EFFECTS OF GRASS-WEED INTERACTIONS ON MORPHO-ECOLOGICAL TRAITS AND WEEDING BENEFITS OF RANGE GRASSES IN SOUTHERN KENYA RANGELANDS †

[EFECTOS DE LAS INTERACCIONES PASTOS-MALEZAS EN LAS CARACTERÍSTICAS MORFO-ECOLÓGICAS Y LOS BENEFICIOS DE LA ELIMINACIÓN DE MALEZAS EN PASTOS DE PASTIZALES EN EL SUR DE KENIA]

Yahya Sabdow Kasai*, Moses Nyangito and Oscar Koech

Department of Land Resource Management and Agricultural Technology, University of Nairobi, P.O. Box 30197-00100, Nairobi, Kenya. Emails: yahyasahiin@gmail.com, mmnyangito@yahoo.com, okkoech@gmail.com
**Corresponding author*

SUMMARY

Background: Weeds invasion into rangeland ecosystems is a precursor for biodiversity loss, increased soil erosion, declining wildlife habitats, and decline in carrying capacity for livestock. These weeds are fierce competitors with range grasses often possessing attributes of high seedling vigor and short life cycles compared to the grasses. Weeds invasion to a pasture land, can starve the grasses grown in the land. **Objective:** To investigate the competitive interactions of three range grasses with weed infestation. **Methodology:** The grasses evaluated were; *Chloris roxburghiana* (CHLORIS), *Cenchrus ciliaris* (CECI), and *Eragrotis superba* (ERASU). Four weed control regimes were applied: Continuous weeding (T_1), weeding on the 8th week (T_2), weeding on 10th week (T_3) and the control (T_4). The grass species Morpho-ecological data was collected on parameters such as; tiller density, grass height, grass density and biomass yield at the grass bloom stage. **Results:** A significant difference in morpho-ecological traits of all the weeding regimes was found. Continuous weed management and weeding at 8th week of establishment, respectively showed the highest performance in all the parameters measured. None-weeding management demonstrated the least performance. **Implication:** These research findings will help in developing a long term pasture weeds management plans to prevent encroachment of problematic weed species and to rehabilitate the already degraded rangelands. **Conclusion:** On all the grass species, continuous, weeding, periodic weeding at 8 weeks and 10 weeks demonstrated an increase in dry matter biomass respectively. None-weeding had the least pasture performance.

Key words: Grasses; weeds; morpho-ecological traits; livestock production; rangelands; Kenya.

RESUMEN

Antecedentes: La invasión de malezas en los ecosistemas de pastizales es un precursor de la pérdida de biodiversidad, el aumento de la erosión del suelo, la disminución de los hábitats de vida silvestre y la disminución de la capacidad de carga para el ganado. Estas malezas son competidoras de las gramíneas de campo ya que a menudo poseen atributos de alto vigor de plántula y ciclos de vida cortos en comparación con las gramíneas. La invasión de malezas en una tierra de pastoreo puede eliminar a los pastos de la pradera. **Objetivo:** Investigar las interacciones competitivas de tres pastizales con la infestación de malezas. **Metodología:** Los pastos evaluados fueron; *Chloris roxburghiana* (CHLORIS), *Cenchrus ciliaris* (CECI) y *Eragrotis superba* (ERASU). Se aplicaron cuatro regímenes de control de malezas: deshierbe continuo (T1), deshierbe en la semana 8 (T2), deshierbe en la semana 10 (T3) y el testigo (T4). De las especies de gramíneas se recolectaron datos morfo-ecológicos sobre parámetros como; densidad de macollos, altura del pasto, densidad del pasto y rendimiento de biomasa en la etapa de floración del pasto. **Resultados:** Se encontró una diferencia significativa en las características morfoecológicas de todos los regímenes de deshierbe. El manejo continuo de malezas y el deshierbe a la octava semana de establecimiento, respectivamente, mostraron el mayor desempeño en todos los parámetros medidos. El manejo sin deshierbe demostró el menor desempeño. **Implicaciones:** Los hallazgos de esta investigación ayudarán a desarrollar planes de manejo de malezas a largo plazo para prevenir la invasión de especies de malezas problemáticas y para rehabilitar los pastizales ya degradados. **Conclusión:** Sobre

