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Where mobile groups settle: Spatial patterns and correlates of Maasai pastoralist sedentarization in Northern Tanzania

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ABSTRACT

In the last century, mobile pastoralists around the world have transitioned to more sedentary lifestyles. Traditionally mobile people can be both pushed to settle by environmental or political forces, and pulled by new economic activities. While researchers have examined the causes and consequences of growing sedentarization, few contemporary studies have focused on the spatial patterns of settlement. This study examines settlement site selection using GIS and remote sensing techniques to quantify patterns and correlates of settlement location in four Maasai communities in northern Tanzania. We identify landscape scale factors that shape settlement locations and test the competing hypotheses that settlement is associated with: (1) resource access; (2) environmental constraints; and (3) infrastructural amenities. Spatial models offer support for each hypothesis, with slight variations. However, a combined model offers the greatest predictive power suggesting significant heterogeneity in site selection and/or a transition in selection criteria over time. These findings characterize a poorly understood aspect of the settlement of mobile groups, and point to new questions regarding the spatial drivers and consequences of sedentarization.

1. Introduction

Over the last century, mobile pastoralists around the world have faced increasing pressures to settle, with many groups becoming more sedentary (Ikeya & Hakubutsukan, 2017; Randall, 2015; Salzman, 1980). Despite this, comparatively little is known about the spatial patterns of pastoralist settlement. Traditionally, studies of pastoralists and sedentarization have focused on the various drivers (Dong et al., 2011; López-i-Gelats, Fraser, Morton, & Rivera-Ferre, 2016) and outcomes (Fratkin, Roth, & Nathan, 1999; Fratkin & Roth, 2005) associated with settlement, but not on the spatial relationship between landscape characteristics and settlement patterns. Settlement locations, however, affect a number of factors that may shape the economic and environmental outcomes associated with settlement, including proximity to water, forage, arable land, and infrastructural amenities. This paper seeks to address this first step towards a better understanding of pastoralist settlement by raising a seemingly simple question: where on the landscape do pastoralists settle?

To guide this inquiry, we adopt a conceptual approach to sedentarization that views settlement locations as integral to pastoralist livelihoods. As a matter of necessity, mobile pastoralists must move their herds to resources, especially water and forage. Furthermore, they bear the attending costs of this movement, which can take the form of animals' energy expenditures and/or increased exposure to predatory wildlife (Homewood, 2008; Little & Leslie, 1999). Economically diversified pastoralists may also seek access to farmland and proximity to roads, schools and health clinics (Baird, 2014; Little, Smith, Cellarius, Coppock, & Barrett, 2001; McCabe, Leslie, & DeLuca, 2010). This constellation of costs and benefits, creates a range of spatial pressures for pastoralists, which few prior studies have examined (Fratkin & Roth, 2005; Western & Dunne, 1979; Worden, 2007).

With this paper, we examine the spatial locations of Maasai pastoralists' settlements, which we refer to as settlement locations or settlement decisions interchangeably. These represent the outcomes of decision-making *processes*, which we do not address directly. The processes surrounding household decisions are complex and shaped by myriad social structures, economic concerns, political dynamics and environmental characteristics. Untangling all of these issues must

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include social-scientific approaches to identify how decisions are made and what mechanisms are causal. Social data for these types of analyses are expensive to collect, both in terms of time and money, for even a small sample of households. Our study, by contrast, seeks to lay the groundwork for future social studies of decision-making *processes* surrounding settlement location by first identifying the spatial *patterns* of settlement locations using remotely-sensed data and spatially-explicit methods. This approach provides a view of the pattern of settlement at a scale that may not be tractable even with multiple seasons of fieldwork. However, it also privileges the environment over critical social and economic drivers of settlement location. Throughout the paper, we strive to be clear about the goals and limitations of our study.

Studies of pastoralists often use a livelihoods framework wherein rural livelihoods are seen to be supported by five types of capital: human, social, financial, physical and natural (Ellis, 2000). Understandably, each type of capital may be comprised of many factors, which can vary in different contexts. Empirical studies typically focus on a subset of these capitals - generally along human/physical lines. Following this pattern, here we focus specifically on measures of physical and natural capital to address a specific research question (RQ): What natural and physical factors are associated with specific settlement locations in four Maasai communities in northern Tanzania?

Over the past few decades, several factors have been linked with reduced mobility and increased sedentarization among pastoralist groups. First, changes in land use, including the expansion of lands for biodiversity conservation and agriculture, have constrained the areas where herding can occur. Second, the presence of amenities in village and sub-village centers, like boreholes, churches, health clinics, and schools, has drawn people into denser, more permanent settlements. Third, ongoing livelihood diversification has encouraged private land tenure, the adoption of agriculture, and alternative forms of mobility, including wage-labor migration, each of which encourages settlement. It follows that as pastoralists embrace more sedentary lives, the spatial location of households may strongly influence access to natural and physical resources and ultimately economic opportunities and outcomes (Rutten, 1992; Western & Nightingale, 2003; Worden, 2007). These trends point to a set of hypotheses, regarding settlement patterns, which may or may not be mutually exclusive.

One hypothesis is that settlement decisions are associated with access to forage and water (H1). Traditionally, pastoralists have sought to balance considerations of resource quality and quantity (which they seek to maximize) with resource variability (which they seek to minimize) over both space and time. Studies have also shown that balancing distance to water and access to forage is critical (Butt, 2010a; Coppolillo, 2000; Jacobs, 1965; Western & Dunne, 1979). Accordingly, we could expect to see higher rates of settlement in areas near water sources and forage resources that exhibit low temporal variability. We call this the livestock hypothesis.

Another hypothesis is that settlement decisions are constrained by other environmental factors (H2). Settlement is denser in better climactic zones and less dense in zones where livestock and human disease vectors are prevalent and where challenging environmental features, like dense vegetation or extreme temperatures, are present. Western and Dunne examined settlement site selection criteria for Maasai in Amboseli, Kenya (1979). They found that Maasai evaluated several landscape-level factors that support livestock and human well-being and that minimize exposure to hazards, including: avoiding certain soil types, settling on favorable slopes, and avoiding areas of dense vegetation. Peterson (1978) also found that settlers avoided these areas, which can serve as tsetse fly habitat, a finding that persisted three decades later (Sachedina & Trench, 2009). We call this the constraints hypothesis.

