Global Ecology and Conservation 30 (2021) e01749

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Medicinal service supply by wild plants in Samburu, Kenya: Comparisons among medicinal plant assemblages

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A R T I C L E I N F O

Keywords:
Samburu
Kenya
Medicinal plant
Supply security
Classification
Ordination

A B S T R A C T

Supply of medicinal plants from African landscapes is crucial because of their widespread use. Rapid climate change and land use change are potential threats to this resource but knowledge about the ecological needs of many of these plants is still rather limited. More knowledge about potential threats to medicinal plants supply and options to prevent future losses are desirable. Therefore, the objectives of the study were to examine (1) the effects of environmental drivers on the occurrence of medicinal plant species, (2) how different vegetation formations contribute to the provision of plants used for the treatment of diseases and (3) how these contributions are secured by redundancy. The analysis was based on a sample of 130 sampling plots in Samburu County, Kenya. We identified patterns in medicinal plants co-occurrences using classification and ordination analyses and analyzed these pattern in terms of environmental drivers, service diversity and service security. The pattern in medicinal plants co-occurrences reflected the distribution of broad formations (bushed grassland, forest, wooded grassland, savanna) driven by differences in grazing pressure, drought, slope and fraction of sand in soils. Each of the formations brought with it its own characteristic endowment with medicinal plants. The formations differed in the diversity and security of medicinal services provided. All resulted as fulfilling unique services with diseases treated by plants occurring exclusively in one or another formation. Forests featured the highest diversity of medicinal services, with medicinal plants used against 67 diseases. The supply security in forests, resulting from redundancy in supply provision, was moderate. In contrast to this, savanna grasslands featured plants with uses against 49 diseases, some of them were treated exclusively by plants from savanna grasslands. This formation also showed the highest redundancy. Wooded grasslands showed very little redundancy and is likely to be adversely affected by climate change. Whereas savannas feature the largest pool of medicinal plants and should receive due attention, urgent and highest conservation priority should, presently and in future, go towards the wooded grassland that had the lowest supply redundancy for traditional medicine.

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https://doi.org/10.1016/j.gecco.2021.e01749
Received 19 April 2021; Received in revised form 23 July 2021; Accepted 9 August 2021
Available online 12 August 2021

1. Introduction

Apart from maintenance of the ecosystem, medicinal plants form a key element of the local medical systems (Dharani and Yenesew, 2010). In many developing countries, they form a major component of the primary health care systems and are used in the treatment of many illnesses, whereas in the developed countries, they provide a broad reservoir upon which potential conventional drugs can be developed (Ngari et al., 2010). According to the World Health Organization, medicinal plants are among the safest ways of ensuring worldwide access to health care (WHO, 2013). Their significance is highlighted by their incorporation into WHO's strategy for attaining the Millennium Development Goals (MDGs), which include improving maternal health, combating HIV/AIDs and other diseases and reducing child mortality (WHO, 2014). A key factor of reaching these ambitious goals is a sound understanding of the supply of medicinal plants, especially in rural areas.

The contribution of spontaneously growing medicinal plants to the health care system especially in rural areas cannot be emphasized enough. For the millions of people in Africa, such medicinal plants are the primary, occasionally the solitary source of medical care that is close to their home (Chalo et al., 2016). The frequent use of medicinal plants in the continent is also attributed to the fact that they are cheap and culturally accepted in many communities (Ngari et al., 2010). In Kenya alone, 80% of the population uses medicinal plants from the wild for their primary health care. This makes sense in light of the figures released by the Ministry of Health in Kenya in 2016. These showed that the budgetary allocation for conventional drugs catered to a mere 30% of the population (Government of Kenya, 2016). The 70% without access to conventional treatments was thus left to depend on traditional treatments based on medicinal plants. Since it seems highly unlikely that medicinal plants might be replaced with pharmaceutical equivalents, at least in the next few decades, the conservation of medicinal plants is of great interest to Kenya's society (Dharani and Yenesew, 2010).

In Kenya, some 1200 plants have scientifically confirmed medicinal value. Apart from their medicinal value, the plants are also a source of income to traditional healers, food (*Rhus natalensis*), appetizers (*Carissa edulis*) and disinfectants (*Acacia tortilis*) (Gakuya et al., 2020). However, decline in medicinal plant resources due to overexploitation, unsustainable harvesting and land use has threatened to take with it medicine that is crucial for treating the country's illnesses (Kamau et al., 2016). Whereas this threat has existed for decades, unprecedented loss of medicinal plants in the country (Wambugu et al., 2011), just like in India (Sharma and Kala, 2018) or Mozambique (Ribeiro et al., 2010) has led to huge decline in medicinal service supply. Conservation of medicinal plants remains key to improvement of medicinal service supply. Additionally, medicinal plants conservation can also provide a base for the conservation of natural habitats (Gafna et al., 2017). Therefore, there is an urgent need to conserve medicinal plants as a means

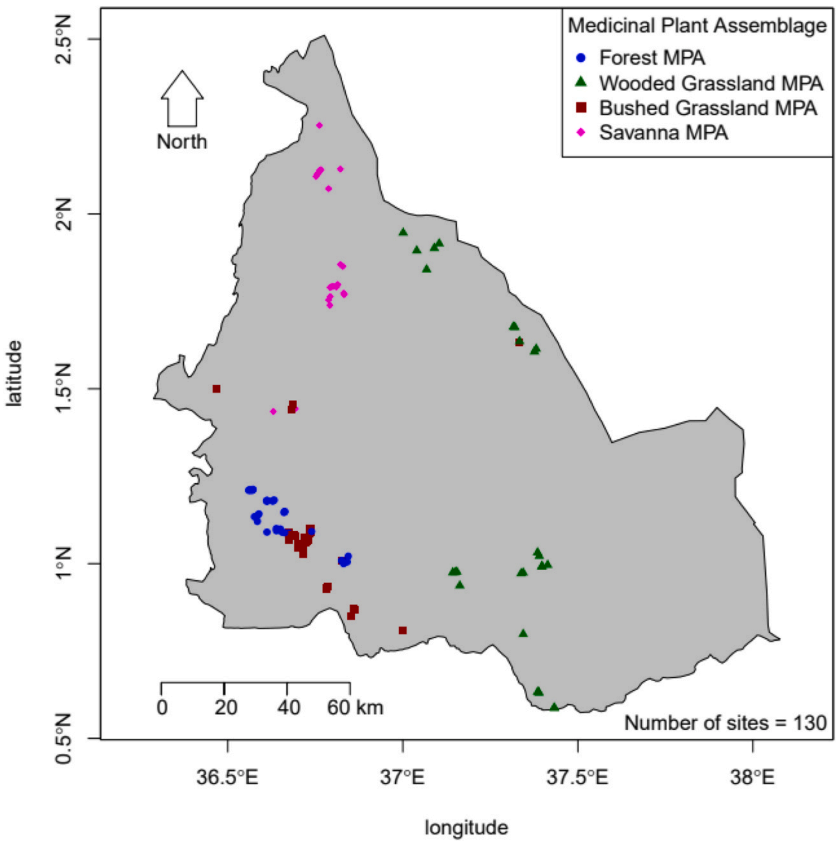

Fig. 1. Map of the study area and sites labeled according to MPA. The map was created using R program version 4.0.2 (R Core Team, 2020; https://www.r-project.org/about.html).

towards improvement of livelihoods and local healthcare in the country (Gakuya et al., 2020). Consequently, a number of recommendations have been made regarding medicinal plants conservation. These include strengthening of customary conservation laws, establishment of species monitoring systems in combination with coordinated in situ and *ex situ* conservation efforts (Nanyingi et al., 2008). Despite these efforts, decrease in medicinal service supply continues (Njoroge, 2012), perhaps because growth conditions deteriorate or scientific insights are not incorporated in the formulation of local conservation programs. Thus, knowledge about the environmental conditions that secure medicinal service supply of ecosystems is crucial for conservation planning.

