EFFECTS OF WEED CONTROL METHODS ON WEEDS AND PRODUCTIVITY OF RANGE GRASSES IN SEMI-ARID KENYA †

[EFECTOS DE LOS MÉTODOS DE CONTROL DE MALEZAS SOBRE LAS MALEZAS Y LA PRODUCTIVIDAD DE LAS HIERBAS DE AGOSTADERO EN LA REGIÓN SEMIÁRIDA DE KENIA]

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SUMMARY

Background: Weeds are a common occurrence and challenge in different crops eventually influencing crop development and yields. Weed control and management are key in enhancing the productivity of cultivated pastures. In semi-arid Kenyan drylands, the main methods employed for weed management are manual cultural practices and recently, the application of commercial herbicides. **Objective:** To evaluate the effects of two weed control methods on weed characteristics and productivity of four rangeland grasses commonly used in reseeding and pasture improvement in a semi-arid environment. **Methodology:** In a randomized complete block design in a field experiment, we determined the effects of two weed control methods (manual and herbicide use) in four rangeland cultivated grasses. These are Buffel grass (*Cenchrus ciliaris*), Horsetail grass (*Chloris roxburghiana*), Masaai love grass (*Eragrostis superba*) and Bush rye (*Enteropogon macrostachyus*). Weed characteristics (species, density, diversity and weed biomass,) were evaluated, as well as the effectiveness of the weed control methods in the grasses. **Results:** Broad-leaved weeds and annual grasses were prevalent in the established grasses. Generally, higher grass dry matter yields were obtained in *Cenchrus ciliaris* grasses (2.05 t h^{-1}) while lowest yields were in *Chloris roxburghiana* (1.2 ton ha^{-1}). Weed management interventions increased biomass production in the grasses by a mean of 19% in general. The mean yield increase varied with species and weed control method ranging from 8-39%. Weed control methods significantly reduced weed density, diversity and eventually weed biomass within the grass species. The efficacy of manual weed control and chemical application was in the range of 27-74%. **Implications:** Weed control is, therefore, necessary if one is to realize higher productivity and returns in cultivated pasture and fodder systems in semi-arid environments. **Conclusion:** Both chemical and manual control methods of weed control are important and effective approaches to manage weeds in pasture systems in semi-arid environments.

Keywords: Dry matter; Livestock; Grazing; Herbicide; Pastures; Rangeland

RESUMEN

Antecedentes: Las malezas representa un desafío común en diferentes cultivos ya que eventualmente influyen en su desarrollo y rendimiento. El control y manejo de malezas son claves para mejorar la productividad de los pastos cultivados. En las tierras secas semiáridas de Kenia, los principales métodos empleados para el manejo de malezas son las prácticas culturales manuales y, recientemente, la aplicación de herbicidas comerciales. **Objetivo:** Evaluar los efectos de dos métodos de control de malezas sobre las características de las malezas y la productividad de cuatro gramíneas de pastizales comúnmente utilizadas en la resiembra y mejoramiento de pastos en un ambiente semiárido. **Metodología:** En un diseño de bloques completos al azar en un experimento de campo, determinamos los efectos de dos métodos de control de malezas (manual y uso de herbicidas) en cuatro pastos cultivados en pastizales. Estos son el pasto Buffel (*Cenchrus ciliaris*), el pasto cola de caballo (*Chloris roxburghiana*), el pasto Masaai (*Eragrostis superba*) y el centeno arbustivo (*Enteropogon macrostachyus*). Se evaluaron las características de las malezas (especies, densidad, diversidad y biomasa de malezas), así como la efectividad de los métodos de control de malezas en las gramíneas. *Resultados:* Las malezas de hoja ancha y las gramíneas anuales predominaron en las gramíneas establecidas. En general, los rendimientos más altos de materia seca del pasto se obtuvieron en pastos *C. ciliaris* (2.05 t h^{-1}) mientras que los rendimientos más bajos fueron en *C. roxburghiana* (1.2 ton ha^{-1}). Las intervenciones de manejo