A third hypothesis is that settlement decisions are pushed or pulled by modern infrastructure like parks, roads, or amenities in village centers (H3). For example, settlement may be less desirable near conservation areas where land tenure uncertainties and conflicts are more likely (Baird & Leslie, 2013). Alternatively, settlers may be drawn to features like roads that facilitate commerce. Maasai are increasingly dependent on diversified and market-driven livelihood strategies to get by. These include agricultural production (McCabe et al., 2010), off-farm employment (Baird & Gray, 2014), wage-labor migration (McCabe, Smith, Leslie, & Telligman, 2014), and gemstone mining (Smith, 2015) where transportation infrastructure is critical. In addition, settlers may want to be near churches, schools and health clinics in village centers (Baird, 2015; Hodgson, 2005). We refer to this pull towards modern amenities as the infrastructure hypothesis.

To test these hypotheses, that settlement locations are associated with forage and water for *livestock* (H1), environmental *constraints* (H2) and built *infrastructure* (H3), we used remotely sensed data products to build and test spatially explicit models of settlement location for all of the homesteads in four ethnically Maasai villages in Simanjiro District, northern Tanzania.

2. Methods

2.1. Study area

The study area is well suited to examine the spatial patterns of pastoralist settlement. First, the four study villages (Loiborsoit A, Emboreet, Terrat, and Sukuro) are spatially expansive and diverse, encompassing more than 1500 square kilometers of various topographical characteristics and climactic zones. Second, the area lies 30 km to the east of Tarangire National Park (TNP), which alienated local Maasai from customary lands when it was gazetted in 1970 and still serves as a driver of human/wildlife conflict (Davis, 2011; Lewis, Baird, & Sorice, 2016). Third, over the past two decades Maasai have variably diversified their livelihoods by incorporating agriculture and other economic strategies (Leslie & McCabe, 2013; Sachedina & Trench, 2009). Fourth, the area is overwhelmingly ethnically Maasai (Mackenzie, Baird, & Hartter, 2014), so land cover and use can be reasonably attributed to Maasai efforts. Lastly, study villages have experienced different levels of infrastructure development over many years (Baird, 2014).

The study site also broadly overlaps with the Simanjiro Plains which is an important dispersal area for wildlife species that migrate out of TNP during the wet season (Kahurananga & Silkiluwsha, 1997) (Kahurananga, 1976; Lamprey, 1963; Morrison & Bolger, 2014). Although the Lokisale Game Controlled Area lies between these villages and TNP (Fig. 1), its designation is contested by the village authorities (Sachedina & Trench, 2009). Although cattle grazing does take place there, Sachedina and Trench (2009) found that there were no permanent structures between the village boundaries and the park.

Overall, the region is semi-arid with high seasonal rainfall variability and frequent prolonged drought (Ericksen et al., 2013; Kiffner, Hopper, & Kioko, 2016).

2.2. Data collection

To test our hypotheses, we first mapped the location of all identifiably active Maasai bomas within the study area (Fig. 2, left panel). The boma, which is a central fixture of Maasai household organization, consists of a round fenced enclosure with an interior array of huts and a central livestock enclosure. Several households may occupy a single boma, each using an exclusive gate in the outer wall. Bomas are visible on high resolution aerial imagery or certain types of multispectral imagery. Here, we used ESA Sentinel 2 imagery at 15m resolution from February 4, 2016. Active bomas show a characteristic "bulls-eye" pattern of bare ground in the central cattle enclosure, while abandoned bomas show a uniform return of nitrogen enriched vegetation (see Fig. 2, middle and right panels). Bomas are not spectrally distinct enough from the surrounding landscape to reliably delineate through an automated classification process, so this was done manually.

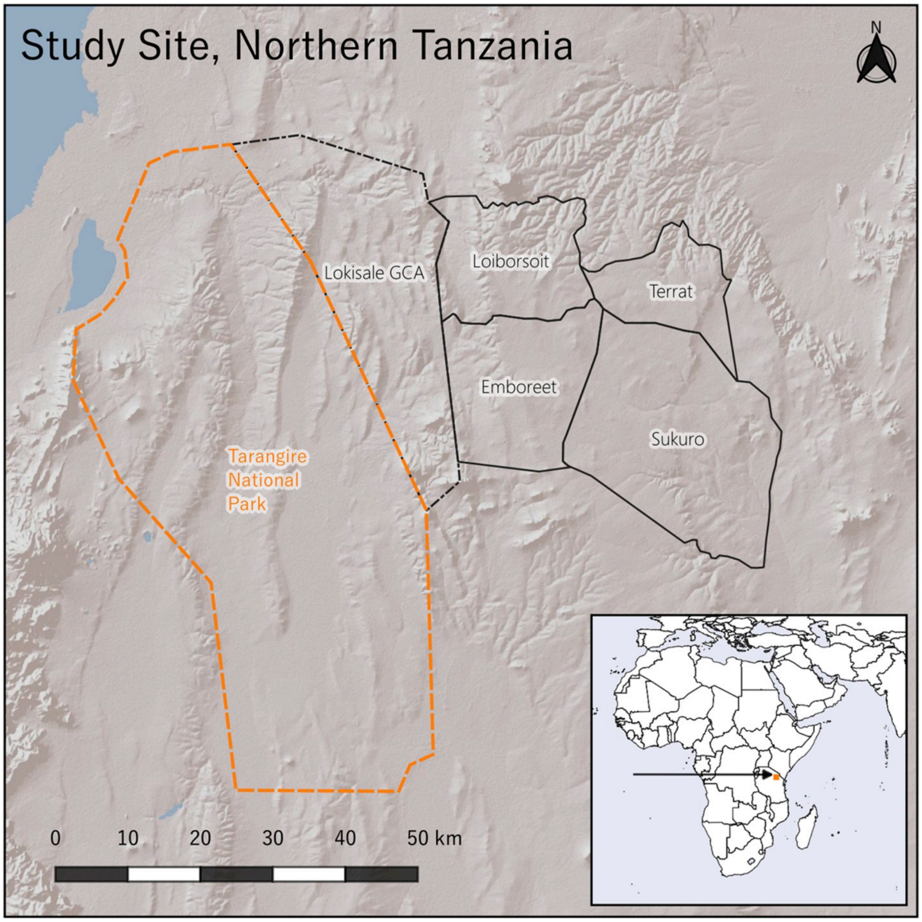

Fig. 1. Study site.

Fig. 2. Left panel: location of 953 bomas identified in study areas; middle panel: example bomas from Google Earth image; right panel: same bomas in a sentinel 2A image.

Next, we produced a suite of geographic variables related to factors that have been identified as potentially influencing settlement patterns. We used 30m resolution digital elevation models from the USGS Shuttle Radar Topography Mission to generate elevation and slope data sets (30m STRM DEM). Given that data on African soils were only available at 250m resolution and were largely interpolated from widely scattered sample locations (Hengl et al., 2015), we manually digitized the extent of "black cotton" vertisols in the study area using, again, ESA Sentinel 2 imagery. These soils, which are notoriously impassable in the wet season, are perceived as important environmental constraints.