Climate change affects these environmental conditions. It may either contract, expand or shift the geographical range of medicinal plants (Kotir, 2011). The report by IPCC (2014) indicates that East Africa will experience increase in temperature by 15% and 8% decreased rainfall by 2050. Growing human population combined with the rural-dependent lifestyle puts pressure on the already vulnerable vegetation formations, highlighting the need for adoption of climate change strategies in the management of medicinal supply. However, the effects of climate change on medicinal supply of spontaneous vegetation is still unclear.

Despite calls to evaluate the medicinal services provided by spontaneous vegetation (Albuquerque et al., 2005), research on that topic is scarce. So far, most studies have exposed the potential of forest types to supply medicinal plants (Shanley and Luz, 2003; Eliáš and Mariničová, 2017). Little effort has been made to extend this to other formations and in particular to undertake detailed quantitative analyses on the impact of environmental conditions on medicinal service supply with regards to individual diseases. We argue that this limits the utilization of the traditional medical system. Medicinal plants management strategies need to be formulated based on the determinants of medicinal plants supply patterns. Such patterns in medicinal plants supply have been found to be determined by abiotic factors, including elevation, climate (Rokaya et al., 2012), land use such as logging and nomadic grazing (Albuquerque et al., 2005) and edaphic factors (Dharani and Yenesew, 2010). These factors generally determine medicinal plants supply by influencing their richness and abundance. Additionally, cultural factors such as knowledge on medicinal plants use also plays a critical role (Gafna et al., 2017). As shown by Chalo et al. (2016), plants are only used for medicinal purposes if they are culturally acceptable to a community.

The current paper aims at answering the following questions: (1) What are the effects of environmental drivers on the occurrence of medicinal plant species in Samburu, Kenya?, (2) how do different vegetation formations contribute to the treatment of diseases through medicinal plants and (3) how are these contributions secured by redundancy of services.

2. Material and methods

2.1. Study area

Samburu County is situated in the arid and semi-arid biogeographic part of northern Kenya and approximately 400 km from Nairobi, the capital city of Kenya (Fig. 1). It encompasses an area of 21,328 km^2 and has a population density of 11 persons per square kilometer (KNBS, 2019). The county has a rugged terrain with different soil types based on topography, geology and climate. The main soil types are deep brown soils, sandy soils and loamy soils. The area receives a mean annual rainfall of 500–600 mm characterized by a bi-modal pattern of distribution with the short rains occurring from July to September and the long rains falling from March to May (Bussmann, 2006). The dry season spans from December to February. River Ewaso Nyiro is the only permanent river in the area. During the wet season, natural water ponds, artificial ponds, laggas and seasonal rivers are filled with water (Omwenga et al., 2014). Annual mean temperature was 29 °C in the time periods from 2010 to 2016. The elevation of the area ranges from 340 to 2780 m a.s.l with great topographic relief on the central region (Nanyingi et al., 2008). The Global Land Cover Characterization depicts evergreen broadleaved forests, closed and open shrub lands, savanna and grasslands as the vegetation forms in the area (United States Geological Survey, 2019). The area is dominated by the Samburu community which practice nomadic pastoralism as the main economic activity (Gafna et al., 2017).

2.2. Vegetation survey

A plant survey of the Samburu area was conducted during periods of peak vegetation cover (July 2016 and September 2016, March 2017 and May 2017). Stratified random sampling was applied to select sites, with strata based on land cover (Anderson et al., 1976), soil type (Dewitte et al., 2013) and protection status (Kenya Wildlife Service, 2010). A total of 68 sites was selected within a buffer distance of not more than 5 km from the main roads due to logistic constraints. These sites were distributed across the strata and are referred to as “primary sites”.

In the event of a nearby corral (within 900 m), we placed two sub-plots at fixed distances from that corral (at 1500 m and 2000 m). Corral and all the three sites where placed on a straight line. Distance from corral served as a proxy for grazing intensity. 19 sites were situated next to the corrals and they were well distributed across the strata. If we noted signs of recent wildfires (deposits of ash on the soil and fire scars on plants) we added a pair of sites (at a distance of 700 m from the primary site and in opposite direction) to assess effects of fire on the occurrence of medicinal plants. One of these sites showed no signs of burning; the other was placed in an area with signs of severe burning. 12 sites were severely burnt and 12 unburnt sites; both types were well distributed across the strata. The plots measured 80 m by 80 m. Within plots, we recorded all occurrences of medicinal plants from a checklist of 133 medicinal plant species present in the Samburu dryland (Bussmann, 2006).

Additional 17 plants that were commonly identified as medicinal by the research assistants were taken to the traditional herbalists who certified their use for medicinal purposes. The taxonomy of the plants followed Heine et al. (1988). Scientific identification and validation of the local names of the collected medicinal plant species was done at the East Africa Herbarium (EA). The flora of

Tropical East Africa was used for identification (Hurskainen, 1994). Verification of the plants was done by Dr. Ombori Omwoyo, from Kenyatta University.

Additionally, the conservation status of all the study taxa was checked from the available relevant literature (Gafna et al., 2017; Dharani, 2011; Dharani and Yenesew, 2010) and the IUCN database (Version 14, (IUCN, 2021)). For instances where the conservation status of a given species differed, the highest assigned conservation status was used.

2.3. Environmental variables

At each site, aspect, elevation, slope and cover of dead plant matter were recorded. Soil moisture was measured in the field using a theta probe at five different points of a plot at a depth of 10 cm. The values were later averaged. In each plot, soil samples were collected from five points (four at the corner and one at the center). The soil samples were extracted using a soil corer (7 cm diameter × 10 cm deep). The soil samples were stored in polythene bags and deposited at the Kenya Agricultural Research Institute laboratory for analysis. Soil texture was estimated using the hydrometer method, soil pH was measured using a pH meter, while the soil salinity was measured using a hand held salinity meter (Beretta et al., 2014). The percent cover of dead plant material was visually estimated.

Corrals within a radius of 900 m of each site (primary and secondary) were searched and their positions recorded. Grazing intensity was measured as the distance from corrals, while expert assessment of recent grazing pressure was applied (Linstädter et al., 2014) by counting of dung and signs of trampling within 200 m radius in each site.

In addition to the field survey data, we used climatic data from WORLDCLIM for the annual precipitation and temperature sums (Hijmans et al., 2005), historical monthly precipitation data covering 2004–2016 (Kenya Meteorological Department, 2019; Essenfelder, 2016) and population density data from KNBS (2019).

2.4. Data analysis

We used a classification approach to find characteristic co-occurrences of medicinal plants. The resulting classes were assigned to broad plant formations and used as reference for our estimates of supply security and supply diversity. Direct ordination was used as a complementary approach to reveal gradients in co-occurrence patterns with linear relations to the included environmental variables.

2.4.1. Classification of medicinal plant assemblages

The species presence/absence was transformed employing the R function decostand with method "normalize" to realize normality and homogeneity of variance. Isopam clustering, with gray distance measure, was used to categorize our vegetation data into assemblages and portray the floristic features provided by the assemblages (Schmidtlein et al., 2010). Data handling and analyses were conducted with the R packages 'vegan' (Oksanen, 2006) and 'isopam' (Schmidtlein et al., 2010). To better describe the patterns and assess the variability of the vegetation formations, we used the nested design during the analysis. Here, we created dummies of our plots and aggregated to primary sites.