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de malezas aumentaron la producción de biomasa en los pastos en un promedio de 19% en general. El aumento medio del rendimiento varió con la especie y el método de control de malas hierbas, entre un 8 y un 39 %. Los métodos de control de malezas redujeron significativamente la densidad y diversidad de malezas y eventualmente la biomasa de malezas dentro de las especies de gramíneas. La eficacia del control manual de malezas y la aplicación química estuvo en el rango de 27-74%. **Implicaciones:** El control de malezas es necesario si se desea lograr una mayor productividad y rentabilidad en los sistemas de pastos y forrajes cultivados en ambientes semiáridos. **Conclusión:** Tanto los métodos de control químico como manual para el control de malezas son enfoques importantes y efectivos para manejar las malezas en los sistemas de pastoreo en ambientes semiáridos.

Palabras clave: Materia seca; ganado; pastoreo; herbicidas; praderas; agostadero.

INTRODUCTION

Weeds are a common phenomenon in terrestrial ecosystems including croplands, established pastures and rangelands growing together with established crops or native vegetation. In the tropics, one of the main challenges of optimum crop cultivation is weeds (Chauhan, 2020). Weeds impact crops in different ways including depressing yields, crop contamination as well as crop competition and eventually leading to economic losses. Weeding generally reduces yield losses in crops (Rodenberg *et al.,* 2019), and is a cultural practice highly recommended for increased productivity.

In tropical savannah grasslands of sub-Saharan Africa, weed diversity is generally high, varying from annuals, perennials and woody species that are mostly native or introduced (Schaffner *et al.,* 2021). Weeds can influence the quality and quantity of pastures and hayfields, reducing the forage value for livestock. In East Africa, large tracts of land in semi-arid areas are infested with weeds which compete with favorable grasses for space, light, nutrients and moisture, limiting the success of reseeding and pasture establishment (Mganga *et al.,* 2021), consequently affecting livestock production. Some weeds in hay pastures can be poisonous (Ekwealor *et al.,* 2019), necessitating the need for eradication before they are mowed together for baling. Smelly weeds in harvested hay may limit the intake of feed in livestock compromising productivity. On the other hand, weeds form an invaluable alternative component of livestock feed in smallholder production systems in the tropics (Khan *et al.,* 2013), where land sizes do not permeate the separate cultivation of pasture. When mowed together with pastures, high quantities of nutritious fodder could be harvested due to the incorporation of leguminous species together with grasses.

In the era of climate change, climatic and weather changes influence the population dynamics of weeds. Extreme weather conditions such as increased precipitation may result in an abundance of certain species and vegetation shifts including establishment, plant physiology and weed biology (Ziska, 2016). For instance, the *Ipomoea* species is a common weed species that mainly spreads after heavy rains in southeastern Kenya and often engulfs germinating grass seedlings (Mganga *et al.,* 2021). It is an invasive species presently causing havoc in the Maasai pastoral grazing lands of Kenya and Tanzania through depressing herbaceous biomass productivity (Manyanza and Ojija, 2021). It is therefore critical to adopt strategies for managing weeds that take into account these changes. Weeds are regarded as a challenge in many areas, cultivated and non-cultivated, compromising the capacity of the land to sustain livelihoods. Globally, *Parthenium hysterophorus* is an alien invasive species currently invading many grasslands across the world (Mao *et al*., 2021). In East Africa, *Prosopis juliflora* (mesquite) is regarded as one of the most noxious weeds in arid and semi-arid lands in Kenya (Huho and Omar, 2020).