Climatic zones were based on the USGS Isobioclimate dataset for Africa, at 1 km resolution (Sayre et al., 2014). Average annual precipitation and temperature were based on the World Climate data, at approximately 1 km resolution (Fick & Hijmans, 2017). Canopy cover was derived from a global canopy cover dataset at 30m resolution (Hansen et al., 2013). Data on the locations of permanent water sources were based on field data collected in 2010 and 2011 and reported on in 2014 (Baird, 2014; Miller, Leslie, & McCabe, 2014). The presence of open water impoundments was confirmed in the February 4, 2016 Sentinel 2 image.

In this region, imagery acquired at the beginning of the growing season, between December and January, allows for distinctions to be made between bare agricultural fields and green-up of local vegetation (Miller, 2015). Agricultural fields were digitized from the February 2, 2016 sentinel data at 15m resolution. The presence of tsetse fly in the study area was bas on UN Food and Agricultural Office GIS models at 1-kilometer resolutions. Although several species of tsetse can be found in the project area, models showed high probabilities of the presence of

Glossina swynnertoni, which was therefore used as an indicator species. These data were originally compiled in 2000, so should be viewed with caution.

Vector files of road infrastructure were extracted from the OpenStreetsMap project and confirmed in Sentinel imagery (OpenStreetMap, 2016). Boundaries for conservation areas were based on World Protected Area Database shapefiles (retrieved 12/13/2016). Village boundaries and population data were based on the Tanzanian National Census (Tanzania National Bureau of Statistics, 2012).

To estimate landscape level forage, imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to derived normalized differential vegetation index (NDVI) measurements for the study site (NASA, 2016). There is extensive literature regarding the use of NDVI to characterize vegetation in Africa (Anyamba & Tucker, 2005; Budde, Tappan, Rowland, Lewis, & Tieszen, 2004; Moritz, Hamilton, Chen, & Scholte, 2014; Pelkey, Stoner, & Caro, 2003; Trench, Kiruswa, Nelson, & Homewood, 2009). Earlier studies in this area used the Advanced Very High Resolution Radiometer (AVHRR) at 1 km resolution (BurnSilver, Boone, & Galvin, 2004). Butt (2010b), however, recommended the use of MODIS 250m 16-day composites to facilitate creation of cloud free time series. Savanna ecosystems are stochastic in both space and time (Homewood, 2008), which creates challenges when attempting to use NDVI values as a proxy for forage resources.

Prior studies estimating NDVI for this region have either used a single date to calculate summary metrics or made distinctions between wet and dry seasons (BurnSilver et al., 2004; Fuda, Ryan, Cohen, Hartter, & Frair, 2016). A single date, however, may not accurately reflect forage availability over longer time periods, which is especially relevant in the context of sedentarization. For this study, summary metrics of NDVI were created based on annual MODIS 250m images from 2001 to 2016. To account for potential influence of low quality pixels created by cloud cover in the raw NDVI, the time series data were smoothed using a double logistic smoother in the Timesat program (Jönsson & Eklundh, 2004). The results of the smoothing are shown in Fig. 3.

Two considerations are important when summarizing NDVI as a metric of forage access in this context. First, given that people are becoming more sedentary (Western & Nightingale, 2003; Worden, 2007), it follows that they are not only evaluating the seasonal productivity of the landscape, but also accounting for forage quality over a longer period of time. Second, prior research suggests that two distinct spatial scales of forage access need to be considered (Butt, 2010b; Coppolillo, 2000, 2001). During the wet season when good forage is more abundant, cattle typically graze within 2 km of the boma. However, during the dry season (excluding drought) cattle may need travel up to 10 km from the boma in order to obtain enough daily forage. Conceptually, we can think of the mean NDVI as a metric of the overall productivity of a given pixel over time. Correspondingly, we can see the coefficient of variation as an expression of how variable a pixel has been over time (Michaud, Coops, Andrew, & Wulder, 2012; Trench et al., 2009).

2.3. Data analyses

To test our three hypotheses, analyses of the above data proceeded in two steps. First, we mapped bomas in the study area and then characterized and evaluated broad patterns in settlement density in relation to landscape scale factors: political boundaries, climactic zones, soils, and agricultural development. Second, we partitioned the study area into occupied and unoccupied areas in order to estimate a series of logistic regression models that tested our hypotheses.

The issue of agriculture in the study raised important considerations for us. While we could speculate that proximity to agricultural plots is associated with a preference for settling near productive soils, it would be better to rely on accurate soils data, which is not available at high resolution in the study area. And while studies from other areas indicate that pastoralist households can cultivate small plots of several acres near the household (Thompson & Homewood, 2002), it is quite common in this study site for households' agricultural plots, sometimes multiple plots, to be located far from their settlements. Furthermore, being relatively new to agriculture, Maasai are not particularly adept at farming (an observation they themselves frequently make), and often hire external farm laborers. Given these communities' general lack of

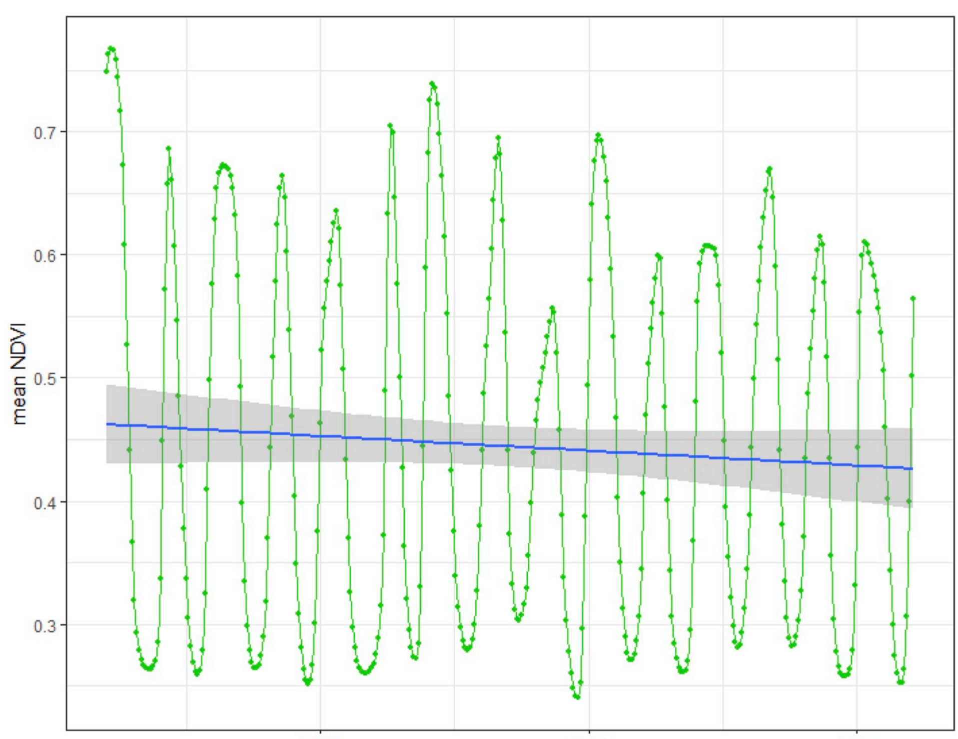

Fig. 3. Average MODIS NDVI values for the study area in 16-day increments from 2001 to 2016; smoothed with linear trend line.