† Submitted October 18, 2022 – Accepted March 8, 2023. http://doi.org/10.56369/tsaes.4584

ISSN: 1870-0462.
Author ORCID Identifier = Yahya Sabdow Kasai: http://orcid.org/0000-0002-2539-6748; **Moses Nyangito**: http://orcid.org/0000-0001-7496-1910; **Oscar Koech**: http://orcid.org/0000-0002-8245-5185

todas las especies de gramíneas, deshierbe continuo, deshierbe periódico a las 8 semanas y 10 semanas demostraron un incremento en la biomasa de materia seca respectivamente. El no deshierbe tuvo el menor rendimiento de la pastura.
Palabras clave: Pastos; maleza; rasgos morfoecológicos; producción ganadera; pastizales; Kenia.

INTRODUCTION

Livestock production is the predominant economic activity practiced by communities residing in rangelands often free-ranging on open grasslands grazing system. However, due to poor grazing management as evidenced by extinction of vital indigenous grasses such *as Chloris roxburghiana* (CHLORIS), *Cenchrus ciliaris* (CECI), *Enteropogon macrostachyus* (ENMA) and *Eragrostis superba* (ERASU) among others, the region continues to be degraded rampantly. Range land degradation poses a critical threat to the community livelihoods in the rangelands (Mganga *et al.,* 2015). In addition, degraded grasslands promote the proliferation of unwanted weed species (Ouko *et al.,* 2020). ASALs landscapes of Kenya have been overrun with noxious weeds such as *Ipomoea kituiensis* Weeds pose a serious problem especially in newly established pastures if weed control is not taken seriously during pasture establishment for reseeding rangelands (Mganga *et al.,* 2010).

The pasture-weed critical period of competition is experienced during the early stages of pasture establishment (About 60 days post emergence). Intense weed control is required, thereafter the weeds that emerge will not have impact on the pastures yields (Mahmoodi *et al*., 2016). Weeds are fierce competitors, often possessing attributes of high seedling vigor and short life cycles (Badhai *et al*., 2021). Generally, pasture weeds negatively impact livestock industry through; reducing quality of forage and quantity of yields, depletion of soil nutrients, grazing interference, poisoning of animals, and increased land management costs (O'Connor *et al*., 2020). They slow pasture production, utilization and longevity (Ghanizadeh *et al.,* 2019). For an effective weed management strategy farmers ought to acquire knowledge on weeds identification, weeds biology, their ecological effects, values and harm to the rangeland pastures (Lemus *et al*., 2010). This study sought to investigate the competitive interactions of three range grasses; CECI, CHLORIS and ERASU that are being promoted for adoption by Agro-pastoral communities for improved rangelands productivity in Southern Kenya. The grasses are suitable as livestock forage and as rangeland species and have been successfully used to rehabilitate degraded semiarid rangelands in Kenya (Mganga *et al*., 2015).

MATERIALS AND METHODS

Study Site

The study was carried out in the marginal areas of Makueni County. The County lies between Latitude 1º 35' south and Longitude 37º 10' and 38º 30' east. The regions are characterized by low rainfall, less than 500mm annually (Gichuki, 2000), and are prone to drought events. Bimodal rainfall season is experienced, with long rains occurring between March and May and short rains between October and December. The short rains usually are more consistent and accounted for 60% of the annual rainfall, with the long rains contributing only about 37% (Gichuki, 2000). This region is hot and dry with a mean annual temperature of 22.6°C, a mean annual maximum temperature of 28.6°C, and an annual minimum temperature of 16.5°C (CYMMIT, 2013). The county marginal area is low-lying grassland and has a high potential for ranching. These regions have limited and seasonal water sources, and therefore agricultural production is mainly undertaken under rain-fed conditions.

