171173	0.32950921	0.198985	0.5715484	0.217313	0.71258	0.476423	0.03937742	0.101528
Field density	0.89648862	0	0.946405	0.06524772	0.82264063	0.483531	0.8082705	0.4050162	0.790235	0.366956	0.45228566	0.633755
Fog	0.00338291	0.94640546	0	0.33855148	0.42734073	0.233171	0.8941996	0.422993	0.69178	0.216501	0.0812172	0.269234
Height above water table	0.61171173	0.06524772	0.338551	0	0.71981127	0.745673	0.6559686	0.4121666	0.888385	0.029347	0.89750184	0.771379
Proportion live matter	0.32950921	0.82264063	0.427341	0.71981127	0	0.05833	0.6041752	0.1946978	0.335646	0.706245	0.22624677	0.53906
Live stems	0.19898478	0.48353062	0.233171	0.74567329	0.05832953	0	0.7913668	0.0435524	0.112889	0.801295	0.27847919	0.728377
Standardized large fruit	0.57154837	0.80827046	0.8942	0.65596863	0.60417523	0.791367	0	0.4185223	0.793233	0.717635	0.83576623	0.232263
Bush height	0.21731302	0.40501623	0.422993	0.41216659	0.1946978	0.043552	0.4185223	0	0.19713	0.806386	0.36830258	0.409436
Herbivory	0.71258039	0.79023479	0.69178	0.88838477	0.3356455	0.112889	0.793233	0.1971304	0	0.524192	0.77033751	0.496769
Diameter	0.47642325	0.36695556	0.216501	0.02934716	0.70624495	0.801295	0.7176353	0.806386	0.524192	0	0.93600064	0.630548
Hummock height	0.03937742	0.45228566	0.081217	0.89750184	0.22624677	0.278479	0.8357662	0.3683026	0.770338	0.936001	0	0.040248
Juveniles	0.10152827	0.6337552	0.269234	0.77137851	0.5390598	0.728377	0.2322633	0.4094361	0.496769	0.630548	0.0402479	0

A Holistic Assessment of Three Factors Limiting !Nara Fruit Productivity: Water, Herbivory, and Biodiversity

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Abstract

Acanthosicyos horridus (!Nara) plays a critical role in the Namib Desert ecosystem and is socio-economically important to the local Topnaar community. Our research assessed three potential factors that might influence female !Nara hummock fruit productivity: water availability, herbivory, and biodiversity. We hypothesized that higher water availability would increase !Nara fruit productivity, so we compared fog concentrations and water table levels with !Nara fruit counts. We also hypothesized that fruit productivity would decrease with increasing herbivory pressure and compared vertebrate diversity and fruit counts of enclosed and open hummocks. Additionally, we used island biogeographic considerations to hypothesize that biodiversity would decrease with increasing distance from the Kuiseb River but increase with greater hummock area. We utilized arthropod traps and track transects to measure arthropod and vertebrate diversity, comparing our results with the hummock distance from the river and area. We then conceptualized arthropod diversity as a proxy for pollinator diversity to understand how pollinators may play a role in !Nara fruit productivity, and analyzed the relationships between arthropod diversity and !Nara fruit/aborted bud counts. We found that water availability was indeed a limiting factor on !Nara fruit productivity, but that herbivory did not limit small fruit production within !Nara hummocks. Finally, we found !Nara hummocks to have greater vertebrate and arthropod diversity than the alternative microhabitats in Station Valley.

Introduction

Productivity is a useful measure for ecosystem functioning that is determined by both biotic and abiotic factors. *Acanthosicyos horridus*, known locally in the Kuiseb Delta region as !Nara, is a dioecious cucurbit endemic to the Namib Desert which gathers sand to build elevated “hummock” structures, photosynthesizes through its modified spines and stems, and produces nutritious melons. The flower and fruit productivity of !Nara affects not only the various arthropods, reptiles, and small mammals that rely on the ecosystem services the plant provides, but also the Topnaar community who reside in the Erongo region of central Namibia and harvest !Nara melons for food, fodder, and medicinal purposes (Henschel et al., 2004). These !Nara melons are an important natural resource with high cultural and economic value to the Topnaar people, and the plant has been identified as a keystone species because they provide shade and food for a plethora of organisms. Because of the unique role !Nara plays in the socio-ecological system of the Kuiseb Delta region, our research project aims to assess three factors that may influence !Nara fruit productivity--water availability, herbivory, and biodiversity.

In hyper-arid desert ecosystems, water is often a limiting factor on plant productivity.
Water availability is thought to influence the capacity and internal storage capabilities of !Nara because fruit production involves a cost-benefit analysis on the part of the plant (Strohbach and Cole, 2005). !Nara plants have finite stores of resources that can be used to produce flowers and fruits, up to the point that “marginal revenue” equals “marginal cost.” In this case, marginal revenue is the increased probability of pollination and seed dispersal as a result of greater flower and fruit production, and “marginal cost” is the drain on the energy reserves !Nara uses to survive and generate new biomass (Strohbach and Cole, 2005). Decreased water availability heightens the relative cost of new biomass generation for the plant, and impacts plant investment in flower and fruit growth when the marginal cost of new growth is too high (Strohbach and Cole, 2005). !Nara has adapted to absorb fog through its stems and use its deep root system to tap into groundwater to survive in the desert (Henschel et al., 2004). Thus, we postulated that fog concentration and water table levels would provide accurate proxies for water availability and that increasing distance from the Kuiseb River would correlate with decreased water availability.

Greater herbivory pressure disrupts the !Nara cost-benefit equilibrium when flowers or fruits are eaten, damaged or removed in the vulnerable production phase (Strohbach and Cole, 2005). If the !Nara plant is grazed upon during fruit maturation process, which occurs between February and April, the plant's stored energy reserves will be prematurely drained and fruit productivity will be reduced that season (Strohbach and Cole, 2005). Thus, we posited that hummocks with fences that exclude vertebrate herbivores would experience greater fruit production success than those without enclosures and that higher vertebrate diversity in !Nara hummocks would negatively impact fruit productivity (although we recognize that vertebrate diversity does not necessarily correspond to vertebrate abundance).

Biodiversity is the diversity of life, or species richness, within a certain ecosystem (Colwell 2009). !Nara plants have long been considered to be a keystone species in the Namib Desert with strong effects on communities and ecosystems (Hebeler, 2000). Pre-existing literature hypothesizes that scattered trees, like !Nara hummocks, are keystone structures because they have a disproportionate effect on the ecosystem relative to their size and the low density of surrounding plants (Manning, 2006). These plants break up the homogeneity of the landscape and create "landscape patchiness," which has been shown to increase local species richness and abundance (Manning 2006). To find out whether !Nara serve as a keystone species in the Namib Desert ecosystem, we explore this idea of 'scattered trees' by comparing biodiversity in !Nara hummocks to biodiversity in alternative microhabitats within the ecosystem. Additionally, we explore the concept of ecological niche differentiation, or complementarity, in considerations of biodiversity. Applied to plant-pollinator interactions, functional complementarity suggests that a higher diversity of pollinators contributes to increased pollination success of the plants, which allows the benefits of investing in productivity to outweigh the costs (Bluthgen and Klein, 2011). So, we predicted that hummocks with greater arthropod biodiversity levels would have greater levels of pollinator diversity, and subsequently greater numbers of fruits.

The theory of island biogeography functioned as a framework for our research design and analysis. The theory contends that the size and distance of 'islands' from a 'source' affect species richness and evenness in those isolated patches, and that larger islands closer to the 'source' host greater biodiversity when compared to smaller, farther islands (MacArthur and Wilson, 2001). In Station Valley, !Nara hummocks are analogous to islands within the desert landscape, while the Kuiseb riverine system is the source. In line with this theory, we expected that larger hummocks closer to the Kuiseb River would exhibit higher levels of biodiversity than smaller hummocks farther away. This theory allowed us to identify trends in factors influencing hummocks across the landscape, and how these factors (differing levels of water availability, herbivory pressure and biodiversity) impact productivity.

