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Herd foraging and vegetation dynamics in a savanna system in Laikipia County, Kenya

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Summary

In Laikipia County, Kenya, landowners involved in livestock and crop production, wildlife conservation, and tourism activities and livestock owners hire pastoralists to herd animals. Pastoralists can encourage herds to use highly palatable and less palatable forage resources within each foraging itinerary. Such a herding strategy could mitigate rangeland degradation while feeding animals adequately. The objectives of this observational study were to examine vegetation dynamics and to determine the driving forces behind biomass utilisation rates (BURs) of herds reflecting the time herds engaged in foraging, walking or resting spent on a unit of area around night resting places (NRPs). Furthermore, this research aimed to measure live weights and to identify factors influencing the length of daily foraging itineraries and area densities of herds over foraging itineraries.

On a ranch (about 11,500 hectares) in semi-arid Laikipia County, one homestead consisting of hired pastoralists, one herd of mature cattle (n = 89), one herd of weaner cattle (n = 86), one mixed herd of goats and sheep (n = 93), and one herd of camels (n = 44) was studied between June and September 2018. Vegetation dynamics were measured along six regularly spaced transects around two consecutively studied NRPs with sampling points at 50, 150, 250, and 350 m distance from the NRPs. Every four days, herbaceous biomass was collected at each sampling point and classified into monocots, dicots, and dead biomass. Biomass samples were analysed for their nutrient content. The BURs were calculated for the sampling points using georeferenced data of daily foraging itineraries recorded in 20-second intervals, area densities of herds measured by a hand-held global positioning system receiver, and live weights of all animals determined monthly. Activities of hired pastoralists and herds were monitored, interviews with locals conducted, and weather data collected. Generalised linear mixed models were developed to analyse the spatially and temporally correlated BURs and the conceivably temporally correlated area densities of herds, whereas structural time series analysis were used to explore the length of daily foraging itineraries.

Vegetation dynamics around NRPs did not reveal any spatial and temporal patterns. The main factor driving BURs was palatability of dominant species on sampling points. All livestock species sought patches dominated by *Cynodon dactylon*, possibly being overgrazed. Patches dominated by either *Andropogon contortus* or *Themeda triandra* around the first night resting place were underused as indicated by biomass accumulation. Average daily live weight gain of mature cattle was higher than the one of weaner cattle, implying the efforts of hired pastoralists to increase milk yields for their personal use. The length of daily foraging itineraries was predominantly determined by the distance travelled the recent days and area densities of herds were mainly controlled by the positions or interventions of hired pastoralists, both demonstrating their importance to targeted foraging.

In this study, the efforts of hired pastoralists did not lead to the desired herding effects. Therefore, motivating hired pastoralists to design foraging itineraries utilising diverse patches intentionally is crucial to an efficient use of rangeland resources while meeting the nutritional requirements of animals.

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ADF	Acid detergent fibre
ADL	Acid detergent lignin
AICc	Akaike information criterion corrected
BUR	Biomass utilisation rate
BURs	Biomass utilisation rates
CA	Crude ash
CP	Crude protein
DM	Dry matter
GPS	Global positioning system
HC	Herd of camels
HGS	Herd of goats and sheep
HMC	Herd of mature cattle
HWC	Herd of weaner cattle
NDF	Neutral detergent fibre
NPR	Night resting place
NRPs	Night resting places
OMD	Organic matter digestibility

1 Introduction

Rangelands in arid and semi-arid environments cover approximately one third of the global land areas (Sharafatmandrad, 2019) and represent the living space of about two billion people (Millennium Ecosystem Assessment, 2005). Rangelands in drylands are ecosystems with natural vegetation dominated by an herbaceous plant cover and characterised by water scarcity (Mannetje, 2002). Semi-arid rangeland ecosystems deliver important resources for human survival, such as plant and animal species to prepare food, forage species to produce dung, leather, meat, milk, wool, and ligneous species to build fires, fences, and houses (Millennium Ecosystem Assessment, 2005; Sala et al., 2017). The varying and unpredictable availability of resources in these ecosystems is mainly driven by both non-equilibrium dynamics such as precipitation fluctuations and equilibrium dynamics like impacts of herbivores (Briske et al., 2003). Traditionally, these ecosystems are utilized by pastoralists efficiently, as foraging areas are accessed at different times of the year to prevent food shortage during the dry season and rangeland degradation (Homewood, 2008). Rangeland degradation refers to a permanent and irreversible decrease in forage production for a certain amount of precipitation (Behnke and Abel, 1996). It can occur if certain parts of the landscape are repeatedly grazed (Fuls, 1992). Herd movements based on the ecological knowledge of pastoralists have preserved the East African rangelands (Bollig and Schulte, 1999; Oba, 2001), since the mobility of pastoral herds enables an opportunistic use of spatially and temporally variable and unpredictable forage resources in semi-arid environments (Turner et al., 2014). The degree of opportunism differs between pastoralist populations (Western and Dunne, 1979; McCabe, 2004) and types of rangeland systems (Cougbenour, 1991; Kimani and Pickard, 1998), but they are all subject to spatial heterogeneity and temporal variability (Vetter, 2005).

Prior to the agreements between the Maasai pastoralists and the British settlers in 1904 and 1911, the area in semi-arid Laikipia County, Kenya, was designated as Maasai land (Hughes, 2006). The movements of the Maasai pastoralists do not vary widely in frequency and distance, and thus they evaluate rangelands at patch level (Mapinduzi et al., 2003). After the declaration of independence in 1963, some properties of the British settlers were acquired and subdivided in non-governmental and governmental land purchase schemes for subsistence farming (Kohler, 1987). These days, Laikipia County comprises privately owned and group ranches, government ranch land, smallholder farms, and wildlife conservancies (Boles et al., 2019). Most of the land is under large-scale ownership and many landowners are engaged in livestock and crop production and wildlife tourism and management (Bond, 2014b). Some landowners have employed pastoralists to tend to livestock on a daily basis (Yurco, 2017). In the daytime, hired pastoralists take the animals to foraging areas and water sources and overnight, animals are corralled in night resting places (NRPs), built from brushes of *Acacia* species. Throughout this paper, the term *night resting place* (NRP) refers to the spatial aspects of the homestead and the term *homestead* comprises the hired pastoralists and the herds that are moved as one unit around the property. Pastoralists can control the diet selection of herds and the foraging areas over daily foraging itineraries in order to stimulate feed uptake of highly palatable and less palatable plants while meeting the nutritional requirements of the animals and potentially mitigating rangeland degradation (Bayer, 1990; Meuret and Provenza, 2014). Furthermore, pastoralists can encourage goats to browse and sheep to be intermediate feeders, and thus reducing the dietary overlap between different livestock species (Samuels et al., 2016). The digestibility of forages is mostly determined by the animal species (Jeroch et al., 1999). Cattle (*Bos indicus*), goats (*Capra hircus*), and sheep (*Ovis aries*) are ruminant species that are characterized by four-chambered stomachs (Balch, 1959), while camels (*Camelus dromedaries*) are non-ruminant species (Swai and Sindato, 2015). In semi-arid rangelands in Kenya, camels are predominantly browsers, whereas cattle are mainly classified as grazers, goats as intermediate selective feeders with preference for browse, and sheep as nonselective intermediate feeders with preference for grasses (Migongo-Bake and Hansen, 1987). The term *browse* here refers to herbs, forbs, and woody plants (Gordon and Prins, 2008).

Most prior work has analysed the impacts of pastoralists on daily foraging itineraries, but do not consider the availability of forage resources (Coppolillo, 2000; Turner and Hiernaux, 2002). Many other studies have related the distribution of livestock to the rangeland resources around livestock concentration locations at the landscape level with little attention directed to herd movements with respect to vegetation resources in close proximity of livestock concentration locations (Turner et al., 2005; Butt, 2010). The lack of intensive and continuous monitoring of interactions between hired pastoralists, herds of different animal species, and their environment at patch level limits the understanding of resource utilisation patterns and variables shaping daily foraging itineraries under restricted mobility and slightly implies strategies to improve rangeland use efficiency on ranches. The examination of variability among individual vegetation patches around NRPs can raise awareness of factors affecting rangeland health and livestock productivity.

In a pre-observation period, general information about the management of the ranch and the homesteads and movement patterns of herds around NRPs was gathered and used for developing an appropriate study design. Through participant observation and full days of herding with hired pastoralists of different homesteads, a suitable homestead was selected and global positioning system (GPS) receivers were tested. To evaluate the attractiveness of vegetation patches in this study, a measure called biomass utilisation rates (BURs) of herds was used. The biomass utilisation rate (BUR) is defined as the live weight of a herd expressed as tropical livestock units (one tropical livestock unit equals 250 kg live weight) on the area covered by the herd (m^2) for the time the herd spent resting, foraging, and walking within the herbaceous biomass sampling area crossed (s/m^2). This research was part of the Ellrichshausen-Stiftung-funded project on *Underutilized or unprotected? New methods for* *analysing diverging perspectives on the large-scale conversion of tropical grassland eco-systems*, which included but was not limited to the assessment of different rangeland use options. An in-depth case study approach was employed with the overall objective to improve the understanding of vegetation dynamics, BURs of herds, and daily foraging itineraries designed by hired pastoralists around the NRPs in a semi-arid rangeland at patch level, providing potential implications for a sustainable use of rangeland resources, also considering climate data on-site. Therefore, the following supportive research questions were addressed:

(I) Are any spatial and temporal patterns of vegetation dynamics around the NRPs detectable?

(II) Does the rearing of different livestock species increase the resource use efficiency of forages around the NRPs?

(III) What driving forces determine the observed BURs?

(IV) Are the selected biomass sampling points appropriate for describing the use of rangeland resources around the NRPs?

(V) Do hired pastoralists meet the nutritional requirements of animals?

(VI) Which factors influence the length of the daily foraging itineraries?

(VII) Which determinants underlie area densities of herds over foraging itineraries?

The following hypotheses corresponding to each of the above-mentioned research questions respectively were examined based on the notion that controlling the movement of animals can mitigate both underuse and over-foraging of plant species around the NRPs while meeting the nutritional requirements of animals:

(I)

- *a.* Vegetation dynamics around the NRPs differ between biomass sampling points.
- *b.* Vegetation dynamics are driven by the BURs of the herds.
- *c.* The effects of animals on the vegetation are more pronounced at the entrances to the NRPs of the cattle herds than at the ones of the other herds.

(II) As herds consist of either foraging, browsing, or intermediate species, they utilise herbaceous biomass sampling points around the NRPs differently.

(III)

- *a.* The BURs are higher at biomass sampling points contiguous to the NRPs compared to those further afield, due to reduced speeds of animals while entering the NRPs.
- *b.* The BURs are highly dependent on the herd species composition, biomass availability, and growth stages of plants and therefore differ between vegetation patches.

(IV)

a. The directions of daily foraging itineraries are closely spaced around the NRPs. As a result, each herd utilises each direction from the NRP in the course of the presence of the homestead.

b. Except for the herd of camels (HC), the herds spend a considerable amount of time within the biomass sampling belts.

(V) Live weights of animals increase gradually in the course of the observational study.

(VI)

a. The length of daily foraging itineraries increases with time.

b. The distance to water sources limits the length of the daily foraging itineraries, in case of the herd of mature cattle (HMC), the herd of weaner cattle (HWC) and the mixed herd of goats and sheep (HGS).

(VII) Over foraging itineraries, area densities of the HC increase with longer distances to the NRPs, whereas the ones of the other herds remain constant.

The current section introduced the traditional use of semi-arid rangelands by pastoralists and the livestock production system on ranches in Kenya and highlighted the relevance of studying the relationship between forage resources, livestock herds, hired pastoralists, and the environment. Section 2 describes the selection of the study area and the used in-depth case study approach, employing both quantitative and qualitative methods. The third section presents the selected ranch and homestead, the analysed climatic conditions, the measured vegetation dynamics, and the calculated BURs and delves into the factors affecting the BURs, the length of daily foraging itineraries, and the area densities of herds over daily foraging itineraries. Based on the findings from this paper and literature, section 4 discusses the mixed method approach, the utilisation of heterogeneous forage resources around NRPs, and the interventions of hired pastoralists in the diet selection process of herds. The concluding section focuses on the main issues of this study and implies further research activities that possibly contribute to an efficient use of forage resources in semi-arid rangelands.

2 Materials and methods

The study in a semi-arid rangeland in East Africa was based on an in-depth case study approach. To improve the understanding of vegetation dynamics, BURs, and daily foraging itineraries around NRPs in a semi-arid rangeland at patch scale, both quantitative and qualitative methods were employed. The different methods including observations of participants and weather, measurements of herbaceous biomass availability, determinations of forage quality and live weights of animals, collections of georeferenced data of foraging itineraries and area densities of herds, and monitoring behaviour of livestock herds are explained in the following. Each subchapter provides information on the activities carried out in the pre-observation period.

2.1 Selection criteria for the study area and its location

Looking for pastoralists who practise herding methods that intervene in the diet selection process and manage shortages that occur due to intra- and interannually unpredictable precipitation with diverse livestock species foraging on heterogeneous vegetation in a semi-arid East African rangeland, indigenous knowledge and practises of ethnic groups such as Turkana, Samburu, Maasai, and Borana were relevant to this study. Laikipia County in Kenya was selected, which is a suitable location to find these settings.

In order to select an appropriate study design, information on the behaviour of pastoralists and the movement patterns of herds in Laikipia County was gathered from locals and researchers in the field. Beyond the bounds of privately owned ranches, the unpredictably varying number of pastoralists and thus livestock herds foraging on an area under investigation leads to difficulties in obtaining reliable quantitative data on BURs in relation to heterogeneous forage availability and factors affecting BURs and daily foraging itineraries. The underlying principles of managing livestock herds and forage resources on privately owned ranches are similar to those applied by pastoral communities in this region. On privately owned ranches, pastoralists have been employed to tend to livestock on a daily basis. Those hired pastoralists take the animals to foraging areas and watering places during the day. Overnight, the animals are corralled in NRPs. These foreseeable foraging itineraries were considered suitable for describing the relationships between vegetation, livestock, and humans in semi-arid rangelands at patch level, especially as hired pastoralists are supposed to intervene in the forage selection process of animals in order to meet their nutritional requirements while insuring renewable forage resources. It was also assumed that the herding methods and their impacts were more profound and controllable on a limited area than on a large one. To account for differences between pastoral communities and hired pastoralists on ranches, qualitative data collection was conducted. In addition to the availability of diverse livestock species, heterogeneous forage resources, and relatively well predictable sizes of herds and movements of hired pastoralists on ranches, the ranch Ol Maisor in Laikipia North constituency was selected due to its relatively good infrastructure and facilities. The ranch, located in the Rift Valley at about 1,870 m above sea level, covers an area of approximately 11,500 ha (Figure 3.1). This ranch is bounded on the east by a privately owned ranch. In the other three cardinal directions, the ranch is surrounded by national reserves, allowing the student to receive an impression of the broader social context in which the ranch is embedded, by occasionally observing the respective conditions of rangelands and herds visually.

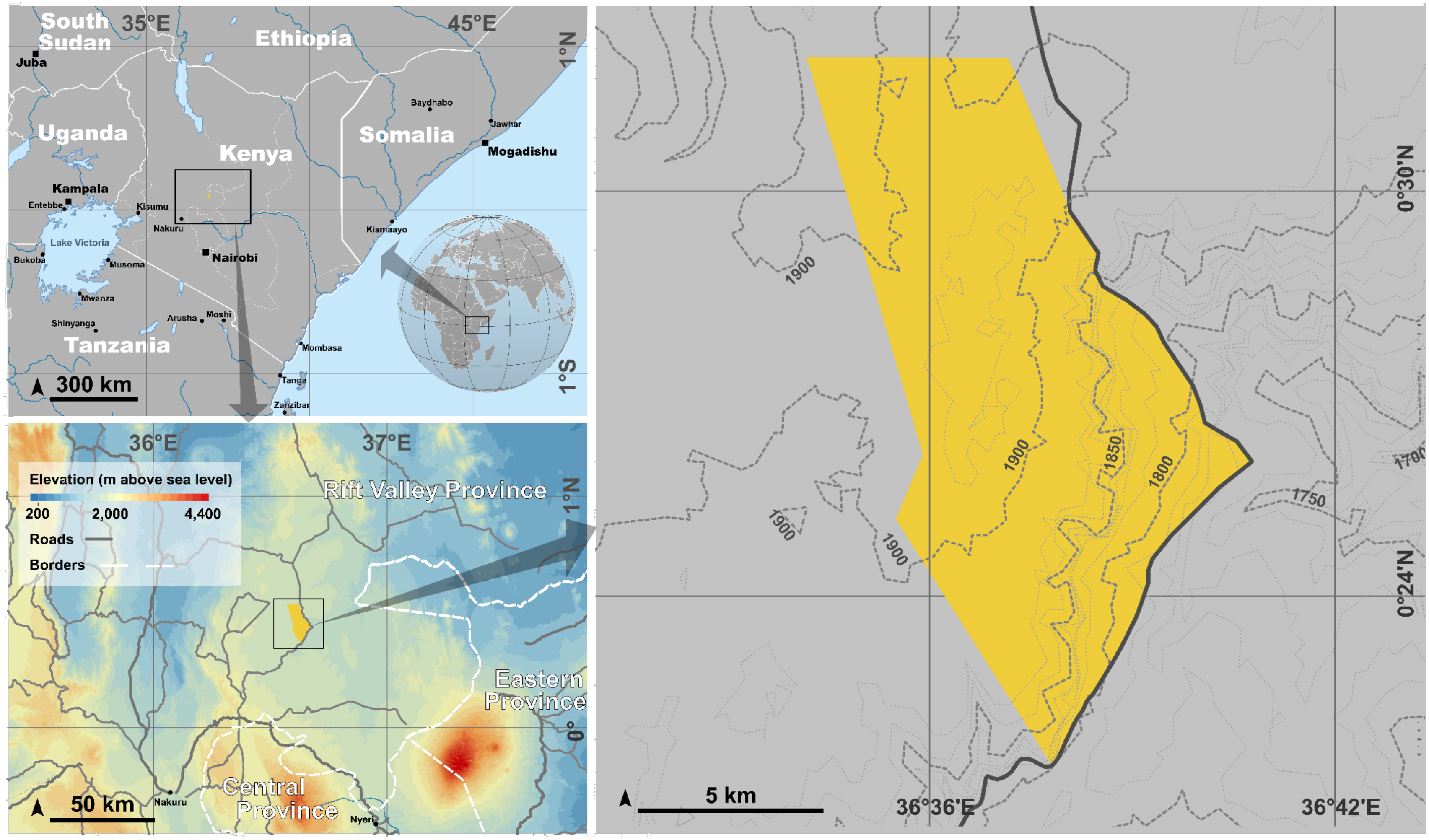


Figure 3.1 Outline of maps showing the study area in Laikipia County, Kenya, generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

2.2 Participant observation and interviews

Qualitative research data were recorded on and near the study area from May to October 2018. By the end of May, direct contact with potential homesteads had been established, with the aim of selecting the most suitable homestead for this research. In accordance with the number of GPS receivers to hand, the homestead studied was selected due to its number and sizes of the herds.

Participant observation involved full days of herding with hired pastoralists and living in their homesteads, to ascertain a greater sense of their living conditions and perceptions. Observed behaviour was used to elicit further information from respondents. Direct personal involvement with respondents fostered a rapport that encouraged respondents to admit their thoughts about environmental and social changes and herding strategies more fully, thus providing insight into herding efforts. Throughout the observational period, detailed notes from participant observation and herd management practises were taken. Interventions and positions of hired pastoralists and resulting herd responses were monitored by visual observation and photographed by a digital camera (Canon PowerShot A620, Canon Inc., Tokyo, Japan) at three-minute intervals during the course of a herding day.

In addition to participant observations, perceptions were collected through in-depth interviews and informal conversations with respondents willing to participate in the surveys, to situate the quantitative research findings and observed herding practices within the social context on the ranch. Discussing the perceptions of social and environmental changes, shifts in land, wildlife, and livestock management strategies, impacts of those transitions and the sustainability of the present management practises, and diverse facets of professional herding jobs without an order or a predetermined formulation of questioning permitted the collection of profound information and exploration of unprompted remarks by informants. Each respondent was informally interviewed on several occasions, separately or in a group of maximal four. A few visitors and current and former labourers spent considerable time with ensuring translations.

2.3 Precipitation and temperature

From early June until late September 2018, precipitation and temperature data were obtained from three rain gauges (IM523, Pessl Instruments GmbH, Weiz, Austria), distributed over the area under study, to monitor spatial and temporal variation in weather data. The tipping buckets, encircled by dense and thorny *Acacia* branches, were installed about 1.7 m above ground level on open plains, with the aim of reducing potential disturbances, caused by the surrounding environment. Each tipping bucket was calibrated to measure 0.2 mm per event and was equipped with a data logger (HOBO Pendant Event/Temp Data Logger, Onset Computer Corp., Bourne, Massachusetts, United States of America). The data loggers measured the exact time and date of each event, recorded by the tipping bucket, and the air temperature in °C every minute. Placing the data loggers on the bottom side of the tipping buckets permitted the collection of accurate air temperature measurements. Every month, records were downloaded to a personal computer, using the HOBOware software (Version 3.7.14), and exported to Microsoft Excel (Version 2016). For the purpose of this study, rainfall intensity in mm/h was calculated as the sum of consecutive events that were less than five minutes apart divided by the respective duration, thus considering rainfall intensities equal to or greater than 0.017 mm/h. Precipitation data were collected at the weather station of the large-scale ranch.

2.4 **Observational design**

To examine the relationships between herd movements directed by hired pastoralists and forage resources in close proximity of livestock concentration locations at patch level, almost regularly spaced transects around NRPs were established between June and September 2018. The number of transects and the angles between adjacent transects were adjusted in order to capture the spatial heterogeneity of rangeland resources and georeferenced data of daily foraging itineraries around the NRPs adequately and to minimise the influence of small paths on the vegetation along transects. The herbaceous biomass sampling points along transects were not protected from wildlife. The length of each transect away from the NRPs and the distance of sampling points along each transect were adapted to the locations of water sources and the potential presence of wildlife. Neighbouring homesteads were instructed to keep their livestock at distances greater than 500 m to the herbaceous biomass sampling points around the studied NRPs to avoid any potential interference with them.

Before the movement of the homestead to the first and second NRP, pictures of the area around the NRPs were obtained by a drone (Mavic Pro, DJI Sciences and Technologies Ltd., Shenzhen, China) and thereafter, by the student from the ground using a digital camera. This was to ensure that the herbaceous biomass sampling points along each transect fell under diverse vegetation patches and thereby, reflecting the heterogeneity of the rangeland resources and to analyse the vegetation structure. Throughout this paper, the vegetation structure was defined according to the classification described by Fisher et al. (2014) and vegetation species were identified by local inhabitants and using literature (Dale and Greenway, 1961; Ibrahim and Kabuye, 1987). The two dominant plant species recorded at each herbaceous biomass sampling point defined vegetation patches. Afterwards, the traits of each dominant plant species were listed. The undisturbed herbage mass accumulation was determined neither under cages nor in fenced areas due to the concern of hired pastoralists arising from cage- or fence-related injuries of animals. Thus, the regrowth of herbaceous biomass is not considered in the following. Vegetation was sampled along transects around

NRPs and BURs of herds at each herbaceous biomass sampling area were calculated. In addition, daily foraging itineraries designed by hired pastoralists were recorded in order to give an indication of the representativeness of the data collected along the set transects and the potential to translate these data into the whole area affected by daily herding decisions.

2.5 Determination of herbaceous biomass and laboratory analysis

Once before the movement of animals and hired pastoralists to the NRPs, herbaceous biomass sampling at each characterised sampling point took place to give baseline conditions for the start of successional measurements. Thereafter, measurements at each herbaceous biomass sampling point were carried out every four days in the presence of NRPs and thrice after the abandonment of each NRP. These representative quadratic sampling areas of one square metre at each herbaceous biomass sampling point, with at least one m distance among them, were randomly chosen by dropping a folding ruler. Then, two folding rulers marked the perimeter of each sampling area around the dropped folding ruler. Before harvesting herbaceous biomass at each sampling point, each sampling area was photographed by a digital camera, positioned erectly over the center of the area at about 1.5 m above ground level. The pictures were processed using the ImageJ software (Version 1.43) to calculate percentages of ground covered by plants. Subsequently, sward heights were measured at 15 regularly spaced points within each sampling area by placing a card with a width of 21 cm, a length of 30 cm, and a weight of 100 g on the vegetation, then reading the heights in cm on a vertically held folding ruler and recording them. The geographical position of each herbaceous biomass sampling area was recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America).