Pastures used for range restoration and fodder improvement have not been spared either. For instance, pasture weeds pose the most challenge to the establishment and success of reseeding due to their competitive nature and negative grass-weed interactions (Mganga *et al*., 2021). Interestingly, attempts to use the same grasses to manage problematic weeds in rangelands continue to be explored (Cowie *et al*., 2021), highlighting the complex nature of interactions between grasses and weeds. Some cultural practices also contribute to weed spread and problems. The use of organic manures to improve fertility can also potentially introduce weeds in cropping systems due to increased weed seed banks (Arif *et al*., 2015). When these eventually grow, they may become hazardous by introducing foreign plant materials as weeds in grazing lands and cultivated crops. Consequently, weeds in pastures eventually affect crop development resulting in decreased yields and seed production. Weeds can replace desirable grasses directly or through allelopathic effects, resulting in an overall reduction in pasture quality and quantity (Ghanizadeh and Harrington, 2019). When not managed, and allowed to mature, weeds reduce the overall seed quality as pasture seeds are harvested. Such seeds may end up being rejected due to failure to adhere to internationally set standards of seed purity, leading to economic losses. Similarly, when weeds are left in pasturelands, they may become established and become difficult to remove (Humphries *et al*., 2020). Their fast propagation potential favors their establishment and adaptability more than the main cultivated pasture species. Due to changing land use and climatic conditions, weeds will continue to pose threats to ecosystems and affect livelihoods.

With the development of forage and pasture value chains and intensification, many farmers have ventured into the cultivation of pastures that are of high quality for their livestock. Specific fodder varieties have been promoted and are currently planted in the drylands of East Africa. These include *Urochloa* varieties, *Panicum maximum*, and fodder sorghums (Mwendia *et al*., 2022; Njarui *et al*., 2016), among others. Indigenous grass species have also been widely promoted and adopted in Kenyan drylands including *Eragrostis superba*, *Cenchrus ciliaris*, *Chloris roxburghiana, Enteropogon macrostachyus* and *Chloris gayana*. These are perennial indigenous species that are well adapted to semi-arid conditions and quickly establish once optimal growing conditions are available (Mganga *et al*., 2019). They are widely grown for fodder bulking, hay production, silage making, forage seed production and rangeland rehabilitation (Kidake *et al*., 2016; Mganga *et al*., 2019).

Despite the availability of various control methods, weeds continue to pose challenges to farmers in cropping systems (Chauhan, 2020). In Kenya, the main methods employed for weed control are manual cultural practices which encompass uprooting and the use of hand tools and herbicides (Tabe-Ojong *et al.*, 2022). Hand weeding mainly involves the use of hand tools and equipment that can be acquired cheaply from markets such as hoes and scythes, and is one of the most common methods of weed control. Herbicide use is mainly practiced in high-value crops such as tomatoes and onions that are market-oriented. However, they are costly and need some know-how in application and utilization. Their use is however gaining traction in many cropping systems due to labour limitations and rising labour wages (Chauhan, 2020). Herbicides play a key role in large-scale systems where hand-weeding may be laborious and tedious. Various types of chemicals i.e. pre/post-emergence and target-specific chemicals are available depending on the types of weeds growing on one's farm with recommendations on how to use them. However, their use is also a case of concern due to the potential contamination of water systems, effects on other organisms, persistence in soil and herbicide resistance (Faisal *et al*., 2018; Peterson *et al*., 2018; Rodenberg *et al*., 2019). Knowledge of herbicide use for weed control is available but the main problem has been a lack of awareness (Grabowski and Jayne, 2016), especially in sub-Saharan Africa.

Initially practiced in other crops such as grain crops, these two methods of weed control have been adopted in cultivated pasture systems and rangelands. Despite being common in cereal, legume and horticultural crops, the use of herbicides and manual control methods in weed control on established rangeland grasses hasn't been widely evaluated in cultivated pasture systems in semi-arid environments of Kenya, where fodder value chains are rapidly evolving (Lugusa, 2015; Omollo, 2017).