We postulated that the productivity of hummocks closer to the Kuiseb River would benefit most from increased arthropod (and by proxy, pollinator) diversity, but be threatened by the higher vertebrate herbivory that occurs along the riverine system because both livestock and wildlife rely on the pods produced by different tree species present along the "linear oasis" year-round (Personal communication at Gobabeb). Further away, however, hummock productivity may be threatened by limited pollinator diversity, a factor which may have the most weight on the cost-benefit equilibrium of !Nara plants. Past projects have looked independently at several of these factors. The Dartmouth research group in 2014 analyzed !Nara pollination processes and identified midge species as pollinators of !Nara. In 2015, the research group assessed !Nara flower densities by plant sex and quantified biodiversity within female hummocks. In 2016, the research group included male hummocks and fog data, and in 2017, the group looked at the impacts of herbivory on biodiversity and measured biomass allocation in reproductive operations. Our project holistically integrates the research on water availability, herbivory, and biodiversity and adds our own empirical data to better assess !Nara fruit productivity over time.

Research Question 1: Is !Nara fruit productivity limited by water availability? (H=hypothesis)
H1: !Nara fruit productivity increases as the concentration of fog increases over time.
H2: !Nara fruit productivity increases as water table levels increase over time.
H3: Flower productivity in female !Nara hummocks decreases with increasing distance from the Kuiseb River.
H4: Fruit productivity in female !Nara hummocks decreases with increasing distance from the Kuiseb River.

Research Question 2: Does herbivory affect !Nara fruit productivity?
H5: Fenced !Nara hummocks experience lower vertebrate diversity than unfenced hummocks.
H6: Fenced !Nara hummocks have greater fruit productivity than unfenced hummocks.

Research Question 3: Are !Nara fruit and flower productivity impacted by vertebrate and arthropod diversity?

A. Vertebrate Diversity (all organisms aside from arthropods)

H7: Larger !Nara hummocks closer to the Kuiseb River experience higher levels of vertebrate diversity than smaller !Nara hummocks further away from the river.
H8: !Nara hummocks experience higher vertebrate diversity than alternative microhabitats in Station Valley.
H9: Male !Nara hummocks experience lower vertebrate diversity than female !Nara hummocks.

B. Arthropod Diversity

H10: !Nara hummocks have higher arthropod diversity than alternative microhabitats in Station Valley.
H11: !Nara hummocks closer to the Kuiseb River with greater areas experience higher levels of arthropod (and by proxy, pollinator) diversity than !Nara hummocks with smaller areas, further away from the river.
H12: Female !Nara hummocks with greater arthropod diversity have smaller proportions of aborted buds to flowers.
H13: Female !Nara hummocks with greater arthropod diversity have more fruits.
H14: !Nara hummocks with higher arthropod diversity have greater proportions of live to dead biomass.
H15: Abundance of potential pollinators such as !Nara flies, blister beetles and midges in the !Nara hummocks will vary across distances from the Kuiseb River.

Methodology

We conducted our study in Station Valley, a region of the Kuiseb Delta in the Namib-Naukluft National Park near the Gobabeb Research and Training Centre from October 28th to November 7th, 2018.

Site Selection

We selected 38 study sites in Station Valley to assess factors, specifically hummock size and distance from the Kuiseb river, that may affect factors impacting !Nara fruit productivity. 20 were !Nara hummocks that are part of the long-term !Nara exclosure experiment that began in 2016,. We paired four sets of control (unfenced) and experiment (fenced) female hummocks (“C” and “E” plants) with nearby male hummocks (“M” plants) for both the near and far distance categories and selected two males in the intermediary zone between the near and far hummocks (Appendix IV). We then randomly chose eight alternative microhabitats (“A” sites), two in each distance category (near, intermediary, far) and two in the riparian zone to determine whether !Nara hummocks act as a keystone species in Station Valley by hosting higher vertebrate and arthropod diversity than the surrounding microhabitats (Appendix V).

Size and Distance Calculations and Mapping Hummocks

To obtain hummock size, we measured the circumferences of each individual plant in the male hummocks with a GPS and retractable tape measure. For female plants, we used aerial map data. For distance, we obtained GPS coordinates for all sampled points, from which we were able to measure the !Nara hummock distance to the Kuiseb River using Google Earth V 9.2.71.3. We measured the distance circumventing the dunes to account for the obstacle the dunes may present to organism movement.

Biodiversity Data Collection

We installed two bee plates (21.5 centimeters in diameter, 1.5 centimeters deep) and two pitfall traps (15.5 centimeters in diameter, 15 centimeters deep) per hummock on the afternoon of November 2nd. For the bee plates, we filled each plate to the brim with a solution of water and a teaspoon of dish soap and set them in locations on the hummock with east-facing downward slopes so that the plates would not be disturbed by the prevailing westward wind. For the pitfall traps, we randomly choose two locations on each hummock and installed them with approximately two inches of sand inside the bucket. These two types of traps allowed us to estimate the biodiversity levels of both flying and crawling organisms.

On the morning of November 3rd, we swept two 66 centimeters by three meters track transects (with a total area of two square meters) per hummock near the pitfall traps. We identified and counted the number of times an individual crossed the transect every morning of field work. For pitfall traps, we used a sifter to comb the sand for arthropods, and for the bee bowls, we used forceps and small jars to collect samples from them every morning. We identified the arthropods we could on sight and classified the unknown arthropods as morphotypes in the laboratory. Using pictures of arthropods from bee plates and pitfall traps, we created identification guides (see Appendix VI).

Pollination Data Collection

On November 5th, at approximately 5:00 p.m., we conducted observations on 10 male and 10 female hummocks we identified as being on a distance gradient from the river. We randomly picked three stems per hummock to observe. Observations lasted a total of five minutes per stem. The first minute was spent waiting quietly for arthropods to acclimate to our presence. We recorded the type and number of arthropods that touched the stem, buds, fruits, or flowers. On the morning of November 6th, we used insect nets and collection vials to capture 10 arthropods from male hummocks to determine whether they carried pollen. We wanted explore the possibility of !Nara flies as pollinators, as they were frequently observed on stems and found in large quantities in the bee plates, so we collected an additional 20 !Nara flies to check them for pollen under a microscope that afternoon.

Productivity Data

We used a long-term data set provided by Gobabeb Research and Training Centre staff that includes monthly data on the number of fruits, flowers, and aborted buds for the 20 female !Nara hummocks under the exclosure experiment. Fruits are divided into four categories (small—up to a tennis ball size, medium—between a tennis ball and a grapefruit, large—larger than a grapefruit, and small with flowers—small-sized fruits with a flower still present) and recorded. We utilized this monthly data to compare individual !Nara hummock fruit productivity to hummock size, distance from the Kuiseb River, and biodiversity around the hummock. We also obtained fog and water table level data recorded from March 2017 to October 2018 from Gobabeb-affiliated weather stations for further analysis.

Biodiversity Indices

We categorized the data set into vertebrates and arthropods and used the Shannon-Wiener index to quantify biodiversity (Colwell 2009). The Shannon-Wiener (Shannon's) index was calculated using the diversity tool within the package "vegan" (v. 2.5-2, Oksanen et al. 2017) in R (v. 3.4.1, R Core Team 2017).

Data Analysis

We performed statistical analysis in JMP Pro 14 Software. To determine the relationship between small !Nara fruit counts from March 2017 to October 2018 and fog concentrations and water table levels, we ran a generalized linear model with a poisson distribution. Before performing this analysis, we standardized fog concentration and water table level data. We then ran an ANOVA in order to analyze the effect of distance from the Kuiseb River on !Nara fruit counts and flower counts from March 2017 to October 2018.

We analyzed the effect of exclosure on both small !Nara fruit counts from March 2017 to October 2018 and Shannon's index for vertebrate diversity in female !Nara hummocks through an ANOVA analysis. In our analysis of the effect of exclosure on !Nara fruit counts, we used the small fruit count instead of the medium or large counts because larger fruits can stay on stems for up to a year, while the smaller fruits grow over time and are less likely to be recounted as small fruits again. This allowed us to avoid recounting fruits.