An ordination analysis revealed how the environment triggered the groups found in classification. Redundancy Analysis (RDA) was used to ordinate the species data since gradient lengths were low (Oksanen, 2006).

Based on our hypotheses, existing theories and removal of highly correlated variables, the following environmental variables were selected for analysis: soil pH, soil salinity, grazing pressure, fire history, grazing intensity, population density, drought, slope, aspect, cover of dead plant matter, sand and clay fractions in soils. The choice of our variables was ascertained using the step-wise selection of variables via adjusted R^2. The Palmer Drought Severity Index (PDSI) (Newman and Oliver, 2005) was calculated and calibrated with the package scPDSI in R program.

A linear environmental fit on the axes 1 and 2 was used to determine the statistical relation between grazing pressure, drought, slope, sand fraction, clay fraction and cover of dead matter on medicinal plants variation. Kruskal-Wallis non-parametric test was used to assess the environmental differences among assemblages. For instances when the Kruskal-Wallis test revealed significant differences ($p < 0.05$), we performed the Bonferroni adjusted Dunn's a post-hoc analysis test to determine which plant formation differed from the other(s) (Dunn, 1964). This test incorporates multiple pairwise comparisons for stochastic dominance and was adopted because our plant formations had unequal number of observations (Zar, 2009).

2.4.2. Supply security

The N + 1 redundancy concept was used to analyze the supply security (Albuquerque and Oliveira, 2007). This concept originates from information technology and is viewed as expression of resilience that ensures that component failure does not compromise system availability. N is the "operational component", for instance a power supply or a computer server system. It is normally N = 1, whereas + 1, + 2, + 3 show the available number of backup systems which performs the same function as N. A backup system could be on standby status, active or passive. In our study, N is a given plant species used against a particular disease whereas + 1, + 2, + 3 represent the number of other plant species which treat the same disease. In case of disorder, for example the loss of a medicinal plant species, redundant species would be able to take over the functionality of the missing medicinal plant species.

We used the medicinal plant assemblages (hereafter, MPA) resulting from the classification analysis to assess the variability in supply diversity and supply security. The N + 1 redundancy was applied to the mean values of medicinal plant species, per disease, in each MPA. The values were categorized as follows: Values less than one were not to be considered, values between one and two were assigned to the category N (not redundant), between two and three to N + 1 (low redundancy), between three and four to N + 2 (moderate redundancy) and greater than four to N + 3 (high redundancy). We calculated the mean of the redundant treatments in all the assemblage to determine the supply security of the assemblages. Besides, we analyzed the key medicinal plant species responsible for the supply security in each MPA. Key medicinal plant species are the species used to treat the highest number of diseases and are well distributed within the MPA. Kruskal-Wallis test was used to assess the possible differences in supply diversity and security among the assemblages. Thereafter, dunn's test was used to identify the difference in supply diversity and supply security among the assemblages. The Pearson correlation between the physical site parameters and supply diversity and supply security in the assemblages was determined. Supply diversity in each assemblage was determined by counting the number of medicinal functions (target diseases) in the assemblages (Albuquerque and Oliveira, 2007).

3. Results

3.1. *Medicinal plants survey*

A total of 77 medicinal plant species in 130 plots (68 primary sites and 62 secondary sites) were present in a sampled area of 83 ha (Table S1). The study species were categorized into six conservation status: Least concern (18 species), near threatened (9 species), vulnerable (29 species), endangered (10 species), critically endangered (2 species) and data deficient (9 species) (Table S1, Fig. S1). An average of 14 medicinal plants was found in each site. The most frequent medicinal plant species was *Solanum incanum* with 82 occurrences while the rarest was *Ajuga remota* with 8 occurrences.

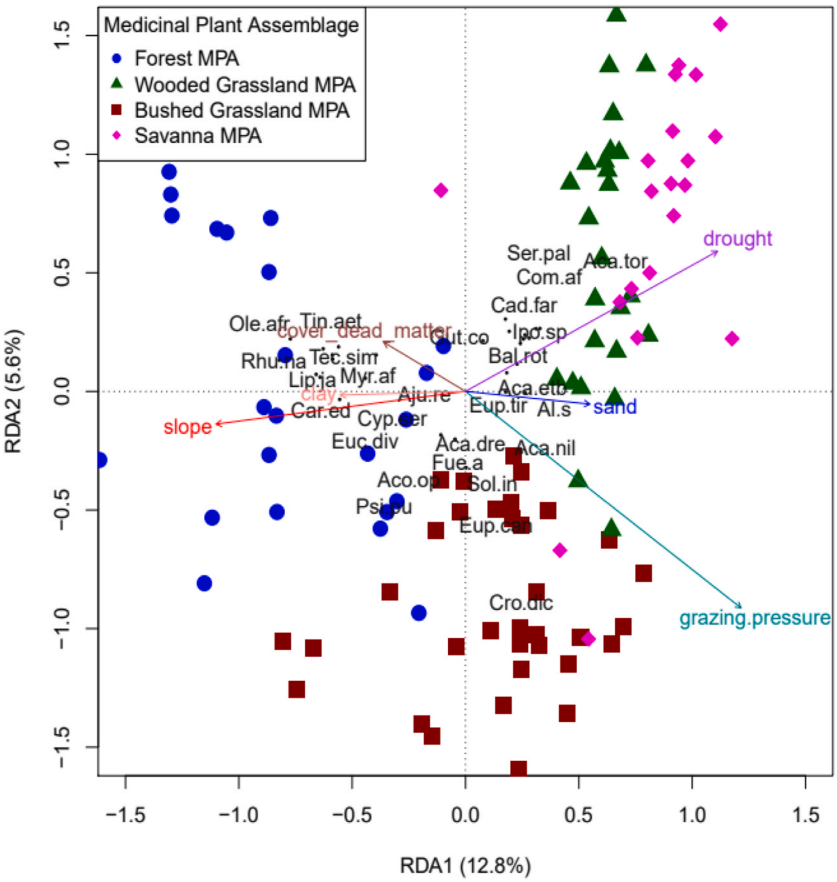

Fig. 2. RDA ordination with environmental fit for some variables. The arrow represent the strength of correlation and direction of variation of the significant variables that determine medicinal plants co-occurrences among the MPAs. Species codes: Aca.dre- *Acacia drepanolobium*; Aca.etb- *Acacia etbaica*; Aca.nil- *Acacia nilotica*; Aca.nub- *Acacia nubica*; Aca.tor- *Acacia tortilis*; Aco.op- *Acokanthera oppositifolia*; Aju.re- *Ajuga remota*; Bal.rot- *Balanites rotundifolia*; Car.ed- *Carissa eduli*; Cro.dic- *Croton dichogamus*; Com.af- *Commiphora africana*; Cyp.ser- *Cyphostemma serpens*; Euc.div- *Euclea divinorum*; Eup.can- *Euphorbia candelabrum*; Fue.a- *Fuerstia africana*; Gut.co- *Gutenbergia cordifolia*; Ipo.sp- *Ipomoea spathulata*; Lip.ja- *Lippia javanica*; Myr.af- *Myrsine africana*; Ole.afr- *Olea africana*; Psi.pu- *Psiadia punctulata*; Rhu.na- *Rhus natalensis*; Sal.per- *Salvadora persic*; Ser.pal- *Sericocompsis pallida*; Sol.in- *Solanum incanum*; Tec.sim- *Teclea simplicifoli*; Tin.aet- *Tinnea aethiopica*.