Study description

A randomized complete block design with split-plot arrangement was used for this study. A total of 36 treatments were evaluated. Four (4) weed management regimes and three (3) grass species constituted the treatments with field experiment of three replicates. The weed control regimes applied were: continuous/ frequent weeding (T_1), weeding on the 8th weeks (T_2), weeding on 10th week (T_3) and none weeding/ control (T_4) while the grass species used were CHLORIS, CECI, and ERASU. The trial was established during the long rain season, at sub plots (3 m x 3 m) with a 1 m boundary. The grass seeds were sown by hand along the furrows at a seeding rate of 5 kg ha^{-1} recommended for pasture grasses indigenous to semiarid areas of Kenya (Mganga *et al.,* 2021). Data on the morpho ecological performance on plant parameters including data on tiller density, height, and biomass were collected at the bloom stage. Plant morpho-ecological indices have been used in earlier studies as a measure of successful ecological rehabilitation (Scotton, 2019). The ability of grasses to outcompete and suppress weeds is determined by their growth and morphological traits.

The number tillers were counted and height was measured from the crown to the base. The grass height was measured from randomly selected plants in each quadrat using a meter ruler from the grass crown to the tip of the grass spike. A 1 m^2 metal frame quadrat was placed in each plot three times, and the above-ground biomass at the stable height of 5cm clipped and the fresh weights measured using an electronic weighing scale. A sample of the harvested herbage was placed in labeled sample bags then oven-dried for 48 hours at 60^0C and the dry matter (DM) weights taken. The sample fresh weight-dry matter conversion factor was used to inferentially estimate the DM weight of the fresh biomass harvested in the quadrat. These weights were then extrapolated to production in kilograms per hectare. The morpho-ecological data, One-way statistical analysis (ANOVA) was done to test for significant differences between the treatments. LSD significance difference post hoc test was used to separate significant differences ($P < 0.05$) between the weeding regimes. All the results indicated arithmetic means of replicates. Pearson correlation analysis was used to examine the relationship between the measured morpho-ecological traits using SPSS software version 22.

RESULTS AND DISCUSSIONS

Morpho-ecological performance

Continuous weed management and weeding at 8th week of establishment, respectively show the highest grass cover, grass density (individual plants per square meter), grass height and tiller density. None-weeding management demonstrate the least performances in all the parameters measured. Biomass performances is highest for continuous and weeding at 8th, 10th week and none weeded in that order for all the treatments as shown in table 1.

Grass density and cover declined with prolonged none-weeded periods as shown in table 1. Grass Cover (%), Grass Density, Grass Height (cm), Tiller Density, Biomass DM (gm^{-2}) tend to increase across the weeding period. The study results (Table 1) show that CECI has the highest grass density, grass cover, tiller density, biomass throughout the weeding regimes as compared to CHLORIS and ERASU. The study results compliment Koech *et al*., (2016), who found highest plant densities and plant cover in CECI as compared to ERASU and CHLORIS. This can also be associated to CECI having a strong spread root system that enables it to tap nutrients and water from deep soils and outcompete weeds (Heuzé *et al.,* 2016). Grasses with higher tiller density have the capacity for restoration improved resilience after defoliation of the above ground biomass and sustenance of food reserves compared to plants with low tiller density (Mganga *et al.,* 2021). While, Tillers supports establishment and development of seedlings in herbaceous plants.

ERASU has the highest grass height in all the weeding regimes compared to the other species. According to Ghajar *et al.,* (2021). Plants height gives the plants a competitive advantage for light with other plants. Grass height greatly contribute to low soil erosion, maintaining vegetation cover and also contributed to reduced grazing pressure (Mganga *et al.,* 2021). While, CHLORIS has the lowest grass density and grass cover as observed in the study. The results can be attributed to seed dormancy as a survival mechanism displayed by most range grasses. According to Baskin and Baskin (2021), 80% of ASALs angiosperms produce seeds that are in a dormant state. Seed dormancy inhibits germination therefore preventing total failure during unfavorable periods for germination. The results are illustrated in figure 1.

Table 1. Behavior of morpho-ecological characteristics with and without the presence of weeds.