We also used an ANOVA analysis to determine the effect of "habitat category" (alternative microhabitats, exclosed (experimental) female !Nara hummocks, control female !Nara hummocks, or male !Nara hummocks) on the Shannon's index for vertebrate diversity and the Shannon's index for arthropod diversity separately. A subsequent post-hoc test was performed on the ANOVA analysis of habitat category and vertebrate diversity to determine the differences in vertebrate diversity. We utilized regression analyses to determine the effect of size and distance of hummocks from the river on both Shannon's Indices for arthropod and vertebrate diversity separately. We used a linear regression analysis to determine the relationships between arthropod diversity and both fruit counts and aborted bud counts. We also used a linear regression analysis to determine the relationship between the number of flowers and the number of aborted buds in !Nara hummocks. We utilized a linear regression analysis to analyze the relationship between distance from the river and !Nara fly, midge, and blister beetle abundance. Lastly, we performed a linear regression analysis to test for the relationship between the proportion of live to total biomass of !Nara hummocks and arthropod diversity under the assumption that a higher proportion of live biomass would attract a higher diversity of arthropods.

We later attempted to identify the primary pollinators of !Nara, assuming that a primary pollinator of !Nara would be found in equal abundances across !Nara hummocks with varying distances from the Kuiseb River. We utilized a linear regression analysis to analyze the relationship between distance and !Nara fly, midge, and blister beetle abundance.

Data and Results

Water Availability

We found a positive relationship between !Nara fruit counts and fog concentrations (Estimate ± SE = 0.05 ± 0.01, $P < 0.01$). There is also a positive relationship between !Nara fruit counts and water table levels (estimate ± SE = 0.20 ± 0.01, $P < 0.01$) (**Fig. 1**).

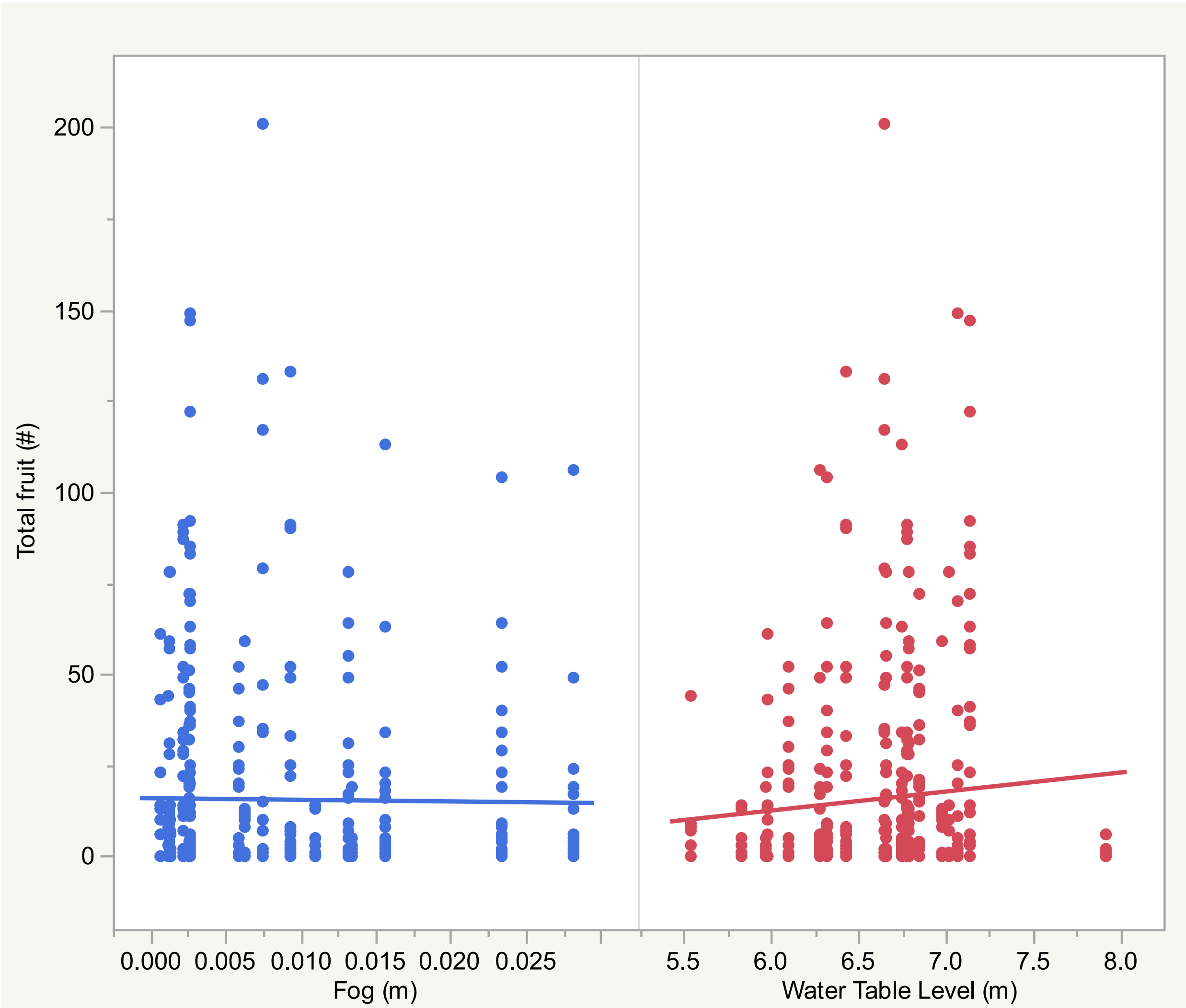

Figure 1. !Nara fruit counts increased with water table levels (estimate ± SE = 0.20 ± 0.01, $P < 0.01$) and fog concentrations (Estimate ± SE = 0.05 ± 0.01, $P < 0.01$).

An ANOVA showed that there is no effect of distance (near/far) on both fruit counts ($F_{1,19} = 4.14$, $P = 0.06$) and flower counts ($F_{1,19} = 3.69$, $P = 0.07$) (**Fig. 2**)