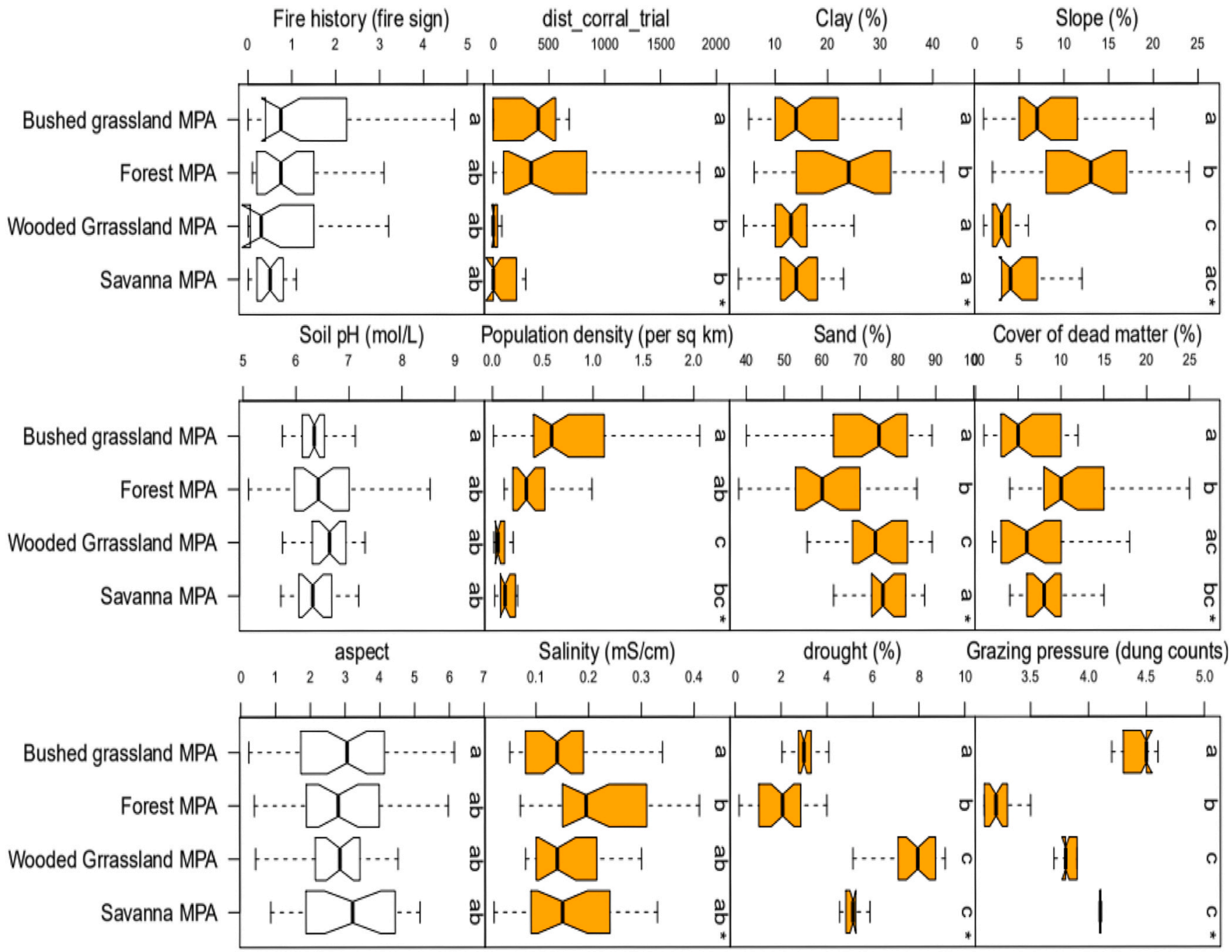

Fig. 3. The distribution of environmental variables across MPA as derived from species composition. One star indicates significant differences between groups according to a Kruskal-Wallis test, while groups sharing a letter are not significantly different according to Dunn's test.

3.2. Drivers of medicinal plants co-occurrence

The isopam algorithm clustered the records into four MPA which were named according to prevailing growth forms or formations. The identified MPA were: bushed grassland, forest, wooded grassland and savanna grassland. Individual plants differentiated between assemblages using the significance of their contribution to separating a class from the rest (Table S2). At a respective 6.8 and 2.9, accounting for 12.8% and 5.6% of the total explained variation in the data set, the eigenvalues of the first two axes were high and were therefore good predictors of medicinal plants co-occurrences (Table S3). Additionally, 27% of the variation in medicinal plants co-occurrences were explained by the environmental variables. The permutation test revealed a significant difference between the eigenvalues of the first two ordination axes ($p < 0.05$) and the environmental variables. The high eigenvalues of the first and second axes along with the permutation test results ($p < 0.05$), indicate a strongly significant correlation between environmental variables and the medicinal plants co-occurrences frequency. The arrangement of medicinal plant species along the first ordination axis included species

Table 1
N + 1 redundancy of all diseases in alphabetic order for each MPA. Blue dots indicate treatments that were available but had no redundant medicinal plants while the green, orange and red dots of various sizes show varying level of redundancy with the largest depicting high redundancy.

Disease	Bushed Grassland MPA	Forest MPA	Wooded Grassland MPA	Savanna MPA
Abortion			Blue	Blue
Acheing joints	Blue	Blue		
Acne		Blue		
Anaplasmosis in livestock	Blue	Blue	Blue	
Anthrax in livestock			Blue	Blue
Antihelmintic		Blue	Blue	
Arrow poison	Blue	Blue	Blue	
Arthritis	Blue	Blue	Blue	Blue
Asthma	Blue	Orange	Blue	Blue
Bilharzia	Blue		Blue	Blue
Bleeding stomach	Blue	Blue		Blue
Body ache	Blue	Blue		
Bronchitis	Blue	Blue	Blue	Blue
Brucellosis			Blue	Blue
Burns	Green	Blue	Blue	Blue
Cerebral malaria	Blue	Blue	Blue	
Chest congestion	Blue			
Chest pain	Blue	Blue	Blue	Blue
Cleansing of blood	Blue	Blue	Blue	
Colds	Blue	Green	Blue	Blue
Collibacillosis	Blue			
Constipation in children				Blue
Diarrhoea	Blue	Blue	Blue	Green
Diarrhoea in livestock		Blue		
Ear ache	Blue	Blue	Blue	Blue
Ectoparasites in livestock	Blue	Blue	Blue	Blue
Eye problems	Blue	Blue	Green	Orange
Fever	Orange	Red (large)	Green	Red (large)
Fungal infection				
Gastrointestinal complications	Blue	Blue	Blue	Blue
Giardiasis	Blue	Blue	Blue	
Gonorrhoea	Blue	Blue	Blue	Green
Head ache	Blue	Blue	Blue	Blue
Heart water	Blue	Blue		
Helmithosis	Blue	Blue	Blue	
Hepatitis	Blue		Blue	Blue
Inducement of vomiting		Blue		
Jaundice		Blue		
Liver problem	Blue		Blue	Blue
Loss of appetite	Blue	Blue	Blue	
Lumbago	Blue	Blue	Blue	Blue
Malaria	Orange	Red (large)	Green	Orange
Malignant	Blue	Blue		

(*continued on next page*)

Table 1 (*continued*)