Species	Weeding Period	Grass Density	Tiller Density	Grass Height (cm)	Grass Cover (%)	Biomass DM (gm^{-2})
CECI	10 weeks	16.7±1.5bc	35.7±5.0cd	83.7 ± 2.4c	80.0 ± 0.0bc	666.45acd
	8 weeks	20.7±0.9acd	42.3±2.6cd	88.3 ± 1.6cd	88.3 ± 1.7ad	849.84bd
	Continuous	29.7±1.2abd	59.7±1.5abd	109.1 ± 3.3abd	93.3 ± 1.7ad	1065.10cad
	None weeded	17.3±0.9bcd	20.3±0.3abc	75.5 ± 0.7bc	73.3 ± 1.7bc	360.35dabc
CHLORIS	10 weeks	7.3±0.9c	12.0±2.1	61.4 ± 3.2c	56.7 ± 6.7d	314.94a
	8 weeks	9.7±0.9cd	15.7±1.8d	68.4 ± 1.0c	56.7 ± 1.7d	440.82b
	Continuous	13.3±0.3abd	19.0±1.2d	84.2 ± 1.8abd	63.3 ± 1.7d	518.58cd
	None weeded	5.7±0.3bcd	7.3±0.3bc	62.8 ± 0.3c	43.3 ± 1.7abc	244.16dc
ERASU	10 weeks	12.7±0.9bc	24.7±3.0c	88.9 ± 2.7c	70.0 ± 2.9bc	453.72acd
	8 weeks	17.0±1.0acd	29.0±1.5cd	94.8 ± 0.9cd	83.3 ± 1.7ad	571.11bd
	Continuous	21.7±1.3abd	41.0±4.7abd	119.1 ± 7.4abd	86.7 ± 1.7 ac	736.45cad
	None weeded	13.0±1.2bc	18.3±0.3bc	83.4 ± 0.3bc	68.3 ± 1.7bc	225.73dabc

CECI (*Cenchrus ciliaris*), CHLORIS (*Chloris roxburghiana*) and ERASU (*Eragrotis superba*).