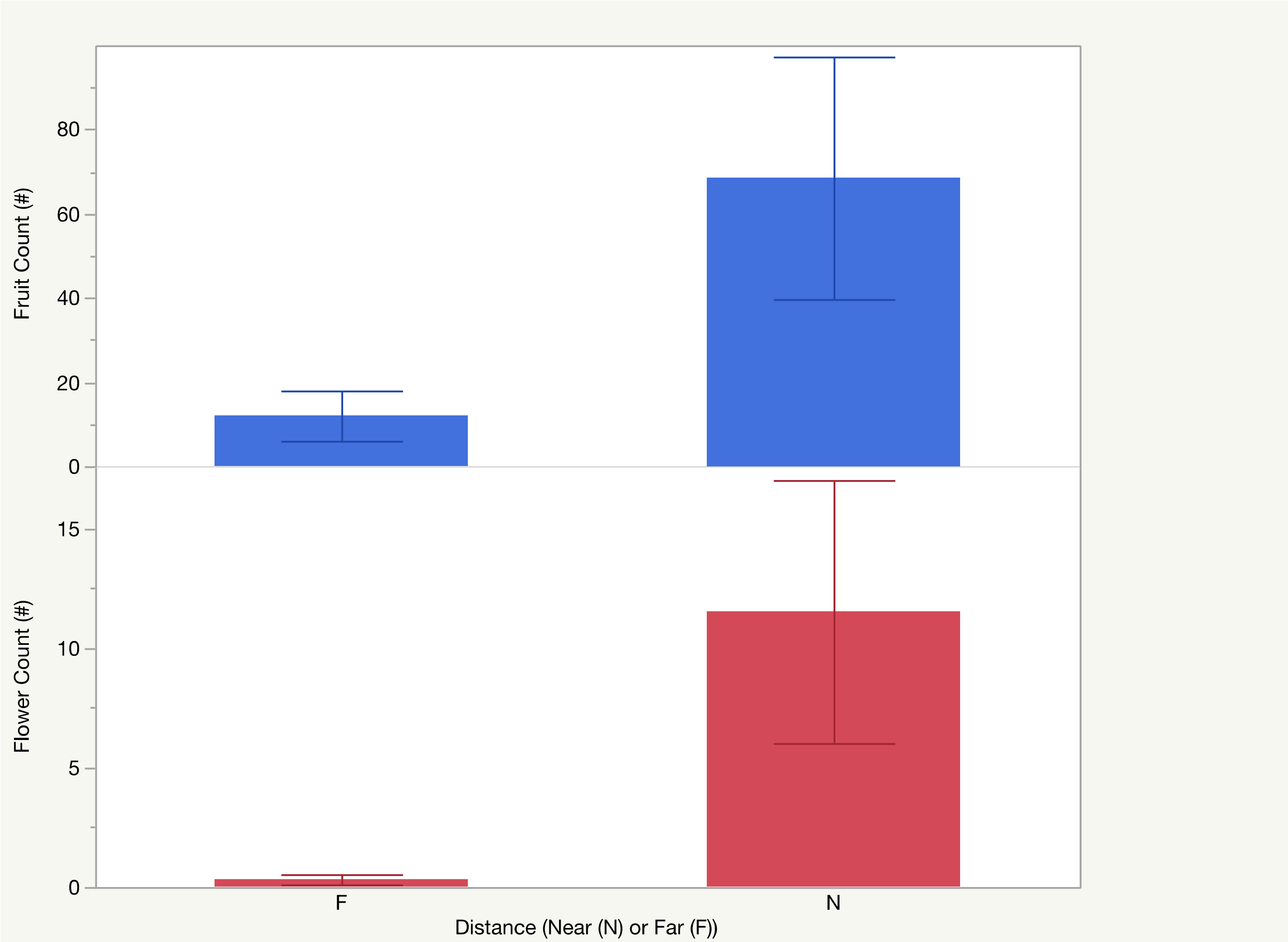

Figure 2. !Nara fruit counts varied between near and far distance hummocks counts ($F_{1,19}$ = 4.14, P = 0.06). !Nara flower counts also varied with distance ($F_{1,19}$ = 3.69, P = 0.07).

Herbivory

We found that there is no effect of exclosures on the total count of small fruits within !Nara hummocks over the past two years ($F_{1,19}$ = 0.11, P = 0.75), and that there is no effect of exclosure on vertebrate diversity ($F_{1,19}$ = 0.98, P = 0.34).

Biodiversity

There is a difference in vertebrate diversity between habitat categories ($F_{3,37}$ = 9.28, p < 0.01). The post-hoc test indicated that there is less vertebrate diversity in alternative microhabitats than in male, experimental female, and control female hummocks (p < 0.05), but that the vertebrate diversity in male, experimental female, and control female hummocks did not differ from each other (**Fig. 3**). There is no difference in arthropod diversity between habitat categories ($F_{3,34}$ = 1.85, p = 0.16).

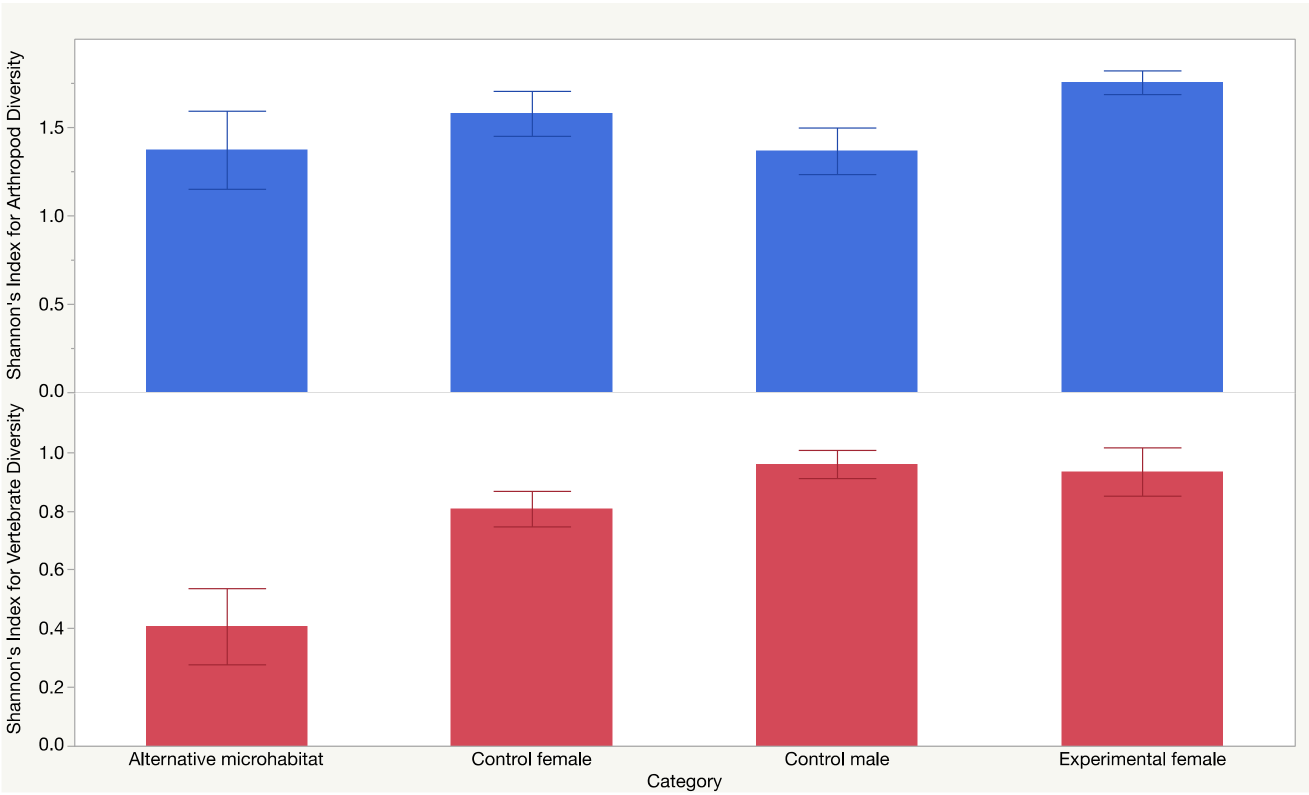

Figure 3. There was greater diversity of vertebrates in unfenced male !Nara hummocks as compared to fenced female hummocks, followed by unfenced female hummocks and then alternative microhabitats ($F_{3, 37} = 9.28$, $p < 0.01$). There is no difference in arthropod diversity among categories ($F_{3, 34} = 1.85$, $p = 0.16$).

There is no significant interaction between distance from the river and size on vertebrate diversity. However, there is a positive effect of distance on vertebrate diversity (**Table 1**).

Table 1. Parameter estimates from a linear regression between Shannon's index for vertebrate diversity found in hummocks and distance of the hummock to the river, size of the hummock, as well as the interaction between distance and size.

Term	**Estimate**	**Standard Error**	**t-value**	**P-value**
Intercept	0.8060123	0.075781	10.64	<0.0001
Distance (m)	6.7013×10^{-5}	0.000029	2.31	0.0293
Size (m^2)	0.0001465	0.000491	0.30	0.7678

Distance*Size	5.5841 $\times 10^{-7}$	3.818 $\times 10^{-7}$	1.46	0.1555

There is no significant interaction between size and distance from the river on arthropod diversity. There is a negative effect of distance on arthropod diversity (**Table 2**).

Table 2. Parameter estimates from a linear regression between Shannon's index for arthropod diversity found in hummocks and distance of the hummock to the river, size of the hummock, as well as the interaction between distance and size.