Mastitis	🔵	🔵		
Measles in children	🔵	🔵	🔵	🔵
Nasal congestion	🔵	🔵	🔵	🔵
Nausea	🔵	🔵	🔵	🔵
Neurosis			🔵	🔵
Pneumonia	🔵	🔵	🔵	🔵
Poison	🔵		🔵	🔵
Polio	🔵	🔵	🔵	🔵
Premature ejaculations	🔵	🟢	🔵	🔵
Respiratory tract infection	🔵	🔵	🔵	🔵
Rheumatism	🔵	🔵	🔵	🔵
Rib pain	🔵	🔵		
Ring worms	🔵	🔵		
Seizures			🔵	🔵
Sexually transmitted infections	🔵	🔵	🔵	🔵
Skin rushes	🔵	🔵	🔵	🔵
Skull fissures	🔵	🔵		🔵
Small pox		🔵		
Snake bite	🔵	🔵	🔵	🔵
Sore throat	🔵	🔵	🔵	🔵
Sterility	🔵	🔵		
Stomach ache	🟠	🟢	🟠	🔴
Stomach ache in children	🔵		🔵	🔵
Dwindling strength		🔵		
Swelling of breasts	🔵	🔵	🔵	🔵
Syphilis	🔵	🔵	🔵	
Tapeworms	🔵	🟢	🔵	🔵
Tapeworms in livestock		🔵		
Ticks in livestock	🔵	🔵	🔵	
Tonic in children	🔵	🔵		
Tooth ache	🔵	🔵	🔵	🔵
Trypanosomiasis in livestock		🔵	🔵	🔵
Tuberculosis	🔵	🟢	🔵	🔵
Ulcers				🔵
Umblical cord healing	🔵	🔵		
Wounds	🟢	🟢	🟢	🟢
Yellow fever			🔵	
Legend				
🔵 (1-2) Not redundant				
🟢 (2-3) Low redundancy				
🟠 (3-4) Moderate redundancy				
🔴 (>4) High redundancy				
Mean Redundancy	3.25	3.62	3.04	4.5

which are vulnerable such as *Euphorbia tirucalli* and *Aloe secundiflora* among others (Fig. 2). The gradient depicted by the second axis was created by the relation of plants that are considered endangered like *Gutenbergia cordifolia* and *Fuerstia africana* among others within the environment.

The natural site characteristics with the highest impact on ordination axes were drought ($r^2 = 0.48$, $p < 0.005$), slope ($r^2 = 0.37$, $p < 0.005$) and sand fraction in soils ($r^2 = 0.09$, $p < 0.005$) (Fig. 2). Grazing pressure was the most important anthropogenic factor ($r^2 = 0.71$, $p < 0.05$). Dead matter cover and fraction of clay in soils were also important but not as the other three (Table S4). Contrarily, pH, aspect and fire history were irrelevant. The environmental fit on the ordination indicated that parameters related to sand and clay fractions in soils varied across the first axis. Cover of dead matter had a higher loading on the second axis. The correlations among the physical site parameters were depicted in the environmental overlays. Slope and clay fraction were strongly positively correlated in their influence on medicinal plants co-occurrences while drought, grazing pressure and sand fraction were strongly negatively correlated to these variables (Fig. 2). The bushed grassland MPA was characterized by high grazing pressure and high population density. The forest MPA was located in areas with relatively steep slope and high clay fraction in soils. The wooded grassland MPA was distributed at dry areas with high sand fraction (Fig. 2, Fig. 3). The RDA results indicate that the occurrence of *Acacia tortilis* (reported as of least concern) was strongly associated with drought, whereas *Carissa edulis* and *Lippia javanica*, reported as vulnerable, were strongly associated with high slope and were mainly found in the forest MPA. Grazing pressure played a significant role in the occurrence of *Acacia nilotica*, which is considered to be near threatened. Contrastingly, plants that were classified as of least concern such as *Croton dichogamus*, *Solanum incanum* among others were not influenced by any of the environmental factors.

A weak overlap was found between wooded grassland and savanna MPA, while the forest and bushed grassland MPA were clearly separated from the other assemblages. Strongly differentiated medicinal plants were associated with the forest and bushed grassland. For instance species that were classified as endangered like *Olea africana* and *Fuerstia africana* respectively. Many medicinal plants were present in the forest and bushed grassland MPA. Moreover, few medicinal plants were held in common by the MPA. The difference in composition of savanna and the forest MPA can be attributed to drought, while the difference in composition between the wooded grassland and forest MPA can be attributed to grazing pressure and sand fraction (Fig. 2). A Kruskal-Wallis test showed that there was a significant difference in drought, population density, slope, grazing intensity and grazing pressure among others among the MPA ($p < 0.001$). Surprisingly, there was no significance difference in aspect, fire history and pH among our assemblages (Fig. 3). Post-hoc analysis using Dunn's test indicated that there was a significant deference in drought, grazing pressure, sand fraction and slope among the forest, wooded grassland and bushed grassland MPA. Besides, there was a significance difference in grazing pressure, population density and cover of dead matter between the bushed grassland and savanna MPA. A significance difference in sand and clay fractions was noted between the savanna and forest MPA.

3.3. Environmental site conditions as drivers of medicinal service supply diversity

The study revealed that the occurring medicinal plants were used to treat 102 diseases. Kruskal Walis tests showed a significant difference in the number of diseases treated by the plants from different assemblages ($x^2 = 59.52$, df= 3, $p < 0.001$). Dunn's post-hoc procedure identified a significant difference in the number of diseases treated by the plants from the bushed grassland, forest and wooded grassland MPA ($p < 0.001$). The forest MPA had the highest supply diversity with plants used against 67 diseases (Table 1).

The bushed grassland and wooded grassland MPA had moderate supply diversity with the plants used against 65 and 57 disorders respectively. The savanna MPA had the lowest supply diversity with the medicinal plants used to cure only 49 illnesses (Table 1).

Accordingly, a negative correlation existed between grazing pressure ($r = -0.44$, $p < 0.005$), fire ($r = -0.03$, $p = < 0.005$), drought, salinity, clay fraction and supply diversity, whereas a positive correlation existed between slope, ($r = 0.45$, $p > 0.005$), sand fraction, population density and supply diversity (Table 2).

Generally the forest MPA, especially those with moderate grazing intensity (intermediate distance to the corrals) had a high supply diversity. The forest MPA, especially those with few signs of fire had a high supply diversity, while savanna MPA with many signs of fire often had a low supply diversity (Fig. 4).

3.4. Medicinal service supply pattern

Among the diseases treated by plants from the forest MPA were asthma, arthritis, colds and polio. Diseases exclusively treated by forest plants were fungal infection, acne, small pox, dwindling strength, jaundice and diarrhoea in livestock (Table 1).

Chest congestion was only treated by plants from the bushed grassland MPA. Other diseases included tuberculosis, pneumonia and gonorrhoea.

Burns and wounds among others were treated by plants from the wooded grassland MPA. Yellow fiver was only treated by plants in this assemblage. Constipation in children and ulcers were only treated by plants from the savanna MPA. Other diseases were tuberculosis and premature ejaculations (Table 1).

3.5. Environmental site conditions as drivers of medicinal service security

Kruskal Walis tests showed a significant difference in the supply security among the assemblages ($x^2 = 45.49$, df = 3, $p < 0.001$). Dunn's test identified a significant difference in the supply security among the forest and wooded grassland MPA ($p < 0.001$). The savanna MPA had the highest supply security for all diseases treated by plants growing in this formation (Table 1) like stomach ache, fever, wounds and eye problems. Supply security of plants used against diarrhoea and gonorrhoea was only found in this assemblage. The high supply security in the savanna MPA was driven by key species like *Aloe secundiflora* and *Balanites rotundifolia*, each used against 9 diseases and was classified as of least concern.