Herbaceous biomass was determined in sampling areas by cutting the sward at about 1.5 cm above ground level using a sickle. Immediately afterwards, herbaceous biomass samples, separated by sampling point, were air dried on paper in a shelter comprising a concrete wall with a height of about 80 cm and a wire mesh fence up to the roof. Hence, samples were protected against direct sunlight, precipitation, animals, and severe wind. Depending on the relative humidity, samples were stored for several days. The drying time of samples was highly dependent on the relative humidity. Before sorting the herbaceous biomass of each sampling point by monocotyledonous and dicotyledonous plants and dead biomass, the weight of the sample was recorded using an electronic weighing balance with an accuracy of ± 0.01 g (KERN KB 2400-2N, Kern & Sohn GmbH, Balingen, Germany). Herbaceous biomass was defined as dead if it was lying on the surface or complete standing shoots showed no sign of life. After the classification, the air-dried fractions were weighed, the weights recorded, and the material manually cut into approximately 1.5 cm pieces by scissors, and stored in a dry and dark place. For the estimation of the remaining moisture content of samples after open-air drying, samples of each cutting time were grouped into categories based on morphological characteristics. All pieces of one category and one cutting time were mixed carefully by hand. Subsequently, representative sub-samples of 50 g were generated, stored in bags, labelled, sealed, and transported to the laboratory at the Jomo Kenyatta University of Agriculture and Technology, Kenya. In the laboratory, all samples were weighed again and analysed for dry matter (DM) concentrations by drying at 105°C for 12 hours in an oven (UNB 200, Memmert GmbH + Co. KG, Schwabach, Germany). The remaining moisture content after open-air drying was calculated by the weight loss during oven drying.

At the end of the study, stored samples were pooled by plant species and month to form one representative composite forage sample for DM determination and nutrient analysis. The resulting homogenised sub-samples of about 200 g were stored in labelled paper bags and sent to the laboratory at the University of Hohenheim, Germany. The similar amount of each sub-sample ensured repeatability of analyses in Germany. Following drying at 60 °C for 48 hours in the laboratory, samples were ground to pass a one-millimetre screen using a mill (SM-100, Retsch GmbH, Haan, Germany).

These pooled samples of biomass were prepared for determination of DM, crude ash (CA), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) concentrations. In addition to the concentrations of DM, crude nutrients and fibre fractions, organic matter digestibility (OMD) was analysed for those samples. Forage analyses were done according to the procedures described in the German Handbook of Agricultural Experimental and Analytical Methods (VDLUFA, 2012), and method numbers are given. The concentrations of DM (method 3.1; VDLUFA, 2012) and CA (method 8.1; VDLUFA, 2012) were determined following the procedures of the Weende analysis. According to this, moisture content was calculated by the weight loss during drying at 103 °C for 12 hours in a convection oven (FD 115, Binder GmbH, Tuttlingen, Germany). Thereafter, the dried material was incinerated in a muffle furnace (N11, Nabertherm GmbH, Lilienthal, Germany) at 550 °C for 5 hours. Nitrogen concentrations were analysed by the Dumas combustion procedure (method 4.1.2; VDLUFA, 2012) using an elemental analyser (Vario MAX, Elementar Analysensysteme GmbH, Hanau, Germany) and the corresponding CP concentrations were estimated by multiplying molecular nitrogen by a conversion factor of 6.25. The fractions NDF (method 6.5.1; VDLUFA, 2012), ADF (method 6.5.2; VDLUFA, 2012), and ADL (method 6.5.1; VDLUFA, 2012) were determined sequentially by the van Soest procedure (van Soest et al., 1991). All extractions were done with an ANKOM^{2000} Fibre Analyser (A2001, ANKOM Technology, Macedon, United States of America) using filter bags (10-µm porosity, F57, ANKOM Technology, Macedon, United States of America). Crude fibre values were expressed exclusive of CA. All above-mentioned analyses were carried out in duplicate. The Hohenheim gas test (method 25.1; VDLUFA, 2012) was conducted to estimate OMD. *In vitro* gas production after 24 h of incubation was measured in triplicate. Equation (1) was used to calculate OMD based on in vitro gas production and crude nutrients (Menke and Steingaß, 1987).

$$OMD\ (g/kg\ DM) = 8.89 \times \text{gas production}\ (ml/200\ mg\ DM\ \text{per}\ 24\ \text{hours}) + 0.448 \times CP\ (g/kg\ DM) + 0.651 \times CA\ (g/kg\ DM) + 149 \quad (1)$$

2.6 Herd movements and live weights

In the early days on the ranch, the measurement accuracy of the GPS receivers (Garmin; TrackStick, Telespial Systems Inc., Burbank, United States of America) logging at 20-, 40-, and 60-second intervals were evaluated by placing them on forage areas for 45 minutes six times. Subsequently, the deviation of the recorded positions from their centroid were calculated. In addition, the receivers were placed on a borehole with known coordinates and the deviation of the recorded positions from the borehole position were calculated, suggesting an accuracy of plus or minus three metres.

The length of daily foraging itineraries of herds was determined in two randomly selected animals of each herd. One animal of a herd was equipped with a TrackStick GPS receiver, the other one with a Garmin GPS receiver. The GPS receivers were housed in plastic containers and mounted on collars (Figure 3.2). The collars were fitted to the animals 21 days before the observation period started. In the morning before the herd left the NRP, the recorded positions of animals were saved on the receivers and the batteries were replaced diurnally. After some days, the animals wore the GPS collars without any obvious irritation and accepted the daily morning procedure. The positions of animals were recorded every 20 s. The interval of 20 s was a reasonable compromise between the required and feasible accuracy of walking animals and the one of resting animals, especially around the NRPs. Due to the storage capacity of the GPS receivers, the stored positions were transferred to a computer every ten days.

Figure 3.2 Illustration of livestock species tracked with global positioning system receivers housed in plastic containers and mounted on collars on a ranch in Laikipia County, Kenya, in 2018 (own source)

In the pre-observation period, the student went along with each herd four times in order to avoid any alterations in animal and human behaviour due to her presence during the observation period. Thereafter, each herd was separately studied by the student through full days of herding twice at the beginning of, in the middle of, and at the end of the existence of the NRPs.

On one occasion of each point in time, intra-herd positions of the animals equipped with GPS receivers and behaviour of herds and hired pastoralists were monitored by visual observation and photographed by a digital camera at three-minute intervals during the foraging itineraries. Interventions and positions of hired pastoralists, the resulting herd patterns, and the vegetation structure were recorded. Intra-herd positions of animals wearing collars were classified into left, to the left, in the midst of, to the right, and right.

The other time, herd areas were measured from the ground by the student walking around the herd and carrying a hand-held GPS receiver. To reduce the potential existence of a temporal correlation between herd areas, they were determined at 20-minute intervals in case of the HMC, the HWC, and the HGS, and at 40-minute intervals in case of the herd HC. Immediately before each measurement time point, the vegetation structure, time of day (hh:mm:ss), and interventions and positions of hired pastoralists were listed. Afterwards, herd patterns, foraging width of the herd (m), and the distance from the middle of the foraging areas of the herds to the NRPs (m) were estimated in QGIS (Version 3.0.3). In addition, herd areas were measured on each herbaceous biomass sampling point whenever possible to calculate the BURs. It was also tested to capture pictures of herd areas and herd patterns using a commercial drone.

Over two days during the observation period, the movement speeds (m/s) of each animal equipped with a GPS receiver were measured and the respective activity of the animal recorded in order to obtain data to group the movement speeds of daily foraging itineraries into potentially resting, foraging, and walking activities. An undisturbed behaviour of the animals was ensured by the student following the animal at a distance of about 2.5 m.

Before the observation period started, all animals were weighed in a squeeze chute in close vicinity to the ranch house in June, using a portable balance with an accuracy of ± 0.5 kg (XR3000, Tru-Test Limited, Auckland, New Zealand). The portable balance was calibrated by weighing a box of known weight each time, before an animal stepped on the balance. Each small ruminant was held by the hired pastoralist whilst standing on the balance. This gave a combined weight, from which the weight of the hired pastoralist was subtracted giving the weight of the small ruminant, which was recorded. With the aim of preventing feed and water intake, all herds were enclosed at the NRP at about 16:00 h the day before weighing and the travel speed of the herds heading to the squeeze chute was accelerated the next morning. Measurements were carried out at about 7:00 h. To account for differences in weight due to water intake, the HC was not taken to water three days before weighing and were weighed bimonthly. The mean live weight of the two days per month was used to calculate the daily live weight gain of camels during the stay at each NRP. All the other animals were weighed again monthly to determine their live weight gain.

2.7 **Statistical analyses**

Precipitation data collected on the ranch between 1928 and 2018 was analysed by using the UCM procedure of SAS to characterise trends, as proposed by Bartzke et al. (2018). The trend component was modelled using a locally linear time trend incorporating level and slope components. In addition to the trend components, the periods and damping factors of the cycle component were estimated. The model was fitted by smoothing algorithm in the UCM procedure. Non-significant parameters were dropped from the model, a P value of less than 0.05 was considered significant.

To determine the BURs, the length of time (s) herds spent on each herbaceous biomass sampling area (m^2) was first estimated. The six major steps established for processing geo-referenced data of daily foraging itineraries of animals in order to calculate the length of time herds spent on each herbaceous biomass sampling area are shown in Figure 3.3. The intra-herd positions of animals wearing collars and the herd areas were used for extrapolating the area of the herd from the track of one animal. The GPS locations recorded with less than 20 s tracking intervals and path segments intersecting the herbaceous biomass sampling areas, each with a three-metre buffer, after destructive herbaceous biomass sampling and characterised by unnatural movement speeds were excluded from the processing steps.

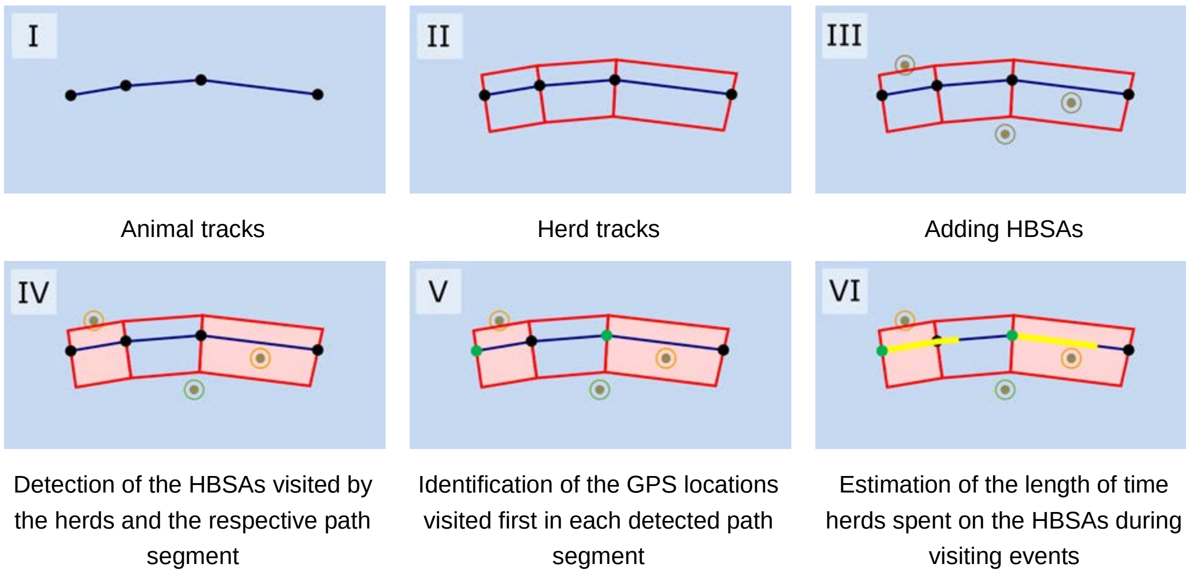


Figure 3.3 Illustration of processing steps extracting the length of time herds spent on the herbaceous biomass sampling areas (HBSAs) during each visiting event
(I) Locations (black dots) recorded by global positioning system (GPS) receivers (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America; TrackStick, Telespial Systems Inc., Burbank, United States of America) attached to two animals in each herd were connected to GPS tracks (blue lines). (II) By generating a herd- and time-specific buffer to this track, a segmented path (red lines) covering the area visited by each herd was constructed. (III) A three-metre radius around the GPS locations of HBSAs was added (orange circles). (IV) Those areas were used to identify the respective path segments relevant to the calculation (rose areas) and then (V) the GPS locations visited first in each detected path segment (green dots). (VI) By considering the direction of the herds and applying an algorithm, the length of time required for the herds to move six metres (yellow lines) from the GPS location visited first was computed. Based on the accuracy of GPS devices and comparisons of speeds of animals at different distances, a distance of six metres appeared to be appropriate to calculate the length of time herds most likely spent on the HBSAs. Steps (I) to (IV) were carried out in QGIS (Version 3.0.3) and steps (V) and (VI) in Microsoft Excel (Version 2016)

For the following analysis conducted with the GLIMMIX procedure of SAS to determine the driving forces behind the observed BURs, the approximated length of time per six metre was brought down to the length of time per 1.4 m equal to the diagonal of one herbaceous biomass sampling area. As the added length of time herds spent on each herbaceous biomass sampling area varied considerably, each herbaceous biomass sampling area was addressed individually. The calculated BURs were power-transformed (HMC, HWC, and HGS: 0.2, and HC: 0.3) to approximate normality because of a skewed distribution of studentized residuals. The full model for each herd and NRP consisted of the quantitative fixed effects date (dd.mm.yyyy), the beforehand measured herbaceous biomass fractions (monocotyledonous and dicotyledonous plants, and litter; g DM/m^2), the specific nutritional quality (CP, NDF, ADF, ADL, DOM; g/kg), mean height (cm), cumulative amount of precipitation (mm), and maximum ambient air temperature (°C). Furthermore, the examination of the qualitative fixed effects included transect, distance to the NRP, identified vegetation patch, palatability, and herbaceous biomass sampling point description. Preselection of relevant effects was done using the GLMSELECT procedure of SAS. Then, in addition to the relevant effects, spatial (GPS coordinates) and temporal (date) autocorrelations were modelled by introducing additive random effects into the model. To identify that all observations derived from the same rangeland, the SUBJECT statement was specified by the intercept. Non-significant effects ($P \geq 0.05$) were dropped from the models in order to obtain a reduced model. Afterwards, the assumption that a spatio-temporal model sharing information across nearby points of time and locations simultaneously provided the best results was assessed by examining the model with and without spatial, temporal, and spatial and temporal autocorrelations. To test the influence of the qualitative fixed effect identified vegetation patch on the effect of location, models were also examined with and without the effect identified vegetation patch. The corrected Akaike information criterion (AICc) was used to evaluate the developed models. To explore significant effects, least-squares means were calculated ($\alpha = 0.05$).

The UCM procedure of SAS was used to identify factors influencing the total length (m) of daily foraging itineraries. Date (dd.mm.yyyy), day of weighing animals (altered, unaffected), duration of daily foraging itinerary (hh:mm:ss), maximum and minimum ambient air temperatures (°C) during the foraging itineraries, total amount of rainfall (mm) and maximum rainfall intensity (mm/h) during the foraging itineraries, and their interactions were added to the model as coefficients. Those coefficients were examined without and with the time-varying regression coefficients hired pastoralist (permanently employed, replacing) and presence of the student (accompanying, absent), using the RANDOMREG statement. Under the assumption that the prior total lengths of daily foraging itineraries are related to the current ones, the DEPLAG statement was used to include the dependent variable as predictors in the model. The least significant coefficient from the model was removed until all remaining coefficients were significant at $P < 0.05$. Following this, the optimisation process outlined above was modified specifying the coefficient total amount of rainfall as a coefficient having a nonlinear relationship with the total length of daily foraging itineraries in the SPLINREG statement and repeated. To find the best model over all models, the fit of the models was compared using AICc.

To assess determinants underlying area densities (kg/m^2) of herds over foraging itineraries, the GLIMMIX procedure of SAS was used. Area densities of all herds and NRPs were log-transformed to normalise the distribution of the data. The full model contained the quantitative fixed effects date (dd.mm.yyyy), time of day (hh:mm:ss), distance to the NRP (m), precipitation intensity (mm/h), and ambient air temperature (°C). In addition, the full model included the categorical fixed effects vegetation structure (less or equal open, greater or equal open-moderate), position of the hired pastoralist (away from, behind, beside, in front of, and within the herd), intervention by the hired pastoralist (none, directing animals by using a stick, and utilizing the voice), and hired pastoralist (permanently employed, replacing). Therefore, a number of quantitative and categorical fixed effects and their interactions were considered as potential determinants. By dropping non-significant effects ($P \geq 0.05$), reduced models for each herd and NRP were obtained. In the case of a significant fixed effect time of day or interactions with this effect, the assumption that measurements of area densities of the HMC, HWC, and HGS at 20-minute intervals and in case of the HC at 40-minute intervals were temporally uncorrelated was tested by introducing an additive random effect into the model. Significant effects were compared using T Grouping of least squares means ($\alpha = 0.05$).

3 Results

Prior to presenting the vegetation dynamics, the BURs of herds, and the driving forces behind the observed BURs around the NRPs, the social, environmental, and ecological initial situation on the selected large-scale ranch is described. The description serves to highlight the complex social relationships between diverse stakeholders and the heterogeneity of available forage resources in particular and situate the produced results within the overall situation on-site. The following characterisation of the daily foraging itineraries, the influencing factors of the length of the daily foraging itineraries, and the underlying determinants of area densities of herds over daily foraging itineraries bring results with respect to the representativeness of the data recorded along the set transects.

3.1 The social context on the ranch

In total, 41 male and 15 female stakeholders were interviewed. Respondents included the landowners (n = 2) and their family members (n = 3), the livestock owners of the selected homestead (n = 2), hired pastoralists of the landowners (n = 12) and the selected homestead (n = 7), visitors (n = 5) and officials (n = 4) from the surrounding area, and labourers of the landowners (n = 18) and the livestock owners (n = 3). These informal conversations lasted between 0.3 and 1.2 hours. Out of the seven hired pastoralists of the selected homestead, four were permanently employed. The remaining hired pastoralists replaced the permanently employed ones temporarily.

The ranch was managed by Africans of British descent, who were engaged in livestock and crop production, wildlife conservation, and tourism activities. They had employed pastoralists to tend to 20 herds of cattle, distributed over the property, three herds of breeding cattle, one herd of small ruminants and one HC, corralled close to the ranch house overnight, on a daily basis. The landowners moved the NRPs of the herds of cattle around the property infrequently in order to mitigate illegal foraging or lion attacks. They attempted to design daily foraging itineraries and control the herd patterns over daily foraging itineraries, revealing that hired pastoralists had no say in forage and livestock management. Hired pastoralists noted that the daily foraging itineraries prescribed by the landowners created imbalances between energy intake and expenditure of animals, due to long walking distances. Therefore, hired pastoralists considered the animal performances as results of the regulated movements. From the point of view of the landowners, hired pastoralists did not guard the herds appropriately and were ignorant of the prevention of thefts and the optimal utilisation of available forage resources on the large-scale ranch. Thus, the hired pastoralists of the landowners were occasionally visited by the landowners day and night, indicating the want of confidence between these two stakeholders. Landowners reported that hired pastoralists neglected animals and forage resources and thus, the NRP of the herds of breeding cattle were permanently situated near the ranch house. In addition to frequent compliance visits, labourers and hired pastoralists were asked to report unauthorised activities of their colleagues to the landowners. Unaccepted behaviours included deviations from instructions for forage and livestock management, the presence of relatives of hired pastoralists on the property, milking, and the consumption of meat available after lion attacks or deaths of animals. The landowners awarded the herd that was best nourished from time to time. Hired pastoralists agreed that this was meaningless, because the daily foraging itineraries were constrained to the instructions of the landowners, suggesting that the opinions of hired pastoralists were rarely integrated. As hired pastoralists looked after the herds full-time and did not receive any commodities from the landowners, labourers noted that they supplied hired pastoralists with corncob flour and matches from time to time. The landowners pointed out that they prioritised crop production over livestock production, as they struggled with hired pastoralists over the quality of daily forage and livestock management and beyond that, crop damage by invaders was harshly penalised compared to illegal foraging.

Besides the herds of the landowners, four herds of cattle, two mixed herds of goats and sheep, and four herds of camels grazed on the large-scale ranch. The livestock owners of those herds were absent most of the time. Therefore, hired pastoralists of the livestock owners made decisions on the movement of the homestead and daily foraging itineraries. The locations of the NRPs were selected based on the availability of palatable forage resources, distance to the water source and other homesteads. The livestock owners engaged labourers to distribute corncob flour, sugar, matches, and soaps periodically. In consultation with the hired pastoralists, the herd owners chose animals for either slaughtering or sale. Hired pastoralists were entitled to milking for their personal use and their family members were occasionally connived to stay with them at the NRPs. These independent actions were acknowledged by all hired pastoralists and labourers on the property. However, they were allowed neither to keep their own livestock nor to have any kind of share in the animals on-site. Hired pastoralists explained that they had utilised forage resources more flexible before working on the ranch. The herd owners and the hired pastoralists admitted that the forage and livestock management was not optimally, as the incorporation of their knowledge to improve the exploitation of patches was compromised by the personal stake to expand contacts, buy *Catha edulis*, or to go hunting. Hired pastoralists added that they spared no effort to satisfy the feeding requirements of the HMC in order to increase milk yields. They felt proud of well-nourished and healthy individuals in the herds, indicated by presenting those animals to other hired pastoralists, labourers, and officials.

In general, labourers and hired pastoralists principally spent the earned money on food, transport to visit relatives, and school fees. When respondents reminisced about the changes in past years, they commonly cited that more weapons were in circulation, increased areas under crops, a growing number of lion attacks and wildlife, and the rules of the landowners became tougher.

3.2 Description of the selected homestead and its environment

As the homesteads of the herd owners were characterised by relatively small sizes of herds and composed of distinct animal species and daily foraging itineraries of herds and movements of the homesteads were regulated by the hired pastoralists, one of them was randomly chosen. Hired pastoralists of the selected homestead were identified as Turkana, Tugen, and Samburu and tended to one HMC, one HWC, one HGS, and one HC. The average age of the hired pastoralists looking after the HMC, the HGS, and the HC was 52 years. The age of the hired pastoralists herding the HWC averaged 28 years. The homestead was studied on two consecutive NRPs, built from brushes of *Acacia* species, to protect animals from theft and predators overnight. Each hired pastoralist lived in a portable shelter constructed of corrugated metal and adjacent to the NRPs (Figure 4.1).

Figure 4.1 Illustration of a portable shelter adjacent to the first night resting place on a ranch in Laikipia County, Kenya, in 2018 (own source)

Around the first NRP with a diameter of 17.7 m, the HMC, the HWC, the HGS, and the HC consisted of 89, 86, 81 to 93, and 44 individuals, respectively. Each herd was moved by one hired pastoralist, who chose daily foraging itineraries for 47 days. In late July, the homestead was moved on the property to offer animals more palatable herbaceous biomass and reduce the risk of carnivore attacks at night and disease outbreaks. The second NRP was 17.1 m in diameter and used for 50 days. With the exception of the HGS with 81 to 96 individuals, two hired pastoralists in turns looked after the HMC, the HWC, and the HC with 105 to 106, 65, and 49 individuals, respectively. During the establishment of the second NRP, some cattle previously belonging to the HWC were shifted to the HMC. Therefore, the herd sizes differed between the first and second NRP. The herds of cattle comprised the Boran breed and its crosses with Swiss Braunvieh and Jersey breeds. The HGS was composed of 76 goats of Boer and Angora breeds and their crosses and 18 sheep of the South African Dorper breed and crossbreeds of Red Maasai and South African Dorper. Camels were of Turkana breed and crossbreeds of either four breeds (Pakistani, Pokot, Somali, and Turkana), three breeds (Pakistani, Somali, and Turkana), or two breeds (Pakistani, Somali). Further details of herd characteristics of each herd are given in Table 4.1.