Term	Estimate	Standard Error	t-value	P-value
Intercept	1.5963543	0.157804	10.12	<0.0001
Distance (m)	-5.845 $\times 10^{-6}$	6.05 $\times 10^{-5}$	-0.10	0.9238
Size (m^2)	-0.000324	0.001022	-0.32	0.7540
Distance*Size	3.5031 $\times 10^{-8}$	7.95 $\times 10^{-7}$	0.04	0.9652

There is no relationship between fruit counts and the Shannon's index for arthropod diversity (estimate ± SE =12 ± 34, P = 0.73, R2 = 0.01). There is no relationship between aborted bud count and the Shannon's index for arthropod diversity (estimate ± SE = 115 ± 130, P = 0.37, R2 = 0.05). However, there is a positive relationship between the number of flowers and number of aborted buds (estimate ± SE = 10 ± 10, P < 0.01, R2 = 0.70). Our results did not change when we considered the relationship between Shannon's index for arthropod diversity and mean fruits and mean aborted buds over a two-year period (results not shown).

Distance from the hummock to the Kuiseb River affected blister beetle abundance (estimate ± SE = 0.0 ± 0.0, P < 0.01 , R2 = 0.22), but not !Nara fly abundance (estimate ± SE = 0.0 ± 0.0, P = 0.24, R2 = 0.05) or midge abundance (estimate ± SE = 0.0 ± 0.01, P = 0.82, R2 = 0.00) (**Fig. 4**).

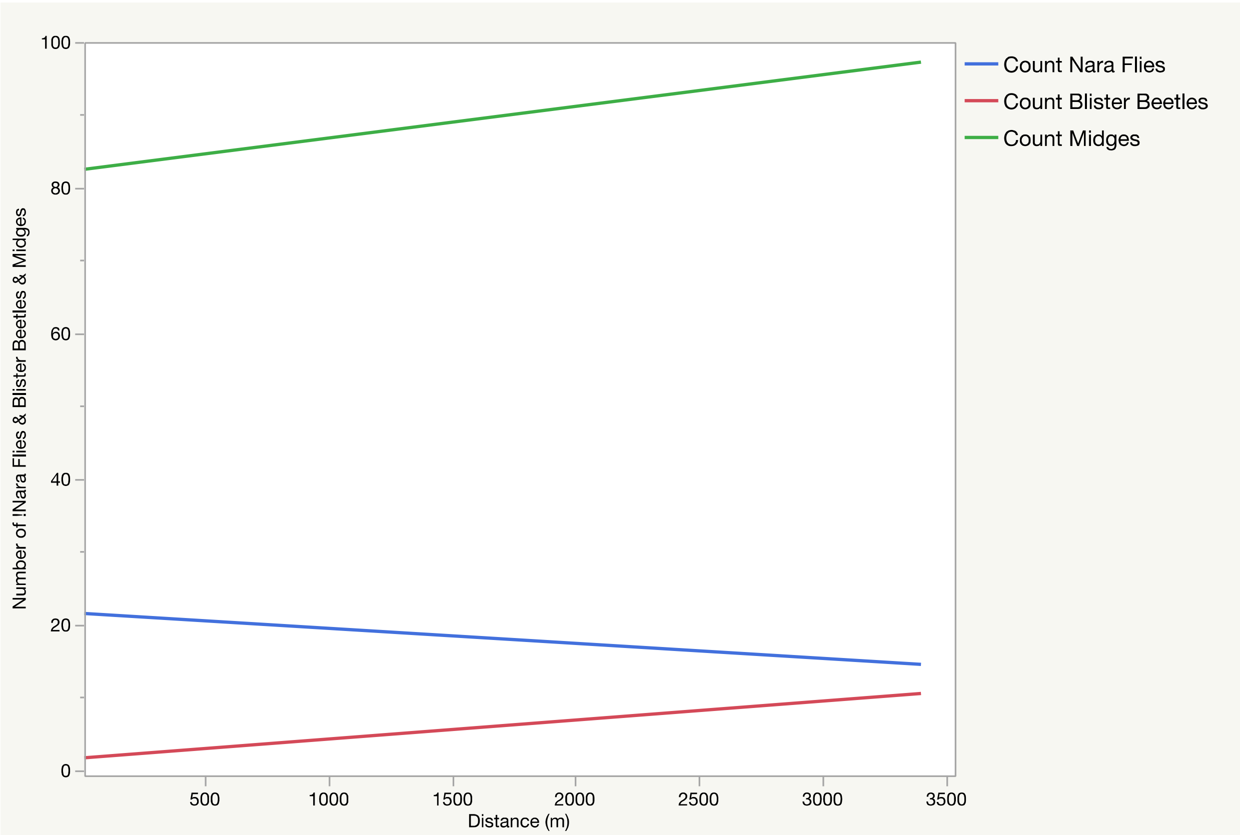

Figure 4. Blister beetle abundance significantly increases as the distance from the river increases (estimate ± SE = 0.0 ± 0.0, P < 0.01 , *R*2 = 0.22).

There is no relationship between the amount of live biomass in !Nara hummocks and the Shannon's index for arthropod diversity (estimate ± SE = 0.0 ± 0.15, P = 0.83, R2 = 0.00).

Out of the 20 samples of !Nara flies we collected, only one !Nara fly had pollen on its body.

Discussion

We found that water availability as measured through water table levels and fog concentrations had an effect on !Nara fruit production as expected in our first and second hypotheses. Both measures in Station Valley exhibited a positive relationship with the number of !Nara fruits. However, we found that distance from the Kuiseb River was not an important factor in determining fruit counts. So although periodic surface flows from ephemeral rivers like the Kuiseb may recharge the subsurface water of surrounding areas during the rainy season, it seems that hummocks rely more on absorbing fog through their stems and tapping into the water table with their root systems than on water that may be abstracted from the Kuiseb River.

We expected that exclosure would increase fruit production in female hummocks but we found that there is no effect of exclosure on the total count of small fruits within !Nara hummocks. Large- and medium-sized vertebrates such as jackals instead feed on ripe !Nara melons (Nel, 1995), which are larger. Subsequently, vertebrates may not impact the quantity of emerging, small fruits in !Nara hummocks. We also found that there is no effect of exclosure on the diversity of vertebrates in female !Nara hummocks, suggesting that vertebrates are not dissuaded from entering female !Nara hummocks by the exclosure.

We found that there is lower vertebrate diversity in alternative microhabitats compared to male, experimental female, and control female hummocks, but that the vertebrate diversity in male, experimental female, and control female hummocks did not differ from each other. This result supports that !Nara hummocks of both sexes are keystone structures that provide a multitude of ecosystem services to organisms in the Namib Desert (Hebeler, 2000). However, we found that there is no difference in arthropod diversity across alternative microhabitats and male, experimental female, and control female hummocks. Interestingly, we also found that alternative microhabitats closer to the Kuiseb River host higher diversity of arthropods than the alternative microhabitats further away from the river (Appendix VIII, Plot 3).

We found that there is no interaction between size and distance from the river on biodiversity, but that distance has a positive effect on vertebrate diversity and a negative effect on arthropod diversity within !Nara hummocks. The negative relationship between distance and arthropod diversity suggests that in Station Valley, distance may be a limiting factor on pollinator diversity and subsequently !Nara fruit productivity because arthropods must expend more energy to travel to !Nara hummocks that are further away from the Kuiseb River. The positive relationship between vertebrate diversity and distance may exist because vertebrates that forage beyond the Kuiseb River area may concentrate more around patches of vegetation with high relative resource densities, which !Nara hummocks provide. Another possible explanation for this positive relationship is that recent rainfall before the time of our study facilitated the growth of grasslands which provided a food source further from the riverine system that livestock and wildlife could utilize opportunistically (personal communication at Gobabeb). Furthermore, while we found that !Nara hummocks of different sizes experienced similar levels of both arthropod and vertebrate diversity, we observed that some species were consistently present in equal abundances across !Nara hummocks while others were less common and more randomly distributed all across the distance and size gradients (Appendix VIII, Plot 1 and 2). We also found that there is no relationship between live biomass and arthropod diversity. This might mean that arthropods are not attracted to green material, in the same way that we found that arthropods may not more attracted to flowers than fruits.