Therefore, the main objective of this work was to determine the effect of weed control methods on the productivity of selected range grasses mainly used for reseeding and pasture improvement and weed characteristics. Specifically, we measured grass morphological characteristics and measured grass biomass, weed density, diversity and weed biomass under two different weed control strategies. Furthermore, the efficacy of the two weed control methods was determined.

MATERIALS AND METHODS

Study site

The study was carried out at the Kenya Agricultural and Livestock Research Organization (KALRO), Kiboko Research Station farm, lying at latitudes 2° 10' and 2° South and longitude 37° 40' and 37° 55' East and 37° 55' East, in Makueni County, South Eastern Kenya. It’s found in agro-ecological zone V, which is semi-arid (Sombroek *et al.*, 1982), receiving an average annual rainfall of 534.3 mm. Temperatures at the station range between 22 °C – and 32 °C with a mean of 27.8 °C (Ndathi, 2012). The vegetation in the area varies with soil types and comprises mainly bushed grassland with a significant presence of woodland. The soils of the region vary from place to place but are mainly red and brown Ferralsols, and Gleysols (IUSS Working Group WRB, 2015). The land at the station and the region is most suitable for extensive livestock production.

Experimental design and crop management

The land where the experiment was carried out was originally a bushed grassland, which was cleared of all vegetation three years earlier. Before this experiment, the land was utilized as an experimental site with sorghum forages for two seasons. A tractor-drawn plough prepared the land to a fine tilth, to prepare a seedbed for the range grasses in October 2020. The experimental design was a randomized complete block design (RCBD) involving 4 rangeland types of grasses, 3 treatments and replicated 3 times giving a total of 36 plots. Four larger plots measuring 5 by 18 meters were demarcated leaving a 2-metre path between the plots. These were subdivided into two weed treatments and a control each. The four rangeland grasses were Buffel grass (*Cenchrus ciliaris*), Horsetail grass (*Chloris roxburghiana*), Masaai love grass (*Eragrostis superba*) and Bush rye (*Enteropogon macrostachyus*).

These were subjected to two methods of weed control – application of a commercial herbicide for weed control and manual weed control where plants were uprooted with hoes and by hand. A control scenario, where no weed management took place over the experimental period was also part of the treatments.

Planting was done by use of vegetative splits that were hand sown in rows 50 cm apart, with a plant-to-plant distance of 45 cm in plots measuring. After establishment, a standardization cut was done at a height of 10 cm above the ground at the end of the first season before treatments began the next season. Well-decomposed cattle manure was applied after the standardization cut at the rate of 10 t ha^{-1} following recommendations after a soil test. To ensure the plants were well established, the crops were irrigated with an overhead sprinkler system once a week for 1 hour to complement the rainfall in the region which is often unreliable and erratic. The plants were then maintained under rain-fed conditions over the experimental period of two seasons. Weed control treatments were initiated four weeks after the standardization cut. For chemical weed control, the selective post-emergent herbicide (2-4-Dichlorophenoxyacetic weed killer) commonly used in Kenya was applied as per the recommendations of the manufacturer.

Data collection

Morphometric attributes of interest in this study were plant height, plant canopy spread and tiller numbers. Plant height and spread were determined through measurement by the use of a metre rule, while tillers were physically counted for three selected plants per treatment. These were recorded at the peak of maturity, i.e. at eight 8 weeks of vegetative growth. The botanical composition of weeds was determined by identifying and recording all species of weeds found in the respective experimental plots. This was done before application of weed management treatments using a 1 m^2 quadrat. These were categorized into three main groups, namely trees/shrubs, forbs and grasses. Their frequency was recorded as absent when none of the species was visible in a quadrat; less frequent if 1-3 individuals were counted; moderately frequent if 4-6 individuals and more frequent if more than six weed individuals were counted. Weed density (numbers of weeds per m^2) and weed diversity were estimated by the use of a quadrat and visually identifying and counting the species and types/species per treatment. Aboveground biomass yields of the grasses and weeds were determined by the clipping method at week 8 where they were clipped at a 5 cm level and weighed in the field. The weeds within the quadrats were also clipped at 5 cm height, weighed and placed in different sample bags. Subsamples were taken to the laboratory for dry matter (DM) determination by oven-drying at 65 °C for 48 hours. To determine the effectiveness of the two weed control methods, weed control efficiency was estimated by using the formula suggested by Mani *et al*. (1973).