Table 4.1 Herd structures attributes around the first and the second night resting place (NRP) under study on a ranch in Laikipia County, Kenya (mean ± standard deviation)

		Herds			
NRP	Parameter	Mature cattle	Weaner cattle	Goats and sheep	Camels
1st	Initial live weight (kg/head)	313 ± 69	177 ± 34	33 ± 13	227 ± 61
	Age of individuals (months)	36 ± 7	18 ± 3	41 ± 17	27 ± 7
	Sex ratio (male/female)	1/6	1/3	1/12	1/4
2nd	Initial live weight (kg/head)	311 ± 70	175 ± 25	34 ± 13	233 ± 62
	Age of individuals (months)	35 ± 8	18 ± 2	41 ± 16	26 ± 9
	Sex ratio (male/female)	1/7	1/3	1/11	1/4

On the basis of the East African rangeland classification of (Pratt et al., 1966) (1966), the property is situated in the ecological zone IV, characterised by a productive rangeland and the encroachment of woody species. Accurate information on the foraging history of the areas around the NRPs and estimations of wildlife abundance on the property were lacking. The area of the ranch was grazed and browsed by livestock and wildlife. Herbivorous wildlife species temporarily found on the property included impala (*Aepyceros melampus*), African buffalo (*Syncerus caffer*), plains zebra (*Equus burchelli*), giraffe (*Giraffa camelopardalis reticulata*), cape hare (*Lepus capensis*), African elephant (*Loxodonta africana*), Grant's gazelle (*Nanger granti*), common warthog (*Phacochoerus africanus*), and African grey duiker (*Sylvicapra grimmia*). Species of carnivores that were present on a temporary basis included spotted hyena (*Crocuta crocuta)*, African lion (*Panthera leo*), and leopard (*Panthera pardus*). No burning of the area took place over the last few years. According to the international standard for soil classification of the WRB IUSS Working Group (2015), the major soil types on the large-scale ranch are Pellic Vertisols and Chromic Luvisols. Both NRPs were situated on the plateau of the ranch and located in Chromic Luvisols (Figure 4.2). One rain gauge was moved with the homestead under study, one installed in the north of the ranch, and one in the middle of the ranch. Water was available from boreholes and dams, distributed over the property.

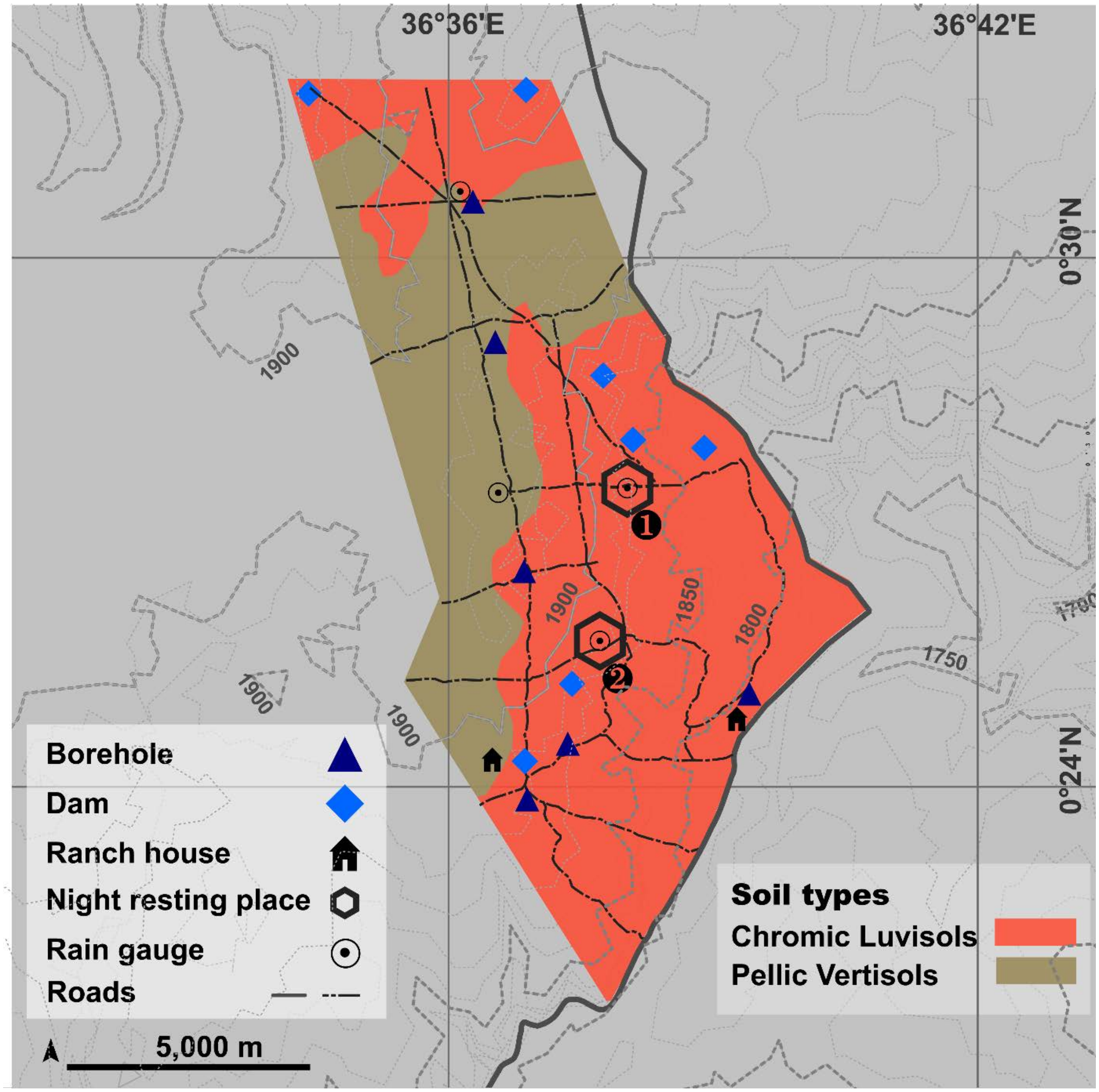
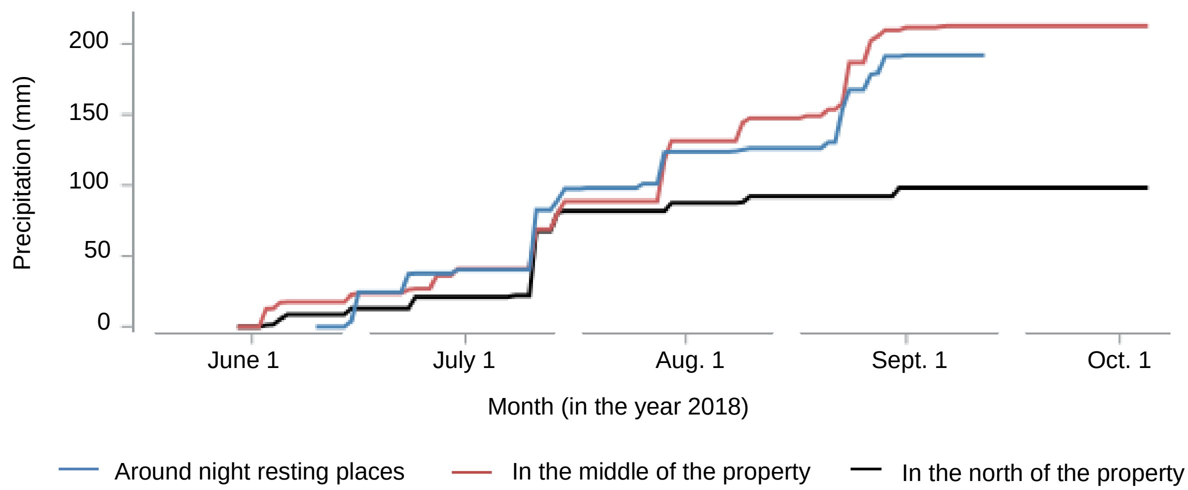


Figure 4.2 Location of the studied night resting places and installed rain gauges on the ranch in Laikipia County, Kenya, in 2018. Maps were generated in QGIS (Version 3.0.3) and symbols were designed using Inkscape (Version 0.92.4)

3.3 Weather and climate data

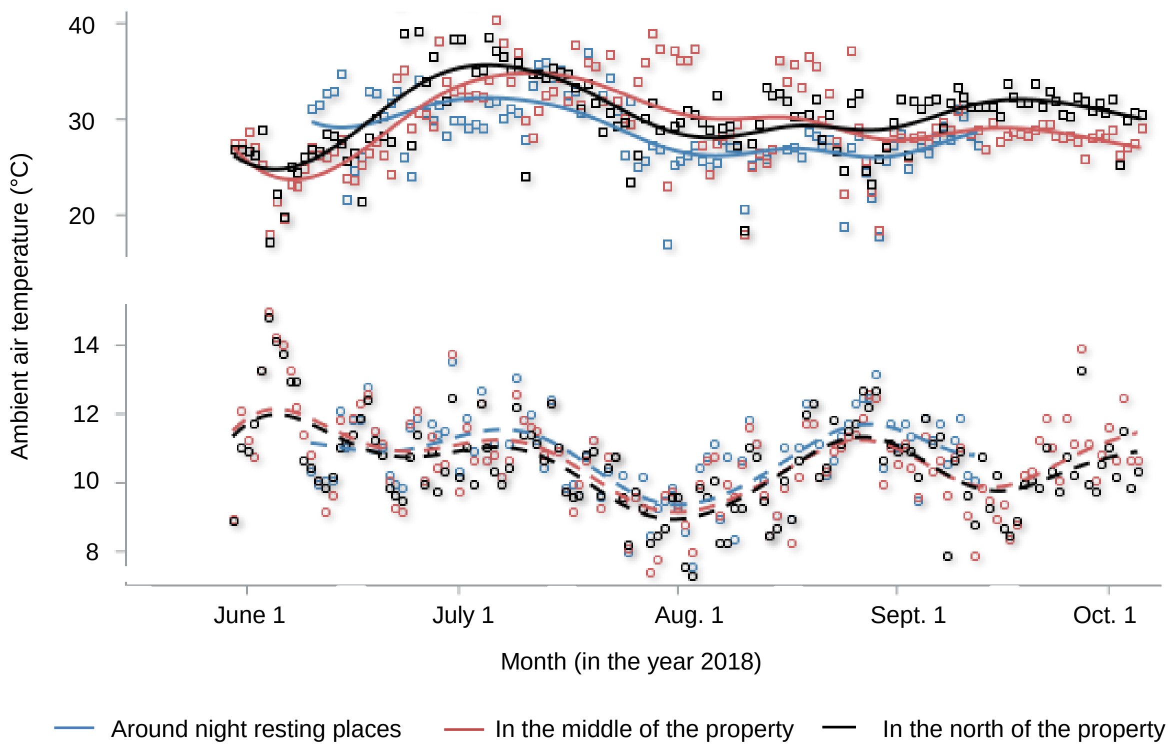
The cumulative precipitation amount over the period of observation was higher around the NRPs (192 mm) and in the middle of the property (213 mm) than in the north of the property (98 mm; Figure 4.3). From September onwards, no precipitation was recorded, indicating the onset of the dry season of this year. Thus, this non-intervention research was conducted during the transition from a wet to a dry season. Between mid-July and mid-October, the total amount of precipitation in the north of the property was less than 18 mm. The highest precipitation intensity measured around the NRPs, in the middle of the property, and in the north of the property was 28, 39, and 35 mm/h and lasted for 28, 44, and 78 minutes, respectively.



Note: Single precipitation events of 0.2 mm logged by the tipping-bucket rain gauges between 5:00 and 6:00 h were not considered. Considering those events resulted in cumulative precipitation amounts of 276, 299, and 193 mm around night resting places, in the middle of the property, and in the north of the property, respectively

Figure 4.3 Cumulative precipitation recorded by three rain gauges (IM523, Pessl Instruments GmbH, Weiz, Austria) on a ranch in Laikipia County, Kenya

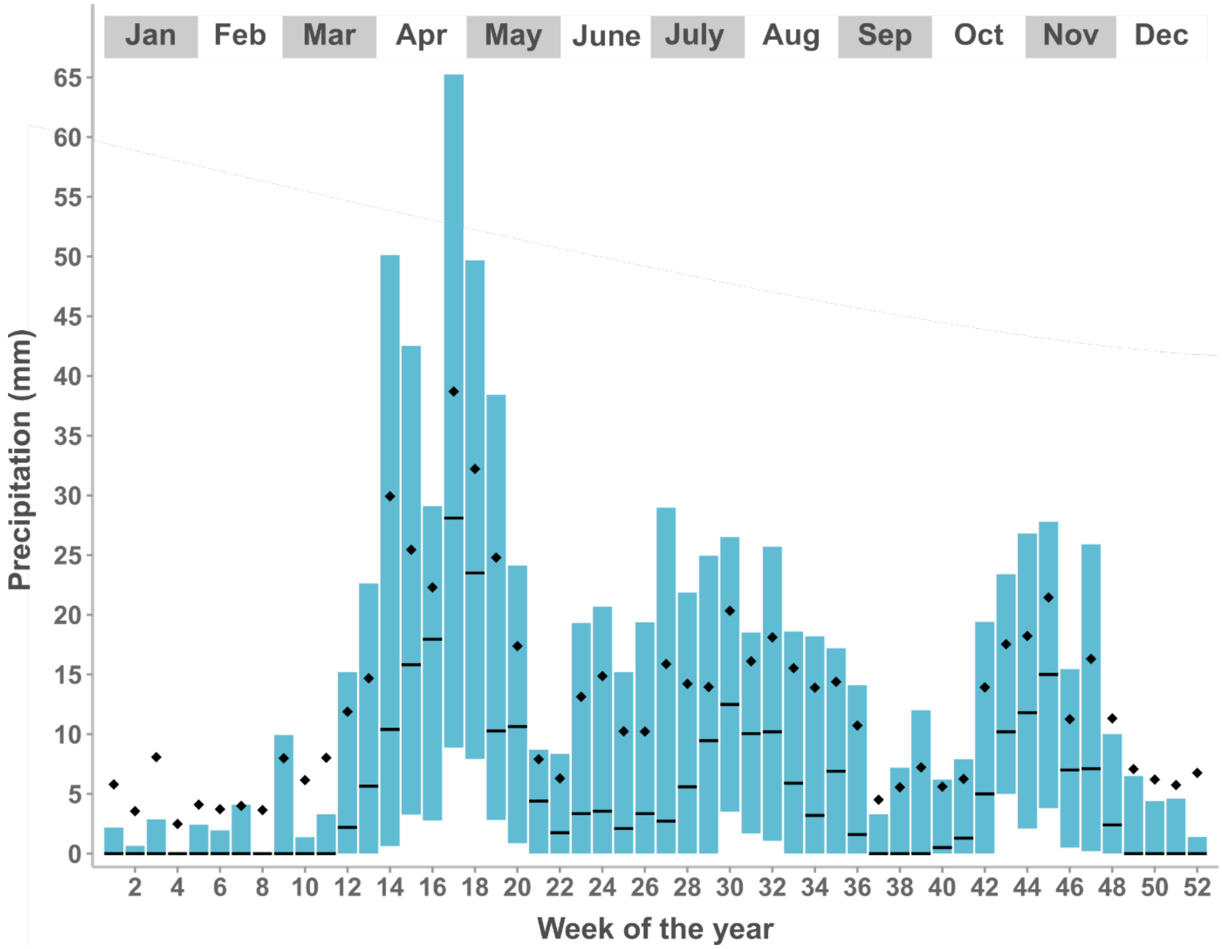
Differences between rain gauges and days were more pronounced for maximum ambient air temperatures than for minimum ambient air temperatures (Figure 4.4). Across all rain gauges, minimum ambient air temperatures ranging between 7 and 15°C were recorded between 4:30 and 4:56 h. Maximum ambient air temperatures were highest in the middle of July around the NRPs, at the beginning of July in the middle of the property, and at the end of June in the north of the property. Across all rain gauges, ambient air temperatures averaged 24°C from sunrise to sunset and 13°C between 18:00 and 06:00 h.



Note: Solid and dashed lines represent fitted p-spline curves using the GLIMMIX procedure of SAS (Version 9.4)

Figure 4.4 Minimum (dashed lines) and maximum (solid lines) ambient air temperatures recorded by three rain gauges (IM523, Pessl Instruments GmbH, Weiz, Austria) on a ranch in Laikipia County, Kenya

The study area is characterised by a semi-arid climate, with mean annual precipitation of 652 mm in the period between 1965 and 2017. Seasonal variation of precipitation indicates a tri-modal precipitation distribution, with high intra- and inter-annual variability (Figure 4.5). The coefficient of variation is 32%. The main rainy season occurs from the end of March to the middle of May with a second rainy season from the middle of June to the beginning of August and a third short rainy season from the end of October to the middle of November, suggesting that the vegetation period lasts for approximately 250 days from April to November. Averages of 32%, 22%, and 11% of annual precipitation occur during the main, second, and third rainy season, respectively. The mean numbers of rainy days per month are highest during the rainy seasons, with seven to ten rainy days per month.



Note: The length of the box represents the interquartile range (the distance between the 25th and 75th percentiles). The symbol in the box interior represents the group mean. The horizontal line in the box interior represents the group median

Figure 4.5 Boxplot of weekly total precipitation recorded on the ranch under study in Laikipia County, Kenya, between 1965 and 2018

Between 1965 and 2018, the monthly total precipitation corresponded with the monthly number of rainy days, except for two periods (Figure 4.6). In the early 1990s, the monthly total precipitation was relatively low, whereas the number of rainy days was relatively high, indicating lower levels of precipitation. From 2015 onwards, the monthly total precipitation and the number of rainy days was inversely related, suggesting that precipitation events occurred less frequently, but with higher amounts of precipitation per event.

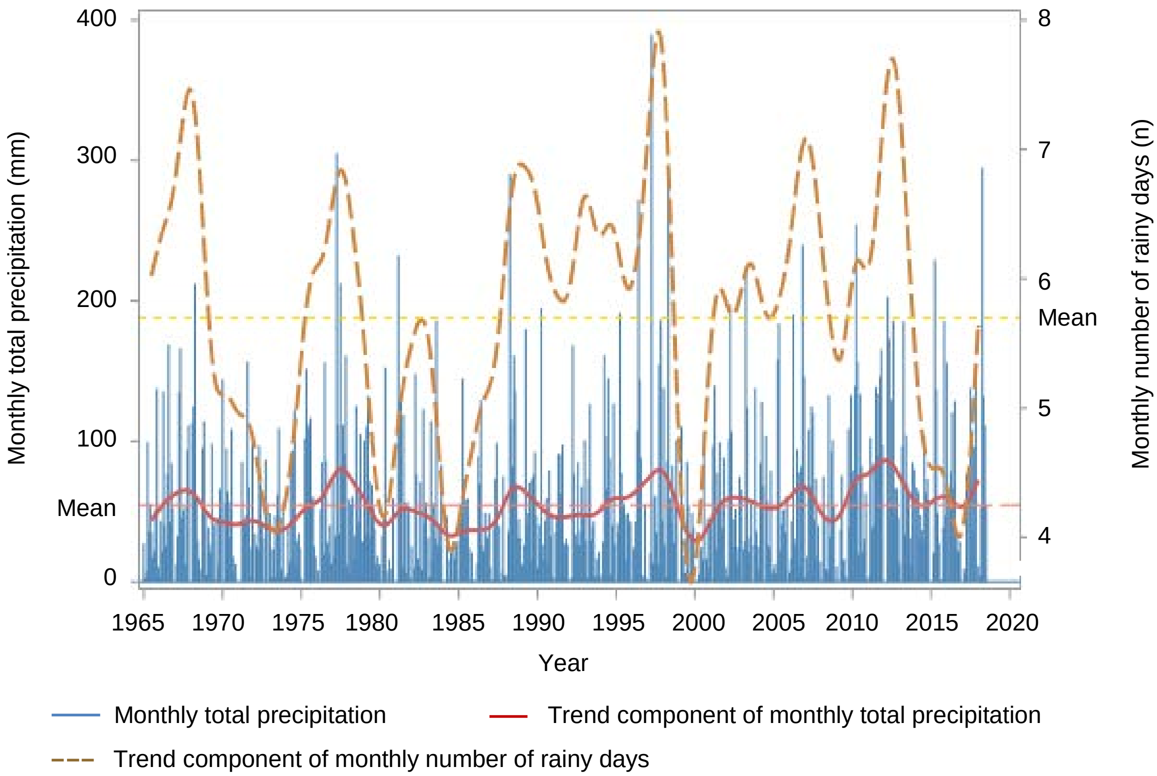


Figure 4.6 Monthly total precipitation and trend component of monthly total precipitation and monthly number of rainy days recorded on the ranch under study in Laikipia County, Kenya, between 1965 and 2018, using the TIMESERIES procedure of SAS (Version 9.4)

According to an unobserved component model, using the UCM procedure of SAS, annual precipitation on the ranch increased from 597 to 696 mm during the last nine decades ($P < 0.01$; Figure 4.7). This trend of annual precipitation was more pronounced between the 1930s and 1940s and between the 1990s and 2010s. Between the 1950s and 1980s and from 2010 onwards, annual precipitation levelled out.

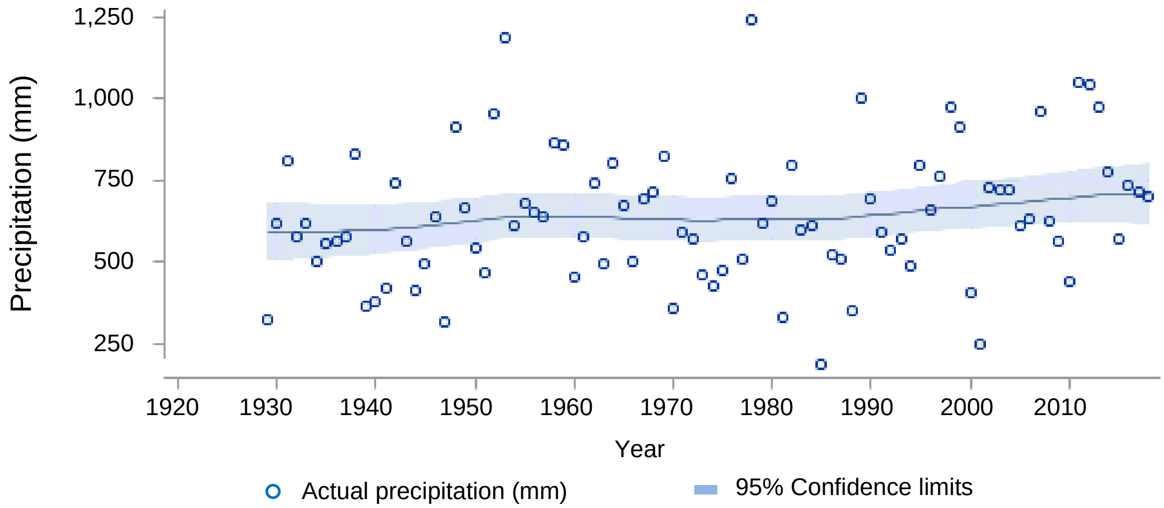
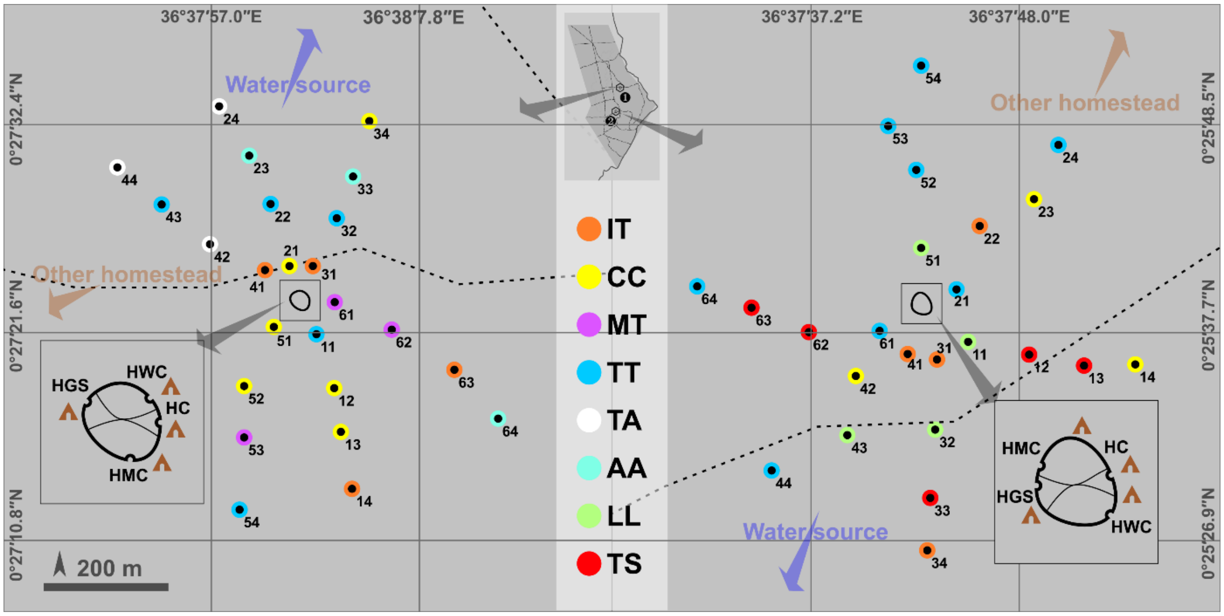


Figure 4.7 Smoothed trend component (solid line) based on the structural time series analysis using the UCM procedure of SAS (Version 9.4) for annual precipitation recorded on the ranch under study in Laikipia County, Kenya, between 1928 and 2018

3.4 **Herbaceous biomass sampling points**

Around both NRPs, six transects were established in order to include irregular vegetation patterns in the circumference of the NRPs and ensure capturing diverse daily foraging itineraries. Small paths and the attempt to consider spatial heterogeneity of rangeland resources around the NRPs (Figure A.1; section Appendix) precluded the same angle of the six transects established on the NRPs (Figure 4.8). Thus, the angle between adjacent transects varied from 45 to 75°. The length of each transect away from the NRPs was 350 m. Larger distances were near a water source and considered to be more affected by wildlife than the defined maximum sampling distance. NRPs were at about 500 m distance from a water source. Within the belt of sampling points, there was no visible impact of wildlife on herbaceous biomass. Each transect was divided into sub-transects to include sampling points at 50, 150, and 250 m length from the NRPs. Shorter distances were used for portable shelters constructed of corrugated metal and serving as sleeping places for herders.