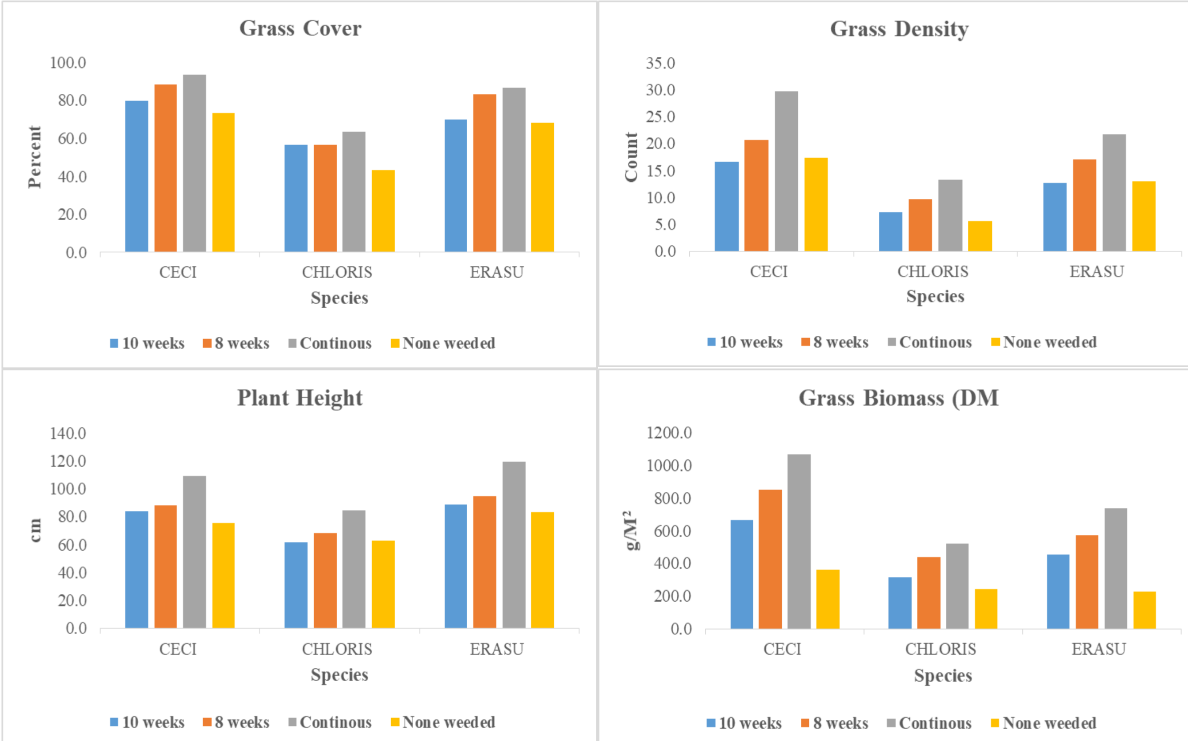

Figure 1. Grass morpho-ecological characteristics.

Grass weed interaction

Continuous weed management and weeding at 8th week of establishment, respectively show the lowest weed cover and weed density. None-weeding management demonstrate the least units in all the parameters measured. The study results displayed lowest weed cover in CECI and corresponding highest plant and tiller densities, grass cover and biomass compared to CHLORIS and ERASU plots. This result in line with earlier findings by Marshall *et al.*, (2012), that areas dominated with CECI had fewer weeds compared to areas with other grasses. This suggests that CECI outcompete and suppress weeds. This can be related to toxic allelopathic trait of CECI toward other plants (Friedel *et al.*, 2006). Additionally, according to Heuzé *et al.*, (2016), CECI has deep, tough roots that can go as deep as 2m and its culms are erect reaching up to 2m high. This gives the grass a competitive advantage over weeds and the rest of the other grass species. On average, the most weeds on all weeding regimes were herb, legume and woody weeds respectively (Table 3).

Table 2. Competitive capacity of weeds in the presence of three species of grass.

Species	Weeding Period	Weed Density	Weed Cover (%)
CECI	10 weeks	6.3±0.3cd	20.0 ± 0.0bcd
	8 weeks	6.0±0.6cd	10.0 ± 0.0acd
	Continuous	0±0.0abd	00.0 ± 0.0abd
	None weeded	9.7±1.7abc	26.7 ± 1.7abc
CHLORIS	10 weeks	3.3±0.3cd	35.0 ± 5.0bcd
	8 weeks	3.3±0.3cd	18.3 ± 1.7acd
	Continuous	0.0±0.0abd	00.0 ± 0.0abd
	None weeded	8.3±0.3abc	56.7 ± 1.7abc
ERASU	10 weeks	5.3±0.9cd	30.0 ± 2.9bc
	8 weeks	6.3±0.9c	15.0 ± 0.0acd
	Continuous	0.0±0.0abd	00.0 ± 0.0abd
	None weeded	8.0±1.5acd	31.7 ± 1.7bc

CECI (*Cenchrus ciliaris*), CHLORIS (*Chloris roxburghiana*) and ERASU (*Eragrotis superba*).

Table 3. Weed classification.

Species	Weeding Period	Legume %	Woody %	Herbaceous %
CECI	10 weeks	32.7	13.2	54.1
	8 weeks	36.7	13.8	49.4
	Continuous	00.0	00.0	00.0
	None weeded	34.4	19.1	46.4
CHLORIS	10 weeks	37.4	18.7	43.9
	8 weeks	35.8	12.3	51.9
	Continuous	0.0	00.0	00.0
	None weeded	30.3	17.6	52.1
ERASU	10 weeks	31.9	19.8	48.3
	8 weeks	34.3	23.0	42.7
	Continuous	00.0	00.0	00.0
	None weeded	32.8	21.3	45.9

CECI (*Cenchrus ciliaris*), CHLORIS (*Chloris roxburghiana*) and ERASU (*Eragrotis superba*)

Table 4. Grass weed Pearson correlation.