experience with agriculture, the inconsistent (and unknown) spatial relationship between settlements and farm plots, and the poor quality of soils data for this area, neither proximity to agricultural plots, nor soils (except for black cotton vertisols, which are discussed below) were included in the modeling of settlement locations.

To partition the study site into occupied and unoccupied areas, we divided the landscape into equally sized units (Michaud et al., 2014). Here, nearest neighbor analysis indicated that the mean distance between mapped bomas was 400 m. Correspondingly, we divided the landscape into continuous, non-overlapping hexagons with centers 400m apart to approximate a unit of selection for individual bomas. Visual inspection indicated that most cells hold no more than one boma. And although some cells do contain two, we decided that 400m served as an effective approximation of households' "decision space." One additional concern was factored into this step of the analysis. As discussed above, "black cotton" vertisols, which become inundated and impassable in the rainy season, do not serve as settlement sites – a fact clearly identifiable on multispectral imagery. Correspondingly, all cells that contained a majority of this soil type were manually removed from the study grid. This left 6,479 cells for analysis, 772 of which were occupied (12%), as shown in Fig. 4a–c. Notably, a minority of cells contained more than one boma. All GIS analyses were conducted in QGIS (Team, 2016). Table 1 presents means for each of the study variables according to occupied and unoccupied strata.

To first evaluate the impact of individual geographic variables on the probability that a given cell was occupied (i.e., contained a boma), we constructed bivariate logistic regression models. Means and coefficients of variation for NDVI were calculated for two buffers (2 km and 10 km) around settlement sites to account for seasonal differences in forage access between wet and dry seasons, as described above. All distances were divided by 1000 to estimate coefficients at 1 km. Elevation in meters was divided by 100. We tested non-linear relationships between distance-related variables and settlement probability (Msoffe et al., 2011; Serneels & Lambin, 2001).

To test our three hypotheses, we created combined logistic models using the individual variables described above, summarized at 400m, to again estimate the probability that cells were occupied. In each case, squared distance terms improved model accuracy and so were included in the final models. Elevation, which was highly positively correlated with annual precipitation (0.80), and negatively correlated with annual

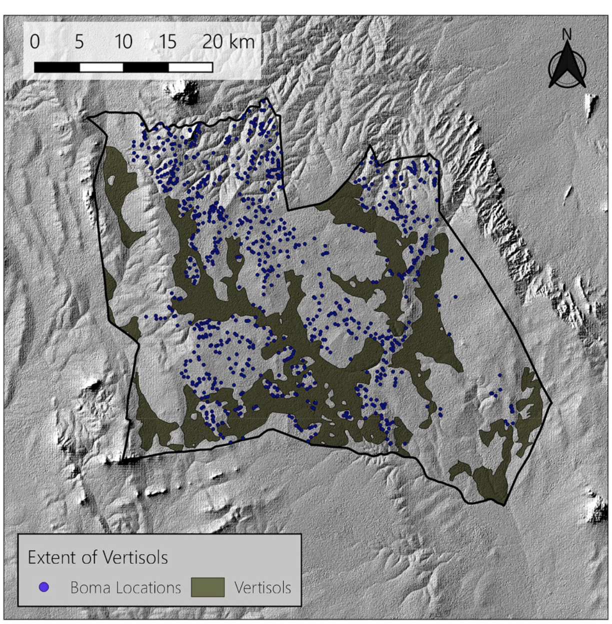

Fig. 4a. Boma locations and extent of 'black cotton' vertisols in the study area, February 2016.

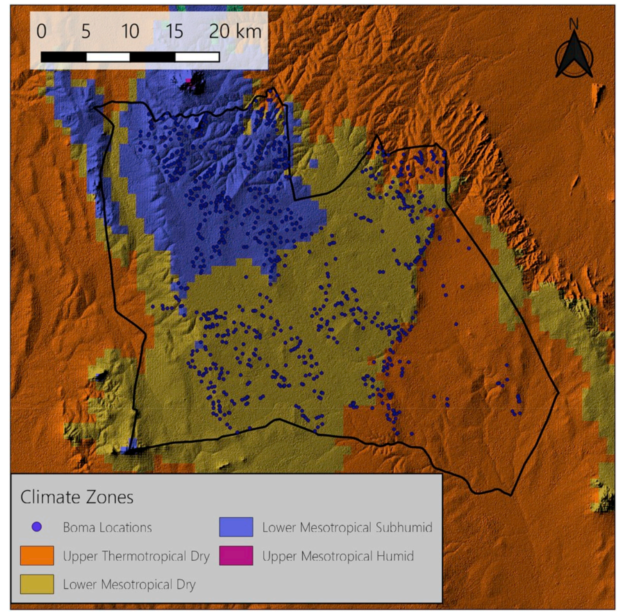

Fig. 4b. Boma locations and major climatic zones in the study area, February 2016.