The description of the 24 herbaceous biomass sampling points per NRP was composed of identified vegetation patch (Figure 4.9), vegetation structure (less or equal open, greater or equal open-moderate), visible history (with no signs of previous NRPs, signs of previous NRPs), and information about terrain (slightly hilly and rocky, flat).



Note: Positions of portable shelters are reflected relative to the entrances to the NRPs of the herd of mature cattle (HMC), the herd of weaner cattle (HWC), the mixed herd of goats and sheep (HGS), and the herd of camels (HC)

Figure 4.8 Location of identified vegetation patches around the studied night resting places (NRPs), dominated by *Indigofera volkensii* and *Themeda triandra* (IT), *Cynodon dactylon* (CC), *Melhania ovata* and *Themeda triandra* (MT), *Themeda triandra* (TT), *Themeda triandra* and *Andropogon contortus* (TA), *Andropogon contortus* (AA), *Lintonia nutans* (LL), and *Themeda triandra* and *Solanum incanum* (TS). Maps were generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

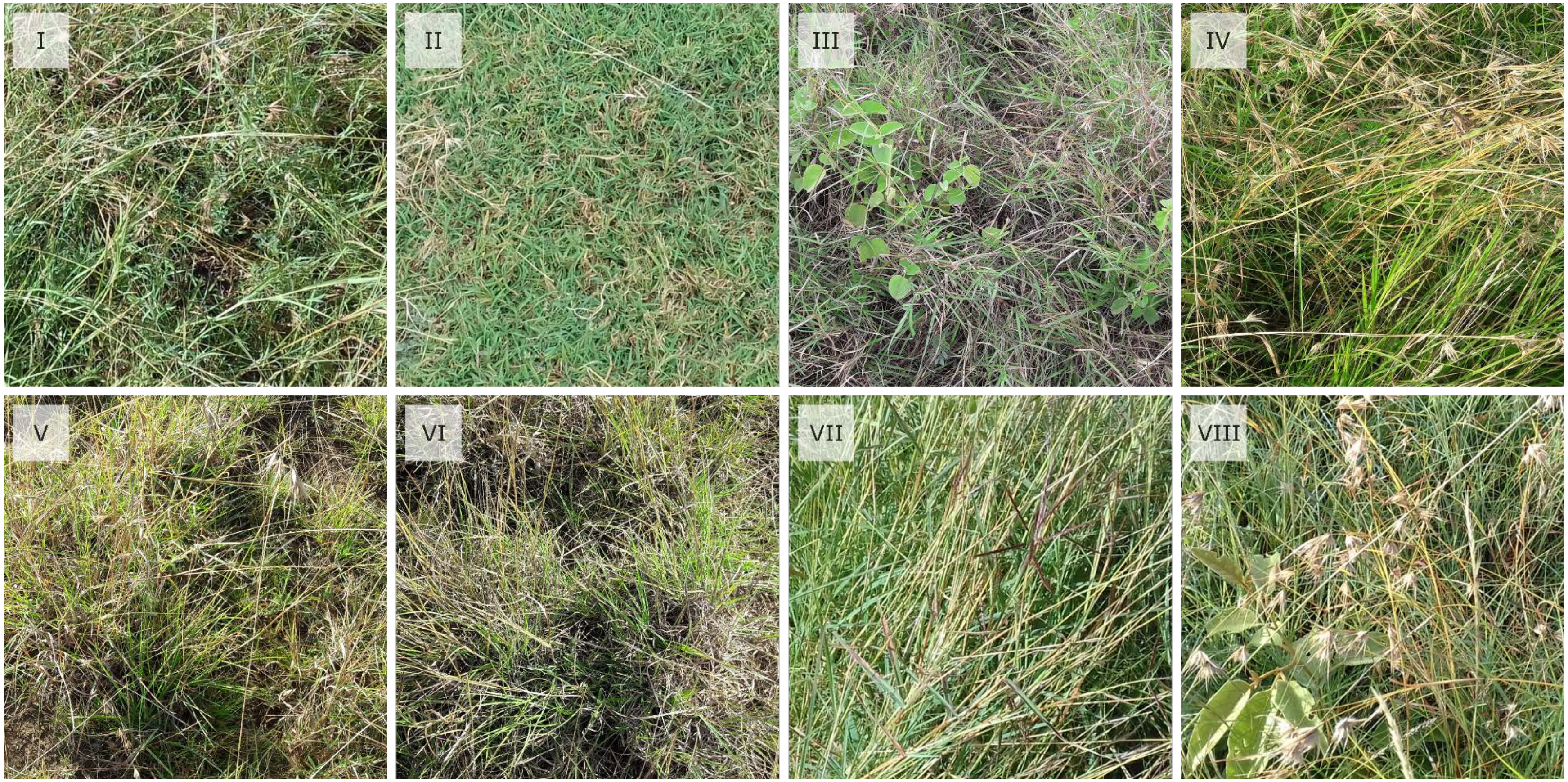


Figure 4.9 Illustration of identified vegetation patches around the studied night resting places, dominated by (I) *Indigofera volkensii* and *Themeda triandra*, (II) *Cynodon dactylon*, (III) *Melhania ovata* and *Themeda triandra*, (IV) *Themeda triandra*, (V) *Themeda triandra* and *Andropogon contortus*, (VI) *Andropogon contortus*, (VII) *Lintonia nutans*, and (VIII) *Themeda triandra* and *Solanum incanum* (own source)

Dominant plant species of identified vegetation patches were related to the other defined descriptive properties of herbaceous biomass sampling points. In addition to the factors determining the occurrence of dominant plant species, relevant properties of the dominant plant species with a dicarboxylic acid pathway of carbon fixation are given in Table 4.2.

Table 4.2 Simplified characterisation of dominant plant species identified around night resting places (NRPs) on a ranch in Laikipia County, Kenya

	Dominant plant species[1]						
Parameter	I	C	M	T	A	L	S
Vegetation structure[2]	†	†,††	†	†,††	†	††	†,††
Signs of previous NRPs[3]	-	x	-	-	-	-	-
Terrain[4]	‖	‖	‖	‖, *	*	‖	‖
Lateral spread[5]	Br	St, Rh	Br	Ca	Ca	St	Br
Nitrogen fixer[3]	x	x	-	x	x	-	-
Palatability cattle[6]	+	++++	+	+++	+	++	+
Palatability goats and sheep[6]	++	++++	+	++	+	+	+
Palatability camel[6]	++++	++	++	+	+	+	+

[1] Species: I = *Indigofera volkensii*; C = *Cynodon dactylon*; M = *Melhania ovata*; T = *Themeda triandra*; A = *Andropogon contortus*; L = *Lintonia nutans*; S = *Solanum incanum*

[2] Vegetation structure described by Fisher et al. (2014): † = less or equal open; †† = greater or equal open-moderate

[3] Signs of previous NRPs, Nitrogen fixer: x = yes; - = no

[4] Terrain: ‖ = flat; * = slightly hilly and rocky

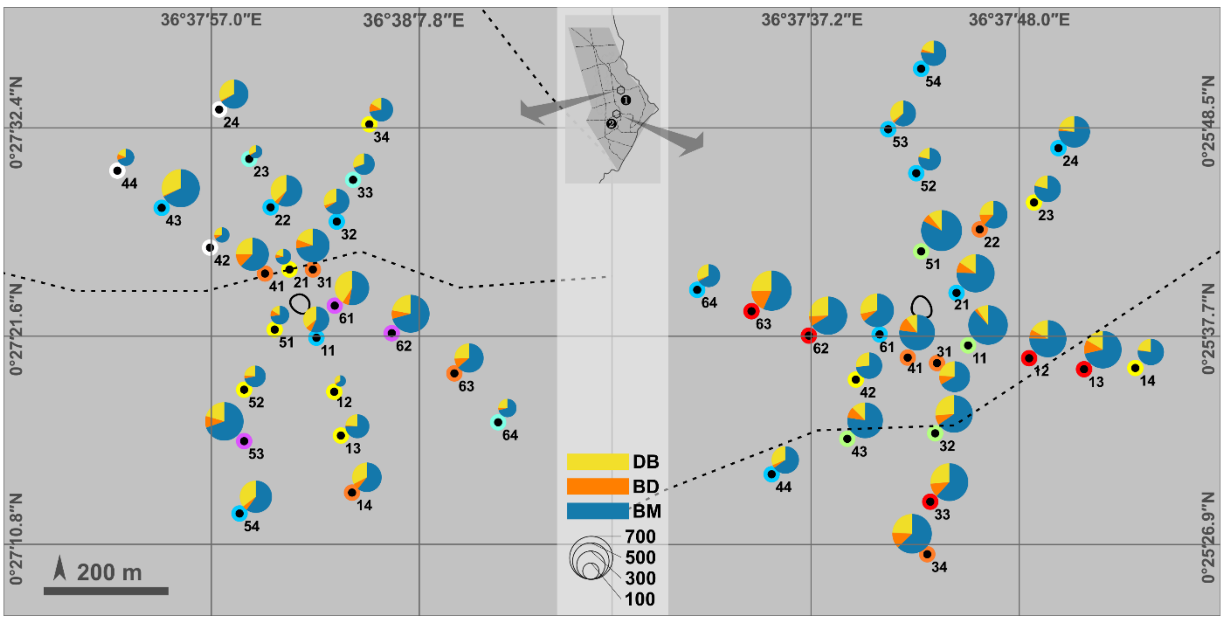
[5] Lateral spread: Br = branching; St = stoloniferous; Rh = rhizomatous; Ca = caespitose

[6] Palatability classified by Ibrahim and Kabuye (1987) and subjectively supported by the opinions of 14 local people and observations of the student (weighted palatability according to the average ratio of goats to sheep of 3.5:1): + = non-palatable; ++ = intermediate palatable; +++ = palatable; ++++ = highly palatable

3.5 **Vegetation dynamics**

Herbaceous biomass sampling took place once before the movement of the homestead to the NRP, 11 times in the presence of the NRP, and thrice after the abandonment of the NRP, resulting in 15 measurements at each herbaceous biomass sampling point around each NRP. For the estimation of the remaining moisture content of samples after open-air drying, samples of each cutting time were grouped into seven categories (dead biomass, *Cynodon dactylon*, *Themeda triandra*, *Andropogon contortus*, monocotyledonous plants excluding the three mentioned grass species, *Indigofera volkensii*, and dicotyledonous plants excluding the legume *I. volkensii*). Across all categories and cutting times, DM concentrations of the first nine cutting times around the first NRP (n = 63) ranged between 96.1 and 98.3 g/100 g.

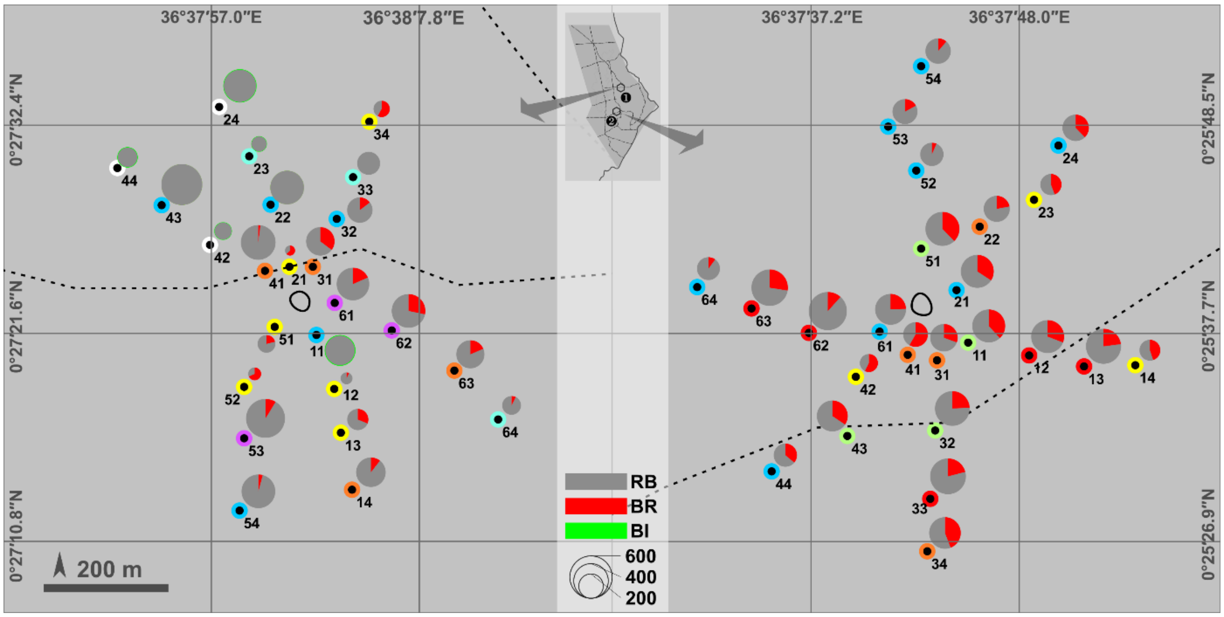
Before the movement of the homestead to the NRPs, DM weights of herbaceous biomass varied between herbaceous biomass sampling points (Figure 4.10), indicating the heterogeneity of forage resources. The percentages of ground covered by plants around the first NRP on herbaceous biomass sampling points 12, 21, 23, 33, 34, 42, 44, 52, and 64 averaged 84, 89, 94, 88, 94, 98, 97, 98, and 98%, respectively, suggesting that bare soil surfaces predominantly occurred on vegetation patches dominated by either *C. dactylon* or *A. contortus*. On the remaining herbaceous biomass sampling points, no bare soil was exposed to different disturbances. Throughout the observational period, the ground surfaces of all herbaceous biomass sampling areas around the second NRP were completely covered by vegetation.



Note: All of the values given in this figure are expressed in terms of g DM/m^2. Sampling points with the same colour belong to the same identified vegetation patch (Figure 4.8)

Figure 4.10 Initial dry matter (DM) weights of dead herbaceous biomass (DB) and herbaceous biomass of dicotyledons (BD) and monocotyledons (BM) around the studied night resting places. Maps were generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

Vegetation dynamics around NRPs differed between biomass sampling points (Figure 4.11). Across all herbaceous biomass sampling points, the removal of herbaceous biomass around the second NRP (31% of all available herbaceous biomass) was higher than the one around the first NRP (13% of all available herbaceous biomass), revealing the low forage availability at the water source around the second NRP. After the abandonment of the first NRP, DM weights of herbaceous biomass ranged from 35 to 562 g/m^2, suggesting that vegetation patches dominated by *C*. *dactylon* were possibly overgrazed and those dominated by either *A*. *contortus* or *T*. *triandra* were most likely underused. In the course of the existence of the first NRP, herbaceous biomass at the entrance to the NRP of the HMC increased from 259 to 295 g DM/m^2, indicating that the directions of the entrances to the NRPs of herds did not affect forage availability next to the NRPs.



Note: All of the values given in this figure are expressed in terms of g DM/m^2. Sampling points with the same colour belong to the same identified vegetation patch (Figure 4.8)

Figure 4.11 Available herbaceous biomass (AB) after the abandonment of the studied night resting places (NRPs), showing herbaceous biomass reduction (BR) and increase (BI) during the existence of the NRPs. Maps were generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

On all herbaceous biomass sampling points around both NRPs, mean herbaceous biomass heights decreased (Table 4.3), suggesting that on herbaceous biomass sampling points characterised by relatively low herbaceous biomass removal, relatively more of the herbaceous biomass was trampled down instead of grazed (Figure A.2, Figure A.3; section Appendix).

Table 4.3 Initial and terminal herbaceous biomass heights measured around two consecutively studied night resting places on a ranch in Laikipia County, Kenya

		First night resting place			Second night resting place		
D[1]	T[2]	Spec[3]	Initial H[4]	Terminal H[5]	Spec[3]	Initial H[4]	Terminal H[5]
1	1	TT	45 ± 13	25 ± 4	LL	86 ± 14	38 ± 8
	2	CC	24 ± 10	5 ± 3	TT	75 ± 17	42 ± 6
	3	IT	43 ± 20	19 ± 5	IT	51 ± 10	36 ± 6
	4	IT	54 ± 21	38 ± 8	IT	66 ± 18	32 ± 8
	5	CC	26 ± 4	12 ± 2	LL	90 ± 22	39 ± 10
	6	MT	57 ± 14	28 ± 5	TT	86 ± 15	42 ± 11
2	1	CC	10 ± 3	3 ± 2	TS	68 ± 14	42 ± 7
	2	TT	52 ± 21	30 ± 7	IT	34 ± 6	23 ± 2
	3	TT	21 ± 20	16 ± 5	LL	70 ± 15	45 ± 7
	4	TA	18 ± 16	14 ± 7	CC	30 ± 3	14 ± 3
	5	CC	29 ± 4	8 ± 2	TT	19 ± 11	11 ± 4
	6	MT	62 ± 15	28 ± 6	TS	77 ± 12	36 ± 9
3	1	CC	25 ± 6	15 ± 3	TS	72 ± 13	46 ± 8
	2	AA	18 ± 19	16 ± 7	CC	25 ± 5	13 ± 3
	3	AA	19 ± 17	15 ± 7	TS	68 ± 14	50 ± 9
	4	TT	72 ± 17	54 ± 13	LL	76 ± 17	50 ± 11
	5	MT	70 ± 15	40 ± 6	TT	18 ± 6	13 ± 6
	6	IT	35 ± 12	22 ± 5	TS	91 ± 11	42 ± 9
4	1	IT	29 ± 20	21 ± 5	CC	27 ± 4	15 ± 3
	2	TA	49 ± 27	41 ± 18	TT	51 ± 10	33 ± 4
	3	CC	15 ± 7	7 ± 4	IT	84 ± 18	59 ± 14
	4	TA	22 ± 19	18 ± 7	TT	54 ± 10	29 ± 5
	5	TT	59 ± 16	38 ± 6	TT	23 ± 9	20 ± 8
	6	AA	26 ± 5	14 ± 6	TT	20 ± 15	13 ± 5

[1] D = distance to the night resting place (1, 50 m; 2, 150 m; 3, 250 m; 4, 350 m)

[2] T = transect identification number (1 – 6; Figure 4.1)

[3] Spec = herbaceous biomass sampling points dominated by the identified species (IT = *Indigofera volkensii* and *Themeda triandra*; CC = *Cynodon dactylon*; MT = *Melhania ovata* and *Themeda triandra*; TT = *Themeda triandra*; TA = *Themeda triandra* and *Andropogon contortus*; AA = *Andropogon contortus*; TS = *Themeda triandra* and *Solanum incanum*; LL = *Lintonia nutans*)

[4] Initial H = initial herbaceous biomass height (cm) measured on 15 points (mean ± standard deviation)

[5] Terminal H = terminal herbaceous biomass height (cm) measured on 15 points (mean ± standard deviation)

Between dominant plant species around the NRPs, nutritional quality varied considerably (Table 4.4). In the course of the existence of the NRPs, CP concentrations in *C. dactylon* increased. Across all months, OMD of *C. dactylon* was greater than OMD of the other dominant

Table 4.5 Recorded and analysed global positioning system (GPS) locations of foraging itineraries and intersections of path segments and herbaceous biomass sampling areas (HBSAs) around each night resting place (NRP) on a ranch in Laikipia County, Kenya

		Herds			
NRP	Parameter	Mature cattle	Weaner cattle	Goats and sheep	Camels
1st	Foraging itineraries (n)	47	47	47	47
	Recorded GPS locations (n)[1]	91,249	70,645	64,869	77,012
	Considered GPS locations (n)[2]	77,150	57,362	48,564	65,151
	Intersections (n)[3]	16,906	3,027	3,647	25,745
	Analysed intersections (n)[4]	8,180	2,120	3,469	15,302
2nd	Foraging itineraries (n)	50	50	50	50
	Recorded GPS locations (n)[1]	107,064	93,434	82,894	62,599
	Considered GPS locations (n)[2]	91,189	78,906	62,571	53,219
	Intersections (n)[3]	3,859	3,824	9,237	16,258
	Analysed intersections (n)[4]	2,571	2,661	8,765	9,031

[1] GPS locations recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America) during daily foraging itineraries around the first NRP (between June and July) and the second NRP (between August and September) in 2018

[2] GPS locations recorded with ≥ 20-second tracking intervals

[3] Intersections = GPS tracks with herd-specific buffer areas (the herd width in metres was adjusted for each identified vegetation patch (Figure 4.8) and measurement time point; positions of animals in the herd: mature cattle = first NRP: 88% left-hand side, 12% right-hand side; second NRP: 90% left-hand side, 10% right-hand side; weaner cattle = first NRP 17% left-hand side, 83% right-hand side; second NRP: 20% left-hand side, 80% right-hand side; goats and sheep and camels = first and second NRP: 50% left-hand side, 50% right-hand side) intersected with HBSAs per NRP (n = 264) each with a three-metre buffer area

[4] Analysed intersections = deletion of intersections after destructive herbaceous biomass sampling and characterised by unnatural movement speeds (Table 4.6)

The observed movement speeds of resting, foraging, and walking and unconsidered path segments due to unnatural movement speeds for a specific time of day differed between livestock species (Table 4.6). Resting comprised lying and standing without foraging. Foraging was defined as walking with the mouth close to the forage and standing while foraging, revealing movement speeds between resting and walking. Walking was observed when the animal moved with the head up, socially interacting. This method did not distinguish between moving slowly and standing still with or without foraging. However, animals rarely moved slowly without being in search of forage or standing still for some time with the head down.