The forest MPA had a moderate supply security (mean redundant treatments = 3.62) (Table 1) and a high supply security of plants used against malaria (mean = 4.72) (Table 1). Supply security of plants used to treat colds, tuberculosis and tapeworms was only present in this assemblage (Table 1). Low supply security of plants used against stomach ache was found in this assemblage. The bushed grassland MPA had a moderate supply security as well. Medicinal plants used to treat burns were only redundant in this assemblage. *Olea africana* and *Rhus natalensis*, which were both classified as endangered were key to the supply security of the forest MPA. Both species were used to treat 8 illnesses. *Croton dichogamus*, considered as of least concern and used against 6 diseases, was the key species in the bushed grassland MPA.

A negative correlation existed between grazing pressure ($r = -0.35$, $p < 0.005$), fire, drought ($r = -0.35$, $p < 0.005$), salinity, clay fraction, pH and supply security, whereas a positive correlation existed between slope ($r = 0.33$, $p > 0.005$), sand fraction, population density and supply security (Table 2).

Wooded grassland MPA had the lowest supply security (Table 1) and a low supply security of plants used to cure malaria, wounds and fever (Table 1). The assemblage did not have a high supply security of plants used against any disease. Key species in this MPA were *Acacia tortilis*, used against 8 diseases, as well as *Cissus quadrangularis* which was used against 7 diseases. The species were classified as of least concern and vulnerable respectively.

The savanna MPA with low grazing intensity (close to corrals) had high supply security while there was low supply security in the wooded grassland MPA, especially those with low grazing intensity. MPA with high supply security tended to feature few signs of fire (Fig. 5).

4. Discussion

We aimed to identify the effects of environmental site conditions on the occurrence of medicinal plant species in MPA and sought to evaluate the security of service supply across MPA and individual diseases.

4.1. Drivers of medicinal plants co-occurrence

The RDA analysis identified the main environmental variables explaining 27% of the variation in medicinal plants co-occurrences. The following discussion will start with this explained part of variation and we will come back to the rest in the end.

The differentiation of MPA based on medicinal plants was found to be related to variation in grazing pressure, drought, slope and fraction of sand in soils. This is in agreement with results from studies on plant communities in general that have been conducted in nearby Tulu Korma, Ethiopia, (Asfaw et al., 2016) and Narok district, Kenya, (Ogutu, 1996). Here, grazing pressure and slope were reported to determine variation in overall plant community composition. All potential determinants of MPA show correlations that hamper interpretation. For example, even if difference in grazing pressure seems to be a parsimonious explanation for differences between MPA, it is itself related to environmental variables such as the occurrence of sand affecting soil drainage, absence of steep slopes, reduced precipitation and higher temperatures (Eldridge and Tozer, 1997). Most humid places (with lower temperatures and high precipitation) are found at higher elevations that also feature steep slopes and less grazing. Differences in fire history appeared to be insignificant for differences between species co-occurrences although we suspect that the methods used may not have allowed a full assessment of this factor. It would be interesting to conduct further assessment on fire history using both MODIS burned product and ground observations since the ground observations only considered the very recent fire history. Among the factors that were important in RDA (grazing pressure, drought, slope and sand fraction), we hypothesize that drought is the most important trigger as soil water clearly limits plant growth in savanna systems (Sankaran et al., 2005). Together with grazing pressure, it is a determinant of the savanna – forest gradient, which makes up much of the differences between MPA.

Soil salinity has been recorded as having a key role in explaining the distribution of plants in tropical savanna by Dharani and Yenesew (2010). This was not the case in Samburu, probably because crop cultivation, related to fertilizer use and changes in soil salinity, was not a dominant activity in the area. In this study, soil nutrients (K, N, Ca, P) were not directly investigated, but clearly,

Table 2
Pearson correlation coefficient (r) between environmental site conditions and supply diversity and supply security. Significance values are denoted by asterisks: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Site condition	Supply diversity	Supply security
Grazing pressure	-0.44***	-0.35***
Fire history	-0.03**	-0.09
Population density	0.05***	0.08**
Drought	-0.48**	-0.35***
Grazing intensity	-0.13	-0.11
Slope	0.45***	0.33***
Aspect	-0.02	-0.07
Clay fraction	-0.18	-0.11
Sand fraction	0.16	0.07
Dead matter cover	0.12	0.09
Salinity	-0.01	-0.26
pH	-0.11	-0.14

drought affects nutrients availability (Vanlauwe et al., 2015) and since drought triggered differentiation of MPA, soil nutrients may be considered as a site factor. The role of soil nutrients, as an important element in plant co-occurrence in semi-arid savanna is also described by Eldridge and Tozer (1997) and deserves further investigation.

In ordination space, savanna and wooded grassland MPA were placed in adjacent positions. This is in agreement with our observation that the assemblages were found in areas with similar environmental conditions but different land use. For other MPA we observed that few medicinal plants were held in common, suggesting strong environmental filtering from the existing pool of medicinal plants. The occurrence of *Acacia nilotica* is associated with high grazing pressure since it protects itself from livestock using thorns and toxins, consistent with Asfaw et al. (2016).

Considering that IPCC (2014) projects that Samburu will experience increased temperatures by 15% and 8% decreased rainfall by 2050, in future, medicinal plants may be under pressure. Because drought is a leading factor for the occurrence of medicinal plant assemblages, the mentioned changes can have detrimental effects. Plants that thrive in wetter areas are likely to decline due to reduced rainfall i.e. *Euclea divinorum*, while those that thrive in drier areas may still have a chance to shift to higher elevations i.e. *Acacia tortilis*.

In RDA we used standardized frequency or cover values since it recognizes the quantitative difference within species (Davis, 2000). RDA was helpful because it detected gradients of measured values along which medicinal plants were correlated (Oksanen, 2006). We examined the correlation structure and considered reasons external to our data set in choosing the environmental variables. Temperature, precipitation, soil moisture and drought were highly correlated with correlation > 0.87. The soil moisture was dropped due to high noise caused by weather and time of the day when it was recorded.

4.2. Environmental site conditions as drivers of medicinal service supply diversity

We found a significant difference in the number of diseases treated by plants from the bushed grassland, from forests and from wooded grassland MPA. This result shows that supply diversity should be taken into account when prioritizing MPA conservation. The forest MPA had the highest supply diversity, consistent with the results of a study by Bussmann (2006) in Samburu County which showed that the locals are dependent on forests for traditional medicine supply. According to this author, favorable conditions like high precipitation or less pronounced drought events led to high medicinal plants diversity, resulting in high supply diversity. Controlled use of forest products by Kenya Forestry Service (Gafna et al., 2017) may have contributed to this richness. Slope gradient determines plant community structure by influencing the land-use and physicochemical soil properties. A moderate positive correlation existed between slope and supply diversity. The steep slope in the forest MPA may have contributed to the high supply diversity by discouraging locals from accessing and overexploiting medicinal plants. Many trees in this MPA besides reducing high slope erodability may also be related to reduced grazing disturbance, thereby enhancing supply diversity.