	1	2	3	4	5	6	7
1. Grass Cover	-						
2. Weed Cover	-0.724	-					
3. Grass Density	0.876	-0.737	-				
4. Weed Density	-0.237	0.664	-0.310	-			
5. Grass Height	0.781	-0.723	0.796	-0.464	-		
6. Tiller Density	0.857	-0.696	0.921	-0.400	0.813	-	
7. Grass Biomass DM	0.734	-0.694	0.805	-0.472	0.650	0.838	-

The Pearson correlation show a positive inter-correlation between grass cover, grass density, grass height, tiller density and grass biomass (DM) parameters; a positive correlation between weed cover and weed density. However, there is a negative inter-correlation between weed cover and weed density with grass cover, grass density, grass height, tiller density and DM. There is a positive correlation between tiller density and grass density from the study findings (Table 3). The study findings compared well with research of Marshall *et al.,* (2012); Bebawi *et al.,* (2013); de Albuquerque *et al.,* (2019) who found a negative interaction between weeds and performance of grass species. However, the results contrasted with Mganga *et al.,* (2021), who observed that weeds interacted positively with ERASU grass species. According to his study, the established plots, both grass and weeds competed to grow higher. Consequently, higher tiller densities in CECI as found in this study, suggests the species have quality forage.

CONCLUSIONS

CECI, CHLORIS and ERASU grass species, continuous and periodic weeding at 8 weeks and 10 weeks demonstrated an increase in dry matter biomass respectively. None-weeding had the least pasture performance. There was a positive inter-correlation between grass morpho-ecological parameters (grass cover, grass density, plant height, tiller density and grass biomass) and a negative inter-correlation between weed plant parameters and grass plant parameters.

Acknowledgement
We acknowledge Arid and Range Lands Research Institute- Kenya Agricultural and Livestock Organization for allowing us to use their land and resources. We are grateful to Benson Mulei for his invaluable statistical input throughout the research process.

Funding. The authors did not receive any financial support from any funding agency for the research, authorship, and/or publication of this article.

Conflict of interest. The authors declare that they have no conflicts of interest.

Compliance with ethical standards. The nature of the work did not require approval by a (bio) ethical committee.

Data availability. All data used in this article are available with the corresponding author: Yahya Sabdow Kasai, Email: yahyasahiin@gmail.com upon reasonable request.

Author contribution statement (CRediT). Yahya Sabdow Kasai- Conceptualization, data curation, formal analysis, resources, writing original draft., **Moses Nyangito**- Investigation, methodology, writing review and editing., **Oscar Koech**- project administration, validation

REFERENCES

Badhai, S., Gupta, A.K., Maurya, S.P. and Koiri, B., 2021. Ecological/cultural measures of weed management for sustainable agriculture. *Journal of Wastes and Biomass Management*, 3(2), pp. 36-38. https://doi.org/10.26480/jwbm.02.2021.36.38

Baskin, J.M. and Baskin, C.C., 2021. The great diversity in kinds of seed dormancy: A revision of the nikolaeva–baskin classification system for primary seed dormancy. *Seed Science*, 31(4), pp. 249-277. https://doi.org/10.1017/s096025852100026x

Bebawi, F.F. Campbell, S.D., and Mayer, R.J., 2013. Can competition with pasture be used to manipulate bellyache bush (*Jatropha gossypiifolia* L.) population biology? *Rangeland Journal*, 35, pp. 393–401. https://doi.org/10.1071/RJ13011

CIMMYT, 2013. Kiboko Crops Research Station: a Brief and Visitors' Guide. *CIMMYT, Nairobi, Kenya.* https://repository.cimmyt.org/handle/10883/3396?locale-attribute=en

De Albuquerque, F.S., Maćias-Rodríguez, M.Á., Búrquez, A. and Astudillo-Scalia, Y., 2019. Climate change and the potential of buffel grass (*Cenchrus ciliaris* L., Poaceae) in biotic communities of southwest United States and northern Mexico. *Biological Invasions*, 21, pp. 3335–3347. https://doi.org/10.1007/s10530-019-02050-5

Friedel, M., Puckey, H., O'Malley, C., Waycott, M.; Smyth, A., Miller, G., 2006. Buffel grass: both friend and foe. An evaluation of the advantages and disadvantages of buffel grass use, and recommendations for future research. *Desert Knowledge Cooperative Research Centre, Alice Springs.* http://hdl.handle.net/102.100.100/174269?index=1