Table 4.6 Unconsidered intersections of path segments and herbaceous biomass sampling areas due to unnatural movement speeds and classification of movement speeds into potential activities of animals derived from geo-referenced data collected around night resting places on a ranch in Laikipia County, Kenya, between June and September 2018

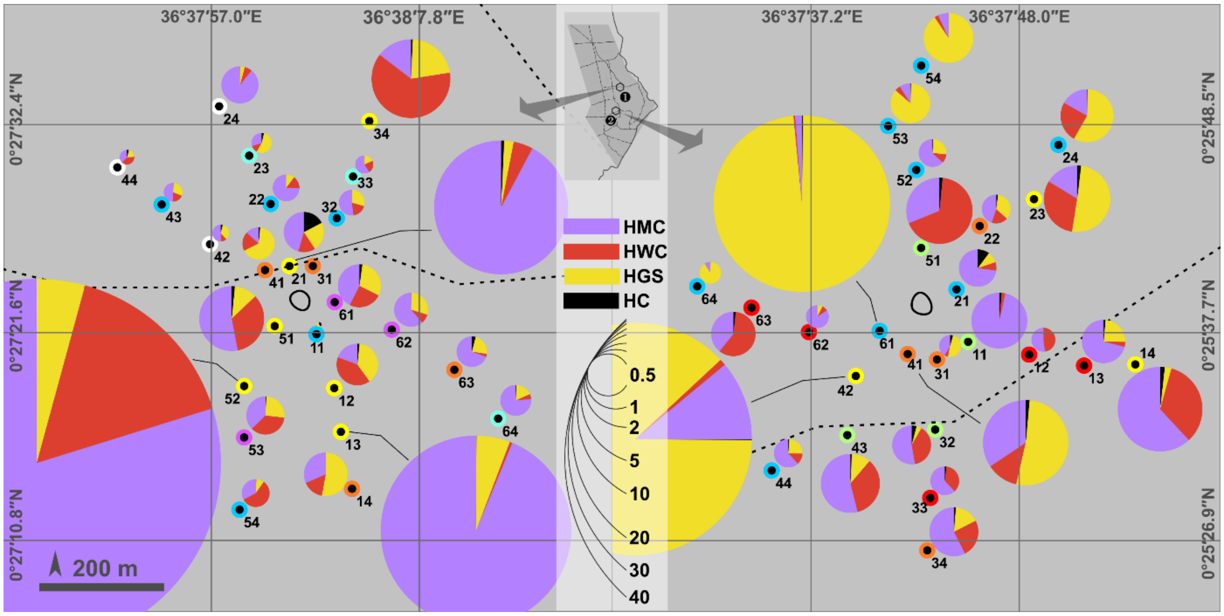
	Livestock species		
Parameter	Cattle	Goats and sheep	Camels
Unnatural behaviour (m/s)	< 0.003 and ≥ 18:30 h	< 0.002 and ≥ 18:00 h	< 0.006 and ≥ 18:00 h
Resting speed (m/s)	0.002 < x ≤ 0.006	0.001 < x ≤ 0.004	0.003 < x ≤ 0.006
Foraging speed (m/s)	0.006 < x < 0.500	0.004 < x < 0.450	0.006 < x < 2.000
Walking speed (m/s)	0.500 ≤ x ≤ 3.000	0.450 ≤ x ≤ 3.000	2.000 ≤ x ≤ 12.000

Note: Intersections encompassing either unnatural behaviour or movement speeds outside the specified ranges were deleted based on records and measurements taken before the observation period started. The estimated movement speeds consider the accuracy of global positioning system receivers (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America; plus or minus three metres)

To capture pictures of herd areas and herd patterns over daily foraging itineraries, the use of the commercial drone on hand has proven to be inappropriate due to three principal reasons. First, animals reacted to the noise of the drone. Moreover, eight batteries with a battery service life of about 15 minutes were available. Thus, the equipment was not suitable for monitoring one foraging itinerary. Third, it was impossible to fly the drone in the rain.

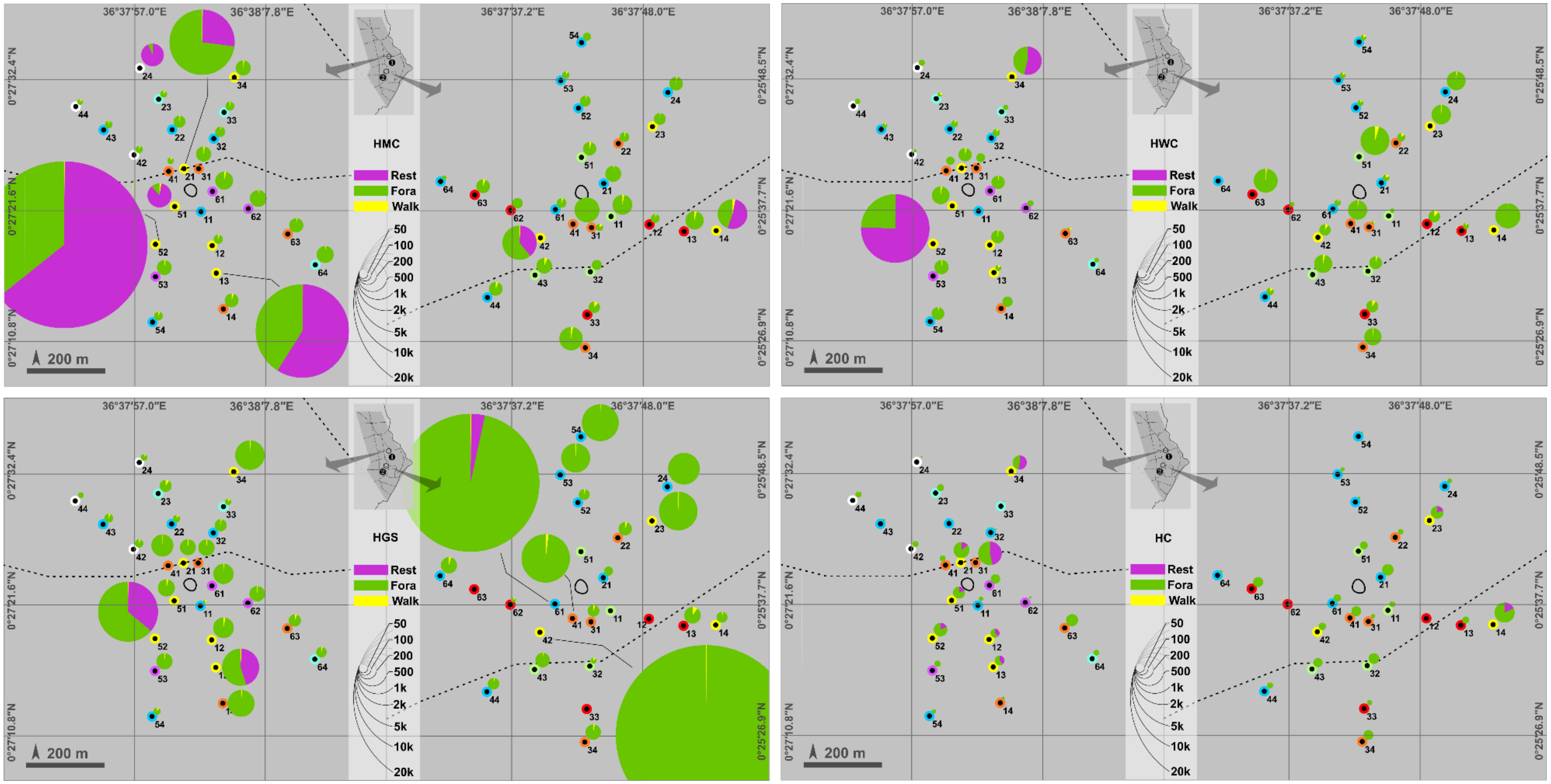
3.7 **Observed BURs and potential activities of herds**

Each herd visited the herbaceous biomass sampling points around both NRPs to a variable extent (Figure 4.12). All herds showed a patchy utilisation of forage resources around NRPs, frequently travelling to the same herbaceous biomass sampling points during the observation period, especially in the morning and in the late afternoon. The high BURs of the HMC around the first NRP were most likely due to the duration of the calving period. As the hired pastoralist of the HMC endeavoured to feed the animals adequately while spending more time around the NRP, he guided the animals to the herbaceous biomass sampling points dominated by *C. dactylon*. Thus, animals primarily rested on these highly palatable vegetation patches (Figure 4.13). The area around the second NRP was predominantly utilised by the HGS, indicating the availability of less palatable herbaceous biomass at the water source and the agreements between hired pastoralists with respect to foraging around the NRP. Hence, goats and sheep principally grazed on the herbaceous biomass around the NRP.



Note: All of the values given in this figure are expressed in terms of 250 kg/m^2 x s/m^2, recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America). Sampling points with the same colour belong to the same identified vegetation patch (Figure 4.8)

Figure 4.12 Biomass utilisation rates of the herd of mature cattle (HMC), the herd of weaner cattle (HWC), the mixed herd of goats and sheep (HGS), and the herd of camels (HC) around the studied night resting places. Maps were generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)



Note: Potential activities of herds in seconds were classified based on observed movement speeds (Table 4.6), recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America). Sampling points with the same colour belong to the same identified vegetation patch (Figure 4.8)

Figure 4.13 Potential activities classified into resting (Rest), foraging (Fora), and walking (Walk) of the herd of mature cattle (HMC), the herd of weaner cattle (HWC), the mixed herd of goats and sheep (HGS), and the herd of camels (HC) around the studied night resting places. Maps were generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

3.8 Driving forces behind the observed BURs of herds

The effects transect, palatability, and DM weight of monocotyledonous herbaceous biomass were important drivers for the BURs of HMC and HWC around the first NRP according to the selected generalized linear mixed models (Table 4.7). Both herds of cattle predominantly sought vegetation patches dominated by the highly palatable grass *C. dactylon* ($P < 0.01$). The fifth transect was established from the NRP towards another homestead and included two vegetation patches that were dominated by *C. dactylon*, indicating the frequent visits by the HMC (65% of all records; $P = 0.83$) and the HWC (76% of all records; $P < 0.01$). The neighbouring fourth transect characterised by palatable and intermediate palatable plant species was sparsely utilised by the HMC (<1% of all records; $P < 0.01$) and the HWC (<1% of all records; $P = 0.06$), revealing that distinct directions were affected by animals differently.

Table 4.7 Solutions for fixed effects influencing daily rangeland resource utilisation of the herds of mature and weaner cattle around the first night resting place on a ranch in Laikipia County, Kenya, between June and July 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t value	Pr > |t|
Mature cattle	Intercept			0.286	0.0850	254	3.37	< 0.01
	MW			0.001	0.0003	254	3.49	< 0.01
	Palatability	1	A	0.802	0.0909	254	8.83	< 0.01
	Palatability	2	B	0.164	0.0922	254	1.77	0.08
	Palatability	3	B	0.069	0.0936	254	0.74	0.46
	Palatability	4	B	0	.	.	.	.
	Transect	1	CD	-0.266	0.0930	254	-2.86	< 0.01
	Transect	2	ABC	-0.121	0.0834	254	-1.45	0.15
	Transect	3	BCD	-0.172	0.0873	254	-1.97	0.05
	Transect	4	D	-0.310	0.0836	254	-3.71	< 0.01
	Transect	5	AB	-0.019	0.0896	254	-0.21	0.83
	Transect	6	A	0	.	.	.	.
Weaner cattle	Intercept			0.141	0.0716	255	1.98	0.05
	Palatability	1	A	0.419	0.0785	255	5.33	< 0.01
	Palatability	2	BC	0.096	0.0708	255	1.36	0.17
	Palatability	3	B	0.150	0.0756	255	1.39	0.05
	Palatability	4	C	.	.	.	.	.
	Transect	1	C	-0.100	0.0803	255	-1.24	0.21
	Transect	2	C	-0.088	0.0721	255	-1.22	0.22
	Transect	3	B	0.057	0.0755	255	0.76	0.45
	Transect	4	C	-0.139	0.0723	255	-1.92	0.06
	Transect	5	A	0.346	0.0768	255	4.50	< 0.01
	Transect	6	BC	0	.	.	.	.

Note: Biomass utilisation rates were power transformed (0.2). Spatial and temporal autocorrelations are not shown due to low covariance parameter estimates

[1] Effect: MW = dry matter (DM) weight of monocotyledonous herbaceous biomass (g DM/m^2); Palatability = palatability specific to animal species (1, highly palatable; 2, palatable; 3, intermediate palatable; 4, and non-palatable), classified by Ibrahim and Kabuye (1987) and subjectively supported by the opinions of 14 local people and observations of the student (weighted palatability according to the average ratio of goats to sheep)

[2] T = T Grouping for the respective effect least squares means (LSMs, α = 0.05). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

The BURs of the HGS and the HC around the first NRP were significantly associated with the effects distance to the NRP, palatability, and DM weight of dicotyledonous herbaceous biomass

(Table 4.8). The HGS and the HC preferably utilised vegetation patches dominated by the highly palatable species *I. volkensii* and *C. dactylon* ($P < 0.01$). Between distances to the NRP, the BUR of the HC varied significantly, indicating the herd gathering in close proximity to the NRP before departure ($P < 0.01$), the tendency of animals to immediately walk off afterwards ($P = 0.31$), and the effort of the hired pastoralist to control the movement of the herd subsequently ($P = 0.23$).

Table 4.8 Solutions for fixed effects influencing daily rangeland resource utilisation of the mixed herd of goats and sheep and the one of camels around the first night resting place on a ranch in Laikipia County, Kenya, between June and July 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t value	Pr > |t|
Goats and sheep	Intercept			0.120	0.0556	259	2.15	0.03
	DW			0.007	0.0019	259	3.61	< 0.01
	Palatability	1	A	0.324	0.0681	259	4.76	< 0.01
	Palatability	2	BC	-0.006	0.0740	259	-0.08	0.93
	Palatability	3	B	0.032	0.0745	259	0.42	0.67
	Palatability	4	C	0	.	.	.	.
Camels	Intercept			0.107	0.0190	257	7.73	< 0.01
	Distance	1	A	0.125	0.0162	257	7.66	< 0.01
	Distance	2	C	-0.016	0.0160	257	-1.01	0.31
	Distance	3	B	0.019	0.0160	257	1.20	0.23
	Distance	4	BC	0	.	.	.	.
	Palatability	1	A	0.098	0.0210	257	4.65	< 0.01
	Palatability	2	B	0.002	0.0195	257	0.12	0.91
	Palatability	3	B	0.010	0.0206	257	0.47	0.64
	Palatability	4	B	0	.	.	.	.

Note: Biomass utilisation rates were power transformed (goats and sheep, 0.2; camels, 0.3). Spatial and temporal autocorrelations are not shown due to low covariance parameter estimates

[1] Effect: DW = dry matter (DM) weight of dicotyledonous herbaceous biomass (g DM/m^2); Palatability = palatability specific to animal species (1, highly palatable; 2, palatable; 3, intermediate palatable; 4, and non-palatable), classified by Ibrahim and Kabuye (1987) and subjectively supported by the opinions of 14 local people and observations of the student (weighted palatability according to the average ratio of goats to sheep); Distance = distance to the night resting place (1, 50 m; 2, 150 m; 3, 250 m; 4, 350 m)

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

The effects palatability and DM weight of monocotyledonous herbaceous biomass were principally responsible for the BURs of the HMC and the HWC around the second NRP (Table 4.9). In addition to the vegetation patches dominated by *C. dactylon*, the HMC was attracted by vegetation patches dominated by the non-palatable grass *L. nutans*.

Table 4.9 Solutions for fixed effects influencing daily rangeland resource utilisation of the herds of mature cattle and weaner cattle around the second night resting place on a ranch in Laikipia County, Kenya, between August and September 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t value	Pr > |t|
Mature cattle	Intercept			0.654	0.0628	259	10.41	< 0.01
	MW			0.001	0.0002	259	2.95	< 0.01
	Palatability	1	A	0.111	0.0671	259	1.66	0.10
	Palatability	2	B	-0.193	0.0500	259	-3.87	< 0.01
	Palatability	3	B	-0.181	0.0517	259	-3.50	< 0.01
	Palatability	4	A	0	.	.	.	.
Weaner cattle	Intercept			0.352	0.0749	259	4.70	< 0.01
	MW			0.001	0.0002	259	3.24	< 0.01
	Palatability	1	A	0.289	0.0801	259	3.60	< 0.01
	Palatability	2	C	-0.135	0.0595	259	-2.27	0.02
	Palatability	3	BC	-0.115	0.0617	259	-1.86	0.06
	Palatability	4	B	0	.	.	.	.

Note: Biomass utilisation rates were power transformed (0.2). Spatial and temporal autocorrelations are not shown due to low covariance parameter estimates

[1] Effect: MW = dry matter (DM) weight of monocotyledonous herbaceous biomass (g DM/m^2); Palatability = palatability specific to animal species (1, highly palatable; 2, palatable; 3, intermediate palatable; 4, and non-palatable), classified by Ibrahim and Kabuye (1987) and subjectively supported by the opinions of 14 local people and observations of the student (weighted palatability according to the average ratio of goats to sheep)

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

The BURs of the HGS and the HC around the second NRP were strongly influenced by the effects palatability, DM weight of dicotyledonous herbaceous biomass, distance to the NRP, and transect (Table 4.10). The HGS mainly utilised the fourth (56% of all records) and the sixth (34% of all records) transect, both transects were directed towards the water source, revealing that the BURs of the HGS were predominantly depended on the direction of the water source.

Table 4.10 Solutions for fixed effects influencing daily rangeland resource utilisation of the mixed herd of goats and sheep and the one of camels around the second night resting place on a ranch in Laikipia County, Kenya, between August and September 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t value	Pr > |t|
Goats and sheep	Intercept			0.401	0.0955	255	4.20	< 0.01
	Palatability	1	A	0.571	0.0986	255	5.79	< 0.01
	Palatability	2	B	0.352	0.0755	255	4.66	< 0.01
	Palatability	3	C	-0.094	0.0907	255	-1.04	0.30
	Palatability	4	C	0	.	.	.	.
	Transect	1	BC	-0.209	0.0920	255	-2.28	0.02
	Transect	2	C	-0.296	0.0949	255	-3.12	< 0.01
	Transect	3	C	-0.308	0.0891	255	-3.45	< 0.01
	Transect	4	AB	-0.027	0.0954	255	-0.28	0.78
	Transect	5	BC	-0.205	0.0943	255	-2.17	0.03
	Transect	6	A	0	.	.	.	.
Camels	Intercept			0.114	0.0225	256	5.06	< 0.01
	DW			0.003	0.0004	256	5.67	< 0.01
	Distance	1	A	0.098	0.0185	256	5.30	< 0.01
	Distance	2	C	-0.013	0.0190	256	-0.71	0.48
	Distance	3	B	0.041	0.0209	256	1.95	0.05
	Distance	4	BC	0	.	.	.	.
	Palatability	1	A	0.152	0.0249	256	6.11	< 0.01
	Palatability	2	C	-0.018	0.0184	256	-1.00	0.32
	Palatability	3	B	-0.169	0.0289	256	-5.84	< 0.01
	Palatability	4	B	0	.	.	.	.

Note: Biomass utilisation rates were power transformed (goats and sheep, 0.2; camels, 0.3). Spatial and temporal autocorrelations are not shown due to low covariance parameter estimates

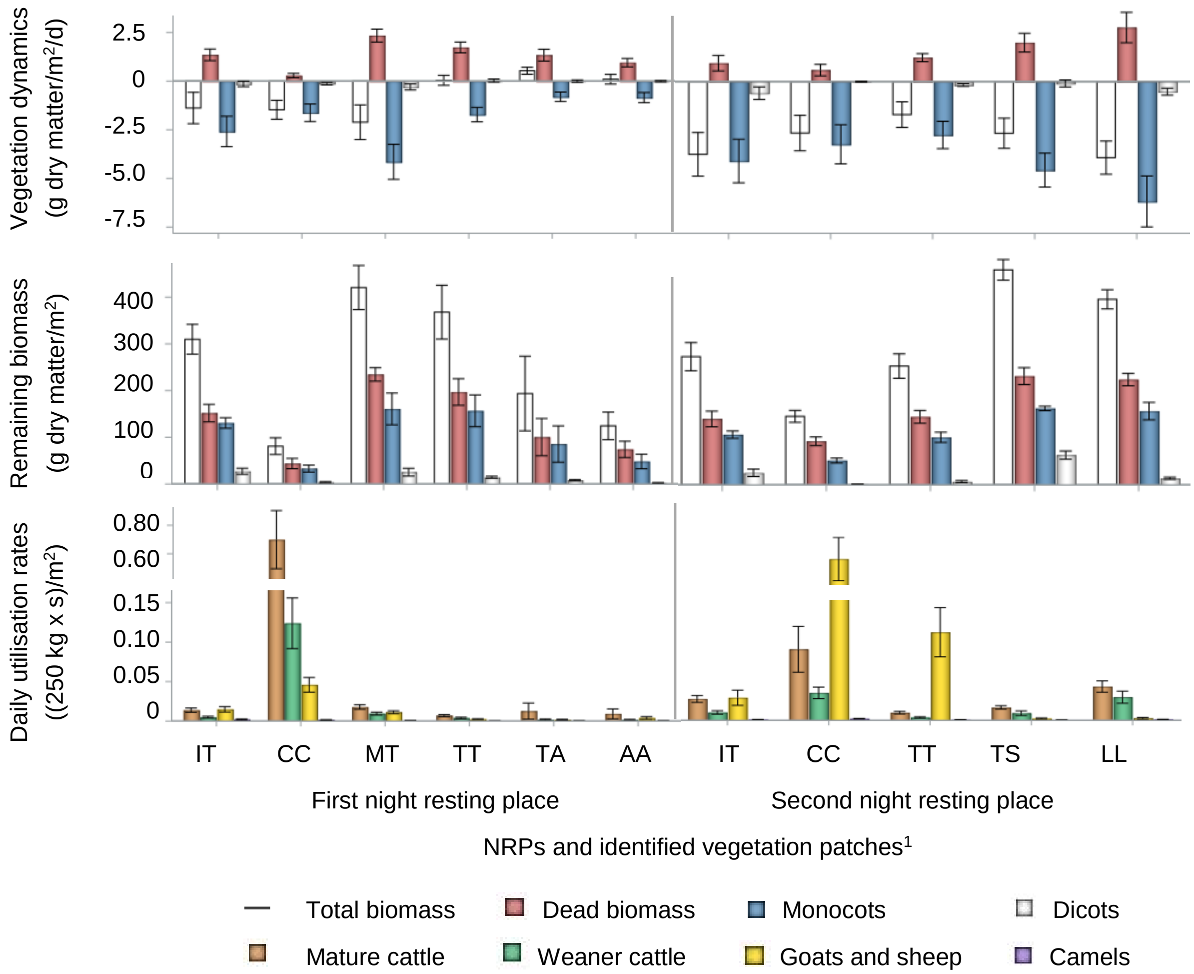
[1] Effect: Palatability = palatability specific to animal species (1, highly palatable; 2, palatable; 3, intermediate palatable; 4, and non-palatable), classified by Ibrahim and Kabuye (1987) and subjectively supported by the opinions of 14 local people and observations of the student (weighted palatability according to the average ratio of goats to sheep); DW = dry matter (DM) weight of dicotyledonous herbaceous biomass (g DM/m^2); Distance = distance to the night resting place (1, 50 m; 2, 150 m; 3, 250 m; 4, 350 m)

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

3.9 Differences between identified vegetation patches

During the observation period, all herds sought patches dominated by *C. dactylon*, whereas identified vegetation patches around the first NRP dominated by either *A. contortus* or *T. triandra* were used less frequently, accumulating herbaceous biomass (Figure 4.14).