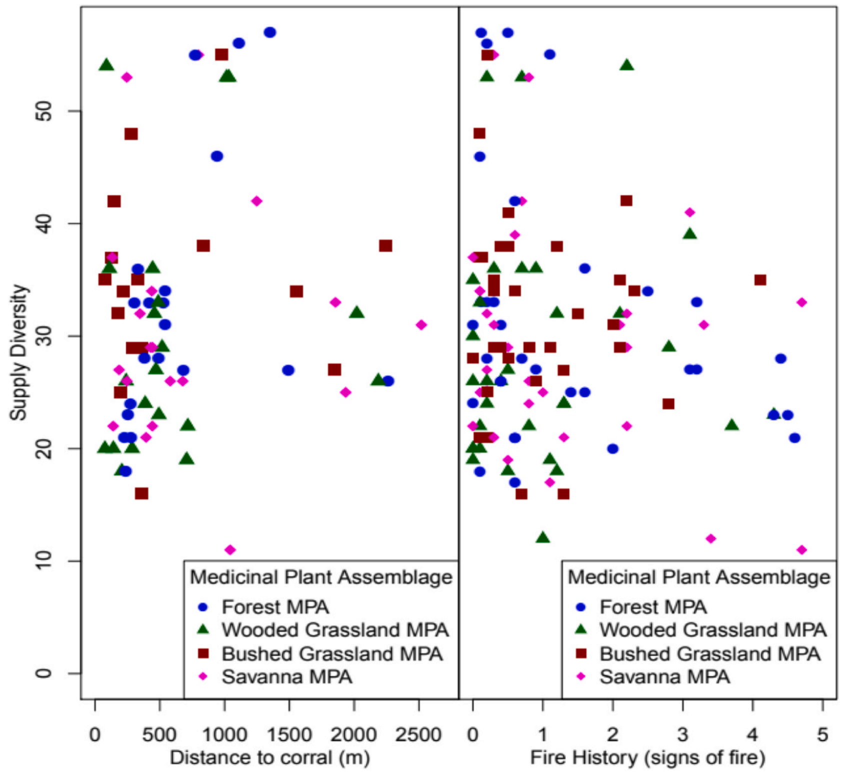

Fig. 4. Differences in supply diversity with regard to distance to corral (grazing intensity) and fire history.

Our results show a significant positive correlation between population density and supply diversity. This could partly be caused by a correlative effect as areas with higher precipitation support a denser human population. We would rather expect that dense human population, associated with urbanization, especially in the bushed grasslands MPA, leads to loss of supply diversity, thus weakening the effect of rainfall in the statistics. Still, supply diversity in the bushed grasslands was moderate with the plants used against 65 diseases, which is similar to the number of diseases treated by plants recorded by Heine et al. (1988) in a similar grassland nearby but contrasting that recorded by Nanyingi et al. (2008) in a similar grassland in the same study area.

Despite being found in dry areas, the wooded grassland MPA still had a moderate supply diversity. This result is in agreement with Omwenga et al. (2014) who observed a similar number of diseases treated by plants in a similar grassland of our same study area. If efforts by Namunyak conservancy to establish wild nurseries in areas where this MPA occurs have led to the moderate supply diversity deserves further research.

African savannas provide many services, including firewood collection and bush food (Tsigemelak et al., 2016) but for medicinal plants, the lowest supply diversity was linked to the savanna MPA. One reason could be that medicinal plants are also highly relied upon for non-medicinal uses like firewood collection, construction of housing and bush food (Tsigemelak et al., 2016) but a more parsimonious explanation is drought as the most important driver. Priority conservation, in the savanna MPA, should be given to the key medicinal plant species, classified as vulnerable like *Salvadora persica*.

Generally, we found a high supply diversity in the forest MPA especially where the intensity of grazing was moderate. This is because moderate grazing intensity within forests can help certain plants through opening up of canopy space (Kikoti and Mligo, 2015). The locals light fire during the honey harvesting process and burn pasture as they move to new areas (Gafna et al., 2017). We found a high supply diversity of plants in the forest MPA where fire intensity was low. According to Hitimana et al. (2011), low fire intensity in forests significantly increases soil fertility because it breaks down nutrients bound in dead plant tissues to forms that are easily available for plants resulting in a high medicinal plants wealth and supply diversity. Savanna MPA, especially those with many signs of fire had a low supply diversity. This is probably because in comparison to other assemblages, the fires in the savanna MPA could have been more frequent due to frequent human use of the savanna, leading to loss of many medicinal plants and low supply diversity. Detailed, larger and long-term data set will undoubtedly give more information on the impact of grazing intensity and fire on MPA.

Given the significance of drought for supply diversity, future climate change may have detrimental effects. IPCC scenarios suggest warmer temperatures and decreased rainfall by 2050 (IPCC, 2014). Therefore, some medicinal plants will shift their ranges or become extinct. This may cause shifts of MPA as well as changes in supply diversity within MPA, due to changes in MPA composition. Drought, due to climate change, will have an impact on medicinal plants co-occurrences.

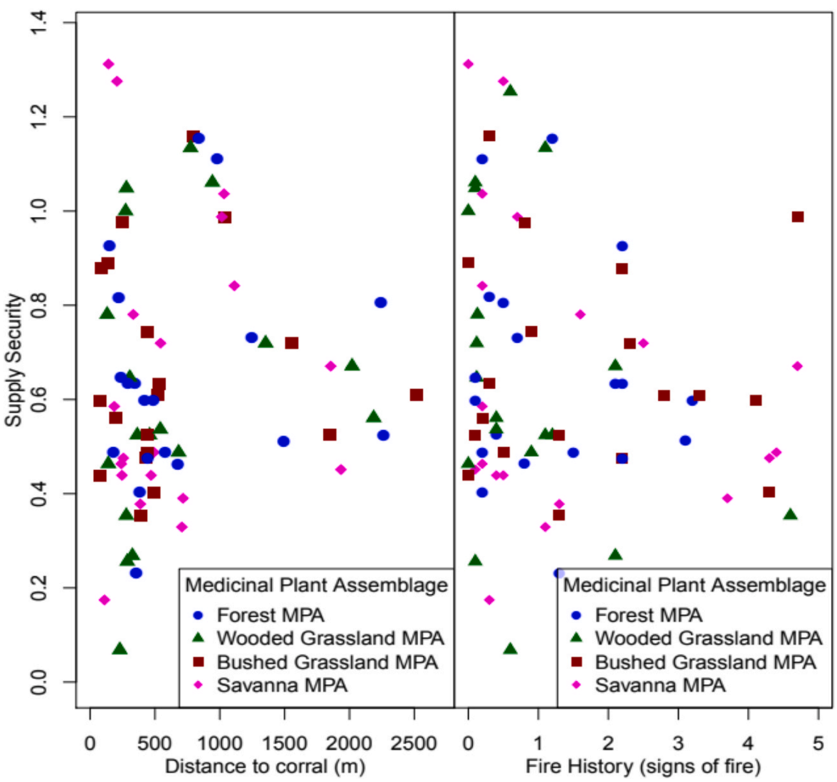

Fig. 5. Differences in supply security with regard to distance to corral (grazing intensity) and fire history.

4.3. Medicinal service supply patterns

We found most plants used against malaria and fever in the forest MPA (Bussmann, 2006). This confirms results by Hitimana et al. (2011) for the Kirisia dryland forest, in the same study area. According to Dharani and Yenesew (2010), there is a tendency of plants from the family *Apocynaceae*, which dominate dryland forests, to stand out in the treatment of malaria, while those from the *Asteraceae* family, known to dominate the highland forests, stand out in the treatment of coughs e.g. *Vernonia amygdalina*. Amuka et al. (2014) reported that coughs and pneumonia were treated by plants in nearby Mau highland forest, Kenya.