Ghajar, S. and Tracy, B., 2021. Proximal Sensing in Grasslands and Pastures. *Agriculture*, 11(8), pp. 740. https://doi.org/10.3390/agriculture11080740

Ghanizadeh, H. and Harrington, K.C., 2019. Weed management in New Zealand pastures. *Agronomy*, 9(8), pp. 448. https://doi.org/10.3390/agronomy9080448

Gichuki, F.N., 2000. Makueni District Profile: Rainfall Variability, 1950-1997. Drylands Research, Working Paper 2. *Drylands Research, Crowkerne, Somerset*, pp.69. https://drylandsresearch.org.uk/pdfs/WP_Gich_Rainfall_variability.pdf

Heuzé, V., Tran, G., Baumont, R. and, Lebas, F., 2016. Buffel grass (Cenchrus ciliaris). *Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO.* https://agritrop.cirad.fr/582563/1/ID582563.pdf

Koech, O.K., 2014. Comparative evaluation of six indigenous rangeland grasses for pasture production under varying soil moisture contents in Tana River County, South Eastern Kenya. Doctoral dissertation, *University of Nairobi.* https://erepository.uonbi.ac.ke/handle/11295/74943

Lemus, R. and Weirich, J., 2010. Making pasture weed control decisions. *Mississippi State University Extension Service.* https://msucares.com/crops/forages/index.html

Mahmoodi, S., Mazaheri, D. and Rahimi, A., 2016. The critical period of weed control in forage corn in Birjand region. *Agronomy Journal*, pp. 100-109. https://agris.fao.org/agris-search/

Marshall, V.M., Lewis, M.M. and Ostendorf, B., 2012. Buffel grass (Cenchrus ciliaris) as an invader and threat to biodiversity in arid environments: a review. *Journal of Arid Environments*, 78, pp. 1–12. https://doi.org/10.1016/j.jaridenv.2011.11.005

Mganga, K.Z., Kaindi, E., Ndathi, A.J., Bosma, L., Kioko, T., Kadenyi, N. and Musimba, N.K., 2021. Plant morpho-ecological traits, grass-weed interactions and water use efficiencies of grasses used for restoration of African rangelands. *Frontiers in Ecology and Evolution*, 8, pp. 484. https://doi.org/10.3389/fevo.2020.613835

Mganga, K.Z., Musimba, N.K., Nyariki, D.M., Nyangito, M.M., Mwang'ombe, A.W., Ekaya, W.N. and Muiru, W.M., 2010. The challenges posed by ipomoea Kituensis and the grass-weed interaction in a reseeded semi-arid environment in Kenya. *University of Nairobi*, *Kenya*. https://erepository.uonbi.ac.ke/handle/11295/85400

Mganga, K.Z., Musimba, N.K.R. and Nyariki, D.M., 2015. Competition indices of three perennial grasses used to rehabilitate degraded semiarid rangelands in Kenya. *The Rangeland Journal*, 37(5), pp. 489-495. https://www.publish.csiro.au/rj/RJ15023

O'Connor, T.G. and van Wilgen, B.W., 2020. The impact of invasive alien plants on rangelands in South Africa. *Biological Invasions in South Africa*, 14, pp. 459-487. https://link.springer.com/chapter/10.1007/978-3-030-32394-3_16

Ouko, E., Omondi, S., Mugo, R., Wahome, A., Kasera, K., Nkurunziza, E. and Wambua, M., 2020. Modeling Invasive Plant Species in Kenya's Northern Rangelands. *Frontiers in Environmental Science*, 8, pp. 69. https://doi.org/10.3389/fenvs.2020.00069

Scotton, M., 2019. Mountain grassland restoration: Effects of sowing rate, climate and soil on plant density and cover. *Science of the Total Environment*, 651, pp. 3090-3098. https://doi.org/100.1016/j.scitotenv.2018.10.192

Smith, A.E. and Martin, L.D., 2017. Weed management systems for pastures and hay crops. *In Handbook of weed management systems*, pp. 477-517. https://www.taylorfrancis.com/chapters/edit/10.1201/9780203752470-12/