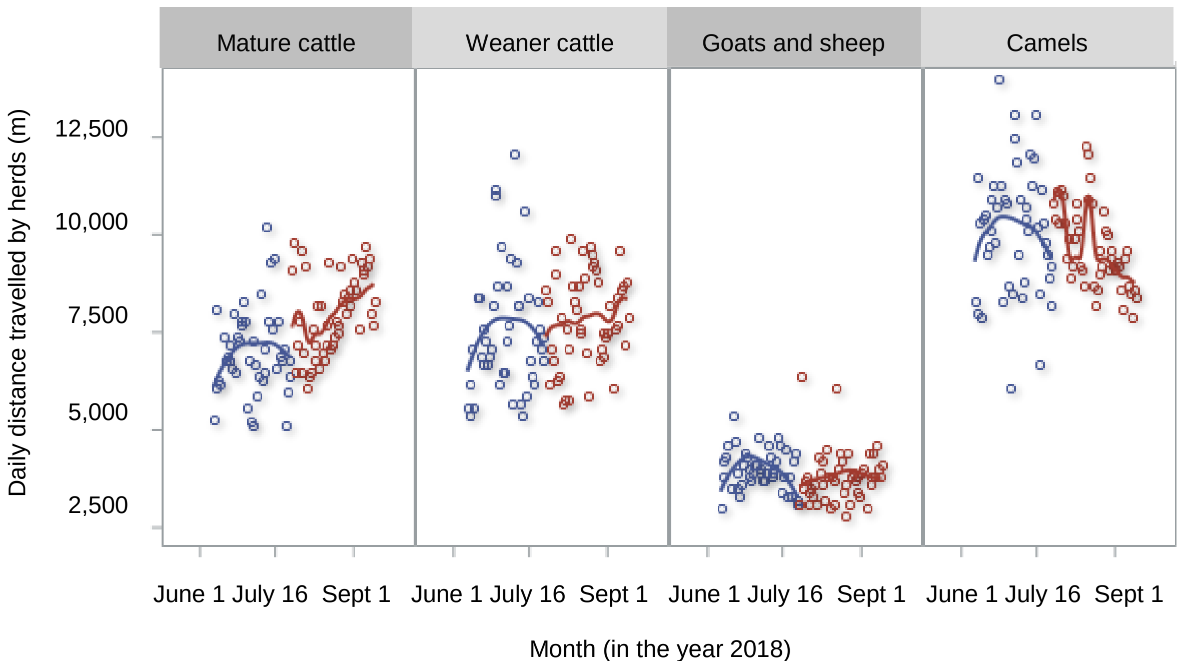


[1] Vegetation patches: IT = *Indigofera volkensii* and *Themeda triandra*; CC = *Cynodon dactylon*; MT = *Melhania ovata* and *Themeda triandra*; TT = *Themeda triandra*; TA = *Themeda triandra* and *Andropogon contortus*; AA = *Andropogon contortus*; TS = *Themeda triandra* and *Solanum incanum*; LL = *Lintonia nutans*

Figure 4.14 Vegetation dynamics, remaining biomass, and daily biomass utilisation rates, recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America), around the studied night resting places (NRPs) per identified vegetation patch (mean ± standard error)

3.10 **Characterisation of daily foraging itineraries and live weight gain**

The longest daily distance was travelled by the herds in the middle of the existence of the first NRP (Figure 4.15), suggesting that the herds were grazed on available forage resources close to the NRP before the movement of the homestead. Except for the HC, the length of the daily foraging itineraries of the HMC, the HWC, and the HGS around the second NRP increased with time, indicating that palatable forage resources near the NRP were exploited.



Note: Solid lines represent fitted p-spline curves using the GLIMMIX procedure of SAS (Version 9.4). Locations were recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America)

Figure 4.15 Daily distance travelled by herds around the first (open blue dots) and second (open red dots) night resting place on a large-scale ranch in Laikipia County, Kenya

Camels covered larger distances and spent less time within the herbaceous biomass sampling belts than cattle, goats, and sheep, whereas the foraging days of the HMC were longer than the ones of the HWC, the HGS, and HC in order to stimulate feed intake (Table 4.11). The daily maximal straight-line distance to the NRP travelled by the HGS implied that animals only walked as far as the water source. Except for the HC, animals were directed to water sources diurnally around midday (Figure 4.16). As the HMC predominantly grazed around the first NRP due to the duration of the calving period, it was watered at a strike situated nearby the NRP. In the morning and in the afternoon, hired pastoralists tending to the HMC, the HWC, and the

HGS collected firewood, prepared food, or brought a bucket of water. Therefore, these herds wandered around the NRPs at those times. Towards the end of the morning, the HGS commonly came together to rest for some time close to the water source. The hired pastoralist looking after the HC guided the animals to specific foraging areas.

The herds around both NRPs went into distinct directions on the same day and each herd spread out in diverse directions on different days, suggesting that hired pastoralists coordinated daily foraging itineraries (Figure A.4; section Appendix). Thus, joint foraging of different livestock species on the rangeland only occurred on occasion, especially in case of mutual assistance between hired pastoralists, when one hired pastoralists looked after two herds while the other one run errands. Across all herds, daily foraging itineraries of the first and the second NRP did not overlap, revealing that an area of available forage resources was not used by livestock and thus, the distance between the two consecutively studied NRPs was too great to exploit forage resources optimally.

Over daily foraging itineraries, each herd produced different herd patterns, indicated by the varying area sizes used by the herds while travelling and the respective herd widths. The identified herd patterns over daily foraging itineraries (Figure 4.17) were principally related to the interventions and positions of hired pastoralists and vegetation structure. Recorded interventions by the hired pastoralists included shouting and making use of a stick or the body. Positions of hired pastoralists were classified into walking, standing, and sitting within, beside, in front of, behind, and out of sight of the herd. Resulting herd responses were divided into reducing or gaining travel speed, following the herder, stopping, and turning.

Most of the time, the pattern of the HMC was encouraged by the hired pastoralist who slowed the movement speed of animals down. The animals of the HWC at the front of the usual circular herd pattern were followed by the other animals that were foraging on forage resources, which were left by the leading animals. Goats and sheep commonly grazed with little distance between individuals intensively, and then the number of foraging animals decreased and animals walked in a column towards another palatable vegetation patch, revealing that forage resources between selected palatable vegetation patches were not utilised. The HC spread out gradually and alternated between foraging and walking generally, indicating the search for specific vegetation patches. On palatable vegetation patches, all herds produced a stationary circular pattern, facing all different directions while foraging intensively.

All branded animals grazed and browsed the natural vegetation around each NRP during the day. In addition to the dominant plant species encountered on the herbaceous biomass sampling areas, the perennial monocotyledonous plant *Pennisetum mezianum* Leeke was abundantly present along the foraging itineraries. Across the rangeland of the study area, the main tree and shrub species *Acacia nilotica, A*. *seyal* var. *fistula*, *A*. *xanthophloea*, *Croton dichogamus* Pax, and *Rhus natalensis* Bernh. ex C.Krauss were found. All herds were provided with minerals about once a month. During the observation period, mean daily live weight gain of individuals in the HMC was higher than the one of those in the HWC. Towards the end of the wet season, mean daily live weight gains of goats, sheep, and camels increased.

Table 4.11 Characteristics of daily foraging itineraries of herds and daily live weight gain (LWGd) of individuals in herds around the first (between June and July) and the second (between August and September) night resting place (NRP) on a ranch in Laikipia County, Kenya, in 2018 (mean ± standard deviation)

		Herds			
NRP	Parameter	Mature cattle	Weaner cattle	Goats and sheep	Camels
1st	Distance travelled (m)	7,016 ± 1,100	7,564 ± 1,600	3,987 ± 506	10,104 ± 1,654
	Maximal distance (m)[1]	1,118 ± 520	1,187 ± 507	530 ± 104	1,757 ± 644
	Duration (hh:mm)	10:12 ± 00:21	09:29 ± 00:27	09:00 ± 00:09	08:33 ± 00:14
	Starting time (hh:mm)	07:25 ± 00:14	08:00 ± 00:22	08:27 ± 00:06	08:54 ± 00:10
	End time (hh:mm)	17:45 ± 00:10	17:22 ± 00:15	17:30 ± 00:07	17:15 ± 00:09
	Within HBSB (%)[2]	31 ± 5	26 ± 3	28 ± 4	6 ± 2
	M_Herd areas (n)[3]	120	120	120	60
	S_Herd area (m^2)[4]	875 ± 222	491 ± 106	209 ± 29	6,310 ± 1,956
	Herd width (m)[5]	61 ± 78	44 ± 47	18 ± 2	115 ± 80
	LWGd (g/head)	363 ± 174	252 ± 167	32 ± 46	102 ± 224
2nd	Distance travelled (m)	8,006 ± 1,023	7,878 ± 1,184	3,814 ± 675	9,688 ± 1,046
	Maximal distance (m)[1]	1,359 ± 468	1,206 ± 544	767 ± 260	2,056 ± 376
	Duration (hh:mm)	10:11 ± 00:17	09:30 ± 00:24	08:56 ± 00:15	08:47 ± 00:23
	Starting time (hh:mm)	07:16 ± 00:11	07:57 ± 00:20	08:30 ± 00:07	08:36 ± 00:14
	End time (hh:mm)	17:39 ± 00:09	17:30 ± 00:10	17:16 ± 00:13	17:20 ± 00:12
	Within HBSB (%)[2]	20 ± 4	22 ± 3	40 ± 5	7 ± 2
	M_Herd areas (n)[3]	120	120	120	60
	S_Herd area (m^2)[4]	619 ± 246	439 ± 97	229 ± 26	6,683 ± 2,909
	Herd width (m)[5]	101 ± 79	76 ± 71	20 ± 5	122 ± 73
	LWGd (g/head)	333 ± 141	259 ± 123	55 ± 30	294 ± 225

Note: LWGd of in-calf cows in the herd of mature cattle (n = 11) were not considered; locations were recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America)

[1] Maximal distance = daily maximal straight-line distance to the night resting place travelled by herds

[2] Within HBSA = proportion of time spent within the herbaceous biomass sampling belt to total time spent outside of the NRP

[3] M_Herd areas = total number of herd areas measured on three different days

[4] S_Herd area = area size used by the herd while travelling

[5] Herd width = mean herd width of area size used by the herd while travelling, depending on the geometrical form of the herd area (circular vs. foraging front)

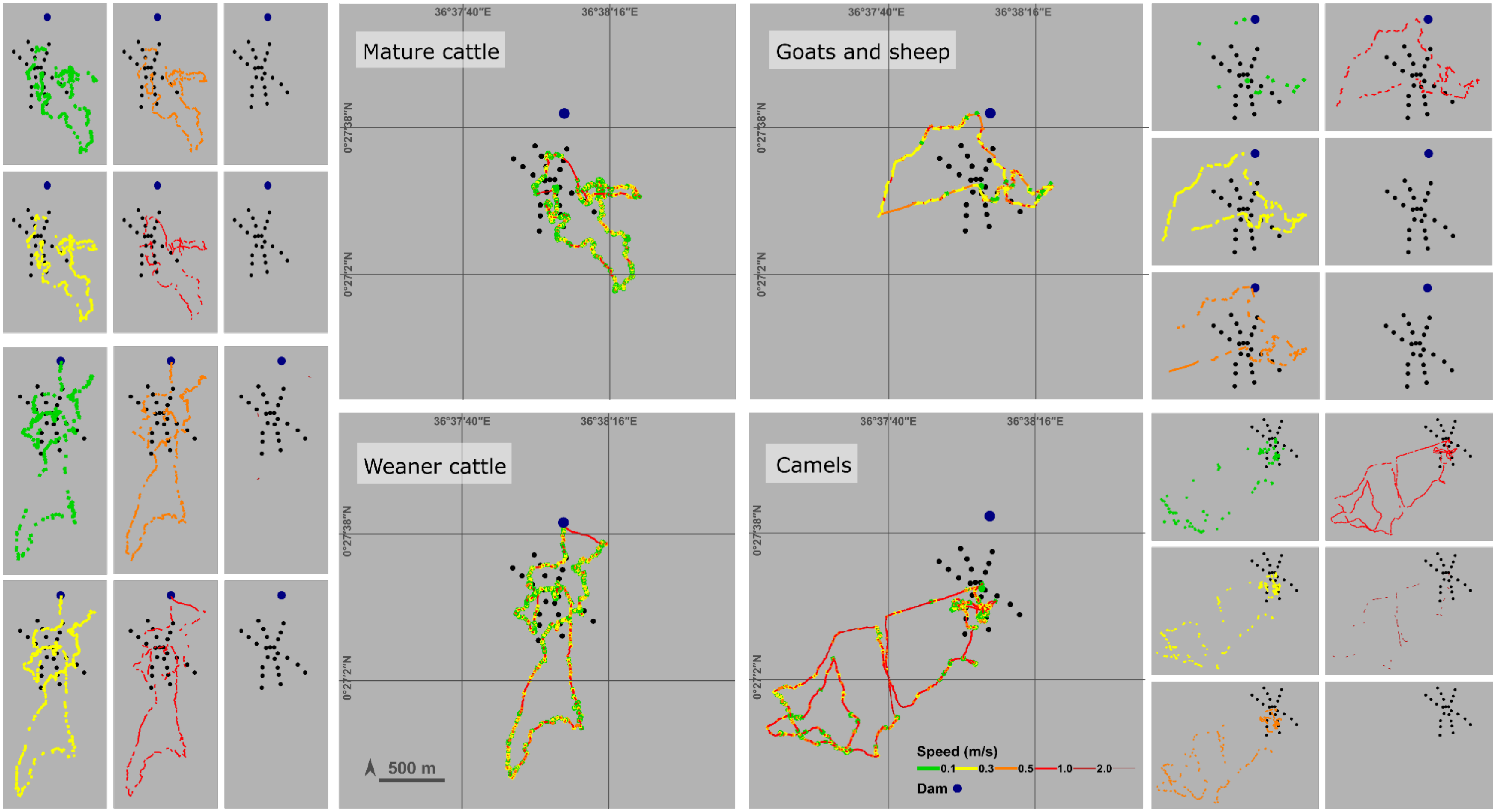


Figure 4.16 Maps showing an exemplary foraging itinerary of each herd designed by a hired pastoralist around the first studied night resting place, recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America), generated in QGIS (Version 3.0.3), and visually optimised in Inkscape (Version 0.92.4)

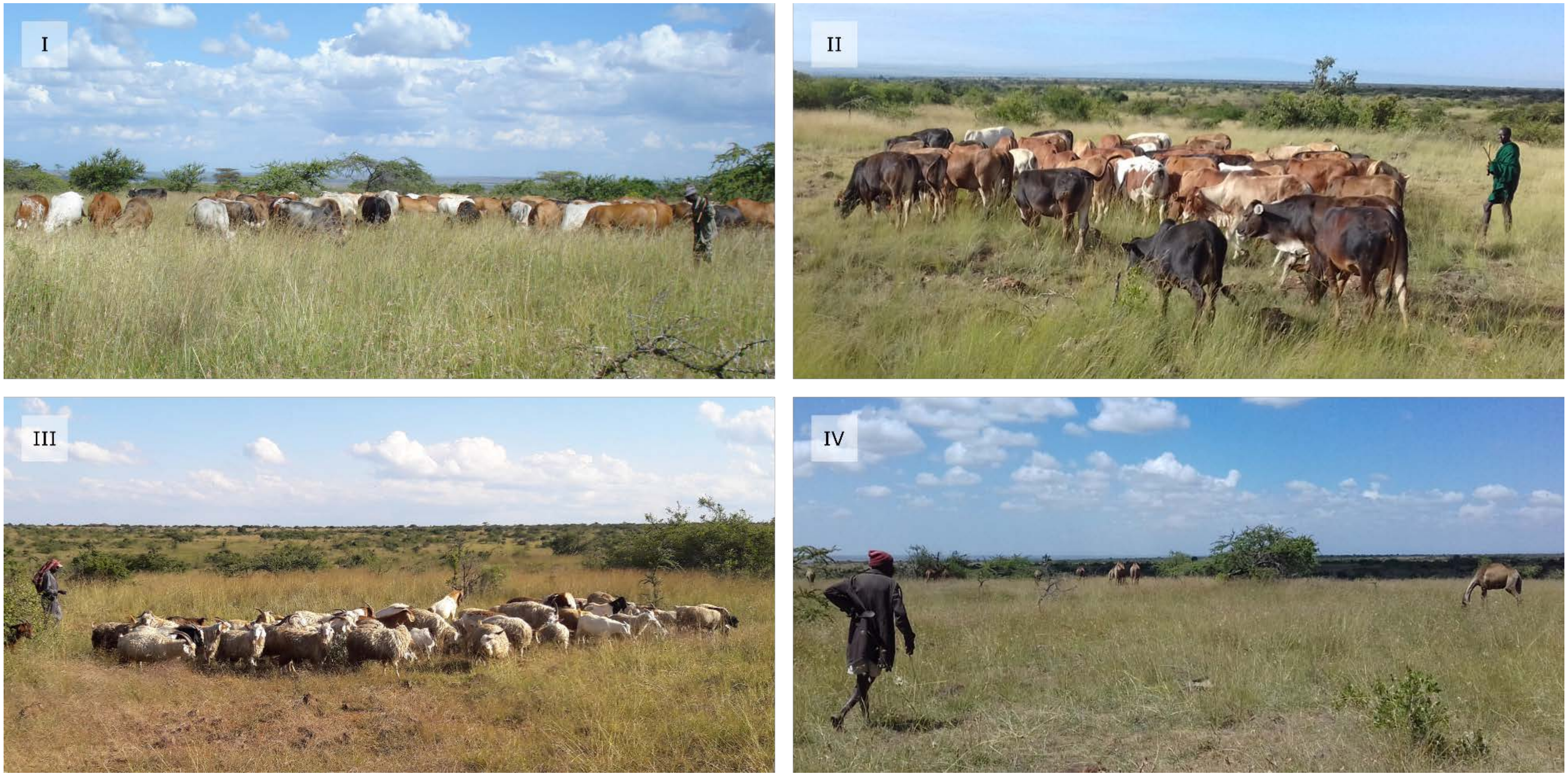


Figure 4.17 Illustration of representative herd patterns of (I) the herd of mature cattle forming a foraging front and travelling side-by-side in the same direction, (II) the herd of weaner cattle describing a circular and a unidirectional pattern, (III) the mixed herd of goats and sheep taking on consecutive funnel shapes, and (IV) the herd of camels producing a fan pattern (own source)

3.11 **Factors influencing the length of daily foraging itineraries**

Of the 18 different components explored in the structural time series analysis, three that were significantly associated with the length of daily foraging itineraries of herds around the first NRP remained (Table 4.12). The non-significant time-varying regression coefficient presence of the student ($P \geq 0.05$) indicated that the student accompanying the herd did not affect the length of the daily walking distance of herds. Across all herds, the distances herds travelled the previous days were principally responsible for the length of daily foraging itineraries. The days of weighing animals increased the average daily walking distance of the HMC, the HWC, the HGS, and HC by about 1,600, 700, 3,300, and 4,300 m, respectively, influencing the daily movements of HMC, HGS, and HC significantly ($P < 0.05$). The hired pastoralists of the HMC and the HC explained that the increased length of daily foraging itineraries on days of weighing animals was due to his efforts to meet the nutritional requirements of animals. At the onset of rain, the hired pastoralists tending to the HMC, the HWC, and the HGS headed to the NRP and the HWC and the HGS continued foraging in close proximity to the NRP. In case of the HMC, animals travelled greater distances on rainy days ($P < 0.05$), revealing the effort of the hired pastoralist to move away from the close proximity to the NRP again after rain in search of palatable forage resources. The significant error variance across all herds implied stochasticity in the length of the daily distance travelled by herds, indicating that the movement patterns were highly variable throughout the observational period.

Table 4.12 Final estimates of the free parameters influencing the distance of daily foraging itineraries around the first night resting place on a ranch in Laikipia County, Kenya, between June and July 2018, using the UCM procedure of SAS (Version 9.4)

Herd	Component[1]	Parameter	Estimate	Standard error	t Value	Approx. P-value[2]
Mature cattle	Irregular	Error variance	949,798.00	209,775.30	4.53	< 0.01
	Precipitation	Coefficient	456.66	141.31	3.23	< 0.01
	Weighing	Coefficient	268.30	12.22	2.19	0.03
	DepLag	Phi_1	0.37	0.10	3.59	< 0.01
	DepLag	Phi_2	0.62	0.10	5.89	< 0.01
Weaner cattle	Irregular	Error variance	320,450.50	67,556.90	4.74	< 0.01
	DepLag	Phi_1	0.44	0.12	3.52	< 0.01
	DepLag	Phi_2	0.55	0.13	4.36	< 0.01
Goats and sheep	Irregular	Error variance	613,624.00	132,337.60	4.64	< 0.01
	Weighing	Coefficient	607.96	98.04	6.20	< 0.01
	DepLag	Phi_1	0.28	0.11	2.58	0.01
	DepLag	Phi_2	0.44	0.10	4.32	< 0.01
	DepLag	Phi_3	0.25	0.11	2.34	0.02
Camels	Irregular	Error variance	403,018.00	85,923.72	4.69	< 0.01
	Weighing	Coefficient	1,372.40	351.32	3.91	< 0.01
	DepLag	Phi_1	0.74	0.13	5.91	< 0.01
	DepLag	Phi_2	0.25	0.13	1.97	0.05[3]

[1] Component: Precipitation = the amount of daily precipitation recorded at the night resting place (mm/day), data obtained from a rain gauge (IM523, Pessl Instruments GmbH, Weiz, Austria); Weighing = the day of weighing animals based on dummy variables; DepLag = DepLag statement (including the dependent variable as predictors in the model)

[2] Based on a Wald test

[3] Rounded up

Around the second NRP, the selected unobserved component model ranked the error variance, the distances herds walked the previous days, herder, weighing, and duration as the most important components (Table 4.13). The daily walking distance of the HMC, the HWC, and the HC varied significantly between permanently employed and replacing hired pastoralists. Permanently employed pastoralists of the HMC, the HWC, and the HC designed foraging itineraries that were on average 500, 300, and 1,900 m shorter compared to replacing pastoralists, respectively. Especially in case of the HC, the animals did not follow the replacing hired pastoralist. In line with this, the length of daily foraging itineraries of the HC increased with decreasing duration of daily foraging itineraries ($P < 0.01$), indicating the importance of the acquainted interaction between permanently employed hired pastoralist and the herd. The replacing hired pastoralist started the foraging itinerary at about 9:00 h and headed back to the second NRP at about 17:00 h, covering a mean distance of 11,100 m per day. The HC herded by the permanently employed hired pastoralist travelled on average 9,200 m per day, departing from the second NRP about 30 minutes earlier and returned about 30 minutes later compared to the daily movements designed by the replacing hired pastoralist. In case of HGS, walking to the squeeze chute to weigh the animals increased the mean length of daily foraging itineraries by 2,700 m ($P < 0.01$).

Table 4.13 Final estimates of the free parameters influencing the distance of daily foraging itineraries around the second night resting place on a ranch in Laikipia County, Kenya, between August and September 2018, using the UCM procedure of SAS (Version 9.4)

Herd	Component[1]	Parameter	Estimate	Standard error	t Value	Approx. P-value[2]
Mature cattle	Irregular	Error variance	108,056.50	22,290.36	4.85	< 0.01
	Herder	Coefficient	380.05	39.92	9.52	< 0.01
	DepLag	Phi_1	0.42	0.13	3.26	< 0.01
	DepLag	Phi_2	0.39	0.12	3.22	< 0.01
Weaner cattle	Irregular	Error variance	199,727.20	40,769.14	4.9	< 0.01
	Herder	Coefficient	280.70	74.07	3.79	< 0.01
	DepLag	Phi_1	0.89	0.06	14.51	< 0.01
Goats and sheep	Irregular	Error variance	556,477.00	114,792.40	4.85	< 0.01
	Weighing	Coefficient	454.68	130.35	3.49	< 0.01
	DepLag	Phi_1	0.41	0.09	4.41	< 0.01
	DepLag	Phi_2	0.57	0.09	6.20	< 0.01
Camels	Irregular	Error variance	402,989.00	83,130.40	4.85	< 0.01
	Duration	Coefficient	1,372.40	212.33	5.48	< 0.01
	Herder	Coefficient	5,333.79	131.86	40.45	< 0.01
	DepLag	Phi_1	0.24	0.11	2.25	0.02

[1] Component: Herder = hired pastoralist (permanently employed, replacing) based on dummy variables; Weighing = the day of weighing animals based on dummy variables; DepLag = DepLag statement (including the dependent variable as predictors in the model); Duration = daily duration of foraging itineraries (hh:mm:ss)
[2] Based on a Wald test

3.12 **Determinants underlying area densities of herds over foraging itineraries**

The generalized linear mixed models for area densities of the HMC and the HWC around the first NRP suggested that the effects time of day, position of the hired pastoralist, and vegetation structure influenced the area densities of those herds significantly (Table 4.14). In both herds of cattle, animals spread out in the absence of the hired pastoralist ($P < 0.01$). Despite the same herd species composition, the positions of hired pastoralists used to generate specific area densities of herds differed, revealing the existence of specialised interactions established by the hired pastoralist and the herd. The hired pastoralist herding the HMC was mainly located within the herd (41% of all records), whereas the hired pastoralist tending to the HWC predominantly walked beside the herd (68% of all records).