We predicted that arthropod diversity, acting as a proxy for pollinator diversity, would increase !Nara fruit counts and decrease aborted bud counts. We found a positive relationship between aborted buds and total flowers, suggesting that fruit production is in fact limited by pollination. We found that there is no relationship between arthropod diversity and both aborted bud counts and fruit counts. This suggests that pollinator diversity may not be a limiting factor in pollination and subsequent fruit production success. Rather, a few distinct arthropods may appear in equal abundances and serve as primary pollinators in this system. We found that there is no relationship between distance from the river and midge and !Nara fly abundance, while there is a negative relationship between blister beetle abundance and distance. This suggests that midges and !Nara flies may be primary pollinators of !Nara, while blister beetles are not. This finding supports previous knowledge that blister beetles may be pollen robbers and ineffective pollinators (Eugene Marais, personal communication). We predicted that !Nara flies may be primary pollinators, but the circumstantial evidence we gathered suggests that !Nara flies, although found in similar abundances across distances, may not be an effective, and therefore primary, pollinator of !Nara.

Final Thoughts

While we found that fog concentration and water table levels impact !Nara fruit productivity, we postulate that the availability of paleo-groundwater in the deep aquifer under Station Valley may also significantly impact !Nara fruit productivity. Since there is no available information on how !Nara might utilize this water resource, we propose further research on !Nara root systems and the accessibility of this deep groundwater. In addition, to provide more robust conclusions on the relationships between large-scale climate data and !Nara fruit productivity, looking into seasonal temperature and precipitation data may yield interesting results, especially since insect-pollinated plants like !Nara are more sensitive to changes in temperature than wind-pollinated plants (Hegland, 2005).

Furthermore, while we focused on the effects of water availability, herbivory, and vertebrate/arthropod diversity on !Nara fruit productivity, future research may focus more on the pollination processes of female !Nara flowers and the effects of pollinator diversity on !Nara fruit productivity. Future studies might identify pollinators by marking flowers on both male and female !Nara hummocks with fluorescent powder and utilizing bee plates to determine which arthropods visit both sexes. The Dartmouth research group in 2014 used this method to identify midges as potential pollinators, but we see opportunities to expand the number of arthropod types under study.

In our study, we conceptualized !Nara hummocks as keystone structures, similar to scattered trees, and as islands, establishing that !Nara hummocks exhibit more biodiversity than alternative microhabitats. Thus, it seems that !Nara plays a critical role as an ecosystem engineer in the sand dunes of the Namib Desert and, as isolated patches of vegetation, increase local species and abundance. However, we found that landscape context and size may affect the diversity of life in different ways. We found a positive relationship between distance from the river and vertebrate diversity and a negative relationship between distance and arthropod diversity, but not between size and either measure of biodiversity. This finding is interesting because previous research found that large, scattered trees provided disproportionate benefits - namely distinct microclimates and structural elements like shade - for biota relative to their size and availability (Le Roux et al., 2018). At a landscape level, these ‘islands’ of biodiversity should theoretically increase spatial heterogeneity and connectivity that can aid species dispersal. Hence, we propose that future research expand the sample size across a more even distance gradient from the Kuiseb River and conduct long-term monitoring to increase the statistical power of data analyses on both size and distance measures. Regarding the distance measures, we recommend that future researchers consider a second possible pathway for arthropods from the river to hummocks near the sand dunes. Our measurement represented the distance between the !Nara hummocks and the Kuiseb River circumventing the dunes but another possible measurement is the shortest distance between the !Nara hummocks and the river. This second pathway may reduce travel time between feedings for arthropods, and thus may be a more accurate measure to use for analysis (Bernhardt et al., 2008).

Lastly, we recognize that our research project focused on the ecological aspects of !Nara in the Kuiseb Delta region. We propose that future research projects highlight the connections between !Nara and people, who are important players in the desert socio-ecological system. We believe that it would be interesting to look into the sustainable utilization and management of !Nara melons by the Topnaar people.

Acknowledgements

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VII. Appendices

Appendix I: One-Page Summary
Appendix II: Protocol
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Appendix IV: !Nara Hummock Coordinates
Appendix V: Alternative Microhabitat Coordinates
Appendix VI: Measurements of Hummock Distance from the River
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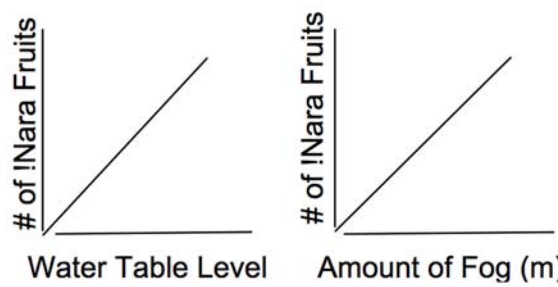
!Nara Melon Growth: Summary of Results

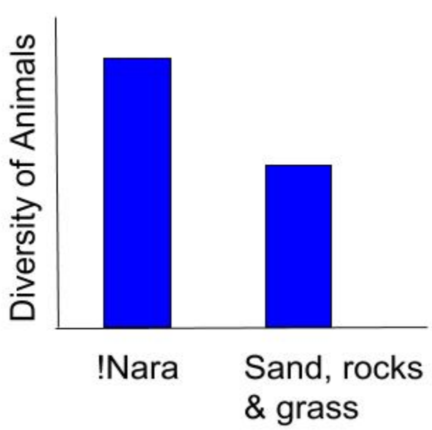
Anela Arifi, Hanna Bliska, Lynette Long, Anna Whitney and Lucia Kafia

We are a group of American university students who traveled to the Gobabeb Research and Training Facility in November, 2018 to study and research !Nara for nine days. Our group was interested in studying the !Nara melons that grow in the valley near Gobabeb.

We wanted to learn about the factors that impact the growth of this plant in the valley, such as the amount of fog or water in the ground, or the presence of animals and insects that might feed on the !Nara plant. We used research that Gobabeb conducted to learn about these factors, and we also conducted our own research. In order to learn about what types of animals and insects visit this plant, we set up a research project that involved placing animal and insect traps at !Nara hummocks to catch and count visiting animals and insects. We also studied and counted the tracks of animals like jackals and birds that visited the !Nara plants. We learned that the availability of water impacts the growth of !Nara melons. The number of !Nara fruits increase when fog and water in the ground increases. We also learned that fences around !Nara plants do not impact the count of small fruits in !Nara plants. We think that this is because larger animals like jackals only prey on bigger, riper fruits, and so fences around !Nara plants do not affect small fruits but may help to increase the counts of larger fruits.



Our research project also found that !Nara plants have more diverse animals visiting them than other areas in the valley that just have sand or rocks. We also learned that there is a greater number of different types of animals visiting !Nara plants as plants get farther away from the river. We think this might be the case because more grass grew with more rain this year. This grass for animals allowed them to travel further than usual from the river. We learned that the number of different types of insects visiting !Nara plants is highest closest to the river. We think that this could impact the fruit production in !Nara plants close to the river, because they might have more insects that help them to pollinate.



The findings of our project are important because !Nara fruit counts impact the amount of melons available for both people and animals. It seems that water, the presence of fencing around !Nara plants, and the diversity of animals and insects all have an impact on the !Nara plant's growth. We hope that future students will be able to come to Gobabeb to study the !Nara plants' fruit production and learn more about pollination.

Appendix II: Protocols

Bee Plates

1. Gather two bee plates per hummock site, insect collection jars, soft forceps, dish soap, and small jars to carry water out to the hummocks.
2. Identify two random points on the east-facing downward slope of each hummock (to avoid the prevailing westward wind).
3. Set the bee plates down and gently push sand under the edges of the plate around the plate's circumference to prevent wind disturbances.
4. Fill each plate to the brim with a solution of water and a drop of dish soap. Make sure to reduce vigorous movement to prevent bubbling.
5. Return to bee plates 1x/day to extract dead insects and place them in collection jars marked with the hummock identifier.
6. Refill bee plates with water/soap solution as necessary (following insect extraction, wind disturbance, or excessive evaporation).
7. Leave bee plates in the field for three days (or extraction cycles).
8. Identify and morphotype insects under lab scope and record IDs and counts.