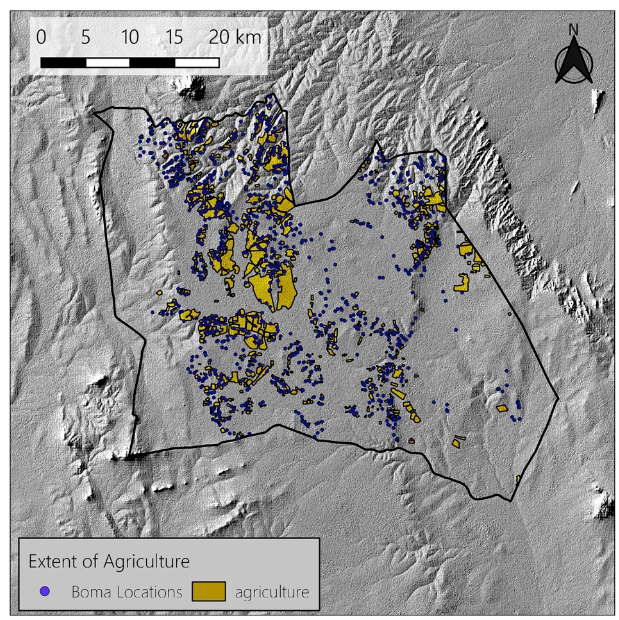

Fig. 4c. Boma locations and extent of agriculture in study area, February 2016.

temperature (−0.96), had the highest level of discrimination between occupied and un-occupied cells. For these reasons, only elevation was retained in the final models. Other studies have also used elevation as a proxy for agro-ecological suitability (Little et al., 2001; Trench et al., 2009). Given that measures of NDVI at 10 km and 2 km were also highly correlated (0.73), the 10 km variable, which had great predictive power for occupancy, was retained in the final models – a decision consistent with other studies of this kind (Trench et al., 2009).

We compared the combined models using the corrected Akaike Information Criteria (AICc) method, which compares model fits, but penalizes models with more parameters to avoid overfitting. A lower AICc indicates a more parsimonious model (Burnham & Anderson, 2004).

Area under the curve (AUC) was also calculated to give an indication of the accuracy of the model, with a level of 0.5 being an even chance of

Table 1
Summary statistics for geographic variables in occupied and unoccupied cells.

Variable	Occupied (mean)	Unoccupied (mean)	Occupied vs. unoccupied[a]
Distance to nearest village center (km)	6.52	9.64	***
Distance to Lokisale GCA (km)	19.76	22.31	***
Distance to permanent water (km)	2.95	4.11	***
Elevation (meters)	1486.17	1447.25	***
Distance to nearest road (km)	1.92	3.09	***
Mean annual temperature (C)	19.02	19.23	***
Mean annual precipitation (mm)	791.44	758.28	***
Mean NDVI @ 2 km	0.396	0.391	***
Mean NDVI @ 10 km	0.402	0.395	***
Tsetse fly probability (%)	61.81	65.22	***
Canopy cover (%)	2.66	3.48	***
Coefficient of variation in NDVI @ 2 km (%)	39.52	40.04	***
Coefficient of variation in NDVI @ 10 km (%)	39.86	40.20	***
Slope (%)	2.72	2.68	–

[a] Difference in means between occupied and unoccupied grid cells using Students *t*-test ***p < 0.001).

predicting the correct category (i.e., occupied vs unoccupied), so larger numbers are indicative of better predictive capacity (Friedman, Hastie, & Tibshirani, 2001). We ran generalized linear models with a binomial link function in base R (R Core Team, 2017). Final models with the greatest predictive capacity were then used to compare predicted settlement patterns with known boma locations.

3. Results

We identified and mapped 953 bomas within the study site (see Fig. 2). We tested the distribution for complete spatial randomness using Ripley's L test (Baddeley, Rubak, & Turner, 2015) and found that the points were non-randomly distributed in a clustered pattern – at least up to the distance of approximately 10 km.

3.1. Landscape scale factors

Three broad landscape scale factors appear to shape settlement in the study site: soil conditions suitable for settlement, favorable climactic conditions, and the extent of agriculture (Fig. 4a–c respectively).

"Black cotton" vertisols, which are clearly visible on aerial imagery of the study area, have a strong effect on settlement locations in the study area (see Fig. 4a). Only three bomas were mapped on this soil type (which is likely a result of the inaccuracy of the digitization of the soil extents). Table 2 summarizes the results of excluding the mapped areas of vertisols from the "habitable" area in the study communities. Excluding these areas increases the divergence from the bounds of spatial randomness in the Ripley's L test indicating increase clustering of settlements. Notably, in 2017, during group interviews in the study area, we asked about the relevance of black cotton soils and respondents indicated that they serve as important grazing areas for small stock. They reported that Maasai traditionally seek to be near these soils, but not on them.

Climactic zones also appear to shape settlement patterns in the region (see Fig. 4b). When excluding black cotton soils, there is evidence of preferential settlement of the wetter, more temperate portions of the study area (Pearson correlation < 0.000). The Lower Mesotropical subhumid zone, which predominates in Loiborsoit had the highest density of bomas (1.3/sq. km), while the Thermotropical Dry zone had the lowest density (0.4/sq. km). These results are summarized in Table 3. To capture a more continuous range of climactic factors in our regression models, we substituted these categorical distinctions with elevation, mean annual precipitation, mean annual temperature.

There are variable amounts of agricultural development across the study site (see Fig. 4c). Agriculture covers 9% of the total study area. However, this increases to 13% if only considering the habitable zones, which appear to limit agriculture as well. Distances to agriculture are summarized in Table 4.

3.2. Logistic regressions

The bivariate results of the geographic variables on settlement probability are summarized in Table 5. Each variable was significantly associated with settlement location, with the exception of slope. Distance to the nearest village center had the strongest association with settlement (in both linear and quadratic forms), followed by distance to Lokisale GCA (quadratic), distance to water (quadratic), elevation, distance to roads (quadratic), temperature, precipitation, NDVI measures and other metrics.

Table 6 presents the results of the multivariate models, including a full model that integrates all the variables from the three thematic models. Table 7 presents model comparisons. The resource access model had the lowest predictive ability and highest AICc. The environmental constraints model had greater predictive ability, but the AUC was only slightly higher than the resource access model. Of the thematic models, the modernization model had the highest AUC (though only slightly higher) and lowest AICc score. The combined model, however, which represents an integration of three other models, had a lower AICc and a 0.06 improvement in the AUC over the modernization model. Fig. 5 compares the known boma locations (left panel) with the predicted probability of settlement from the combined model (right panel). And Fig. 6 presents a cumulative distribution plot of the percentage of occupied cells predicted correctly against the modeled occupation probability.

4. Discussion

Despite widespread agreement among scholars that traditionally mobile pastoralists are transitioning to more sedentary lifestyles, few studies have directly addressed the question of where groups settle (Fratkin & Roth, 2005; Western & Nightingale, 2003; Worden, 2007). This study has sought to examine this issue for four Maasai communities in northern Tanzania. Working in this same study area, Leslie and McCabe (2013) have highlighted the importance of this issue pointing out that the spatial arrangement of settlement, together with the livelihoods people pursue in different parts of the landscape, will influence

Table 2
Settlement density accounting for vertisols.