Table 4.14 Solutions for fixed effects influencing area densities of the herds of mature and weaner cattle over their daily foraging itineraries around the first night resting place on a ranch in Laikipia County, Kenya, between June and July 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t value	Pr > |t|
Mature cattle	Intercept			3.238	0.0845	113	38.33	< 0.01
	Time			< 0.001	< 0.0001	113	2.52	0.01
	Pos_H	1	A	-0.397	0.0476	113	-8.33	< 0.01
	Pos_H	2	C	-0.201	0.0898	113	-2.24	0.03
	Pos_H	3	ABC	-0.247	0.1273	113	-1.94	0.06
	Pos_H	4	BC	-0.044	0.0361	113	-1.22	0.22
	Pos_H	5	B	0	.	113	.	.
	Vegetation	1	B	0.246	0.0361	113	6.81	< 0.01
	Vegetation	2	A	0	.	.	.	.
Weaner cattle	Intercept			3.349	0.1937	115	17.29	< 0.01
	Time			< 0.001	< 0.0001	115	6.13	< 0.01
	Pos_H	1	A	-0.575	0.1829	115	-3.14	< 0.01
	Pos_H	2	B	-0.312	0.1804	115	-1.73	0.09
	Pos_H	3	C	-0.193	0.1875	115	-1.03	0.30
	Pos_H	4	BC	0	.	.	.	.

Note: Results on the log-transformed data are given

[1] Effect: PreInt*Temp = interaction between precipitation intensity (mm/h) and temperature (°C); Time = time of day (hh:mm:ss); Pos_H = Position of the hired pastoralist (1, absent; 2, behind the herd; 3, beside the herd; 4, in front of the herd; 5, within the herd); Vegetation = vegetation structure (1, less or equal open; 2, greater or equal open-moderate) according to Fisher et al. (2014)

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

The effects intervention by the hired pastoralist, vegetation structure, time of day, distance to the NRP, and the interaction between time of day and intervention by the hired pastoralist were principally responsible for the area densities of the HGS and the HC around the first NRP (Table 4.15). Goats and sheep walking in a greater or equal open-moderate vegetation scattered in more or less divergent directions and thus foraging on larger areas than in less or equal open vegetation ($P < 0.01$). From time to time during daily foraging itineraries, goats and sheep came together to rest for a while. Therefore, setting the direction by using a stick tended to result in decreased area densities of the HGS ($P = 0.72$), whereas the same intervention enabled the hired pastoralist to increase the area densities of the HC in the morning and evening ($P = 0.02$). As the hired pastoralist kept sight of the camels and utilised his voice consistently, area densities of the HC during the day varied little (between 1.4 and 1.6 kg/m^2), most likely explaining the temporal correlation of sequential measurements of area densities of the HC.

Table 4.15 Solutions for fixed effects influencing area densities of the mixed herd of goats and sheep and the one of camels over their daily foraging itineraries around the first night resting place on a ranch in Laikipia County, Kenya, between June and July 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t Value	Pr > |t|
Goats and sheep	Intercept			2.758	0.1219	116	22.64	< 0.01
	Int_H	1	A	-0.198	0.1229	116	-1.61	0.11
	Int_H	2	B	-0.045	0.1258	116	-0.35	0.72
	Int_H	3	AB	0	.	.	.	.
	Vegetation	1	A	0.133	0.0225	116	5.91	< 0.01
	Vegetation	2	B	0	.	.	.	.
Camels	Intercept			-3.853	3.3895	9	-1.14	0.29
	Distance			< -0.001	< 0.0001	42	-3.53	< 0.01
	Time			< 0.001	< 0.0001	9	1.33	0.21
	Time*Int_H	1		< -0.001	< 0.0001	44	-3.09	< 0.01
	Time*Int_H	2		< 0.001	< 0.0001	44	2.37	0.02
	Time*Int_H	3		0	.	.	.	.
	Cov Var			0.003	0.0034			
	Cov Residual			0.028	0.0006			

[1] Effect: Int_H = intervention by hired pastoralist (1, no intervention; 2, setting direction; 3, utilizing voice); Vegetation = vegetation structure (1, less or equal open; 2, greater or equal open-moderate) according to Fisher et al. (2014); Distance = distance to the night resting place (m); Time = time of day (hh:mm:ss); Time*Int_H = interaction between time of day and intervention by the hired pastoralist; Cov Var = covariance parameter var [P-Spline (Time)]; Cov Residual = covariance parameter residual

[2] T = T Grouping for the respective effect least squares means (LSMs, α = 0.05). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

The area densities of the HMC and the HWC around the second NRP were strongly influenced by the effects distance to the NRP, time of day, date, vegetation structure, position of the hired pastoralist, intervention by the hired pastoralist, hired pastoralist, and the interaction between time and intervention by the hired pastoralist (Table 4.16). Between recorded positions of the hired pastoralists, the area densities of the HMC did not vary. Hired pastoralists tending to the HMC travelled long distances away from the NRP in order to meet the nutritional requirements of the animals, offering them palatable rangeland resources. While walking to those vegetation patches, animals were guided by the hired pastoralists having little distance between each other and on those vegetation patches, the HMC described a circular and a unidirectional pattern, indicated by the increasing area densities of the herd with increasing distance ($P < 0.01$). The average area densities of the HMC of 40.2 kg/m^2 between 07:28 and 07:53 h, 38.5

kg/m^2 between 10:07 and 10:48 h, 40.8 kg/m^2 between 12:24 and 13:00 h, and 43.6 kg/m^2 between 15:36 and 16:20 h were lower than the ones between 58.2 and 75.6 kg/m^2 during the rest of the day. Towards the end of the morning and around midday, animals tended to move to the right and the left occasionally, searching for palatable rangeland resources. Shortly after the departure from the NRP and late in the afternoon, the interaction between the hired pastoralist and the herd was temporarily interrupted by the hired pastoralist looking after the calves of the herd ($P < 0.01$). In general, towards the end of the daily foraging itinerary, animals appeared to be adequately fed, walking faster and carrying out rapid and infrequent selection on the way back, indicated by a decreasing distance between animals with increasing time ($P < 0.01$). The average area density of the HMC herded by the permanently employed hired pastoralist (49.4 kg/m^2) was lower compared to the one generated by the replacing hired pastoralist (66.9 kg/m^2; $P < 0.01$). In case of the HWC, the replacing hired pastoralist allowed for lower area densities of the herd (29.7 kg/m^2) than the permanently employed hired pastoralist (32.4 kg/m^2; $P < 0.01$). Early in the morning (between 08:07 and 08:59 h), at midday (between 11:28 and 12:16 h), and in the afternoon (between 14:49 and 16:02 h), the hired pastoralists herding the HWC did not intervene in the herd pattern due to either feeling tired, carving a new stick, or waiting for people ($P = 0.04$).

Table 4.16 Solutions for fixed effects influencing area density of the herds of mature and weaner cattle over their daily foraging itineraries around the second night resting place on a ranch in Laikipia County, Kenya, between August and September 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t Value	Pr > |t|
Mature cattle	Intercept			3.821	0.1528	110	25.01	< 0.01
	Distance			< 0.001	0.0001	110	2.49	0.01
	Time			< 0.001	< 0.0001	110	3.06	< 0.01
	Herder	1	A	-0.339	0.0549	110	-6.17	< 0.01
	Herder	2	B	0	.	.	.	.
	Int_H	1	A	-0.101	0.0628	110	3.06	< 0.01
	Int_H	2	B	0.122	0.0739	110	1.64	0.10
	Int_H	3	AB	0	.	.	.	.
	Pos_H	1	A	-0.460	0.1086	110	-4.24	< 0.01
	Pos_H	2	AB	-0.1710	0.1691	110	-1.01	0.31
	Pos_H	3	B	-0.126	0.0682	110	-1.85	0.07
	Pos_H	4	B	-0.081	0.0664	110	-1.23	0.22
	Pos_H	5	B	0	.	.	.	.
Weaner cattle	Intercept			-0.555	0.5518	113	-1.01	0.32
	Date			0.269	0.0366	113	7.34	< 0.01
	Time*Int_H	1		< -0.001	< 0.0001	113	-2.07	0.04
	Time*Int_H	2		< 0.001	< 0.0001	113	0.12	0.90
	Time*Int_H	3		< -0.001	< 0.0001	113	-1.63	0.11
	Herder	1	B	0.362	0.0632	113	5.73	< 0.01
	Herder	2	A	0	.	.	.	.
	Vegetation	1	B	0.342	0.0637	113	5.36	< 0.01
	Vegetation	2	A	0	.	.	.	.

[1] Effect: Distance = distance to the night resting place (m); Time = time of day (hh:mm:ss); Herder = hired pastoralist (permanently employed, replacing); Int_H = intervention by hired pastoralist (1, no intervention; 2, setting direction; 3, utilizing voice); Pos_H = Position of the hired pastoralist (1, absent; 2, behind the herd; 3, beside the herd; 4, in front of the herd; 5, within the herd); Date = date (dd.mm.yyyy); Time*Int_H = interaction between time of day and intervention by hired pastoralist; Vegetation = vegetation structure (1, less or equal open; 2, greater or equal open-moderate) according to Fisher et al. (2014)

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

Precipitation intensity, vegetation structure, distance to the NRP, intervention by the hired pastoralist, and the interaction between time and intervention by the hired pastoralist were significantly associated with area densities of the HGS and the HC around the second NRP

(Table 4.17). With increasing precipitation intensity, goats and sheep came closer together, resulting in higher area densities ($P < 0.01$). The area density of the HGS on a day without rain and at a precipitation intensity of about 10 mm/h averaged 14.6 and 19.0 kg/m^2, respectively. During rainfall, camels also changed their behaviour, but the area densities of the HC did not vary significantly, as small groups of three to five individuals shaking with cold and standing side by side under trees were distributed over the foraging area of the herd. This time, the hired pastoralist designing the foraging itineraries of the HGS utilised either his voice or a stick to increase area densities of the herd ($P < 0.01$), however, most of the time, he did not intervene in the herd pattern (79% of all records). Late in the morning (between 09:54 and 11:13 h), the hired pastoralists herding the HC mainly utilised their voices to direct the animals ($P = 0.05$), whereas around midday (between 12:51 and 13:18 h), they predominantly followed the herd ($P = 0.01$).

Table 4.17 Solutions for fixed effects influencing area density of the mixed herd of goats and sheep and the one of camels over their daily foraging itineraries around the second night resting on a ranch in Laikipia County, Kenya, between August and September 2018, using the GLIMMIX procedure of SAS (Version 9.4)

Herd	Effect[1]	Class values	T[2]	Estimate	Standard error	DF[3]	t Value	Pr > |t|
Goats and sheep	Intercept			2.719	0.0251	115	108.17	< 0.01
	PreInt			0.010	0.0015	115	6.66	< 0.01
	Int_H	1	A	-0.0864	0.0265	115	-3.26	< 0.01
	Int_H	2	C	0.107	0.0325	115	3.27	< 0.01
	Int_H	3	B	0	.	.	.	.
	Vegetation	1	B	0.254	0.0364	115	6.97	< 0.01
	Vegetation	2	A	0	.	.	.	.
Camels	Intercept			1.967	0.3215	55	6.12	< 0.01
	Distance			< -0.001	< 0.0001	55	-6.34	< 0.01
	Time*Int_H	1		< -0.001	< 0.0001	55	-2.71	0.01
	Time*Int_H	2		< -0.001	< 0.0001	55	-1.22	0.23
	Time*Int_H	3		< -0.001	< 0.0001	55	-2.05	0.05

[1] Effect: PreInt = precipitation intensity (mm/h), data obtained from a rain gauge (IM523, Pessl Instruments GmbH, Weiz, Austria); Int_H = intervention by hired pastoralist (1, no intervention; 2, setting direction; 3, utilizing voice); Vegetation = vegetation structure (1, less or equal open; 2, greater or equal open-moderate) according to Fisher et al. (2014); Distance = distance to the night resting place (m); Time = time of day (hh:mm:ss); Time*Int_H = interaction between time of day and intervention by hired pastoralist

[2] T = T Grouping for the respective effect least squares means (LSMs, $\alpha = 0.05$). LSMs with the same letter are not significantly different

[3] DF = degrees of freedom

4 Discussion

The above-mentioned results provide the basis for reviewing the employed method for analysing the vegetation dynamics, the BURs of herds, and the daily foraging itineraries designed by hired pastoralists. The findings of this study are comprised to elaborate on mutual interactions between herds and forage resources around NRPs, including the examination of the utilisation of different vegetation patches with diverse livestock species, and to address the effects of hired pastoralists on movements of herds, also considering the social setting. Following this, alternatives to a rotational foraging system implemented by hired pastoralists are explored, directing attention to the precipitation trend as well.

4.1 Usefulness of employed method

As demonstrated in this study, the establishment of several transects around NRPs in order to include different vegetation patches and unforeseen factors that influenced the decision-making of hired pastoralists allowed for a refined analysis of BURs and vegetation dynamics at patch scale. This observation design differs from the ones employed in other studies that also focused on the immediate proximity of NRPs, but did not consider different directions around NRPs (Stelfox, 1986; Vuorio et al., 2014). Although the length of each transect away from the NRPs was 350 m, the heterogeneity was captured by subdividing the rangeland into vegetation patches, each having a functional relevance to the foraging herds (O'Neill et al., 1986). Except for the HC, the herds spent a considerable amount of time within the herbaceous biomass sampling belts.

Since the DM concentrations in the herbaceous biomass samples after open-air drying were similar to the ones after oven drying at 70 °C for 48 h (Safari et al., 2011), the samples taken after the ninth cutting time around the first NRP were not sent to the Kenyan laboratory in order to determine DM concentrations. The collected data on plant heights and the chemical composition of herbaceous biomass samples provided detailed indications of the interactions between forage availability and herd movements, which mutually determine each other (Butt, 2010). One limitation concerned the approach chosen to estimate the removal of herbaceous biomass around NRPs by herds, as it could not relate the vegetation changes at each herbaceous biomass sampling point to consumption by herds, natural variability, and regrowth rates. However, this research has demonstrated that some herbaceous biomass sampling points around NRPs were more prone to the impacts of BURs compared to others.

Several studies have relied on the integrated use of GPS and geographic information systems in order to analyse the spatial and temporal distribution of animals on the landscape, often at a relatively coarse scale (Coppolillo, 2000; BurnSilver et al., 2003). However, when aiming at collecting geo-referenced data of daily herd movements at patch scale, the spatial and temporal scale of the analyses has to be relatively fine. Therefore, the Garmin GPS receivers appeared to be appropriate, even though this GPS technology was more labour intensive than others (Sonneveld et al., 2009), since the batteries had to be exchanged diurnally. On the other side, the close and consistent interaction between the student and the herd most likely facilitated the measurements of the area densities of the herds over daily foraging itineraries, as animals were adapted to the presence of the student. Although the hired pastoralists designed the daily foraging itineraries of herds, they occasionally were not representative of the geo-referenced location of the herd due to activities such as sitting down, staying behind, collecting firewood, preparing food, bringing a bucket of water, or going hunting, and thus it was important that animals carried the GPS receivers. The GPS receivers recorded geographic coordinates at 20-second intervals as a reasonable compromise between the required and the feasible accuracy of walking animals and the one of resting animals. Shorter intervals as recommended by Swain et al. (2008) and Moritz et al. (2010) could have resulted in greater distances travelled by herds recorded for a given foraging itinerary due to unfavourable satellite signals. Past work by Moritz et al. (2012) found that studying the behaviour and movements of one animal was representative of the entire herd. A second limitation of the approach employed to calculate the time herds spent foraging on herbaceous biomass sampling points lied in the fact that animals foraged while standing still and rested while foraging. As a result, the foraging time had to be considered with care. Likewise, inaccuracies of GPS receivers resulted in movement speeds that were lower or higher than the actual movement speed of the animal (Schlecht et al., 2006). However, Homburger et al. (2014) argue that geo-referenced data have a large potential for the prediction of animal behaviour.

The results of this study also provide support to arguments that GPS technology has to be matched by anthropologic understandings of the system (Moritz et al., 2012) and availability of forage resources (Turner et al., 2005), since the obtained data on daily grazing itineraries was stochastic and specific herbaceous biomass sampling points were considerably more utilised than other ones. Likewise, Zengeya et al. (2015) highlight that the animal behaviour has to be linked to herding activities.

4.2 Mutual interactions between herds and forage resources around NRPs

The study has experienced the same trends as those described for the region, since the foraging area was bounded by the property size and the daily walking ability of animals. The access to a relatively small foraging area in semi-arid rangeland ecosystems often leads to relatively low livestock populations adjusted to the forage availability in the dry season, and thus herbaceous biomass may increase beyond what can be consumed by animals in the wet season (Boone, 2005). This was quite evident when the herbaceous biomass removal of the first and the second NRP was interpreted carefully. Neither the vegetation dynamics nor the

BURs around NRPs showed either an evenly distributed foraging intensity as described by Homewood and Rodgers (1991), a decreasing one with distance in all directions or skewed toward the water source as proposed by Spencer (1973), or an increasing one with distance in two opposite directions as assumed by Western (1975). Although the distance to the water source most likely limited the length of the daily foraging itineraries of the HGS, the BURs were not skewed toward the water sources. The distance in case of the HC and the directions in case of the other herds were not gradually predictable. Although, animals avoid foraging near dung pats (Gibb and Ridout, 1986), this study demonstrates that highly palatable herbaceous biomass sampling points around both NRPs were visited considerably more by herds compared to those characterised by less palatable forage resources. This is consistent with previous work at finer scales (Provenza, 1996). Therefore, the relatively high BURs around NRPs did not change the diet selection process of animals, but rather increased the rate at which palatable herbaceous biomass was defoliated (Bailey and Brown, 2011). This was evidenced by low plant heights and DM weights of the palatable forage *C. dactylon* that grows on abandoned NRPs. Thus, the results of this study also provide support to recognitions that *C. dactylon* is one of the most preferred forages in East Africa (Pratt and Gwynne, 1977).

It seems likely that the intense utilisation of *C. dactylon* by ruminants can be ascribed to the relatively high CP concentrations, relatively high OMD, and relatively low fibre concentrations, since rumen microbes are capable of breaking down fodder with CP concentrations above 8 g/100 g DM (Soliva et al., 2015). Past work by Riaz et al. (2014) has found that low CP concentrations slightly inhibit DM intake of ruminants, which may result in a significant reduction of live weight gain. This in turn highlights the relevance of abandoned NRPs, dominated by one or two plant species (Porensky et al., 2013), to ruminant feeding (Muchiru et al., 2008). Likewise, Sibanda et al. (2016) conclude that NRPs having existed for one week develop into highly palatable and productive vegetation patches that improve heterogeneity in the rangelands, due to dung accumulation (Young et al., 1995). The increasing CP concentrations in *C. dactylon* in the course of the existence of the NRPs can most likely be traced to the regrowth of herbaceous biomass after removal (Kirchgeßner, 2008). For restoration of degraded semi-arid rangelands in Kenya, *C. dactylon* has a high potential (Musimba et al., 2004).

The results of this study also provide support to arguments that *T. triandra* is one of the most prominent grass species in the diet of ruminants (Ego et al., 2003), since the more palatable species *C. dactylon* was relatively scarce. Although identified vegetation patches around the first NRP dominated by either *A. contortus* or *T. triandra* were underused, as indicated by biomass accumulation, the total DM weight of *T. triandra* removed was highest. Most likely, the development of seeds with a sharp spike reduced the palatability of *A. contortus*. Through trampling, biomass is broken down, forage seeds are incorporated into the soil, the establishment of forages is enhanced (Savory and Butterfield, 2016), and soil organic matter increases (Byrnes et al., 2018). The number of cattle and their movements appeared to be insufficient to promote plant growth by herd effects around NRPs on the studied ranch under the current management, since the vegetation at the entrances to the NRPs of the cattle herds was not largely affected by intensive trampling and foraging, despite relatively high precipitation intensities. It seems likely that when comparing the grounds of NRPs of diverse livestock species that cattle had the highest potential of visible hoof impacts on standing biomass (Figure A.5; section Appendix).

In addition to the vegetation patches dominated by *C*. *dactylon* around the second NRP, the HMC was attracted by vegetation patches dominated by the non-palatable grass *L*. *nutans* (Dougall and Bogdan, 1960), suggesting that the hairs did not decrease palatability considerably. Past work by Ego et al. (2003) found that *L*. *nutans* contributed relatively more to the diets of cattle during the dry season than during the wet season, while *T*. *triandra* made up a relatively smaller part of the diet during the dry season than during the wet season. Under moisture stress conditions, the moisture content of leaves of *T*. *triandra* and *A*. *contortus* drops relatively quickly and aerial parts of the plants die back (Opperman and Roberts, 1977). This may explain why cattle preferred *L*. *nutans* to *T*. *triandra* at the onset of the dry season, besides the relatively higher nutritional value of *L*. *nutans*.

Although the CP concentrations in the leguminous plant *I*. *volkensii* were relatively high, it was only browsed by camels. Previous work has found that this plant species is the most important one in the diet of camels and goats if available (Lusigi and Glaser, 1984). The results of this study differ from the findings of Glover et al. (1966) who report that *I*. *volkensii* is consumed by all livestock species. This may be due to four principal reasons. First, throughout the observational period, the forage resources were abundant, and thus more palatable plant species were most likely preferred by ruminants (Morgan, 1981). Second, plant species with relatively high lignin concentrations are considered to be of relatively low quality, since forages with relatively low fibre concentrations are readily fermented in the rumen (Getachew et al., 1998). Cattle and sheep adapt to relatively high fibre concentrations in forages by retaining feed particles in the forestomaches for longer periods, whereas camels and goats are able to forage selectively (Lechner-Doll et al., 1990). Therefore, camels are able to maintain diets characterised by relatively high CP concentrations in the dry season, when cattle grazes on forages with relatively low CP concentrations (Payne, 1990). Third, the relatively low OMD probably inhibited forage intake by ruminants. Fourth, it is widely recognised that *I*. *volkensii* contains indospicine, a non-proteinogenic analogue of arginine, which depresses live weight gain and damages livers in rats (Aylward et al., 1987). It is also toxic to cattle and sheep (Norfeldt et al., 1952).

Studies carried out in Kenya showed that the dietary overlap between cattle and camels was relatively low year-round (Rutagwenda et al., 1990; Leparmarai et al., 2018). The height of camels allows them to utilize forage resources inaccessible to other livestock species. Previous work by Venter et al. (2018) has found that browsers can mitigate woody plant encroachment. However, the diversification of animal species does not relieve foraging pressure on either severely grazed or browsed plant species, but it potentially maximises the exploitation of rangeland resources. Previous research has found that animals forage more efficiently when the daily distance they travel was reduced (Sevi et al., 1999). The increase in the mean daily live weight gains of goats, sheep, and camels towards the end of the wet season can possibly be attributed to a greater availability of plant species to browse on than to graze on around the second NRP compared to the first NRP.

4.3 **Impacts of hired pastoralists on movements of herds**

The results of this study also provide support to arguments that herd activities are significantly influenced by pastoralists (Zengeya et al., 2015), as animals spread out in the absence of hired pastoralists. This indicates the continuous interaction between hired pastoralists and herds over daily foraging itineraries (Liao et al., 2018) and their ability to intervene in the forage selection process. Constant area densities of the HMC over daily foraging itineraries between recorded positions of the hired pastoralists suggest that the hired pastoralists were in control of the herd patterns from every position. Over daily foraging itineraries, the hired pastoralists herding the HMC slowed the movement speed of animals down by forming a foraging front, most likely mitigating rapid selection. The animals of the HWC at the front of the usual circular herd pattern probably carried out rapid selection due to the following animals, while the animals in the middle and at the back of the herd grazed the forage resources left by the leading animals.