Pitfall Traps

1. Gather two pitfall traps per hummock site, slotted spoon, sifter, and research journal.
2. Randomly choose two locations on the hummock.
3. Dig out sand using the pitfall bucket and place the bucket lip flush with the sand surface, leaving approximately two inches of sand inside the bucket.
4. Return to traps 1x/day, using slotted spoon and sifter to find insects and animals within the buckets.
5. Identify and record insect names and counts.
6. Take photographs of insects you are unable to identify in the field.
7. Repeat process over three days.

Track Transects

1. Sweep a 66-centimeter-by-3-meter transect perpendicular to the two pitfall trap sites using a large broom or window-cleaner (as landscape allows and taking care to provide a route of access to the pitfall traps that does not disturb the transect).
2. Return to transect 1x per day (at same time) to observe the number of unique animal tracks within the transect (every line of tracks that crosses into the transect counts as one distinct individual).
3. Identify and record the vertebrate/insect IDs and track counts.
4. Re-sweep the transect.
5. Repeat process over three days.

Observations

1. Identify twenty hummocks across a distance gradient to perform observations on.
2. Randomly choose three stems per hummock to observe. The stem encompasses all the flowers and as far down towards the roots that you can visually follow.

3. Sit in front of one stem and sit quietly for one minute to allow insects to adjust to your presence.
4. Spend four minutes identifying and recording every individual to touch a flower within your distinct stem.
5. Repeat for the two other stems within the hummock.
6. Repeat 2-6 for all hummocks.
7. Repeat protocol as necessary for your research question.

Trapping Potential Pollinators

1. Gather small insect jars and butterfly nets.
2. Identify insects of interest within !Nara flowers.
3. Lay in wait.
4. Slowly inch toward the insect (take care with stinging insects).
5. Quickly trap them in your jar. If flying insect, trap them using the butterfly net.
6. Freeze insects in a freezer for fifteen minutes.
7. Using laboratory microscope to identify presence of pollen grains on insects.

Monthly Monitoring

1. Perform and record counts of donkey, cow, and oryx dung within the hummock parameters. Record presence of springbok/goat dung, if applicable.
2. Perform closed bud, open flower, small fruit with flowers (approx. tennis ball size), small fruit (approx. tennis ball size), medium fruit (between tennis ball and grapefruit), large fruit (larger than a grapefruit), aborted fruit, fruits herbivorized by vertebrates, and fruits herbivorized by insects) counts on !Nara hummocks within the exclosure experiment.
3. Record data points in the following table for each hummock:

Replicate # _________ Time (24:xx):__________

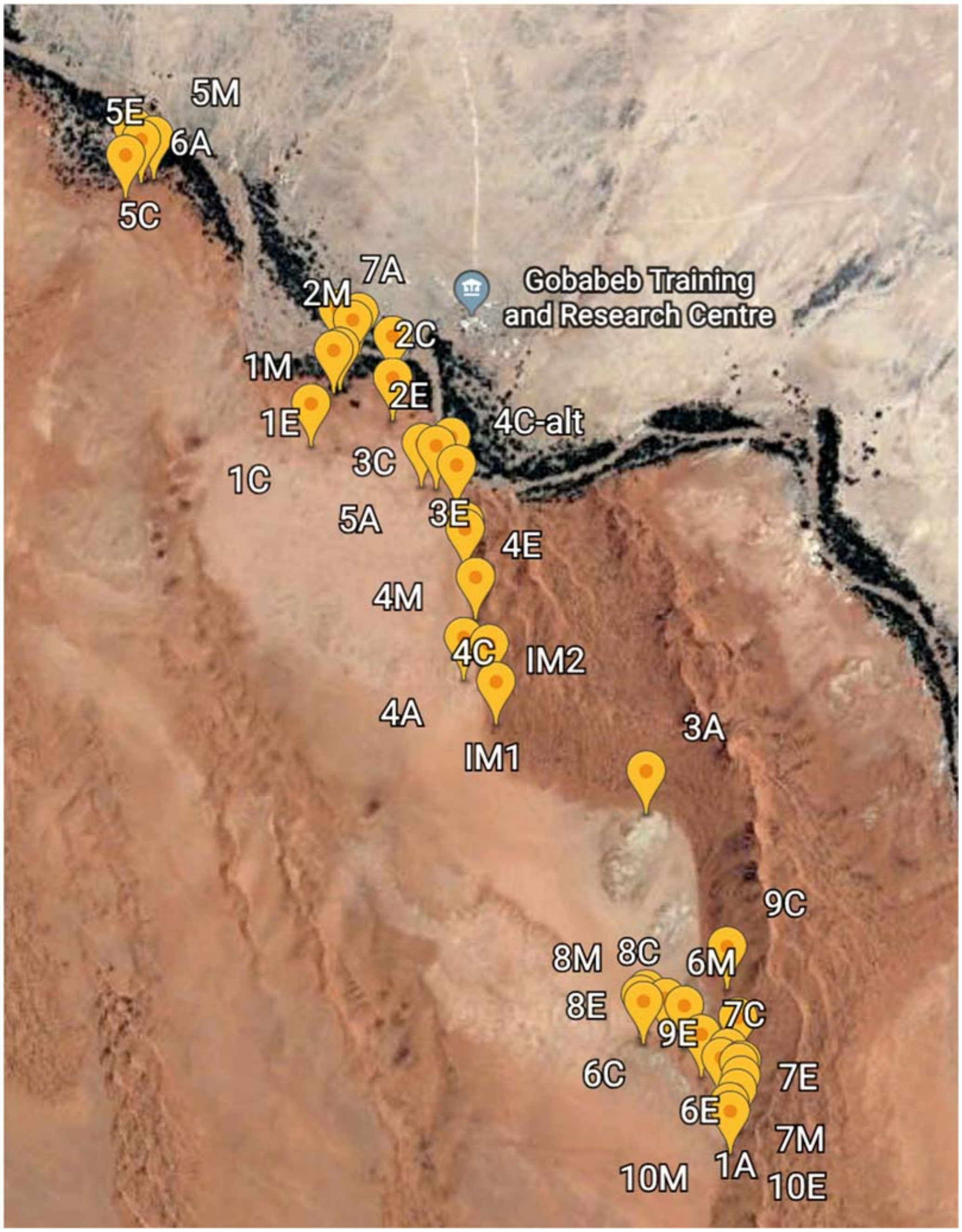
Dung:

	Donkey	Cow	Oryx	Springbok/goat
Count				
Field dry weight				

Fruit/Flowers:

	Closed bud	Open Flowers	Sm. Fruit w/flower	Small Fruit	Medium Fruit	Large Fruit	Aborted Fruit	Vert. Fruit	Insect Fruit
Count									

Appendix III: Mapped Study Sites



Appendix IV: !Nara Plant Coordinates

!Nara Hummock ID	Latitude	Longitude	Treatment	Gender
1E	-23.5644	15.0361	Fenced	Female
1C	-23.564515	15.034981	Unfenced	Female
1M	-23.5645	15.0352528	Unfenced	Male
2E	-23.5634	15.0366	Fenced	Female
2C	-23.5655	15.0382	Unfenced	Female
2M	-23.563972	15.038194	Unfenced	Male
3E	-23.56766	15.04049	Fenced	Female
3C	-23.56796	15.03991	Unfenced	Female
4E	-23.57096	15.041061	Fenced	Female
4C	-23.572714	15.041466	Unfenced	Female
4M	-23.570694	15.041028	Unfenced	Male
5E	-23.55741	15.02765	Fenced	Female
5C	-23.55685	15.02824	Unfenced	Female
5M	-23.556722	15.02875	Unfenced	Male
6E	-23.58928	15.05035	Fenced	Female
6C	-23.587958	15.048973	Unfenced	Female
6M	-23.58825	15.049694	Unfenced	Male
7E	-23.59021	15.05194	Fenced	Female
7C	-23.5901	15.05114	Unfenced	Female
7M	-23.590306	15.051833	Unfenced	Male
8E	-23.587668	15.048183	Fenced	Female
8C	-23.587848	15.047976	Unfenced	Female
8M	-23.588083	15.048639	Unfenced	Male
9E	-23.58867	15.05181	Fenced	Female
9C	-23.58611	15.05138	Unfenced	Female
10E	-23.59204	15.0515	Fenced	Female
10C	-23.59077	15.05191	Unfenced	Female
10M	-23.591722	15.051472	Unfenced	Male
4C-alt	-23.56866	15.04072	Unfenced	Female
IM1	-23.576528	15.042278	Unfenced	Male
IM2	-23.575167	15.042	Unfenced	Male