Village	Bomas	Sq. km	Settlement Density	Vertisols extent (sq. km)	Vertisols (% surface area)	Habitable area (sq. km)	Bomas per habitable area
Loiborsoit	373	316.9	1.18	34.3	11	282.6	1.32
Terrat	152	200.4	0.76	46.7	23	153.7	0.99
Emboreet	250	462.5	0.54	150.2	32	312.3	0.80
Sukuro	178	552.4	0.32	172.8	31	379.6	0.47
Totals	*953*	*1532.3*	*0.62*	*404.1*	*26*	*1128.2*	*0.84*

Table 3
Settlement density by climactic zone.

Climate Zone	Habitable area (sq. km)	% of total area	Bomas (#)	Bomas (%)	Bomas (per km)	Divergence (%)
Lower mesotropical subhumid	303.0	26.9	395	41.5	1.3	14.6
Lower mesotropical dry	477.2	42.1	418	43.9	0.9	1.7
Thermotropical dry	350.1	31.0	140	14.7	0.4	−16.3

Table 4
Settlement distances to agriculture.

Village	Mean distance (m)	Min distance (m)	Max distance (m)	Quantiles (25%)	Quantiles (50%)	Quantiles (75%)	ANOVA $p < 0.001$
Emboreet (E)	180	0	1495	58	98	170	S, T
Loiborsoit (L)	203	0	1958	37	76	195	S, T
Sukuro (S)	653	24	4228	126	276	1011	E, L
Terrat (T)	581	0	3626	74	219	829	E, L
Total	*342*	*0*	*4228*	*57*	*112*	*343*	-

Table 5
Bivariate logistical regression of geographic variables on settlement patterns.

Parameter	Estimate	SE	Odds Ratio	Generalized R-squared	AUC
Distance to village center (km)^2	−0.189 (−0.010) ***	0.014 (0.002)	#	0.098	0.688
Distance to village center (km)	−0.169***	0.083	0.845	0.092	0.688
Distance to Lokisale GCA (km)^2	−0.019 (−0.005) ***	0.004 (0.000)	#	0.091	0.678
Distance to Lokisale GCA (km)	−0.015***	0.003	0.985	0.008	0.545
Distance to permanent water (km)^2	−0.287 (0.055)***	0.000 (0.011)	#	0.046	0.640
Distance to permanent water (km)	−0.260***	0.027	0.771	0.039	0.638
Elevation (m)	0.730***	0.057	2.075	0.039	0.643
Distance to roads (km)^2	−0.205 (−0.025) ***	0.022 (0.009)	#	0.050	0.626
Distance to roads (km)	−0.226***	0.020	0.798	0.047	0.626
Mean annual temp. (C)	−1.108***	0.094	0.33	0.045	0.627
Mean annual precip. (mm)	0.007***	0.0006	1.007	0.045	0.626
Mean NDVI (2 km – standardized)	0.335***	0.039	1.399	0.022	0.594
Mean NDVI (10 km – standardized)	0.343***	0.041	1.409	0.022	0.594
Tsetse fly probability (%)	−2.624***	0.330	0.725	0.013	0.597
Canopy cover (%)	−0.110***	0.015	0.896	0.018	0.570
CV NDVI (2 km – standardized)	0.807***	0.036	0.333	0.010	0.552
CV NDVI (10 km – standardized)	−0.247***	0.035	0.306	0.014	0.539
Distance to Lokisale GCA (km)	−0.015***	0.003	0.985	0.008	0.545
Slope (%)	0.035	0.031	1.036	0.000	0.514

$p < 0.05$, $**p < 0.01$, $***p < 0.001$, # odds ratios are not interpretable for compound effects.

Table 6
Results of multivariate models.

Variable	Coefficient	SE	Odds Ratio	Prob > ChiSq
Resource Access Model				
NDVI (standardized mean @ 10 km)	0.302	0.043	1.35	<0.0001***
NDVI (standardized CV @ 10 km)	−0.124	0.092	0.88	0.0004**
Distance to water (km/1000)	−0.275	0.027	0.76	<0.0001***
Distance to water (km/1000)^2	−0.052	0.011	#	<0.0001***
Environmental Constraints Model				
Elevation (m/100)	0.774	0.061	2.167	<0.001***
Canopy cover (%)	−0.197	0.018	0.821	<0.001***
Mean slope (%)	0.196	0.035	1.216	<0.001***
Tsetse probability (%)	−2.413	0.373	0.090	<0.001***
Modernization Model				
Distance to village center (km)	−0.110	0.017	0.992	<0.001***
Distance to village center (km)^2	−0.008	0.003	#	<0.001***
Distance to road (km)	−0.158	0.025	0.985	<0.001***
Distance to road (km)^2	−0.117	0.009	#	0.0641
Distance to Lokisale GCA (km)	−0.013	0.004	0.998	0.003**
Distance to Lokisale GCA (km)^2	−0.002	0.001	#	<0.001***
Full Model				
NDVI (standardized mean @ 10 km)	0.706	0.076	2.025	<0.0001***
NDVI (standardized CV @ 10 km)	−0.054	0.059	0.947	0.354
Distance to water (km/1000)	−0.136	0.032	0.933	<0.001***
Distance to water (km/1000)^2	−0.030	0.013	#	0.021*
Elevation (m/100)	0.597	0.149	1.817	<0.001***
Canopy cover (%)	−0.167	0.021	0.846	<0.001***
Mean slope (%)	0.117	0.049	1.124	0.016*
Tsetse probability (%)	−1.011	0.409	0.364	0.014*
Distance to village center (km)	−0.034	0.018	0.967	0.060
Distance to village center (km)^2	−0.008	0.003	#	0.006**
Distance to road (km)	−0.129	0.031	0.828	<0.001***
Distance to road (km)^2	0.006	0.011	#	0.568
Distance to Lokisale (km)	0.042	0.011	1.021	<0.001***
Distance to Lokisale (km)^2	−0.002	0.001	#	<0.001***

$*p < 0.05$, $**p < 0.01$, $***p < 0.001$, # odds ratios are not interpretable for compound effects.

Table 7
Model comparisons.

Model	AICc	Delta AICc	No. of parameters	Generalized R-squared	AUC
Resource Access	4441.0	332.2	4	0.064	0.684
Environmental Constraints	4395.7	287.0	4	0.101	0.696
Modernization	4307.0	198.3	6	0.127	0.706
Full	4108.8	0.0	14	0.185	0.768

both the ecology of the region and the resilience of human communities.