This can for example be shown for plants in the Bushed Grassland MPA that were often used against eye problems and gonorrhoea (Gafna et al., 2017). Also the finding that chest congestion was only treated by plants from this assemblage is important because chest congestion is common in the study area due to the smoky Samburu huts that have poor ventilation, with only a small door or window. In a similar grassland in the neighboring Nyeri County, Kamau et al. (2016) found plants to be used for the treatment of convulsions and joint pain, whereas Chalo et al. (2016) identified treatments of scabies and tonsillitis as the most prominent applications of plants from a similar grassland in the nearby Kajiado County. This difference in supply identity could be due to differences in floristic composition or due to different approaches (i.e. personal interviews versus literature study for identifying applications of individual plant species). But these discrepancies may also illustrate the importance of differences in local knowledge for the actual use of medicinal plants. When interpreting these pattern we need to keep in mind that they reflect not only biogeographic patterns but also patterns of knowledge: It is possible that we did not consider useful medicinal plants because people had no knowledge on their medicinal use.

Yellow fever was only treated by plants from wooded grassland MPA, consistent with Omwenga et al. (2014) in a similar MPA in the same study area. This is because *Kedrostis pseudogije*, the only species used against yellow fever in the study area (Omwenga et al., 2014), thrives in gentle slopes with high temperatures which are associated with the wooded grassland MPA (Dharani, 2011). In fact Dharani and Yenesew (2010) showed that the seeds of *Kedrostis pseudogije* rarely disperse to and germinate in other vegetation types. Considering that the species was classified as endangered, our findings reinforce the need to cultivate and prohibit excessive collection of the species.

Plants used against pneumonia and constipation in children were present in the savanna MPA. This is in contrast to surveys by Bussmann (2006) who reported plants used against dysentery and joint pain. Such differences in plant applications are likely because, unlike earlier years, species used against constipation in children and pneumonia such as *Santalum album* is presently extensively protected due in part to its use in making perfumes (Dharani and Yenesew, 2010). Plants used against ectoparasites in livestock and tuberculosis were documented for the first time in regards to the medicinal plants present in the savanna MPA, indicating that the plants used against these diseases could be endemic to the study area.

4.4. Environmental site conditions as drivers of medicinal supply security

In this study, species richness and not abundance was used in determining the supply security. The N + 1 redundancy concept was effective in identifying diseases with functionally redundant medicinal plant species since it did not portray MPA with many sampled sites as having a high redundancy.

The savanna MPA had the highest general supply security, with a focus on plants used against fever and stomach ache. The finding that supply security of plants used against diarrhoea only existed in this assemblage is important because diarrhoea is common in the study area since the locals frequently share unclean water with wild animals and their livestock (Omori et al., 2012). Further research aimed at developing a redundancy model to test whether the high supply security in the savanna MPA is affected by the use of medicinal plants is needed.

The forest MPA had a moderate supply security and a high supply security of plants used against malaria, a major threat to the local population. The high redundancy of anti-malarial plants in this MPA may be due in part to the many occurrences of the disease around the forests, as medicinal plants redundancy correlates with disease occurrence (Albuquerque, de and Oliveira, 2007). The low supply security for medicinal plants used against stomach ache in this assemblage was most likely caused by logging of plants such as *Juniperus procera* that are used against stomach ache (Ngari et al., 2010). Conservation priority should therefore be given to *Juniperus procera*, since it was also classified as vulnerable. To improve the supply security in this MPA, effective conservation of vulnerable medicinal plant species in the MPA, key for the moderate supply security should be conducted i.e. *Carissa edulis* and *Olea africana*. The steep slope in the forest MPA enhanced its supply security since a weak positive correlation existed between slope and supply security. Despite this positive correlation which should have led to a high supply security in the forest MPA, deforestation in this MPA led to the moderate supply security. Hence, it is challenging for ecologists and policy makers to enhance medical supply in semi-arid areas where deforestation is still practiced. The high salinity in this assemblage may have also lowered the supply security, since a weak negative correlation existed between salinity and supply security. This suggests that curbing salinization could increase supply security.

The bushed grassland MPA had a moderate supply security and was the only MPA with supply security of plants used against burns. The weak negative correlation between grazing pressure and supply security is due to the nomadic lifestyle of the Samburu people who move to the neighboring counties in search of pasture (Bussmann, 2006). Despite the positive influence of precipitation in this MPA, the utilization of some medicinal plants used against individual diseases as livestock fodder may have led to the moderate supply security. Therefore reduction of the grazing pressure by the local population is vital for the enhancement of medicinal supply security.

Lowest supply security was found in the wooded grassland MPA, with a low supply security of plants used against fever and wounds. According to Dharani and Yenesew (2010) communities that live in humid areas or next to forests tend to use leaves for disease treatment while those in wooded grasslands tend to use roots since plant leaves are not always available due to drought. Due to the location of the wooded grassland MPA in dry areas, it is likely that unsustainable harvesting practices such as uprooting of plants used against individual diseases led to the low supply security. Instead of digging out the main roots, sustainable harvesting in this MPA could be conducted by cutting the offshoots of the main roots to minimize the loss of medicinal plants. Gentle slope in this MPA may have also enhanced accessibility of medicinal plants used against individual diseases leading to low supply security (Kareru et al., 2006). We did not find a high supply security of plants used against any disease in the wooded grassland MPA probably due to its location in dry areas and unsustainable harvesting. This finding reinforces the need to conserve the redundant species in the MPA, especially those that are classified as vulnerable i.e. *Salvadora persica*.

A high supply security existed within the savanna MPA, especially where grazing intensity was low. Low grazing intensity within the savanna MPA allows the soil to gain nutrients which facilitates growth and regeneration of plants used against individual diseases (Kioko et al., 2012).

Climate change as suggested by current scenarios would also affect supply security due to the projected increase in temperature and decrease in precipitation by 2050. Considering the negative correlation between drought and supply security, increased drought incidences due to climate change will most likely adversely affect the wooded grassland MPA since it had a low supply security and is found in dry areas that are likely to become drier.

5. Conclusion

This study shows the impact of environmental conditions on medicinal plants co-occurrences, supply diversity and redundancy. Our data along with climate scenarios suggests possible future loss of medicinal plants, therefore, e*x–situ* cultivation of medicinal plants (considering drought and grazing pressure) is advisable. Urgent and highest conservation priority should go toward the wooded grassland MPA that had the lowest supply security for traditional medicine. There is a need to adopt sustainable medicinal plants conservation strategies which will enhance sustainable harvesting particularly in the wooded grassland. The adverse effects of climate change on supply diversity and security can be mitigated by conservation of critically endangered, endangered and vulnerable key medicinal plant species. Additionally, the vulnerability of supply security to climate change could be reduced by conservation of redundant medicinal species especially in the wooded grassland MPA. In order to reduce the severity of anthropogenic pressure on medicinal supply, we suggest that the local county government should consider the impact of anthropogenic activities on supply diversity and supply security when formulating medicinal plants management policies and legislation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the East Africa Herbarium for helping with identification of medicinal plants. We express our gratitude to Lelesit Saitoti, Letinini Gabriel, Lewarani Moses and Amos Lemunen for their hard work as field assistants during the vegetation survey. We thank Deutscher Akademischer Austauschdienst, Bonn, Germany and National Research Fund, Nairobi, Kenya for funding the studies of DG at Karlsruhe Institute of Technology (KIT), Germany [Grant number 91609244] and Deutscher Akademischer Austauschdienst, Bonn, Germany for funding a research stay of KD in Kenya [Grant number 91609244]. The research was further supported through the Graduate School of Climate and Environment at KIT. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of Karlsruhe Institute of Technology for providing the publication fund.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01749.

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