Previous research has found that animals without interventions of pastoralists seek for vegetation patches dominated by highly palatable and high-quality plant species, whereas animals under the guidance of pastoralists also feed on areas characterised by less preferred plant species (Odadi et al., 2018). This is particularly important on palatable vegetation patches, where herds produced a stationary circular pattern while foraging intensively in order to avoid over-foraged vegetation patches (Kellner and Bosch, 1992). Although pastoralists are able to reduce BURs on palatable vegetation patches (Crawford et al., 2019), the herding efforts of hired pastoralists tending to the HMC were mainly aimed at increasing milk yields for their personal use and not at an efficient use of rangeland resources around NRPs. This is also suggested by the higher mean daily live weight gain of individuals in the HMC compared to the one of those in the HWC. Therefore, this study area has experienced the same herding strategy as that described for the grazed floodplain in west Zambia (Baars and Ottens, 2001). Ironically, the right to consume milk is an attempt to motivate hired pastoralists to incorporate their knowledge to exploit forage resources, which are varying temporally and spatially, sustainably

(Bassett, 1994). The lack of incentives to distribute herds in relation to rangeland resources intentionally all day may lead to rangeland degradation (Turner, 1999). The low commitment to work throughout the overall duration of foraging itineraries was partly based on the cultivation of contacts and the preparation of meals. The insignificant dedication became most noticeable when the distances the herds travelled the previous days mainly influenced the length of the daily foraging itineraries. However, in the course of the observational study, live weights of all herds increased, and well-nourished and healthy animals were presented to other people on the property, revealing that hired pastoralists ensured that the feeding requirements of animals were satisfied and that they were concerned about their repute. This is consistent with past work by Turner and Hiernaux (2008), who relate herding efforts to the reputations of hired pastoralists, besides self-ownership rates and benefits from milk production. As the daily foraging itineraries of herds around the two studied NRPs did not overlap, an area of forage resources was not utilised, indicating that the distance between the two NRPs was too great to exploit forage resources optimally and that the focus was on livestock production, rather than on rangeland health.

Greater distances of daily foraging itineraries and higher area densities of the HMC and the HWC over daily foraging itineraries generated by the replacing hired pastoralists compared to the permanently employed hired pastoralists suggest that herding efforts were also related to the familiarity with the environment. This was particularly evident in the HC when the replacing hired pastoralist had no control over the herd, resulting in an increased length of daily foraging itineraries and in a reduced duration of daily foraging itineraries. This differs from the findings of Michler et al. (2019), who only focused on the duration of the labour agreement and did not consider the potential importance of the acquainted interaction between permanently employed pastoralists and the herd. Since the area densities of the HMC and the HWC herded by the permanently employed hired pastoralists were lower compared to the ones formed by the replacing hired pastoralists, the permanently employed hired pastoralists most likely minimised the selective feeding behaviour of the animals to a lesser extent than the replacing hired pastoralists did (Odadi et al., 2018).

4.4 **Are hired pastoralists replaceable?**

When aiming at an efficient utilisation of forage resources in a semi-arid rangeland ecosystem, the foraging system has to be flexible in order to adapt to the highly dynamic spatial and temporal variability (Savory and Butterfield, 2016). The rangeland management on the ranch under study implemented a rotational foraging system, in which the foraging area is subdivided into units that are recurrently utilised by livestock, using hired pastoralists (Vallentine, 2001). It seems likely that when the precipitation distribution varied within the property and the quality and quantity of forage resources differed at the micro level, such a foraging system was suitable to respond to heterogeneity compared to continuous foraging methods that allow animals to utilise the foraging area uninterruptedly. This view on rotational foraging systems is contested by Briske et al. (2008), who argue that the area has to maintain sufficient forage resources to carry animals during periods of forage scarcity, irrespectively of the management system. However, this work has not considered the knowledge of pastoralists, who are able to improve the performance of animals by altering the movements of herds (Odadi et al., 2017). Likewise, Salomon et al. (2013) acknowledge that pastoralists are aware of seasonally palatable vegetation patches. Since the herds around both NRPs went into distinct directions on the same day and each herd spread out in diverse directions on different days, hired pastoralists most likely coordinated daily foraging itineraries. Previous research by Ohta (1982) suggests that the movement of NRPs on the ranch preclude autonomous foraging itineraries of animals, highlighting the relevance of hired pastoralists to design daily foraging itineraries. The small-sized cattle herds of 100 individuals guided by pastoralists in this study can compensate for unrestricted foraging time (Odadi and Rubenstein, 2015).

As pastoralists lived full time around the NRPs, they most likely improved the health condition of the herds by continuously monitoring the well-being and nutritional status of the animals and curing diseases such as orf infections using *A. nilotica*, as described by Musimba et al. (2004). On the other side, changes in livestock behaviour that are related to diseases and other animal welfare concerns can be identified using both GPS tracking and accelerometers these days (Bailey et al., 2018). Since the ranch under study overlapped with wildlife habitats, fencing can intensify the human-wildlife conflict on the property (Redpath et al., 2013), whereas pastoralists can coexist with wildlife (Yurco, 2017). Furthermore, the presence of pastoralists day and night can reduce the risk of carnivore attacks (Woodroffe et al., 2007) and thefts (Bond, 2014a). The construction of foraging units by employing portable electric fencing (Venter et al., 2019) may be challenging due to the heterogeneity of forage resources at micro level, the presence of different animal species, and the non-existent infrastructure on the property. Not only has the annual amount of precipitation increased over the last decades, but also the variability in the last few years, this is consistent with previous work in the region (Huho and Kosonei, 2013). As a result, the availability of rangeland resources are less predictable (Sullivan and Rohde, 2002). Therefore, the foraging system has to be sufficiently flexible to fluctuations in the quantity and quality of rangeland resources (Fynn, 2012). A herding system as practised on the ranch under study has the potential to respond to naturally varying forage resources and to induce functional heterogeneity by building NRPs. To exploit the rangeland resources more efficiently, hired pastoralists have to be motivated to intervene in the diet selection process of animals all day to avoid high BURs on specific locations around NRPs, while diluted impacts of BURs on others reduce palatability, and to encourage goats to browse. It is therefore important to ascertain the underlying reasons behind little incentives. Simple measures that could be taken to facilitate an efficient use of rangeland resources may include hiring two permanently employed pastoralists per herd, introducing an offspring-sharing system, and negotiating agreements with neighbours to increase herd mobility in case of need. The investigation of an optimal grazer-browser-intermediate feeder ratio may contribute to the increase in resource use efficiency.

5 Conclusions

The employment of both qualitative and quantitative methods that matched herd movements with the collected influencing factors offered insights into the utilisation of heterogeneous forage resources around NRPs and the interactions between the herds and the hired pastoralists over daily foraging itineraries.

The quality and quantity of forage resources and the vegetation dynamics around both NRPs varied between herbaceous biomass sampling points, not revealing any spatial and temporal patterns. Contrary to the expectation, the vegetation at the entrances to the NRPs of the cattle herds was not largely affected by intensive trampling and foraging. The mixed methods approach was suitable for measuring the efforts of hired pastoralists to utilise different forage resources, revealed by the BURs, and the effects of their herding techniques, indicated by the vegetation dynamics, implying potentially over-foraged and underused herbaceous biomass sampling points. However, analyses to describe the relationships between BURs (explanatory variables) and vegetation dynamics (response variables) were not applied in the present study for two main reasons. First, the vegetation was patchy within herbaceous biomass sampling points, and thus differences between consecutive measurements were partly related to natural variability. In addition, regrowth of herbaceous biomass was not determined. Second, besides inaccuracies in GPS readings and herd tracks, the BURs did not distinguish between the activities of herds. Therefore, high BURs did not necessarily result in significant removals of herbaceous biomass. To develop mathematical models for further interpretations, subsequent studies have to address those uncertainties.

Camels preferably grazed on the legume *I. volkensii*, whereas cattle, goats, and sheep intensively foraged on the grass *C. dactylon*. Throughout the observational period, forage resources were abundant. Hence, the increased resource use efficiency by rearing foraging, browsing, and intermediate species has to be further investigated during periods of forage scarcity.

Not forage nutritive value, but palatability of dominant species on herbaceous biomass sampling points mainly influenced the BURs. All livestock species preferably utilised vegetation patches dominated by *C. dactylon*, probably being overgrazed. Herbaceous biomass accumulated on vegetation patches dominated by either *A. contortus* or *T. triandra* around the first NRP, indicating that these forage resources were underused. Except for the HC, the distance to the NRPs had no effect on BURs. To gain a better understanding of the BURs at patch level and to establish the following NRP based on the previous use of forage resources, further studies have to include herbaceous biomass sampling points at greater distances to the NRPs.

During the existence of the NRPs, each herd moved in all directions, but some directions were visited more frequently than other ones, implying the importance of covering diverse directions to account for unforeseen factors such as other homesteads, collection of wood, and presence of wildlife. Except for the HC, the time herds spent within the herbaceous biomass sampling belts suggests that the herbaceous biomass sampling points were appropriate for describing the use of rangeland resources around the NRPs.

In the course of the observational study, average live weights of the herds increased, confirming the hypothesis that hired pastoralists meet the nutritional requirements of animals. However, the higher mean daily live weight gain of mature cattle compared to the one of weaner cattle indicated that the efforts of hired pastoralists tending to the HWC were improvable. Therefore, further studies have to identify the underlying causes of the efforts of hired pastoralists in order to contribute to a sustainable use of forage resources.

The fitted curves of the length of daily foraging itineraries around the first NRP over time showed parabolas that were open downward, whereas the length of the daily foraging itineraries of the HMC, the HWC, and the HGS around the second NRP increased with time. The distances herds travelled the previous days were principally responsible for the length of daily foraging itineraries. In case of the HGS, the distance to the water sources limited the length of the daily foraging itineraries. As the length of daily foraging itineraries varied between permanently employed and replacing hired pastoralists significantly and was stochastic for several reasons, further research has to select a larger sample size in order to distinguish influencing factors that can be translated to herd movements in the surrounding area from those that are either human-, herd-, or site-specific.

The area densities of herds over foraging itineraries were mainly associated with positions or interventions of hired pastoralists, confirming the hypothesis that the distances to the NRPs were not responsible for area densities of the herds, except for the HC. Since hired pastoralists were in control of area densities of herds to target foraging, further studies can explore vegetation-specific ratios of foraging, intermediate, and browsing livestock species in order to improve the utilisation of forage resources.

Principally, the used mixed methods approach to understand the distribution of livestock over available resources can be applied to herding systems where impacts of animals on vegetation are distributed around a fixed location for a time and are solely attributed to a known number of herds with constant sizes.

In general, hired pastoralists did not intervene in the forage selection process throughout the day in order to utilise diverse vegetation patches efficiently, as they were also engaged in personal issues such as social contacts and preparation of meals. Therefore, the efforts of the hired pastoralists in this research did not lead to the desired herding effects. To ensure a sustainable use of forage resources while feeding the animals adequately, it is essential to motivate hired pastoralists to implement their knowledge. Central to the observed herding strategies was the autonomy of decision of hired pastoralists that resulted in a compromise between personal interests and full incorporation of their knowledge. It is likely that either under better working conditions or with a different property situation hired pastoralists are more incentivized to maintain or improve forage availability on rangelands and livestock productivity. However, these conclusions have to be interpreted carefully, since the interactions between the diverse elements of this system are complex. Nevertheless, the presented results are of relevance to progressive discussions on management of rangeland resources, as greater attention has to be paid to the relationship between landowners, livestock owners, and hired pastoralists.

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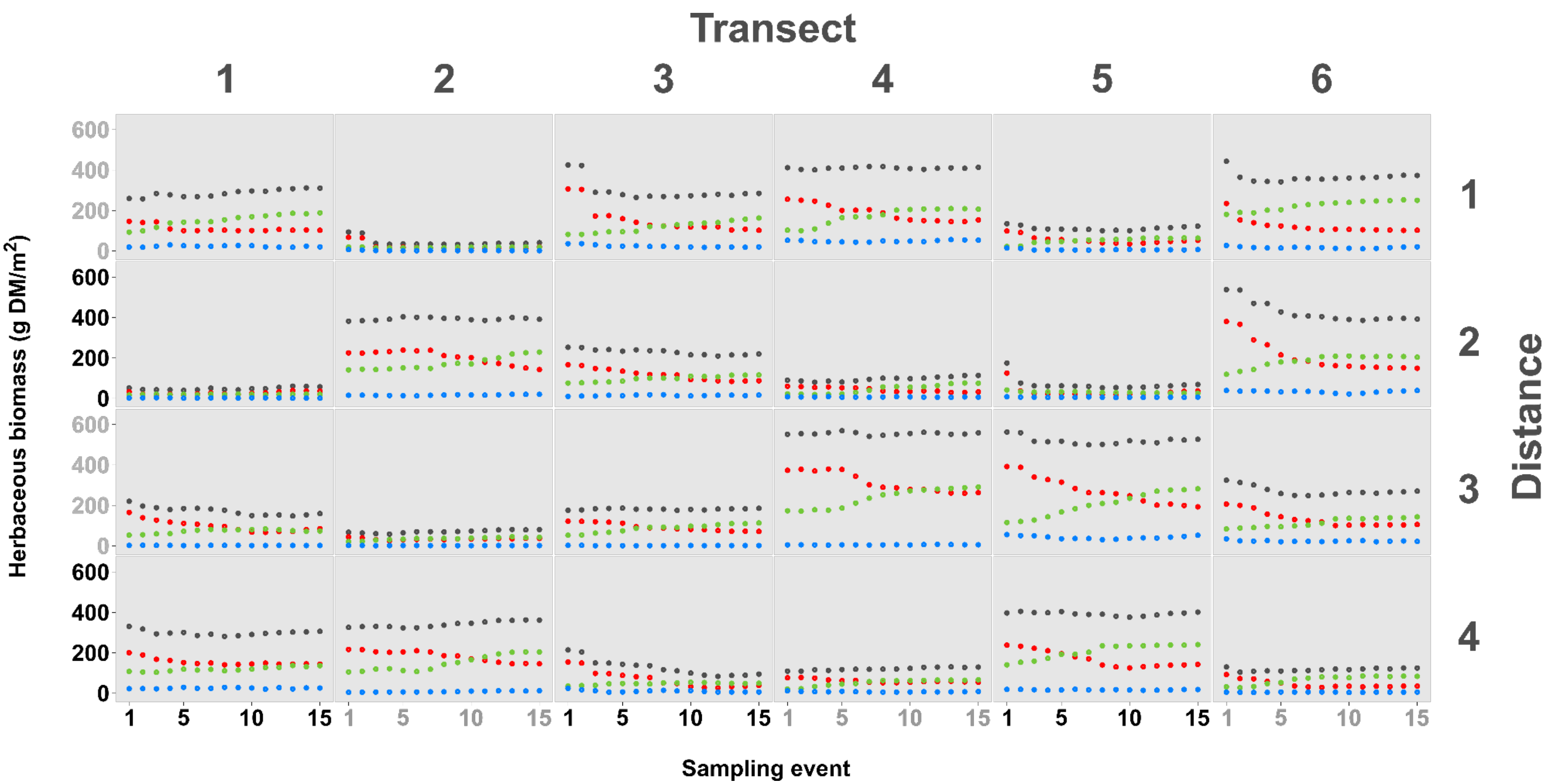
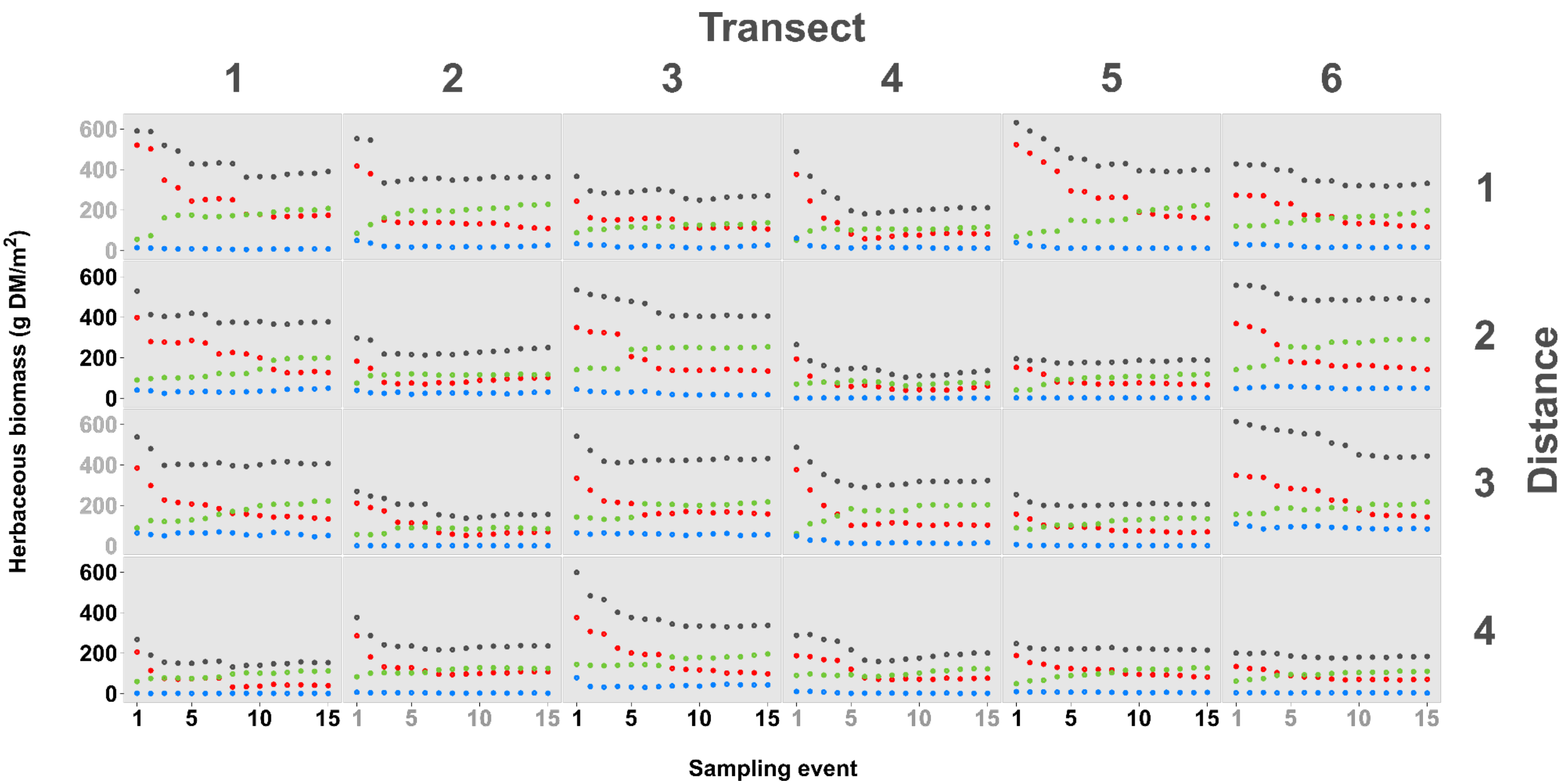
7 Appendix

Figure A.1 Illustration of spatial heterogeneity in the foraging area around the first night resting place (own source)



[1] Distance = distance to the night resting place (1, 50 m; 2, 150 m; 3, 250 m; 4, 350 m)

Figure A.2 Dry matter (DM) weights of monocotyledonous (red dots), dicotyledonous (blue dots), dead (green dots), and total (black dots) herbaceous biomass around the first night resting place



[1] Distance = distance to the night resting place (1, 50 m; 2, 150 m; 3, 250 m; 4, 350 m)

Figure A.3 Dry matter (DM) weights of monocotyledonous (red dots), dicotyledonous (blue dots), dead (green dots), and total (black dots) herbaceous biomass around the second night resting place

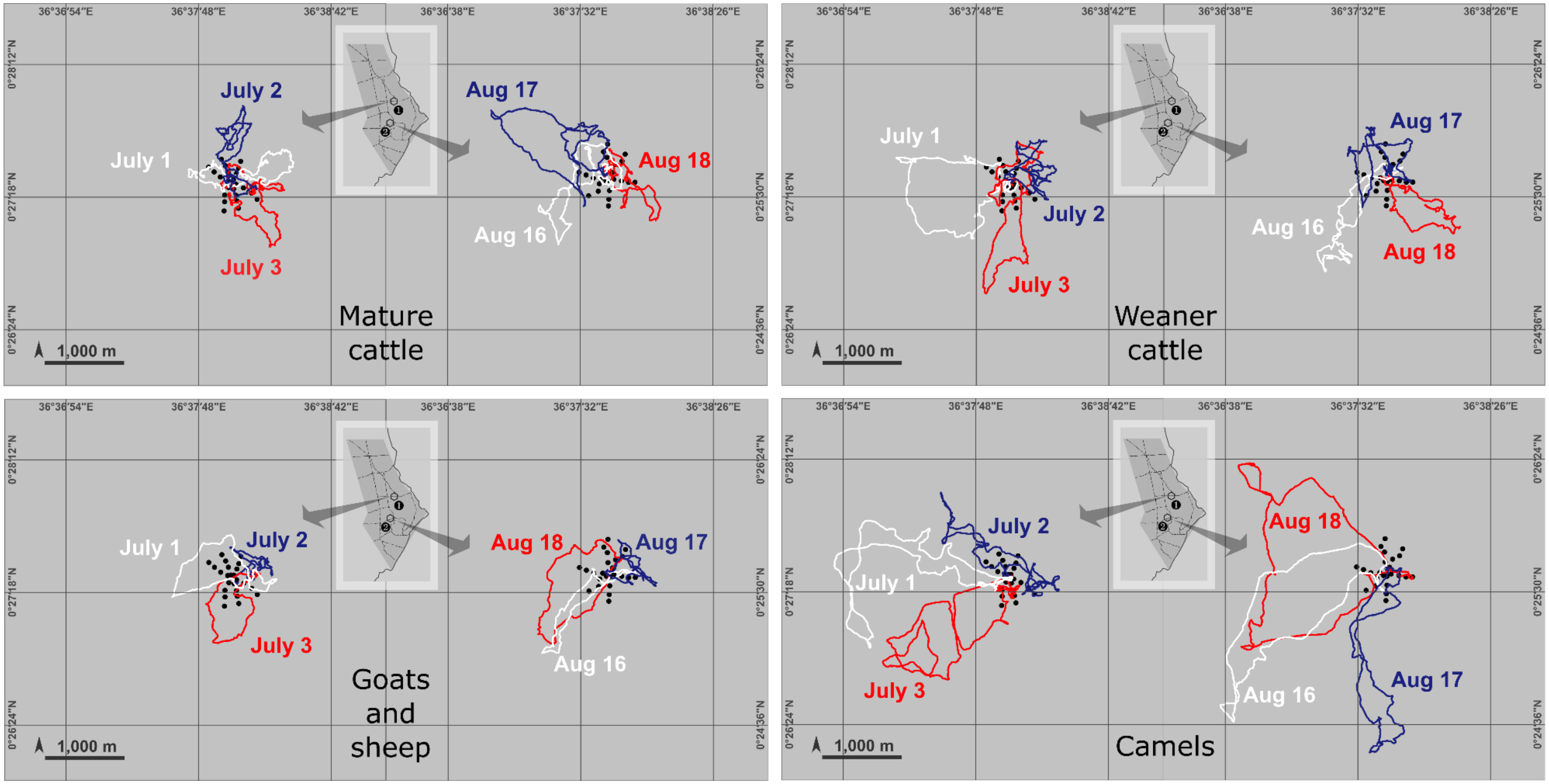


Figure A.4 Maps of the two consecutively studied night resting places showing exemplary foraging itineraries of livestock herded by hired pastoralists, recorded using a GPS receiver (Garmin eTrex Vista HCx, Garmin International Inc., Olathe, United States of America) and generated in QGIS (Version 3.0.3) and visually optimised in Inkscape (Version 0.92.4)

Figure A.5 Illustration of the impact of (I) the herd of mature cattle, (II) the herd of weaner cattle, (III) the mixed herd of goats and sheep, and (IV) the herd of camels on the ground in the first night resting place after 28 days (own source)