The results of the spatial modeling support the idea that both built and natural environments are associated with settlement patterns in the study area, findings that both contrast, and align, with those from decades ago (Western & Dunne, 1979). The most parsimonious model combined factors from each hypothesis, suggesting that decisions surrounding settlement location involve diverse factors. Alternatively, settlement decisions may be transitioning to privilege infrastructural concerns over environmental ones, a possibility that these analyses are not able to address. The spatial patterns identified here shed some new light on the ongoing diversification of pastoralist livelihoods, the importance of diverse resources, and a range of environmental considerations facing modern pastoralists (Baird & Hartter, 2017; Homewood, Trench, & Kristjanson, 2008; Little et al., 2001; McCabe et al., 2010). Certainly, these findings are functions of the data resolution we selected. Given the limited data availability for this study area, however, we believe that 400m resolution is justifiable for the reasons described above.

Our analyses show that geophysical features broadly shape settlement patterns. "Black cotton" vertisols especially have a visibly evident effect on the distribution of bomas in the study area. These soils cover approximately 26% of the area, are seasonally impassable and are uniformly uninhabited, findings consistent with prior research (Western & Dunne, 1979). However, as noted above, Maasai respondents have reported that these soils do have considerable value as forage areas for wildlife and livestock (MARI, 2006).

Settlement densities vary significantly across the study area, even controlling for the extent of uninhabited soils. Our findings show that bomas are more clustered than would be expected if they were distributed randomly. Notably, we did not find evidence of strong resource competition, which can push individual settlements to maximize their distance from other settlements in order to have exclusive access to local resources as was found in Kenya following the sub-division of land (Worden, 2007).

Ultimately, our modeling approach provides a view of the overall pattern of settlement in the study area at a scale that may not be achievable even with multiple seasons of dedicated field work. This view suggests that many factors are associated with settlement location and none of the hypotheses presented here can be rejected. Furthermore, our observation about the strong relationship between black cotton soils and the pattern of settlement is important – and unlikely to be gained through other methods. But this approach inherently privileges the environment and is not well suited to address larger questions related to sedentarization. Specifically, social scientific approaches are needed to fully examine individual household decision-making processes across a range of political and economic circumstances in order to truly understand settlement location decisions. Nonetheless, our approach provides some insights regarding settlement, raises new questions, and points towards new strategies.

The causes and consequences of settlement density are still open questions in the literature on pastoralist sedentarization. Little et al. (2001) observed that the more densely populated an area is, the less land is generally accessible for communal grazing. Respondents in our study area have complained for years that population is increasing, but it's unclear to what extent higher levels of density in parts of the study site would be considered "crowded" – or if there are agreed upon upper limits. In fact, little is known about how settlement density affects settlement decisions. It may be tempting to hypothesize that less dense areas afford greater flexibility and stronger relationships between settlement locations and landscape features. However, policies surrounding land-tenure, land use, and conservation likely impose constraints and opportunities across scales that confound simple density/settlement relationships. These issues are ripe for research as populations continue to grow and frontier areas become denser.

Of the three *a priori* spatial models, our modernization model performed the best – though it showed only a small improvement over the other two models. This would seem to suggest a few alternative scenarios. First, it may be that no single strategy dominates settlement location decisions. Households are diverse and have diverse perspectives on where to settle with some focused more on resources, others on environmental constraints, and still others on modern amenities. Second, households may be similar in how they balance between these different criteria. A third possibility, which a historical, longitudinal assessment of settlement could afford, is that one of these strategies offers a clear advantage in the early stages of settling in a low-density area, whereas other strategies are preferred in subsequent stages as

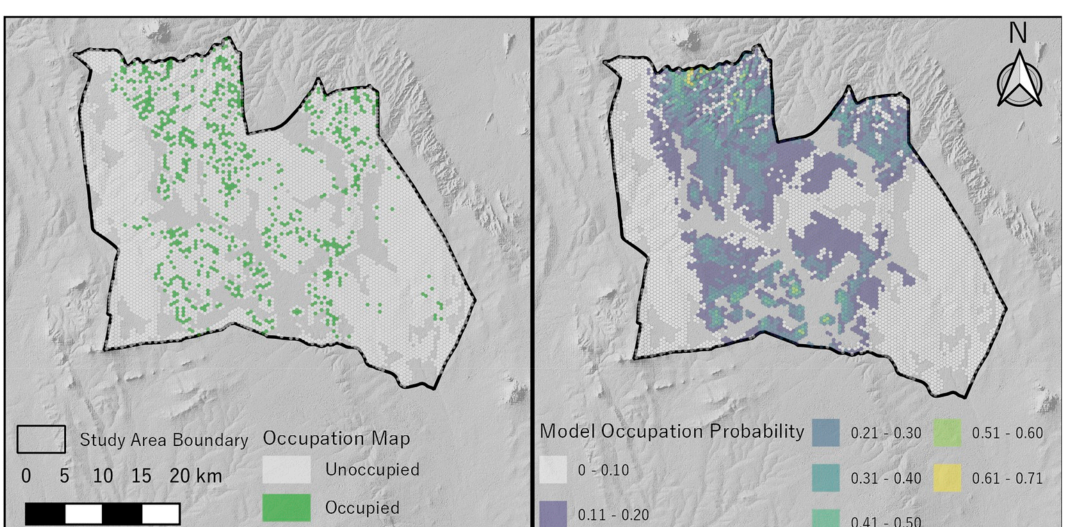

Fig. 5. Known occupied areas (left panel) and modeled occupation probabilities (right panel).