$$WCE = \frac{\text{Dry weight of weeds in unweeded plots - dry weight of weeds in treatment plots}}{\text{Dry weight of weeds in unweeded plots}} * 100$$

Data analysis

Data collected were subjected to statistical analyses through Analysis of Variance using the Genstat software (19th Edition) to test for differences in the relevant attributes (morphological parameters, plant biomass, weed biomass, weed density and diversity among the different weed control methods in the grasses. The least significant difference (LSD) was set at 5% and means separation was performed using Tukey tests.

RESULTS AND DISCUSSION

Grass morphometric attributes

The plant characteristics measured were as shown in Table 1. There were no significant differences in grass morphological characteristics among the different weed control methods. Since the target of the control methods were the weeds in the first place, their removal did not have an immediate effect on the selected morphological traits of grasses. As for the grasses, with their already well established root system and growth habits, weeds may not likely have an impact on the selected morphological traits. However, *Chloris roxburghiana* grass species produced significantly taller plants ($p < 0.05$) among the four grass species and equally had the largest canopy plant spread. Tiller numbers were however lowest in *Eragrostis superba* grass. Morphological traits differ with individual grass species (Mganga *et al*., 2019).

Plant height values for all four grass species obtained from this work fall within the range described by Mganga *et al*., (2019) in semi-arid Kenya. Plant height is an effective indicator of plant performance in cultivated pastures and rangeland restoration aspects. Height has been noted to correlate well with parameters such as herbage yields in range grasses (Mganga *et al*., 2021) where taller plants are expected to result in higher biomass yields. More importantly, in the context of this work, structural characteristics of the perennial grasses influence weed dynamics. For instance, having a taller grass species is likely to inhibit the growth of annual weeds through shading out weeds and blocking out light (Rayburn and Griggs, 2020). Canopy spread and tillering all contribute to the canopy architecture which influences the microclimate around plants (Gao and Schwilk, 2018), creating conducive or non-conducive conditions for weed growth. Other than *Cenchrus ciliaris*, which exhibited profuse tillering, the other grass species are likely to provide conducive conditions for weed growth on the surface due to open canopies and less tillering.

Upon establishment, as was the case in this work, morphological characteristics evaluated (height, spread and tiller numbers) are insignificantly ($p > 0.05$) affected by weed control methods. A long-term study would probably have produced more conclusive results due to the effects of reduced weed infestation as a result of control and improved plant growing environment. However, individual species have different growth requirements including light, nutrients, space and water and the presence and variability of these factors influence competitive interactions with weeds (Tozer *et al.,* 2016).

Botanical composition of weeds under different grass species

The most common weeds found in the plots before the treatments are indicated in Table 2.

Table 1. Morphological parameters of the four grasses under two different weed control methods.

		Morphological characteristic		
Factors	**Treatments**	**Height (cm)**	**Tillers numbers**	**Spread (cm)**
Grass species	*Chloris roxburghiana*	96.94 d	41.81 a	49.42 b
	Eragrostis superba	80.40 b	37.20 a	43.61 a
	Enteropogon macrostachyus	86.71 c	50.89 b	44.89 a
	Cenchrus ciliaris	61.87 a	66.48 c	47.31 ab
Weeding technology	Control	81.63 a	49.99 a	46.83 a
	Herbicide	83.40 a	48.01 a	47.43 a
	Manual	79.42 a	49.29 a	44.66 a
S.E.M $_{0.05}$ (Grass)		1.753	2.87	1.335
S.E.M $_{0.05}$ (Weed technology)		1.518	2.48	1.156
CV%		15.8	42.9	21.2

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$).