Appendix V: Alternative Microhabitat Coordinates

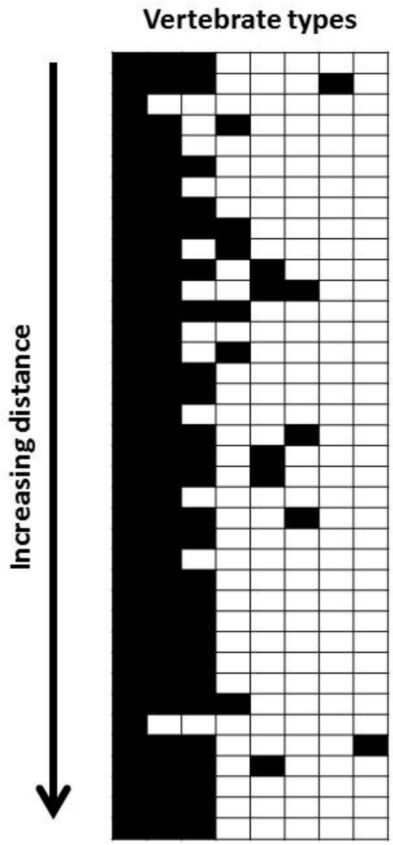
Alternative Microhabitat ID	Latitude	Longitude	Description
1A	-23.59125	15.051778	Dune grass (*Stipagrostis sabulicola*)
2A	-23.589778	15.051417	Short grass (*Stipagrostis ciliata*)
3A	-23.579917	15.045417	Short grass (*Stipagrostis ciliata*) in a patch with sand and small gravel rock pieces
4A	-23.574917	15.041	Short grass (*Stipagrostis ciliata*) in a patch with sand and small gravel rock pieces
5A	-23.567889	15.039333	Rock outcroppings
6A	-23.556389	15.027917	In sandy area, near riverine trees
7A	-23.563111	15.036861	Sandy patch in the riverine vegetation area
8A	-23.563	15.036028	Riverine vegetation

Appendix VI: Distance (Kuiseb→Hummock) Measurements

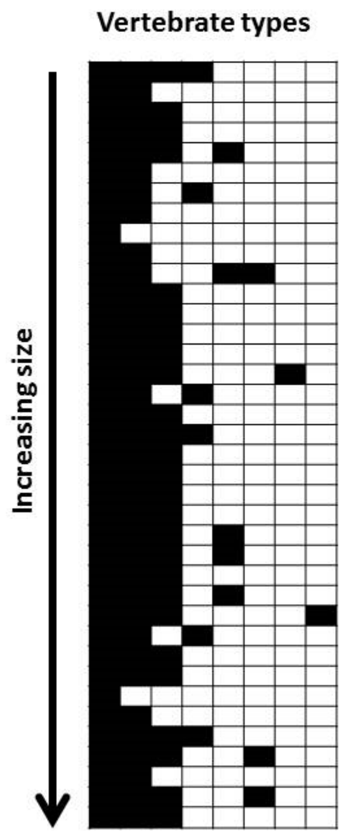
Hummock ID	Closest Distance	Distance between !Nara hummock and the Kuiseb river (m)
1E	Regular Path	200
2E	Regular Path	78
3E	Regular Path	54
4E	Regular Path	399
5E	Regular Path	314
6E	Regular Path	2674
	Across the dune	1416
7E	Regular Path	3084
	Across the dune	1345
8E	Regular Path	2408
	Across the dune	1522
9E	Regular Path	2921
	Across the dune	1256
10E	Regular Path	3240
	Across the dune	1498
1C	Regular Path	465
2C	Regular Path	187
3C	Regular Path	117
4C	Regular Path	594
	Across the dune	578
5C	Regular Path	232
6C	Regular Path	2500
	Across the dune	1469
7C	Regular Path	3064
	Across the dune	1402
8C	Regular Path	2512
	Across the dune	1554
9C	Regular Path	2636
	Across the dune	1155
10C	Regular Path	3163
	Across the dune	1382
1M	Regular Path	222
2M	Regular Path	128
4M	Regular Path	369
5M	Regular Path	192
6M	Regular Path	2629
	Across the dune	1422
7M	Regular Path	3093
	Across the dune	1358

8M	Regular Path	2453
	Across the dune	1559
10M	Regular Path	3229
	Across the dune	1481
IM1	Regular Path	1031
	Across the dune	981
IM2	Regular Path	868
	Across the dune	839
1A	Regular Path	3230
	Across the dune	1427
2A	Regular Path	2037
	Across the dune	1351
3A	Regular Path	1755
	Across the dune	1548
4A	Regular Path	842
5A	Regular Path	152
6A	Regular Path	200
7A	Regular Path	38
8A	Regular Path	56
4C-alt	Regular Path	149

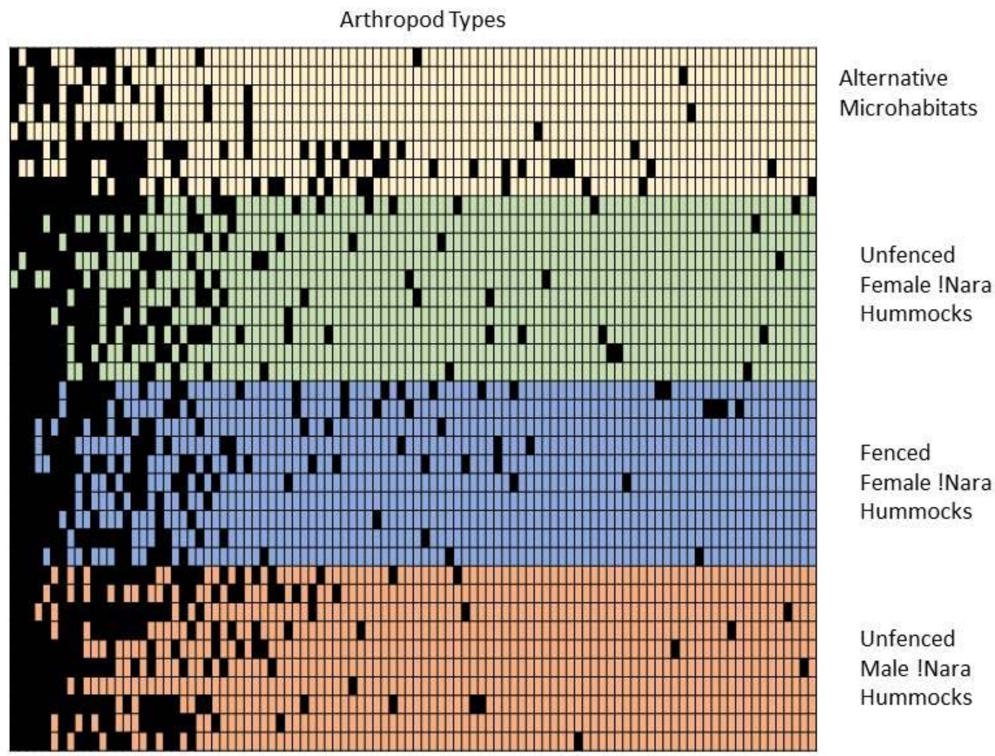
Appendix VII: Tile Plots



Plot 1: Vertebrate community composition of !Nara hummocks by increasing distance



Plot 2: Vertebrate community composition of !Nara hummocks by increasing size



Plot 3: Arthropod community composition of !Nara hummocks by habitat category