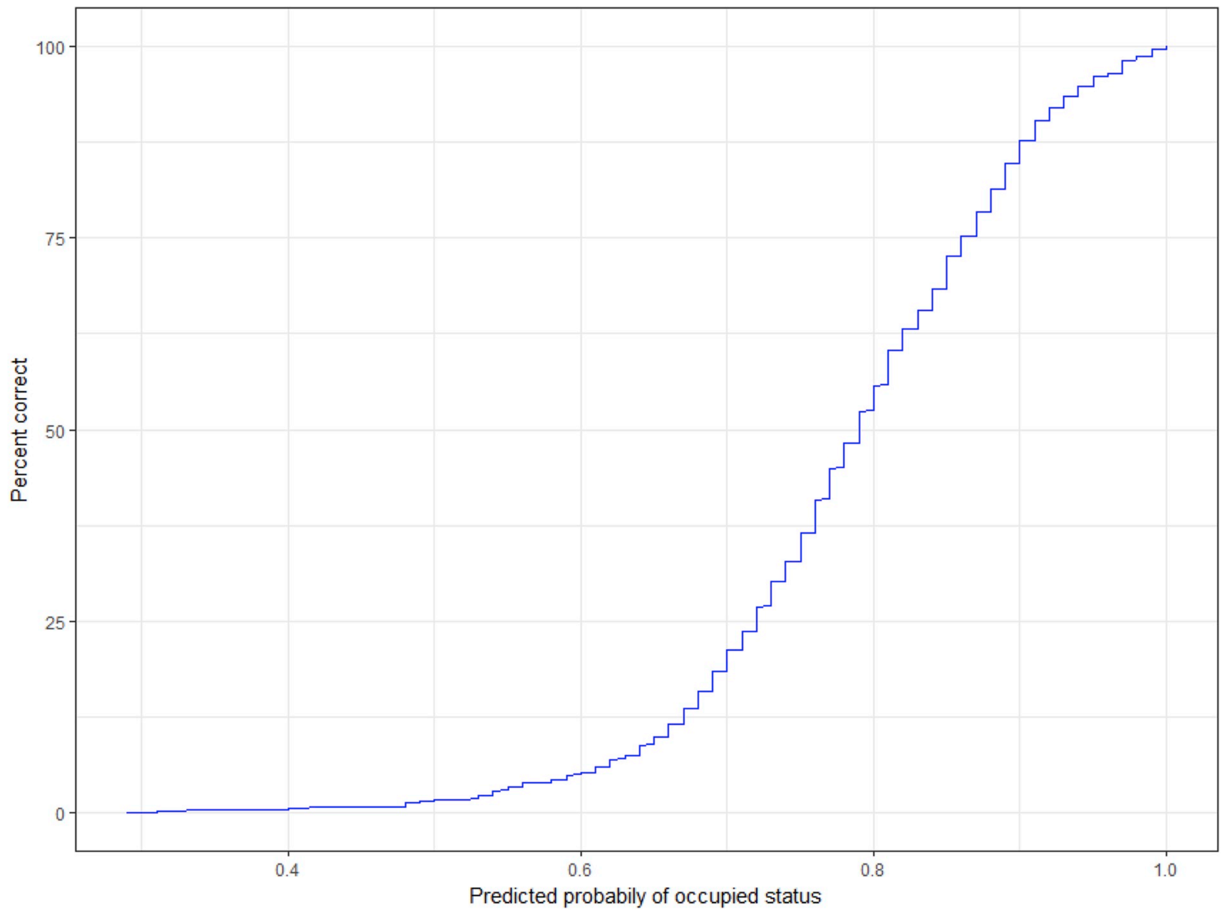

Fig. 6. Cumulative distribution of modeled occupation probability and percent of occupied cells correctly identified.

density increases. For this study, however, our combined model shows marked improvement over the other three models in predicting settlement locations.

Overall, our findings are consistent with strong currents in pastoralist research, which have shown that groups are shifting from highly mobile livelihoods that rely on seasonably variable resources to more sedentary livelihoods that draw on more spatially fixed, albeit diverse, resources (Homewood, , Kristjanson, , & Trench, 2009; Leslie & McCabe, 2013). At the landscape scale, there is broad agreement between our full model and the known settlement pattern in the study area (Fig. 5). Still, the modest AUC of the full model (0.768) indicates that the predictive power at the grid cell level could be strengthened. Future analyses could focus on village land allocation policies as well as norms surrounding the subdivision of allocated land at the household level. Also, many of the cells with a high probability of being occupied in the model, but which are not, are covered by agricultural fields.

Accounting for the effect of agriculture on settlement patterns proved difficult to model. At the grid cell level, many bomas were located in cells that contained a mix of agricultural plots. Furthermore, given the recent and rapid expansion of agriculture in the study area, it was difficult to untangle the interplay between settlement patterns and agricultural development. Based on our experience in the study area since 2005, it is much more likely that the development of agricultural plots has followed settlement than that settlement has been limited by agriculture. For these analyses, therefore, we took the more conservative approach of not excluding agricultural plots from the models. Going forward, however, this temporal order could shift. In other parts of East Africa, pastoralists have expressed concerns that agriculture is crowding out opportunities for livestock keeping (Kimiti, Wasonga, Western, & Mbau, 2016; Western, Groom, & Worden, 2009), concerns that are common in our study area. These highlight the importance for new modeling and/or qualitative approaches to examine the spatial and temporal dynamics of settlement patterns and agricultural development.

Another limitation of this study was the difficulty associated with modeling forage access at scale. Here we used smoothed time-series data to account for broader trends in NDVI while adjusting for the types of noise inherent in these data (Shao, Lunetta, Wheeler, Iiames, & Campbell, 2016). Wet season (2 km) and dry season (10 km) measures of NDVI were strongly correlated, so only 10 km values were retained in the final models. And while mean NDVI had the strongest effect of any of the individual variables in the full model, this result should be viewed with some caution. Remote sensing can evaluate metrics like NDVI at large scales in pastoralist environments (Butt, 2010b; Coppolillo, 2001; Moritz et al., 2014; Trench et al., 2009), but it remains difficult to identify resource areas in the larger landscape that are critical sources of forage access (BurnSilver et al., 2004; Coppolillo, 2000; Miller, 2015). Furthermore, it is unclear to what extent differences detectable with remote sensing represent actual differences on the landscape that Maasai would recognize and act on. In other areas, researchers have used GPS tracking to trace and quantify herd movements (Butt, 2010a, 2010b; Coppolillo, 2000; Moritz, Galehouse, Hao, & Garabed, 2012), which can give a better picture of resource use at a fine scale, but is difficult to generalize to other landscapes. Agent-based modeling may be a better approach to model forage resource access, but it requires significant technical and computing resources (Moritz et al., 2010). And while Maasai are certainly dependent on local resources, they have culturally-prescribed strategies to deal with highly variable resource access, including local social networks of reciprocity (Baird & Gray, 2014) and clan-based networks that extend to distance lands where livestock can be moved in search of better conditions (Butt, 2011;

McPeak & Little, 2005; Sachedina & Trench, 2009). These factors greatly complicate efforts to model resource access around a given location. Correspondingly, the generalized forage access model presented here could be significantly refined by qualitative research addressing these issues.

This research represents a single snapshot in time, so inference about how settlement patterns are changing is limited. Our understanding of sedentarization would be greatly enhanced by a longitudinal approach that mapped changes in settlement over time. The widespread availability of free, high-resolution remote-sensing data makes this much more feasible than it has been in the past. In Kenya, Worden (2007) worked with local informants to recreate historic settlement patterns. While this approach provides rich data, it is also extremely labor intensive.

The main disadvantage of using a remote sensing approach to evaluate settlement is that we know very little about the identified households beyond their location. These methods are poorly suited to explain household-level decisions, which are highly contingent on households' individual circumstances. There are numerous cultural, social, political and economic pressures that affect what portions of the landscape become settled that cannot be captured in a study like this. Advances in this type of modeling would include qualitative field work to further refine and test spatially driven hypotheses and observations.

Declaration of competing interestCOI

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2019.102086.

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