Table 2. Common weed species found in the established rangeland grasses and their prevalence.

			Grass species			
Weed type/species	**Family**	**Life cycle**	***Cenchrus ciliaris***	***Chloris roxburghiana***	***Enteropogon macrostachyus***	***Eragrostis superba***
Trees/shrubs						
Acacia mellifera	Fabaceae	Perennial	-	*	*	-
Acacia tortilis	Fabaceae	Perennial	-	-	*	-
Commiphora africana	Burseraceae.	Perennial	-	-	-	*
Omacapum kirkii	Fabaceae	Perennial	-	*	-	-
Hermannia alhensis	Malvaceae	Perennial	-	-	*	-
Forbs/herbs						
Acanthospernum hispidum	Asteraceae	Annual	-	*	*	-
Clitoria ternatea	Fabaceae	Perennial	-	*	-	-
Commelina benghalensis	Commelinaceae	Annual	-	**	***	*
Datura stramonium	Solanaceae	Annual	-	**	***	-

			Grass species			
Weed type/species	**Family**	**Life cycle**	***Cenchrus ciliaris***	***Chloris roxburghiana***	***Enteropogon macrostachyus***	***Eragrostis superba***
Solanum incanum	Solanaceae	Perennial	-	**	*	*
Gynandropsis gynandra	Cleomaceae	Annual	-	***	**	-
Ipomoea spp.	Convolvulaceae	Perennial	-	**	*	**
Ocimum gratissimum	Lamiaceae	Annual	-	*	*	-
Senna occidentalis	Fabaceae	Biennial	*	**	**	-
Indigofera spinosa	Fabaceae	Perennial	-	***	***	*
Neonotonia wightii	Fabaceae	Perennial	-	*	-	-
Sida ovata	Malvaceae	Perennial	-	*	*	-
Sonchus oleraceus	Asteraceae	Annual	-	*	*	*
Tephrosia villossa	Fabaceae	Annual	-	**	*	-
Forbs (unknown)		Annual	-	**	**	*
Grasses						
Bracharia spp.	Poaceae	Annual	*	-	**	-
Digitaria scalarum	Poaceae	Annual	-	***	***	**
Digitaria macroblephara	Poaceae	Perennial	-	*	-	-
Cyperus rotundus	Cyperaceae	Perrenial	-	**	***	-
Latipes senegalensis	Poaceae	Annual	-	*	**	-
Aristida kenyensis	Poaceae	Annual	-	*	*	*
Several annual grasses	Poaceae	Annual	*	***	***	-

Key: - Absent *less frequent ** moderately frequent *** highly frequent

The grasses were infested with diverse weed flora including shrubs, forbs, sedges, grasses and herbs – with broad-leaved species forming a large percentage of total weeds recorded. The woody species were minimal in this study as most of them had already been removed during the establishment of experiments at the site. However, about 4 woody species spotted were mainly native shrub seedlings which predominate the surrounding environment, probably left behind in soil seed banks or brought in during the growing season. Forbs and herbs constituted the larger component and a wider diversity of weeds in the established grasses. Among the major broad-leaved weed species were *Commelina benghalensis, Indigofera spinosa, Senna occidentalis* and *Datura stramonium* which were highly frequent within the plots. One potential source of some of these weeds could be the manure applied to enhance the regrowth of the pasture crop. Manure from livestock sometimes contains weed seeds and can potentially cause weed problems (Arif *et al.,* 2015). Annual grasses, common in the semi-arid rangelands of Kenya were also found in the plots and these included *Aristida kenyensis* and *Latipes senegalensis* among others. The seeds of these weeds are mostly found within the soil seed bank awaiting for right appropriate germination conditions. They typically sprout after the first rains taking advantage of available soil moisture. The practice of reducing weed seed banks through uprooting, spraying and managing unwanted plants or weeds before they mature and shed seeds is crucial to prevent the next generation of weeds from establishing.

Our results also suggest that two of the grass species (*Enteropogon macrostachyus* and *Chloris roxburghiana*) were highly invaded by different weeds, mainly forbs and herbaceous species, more than the other two species (*Cenchrus ciliaris* and *Eragrostis superba*). This is mainly due to their growth habits and the competitive nature of *Cenchrus ciliaris* and *Eragrostis superba* that limited weed growth within their vicinity. Similar results of more weed populations in *E. macrostachyus* have been reported by Mganga *et al.*, (2021) but not under *E. superba* as is the case with this work. The probable difference could be brought about by differences in soil types and other environmental conditions influencing weed growth and prevalence.

Effects of weed control method on weed density and diversity

Under the different treatments, weed density and diversity remained high in the control (unweeded) plots as compared to the other two treatments as shown in Table 3.

Both control methods (manual and herbicide) significantly ($p < 0.05$) reduced the density and diversity of weeds in the experimental plots with the grasses. It should however be noted that the weeds found in the site were mostly secondary species hence the low density and diversity. Grass species and species differences significantly influenced weed diversity and density in this work. In semi-arid grasslands, weed density and diversity increases considerably based on different factors such as fertility, tillage practices, soil disturbance, overgrazing, and increased rainfall among others (Adewale, 2017; Travlos *et al*., 2018). *Cenchrus ciliaris* grass in particular due to its allelopathic nature is more likely to have suppressed weed growth (Mganga *et al*., 2021; Wright *et al*., 2020). *C. roxburghiana* on the other hand had a significantly ($p < 0.05$) higher weed diversity only comparable to *E. macrostachyus*, as well as a higher weed density. Herbicide use and manual control methods did not however differ from each other in this study, but clearly showed significant effect on weed density and diversity when compared to the control plots. In order to produce clean seed and hay, the surrounding pasture and hay production fields have been subjected to weed control over time, likely contributing to low weed diversity and density in the experimental site. Additionally, weed spread by other agents such as wind, animals and water was therefore minimized. When establishing pasture grasses in pure stands, it is recommended that farmers select appropriate sites that have less interference and those likely to give higher yields.

Effect of weed control method on aboveground grass and weed biomass

Overall, grass biomass was highest in *Cenchrus ciliaris* (2,049 kg ha^{-1}) followed by *Enteropogon macrostachyus* (1,425 kg ha^{-1}), *Eragrostis superba* (1,348 kg ha^{-1}) and *Chloris roxburghiana* (1,186 kg ha^{-1}). Weed biomass was however lowest in the *Cenchrus ciliaris* (123.9 kg ha^{-1}), comprising only 6% of the total dry matter harvest from the plot. However, weed biomass in *Eragrostis superba* was 208.6 kg ha^{-1} (13%) compared to *Enteropogon macrostachyus* (802.8 kg ha^{-1}) – 36% and *Chloris roxburghiana* (875.3 kg ha^{-1}) – 42% of total plot dry matter yields respectively. This is presented in Table 4.

Overall, the use of manual control method increased biomass yields by 21% while use of herbicides increased yields by 17%. When species were considered, the use of herbicides to control weeds marginally increased dry matter yields of *C. ciliaris* by 8%, *Chloris roxburghiana* (19%), *Enteropogon*

Table 3. Weed density and diversity under the two grass species and weed control methods.

Factors	Treatments	Weed Density	Weed Diversity
Grass species	*Chloris roxburghiana*	5.37 d	3.37 c
	Eragrostis superba	3.15 b	2.67 b
	Enteropogon macrostachyus	4.11 c	3.26 c
	Cenchrus ciliaris	0.70 a	0.70 a
Weeding technology	Control	4.47 b	3.56 b
	Herbicide	2.83 a	1.89 a
	Manual	2.69 a	2.06 a
S.E.M $_{0.05}$ (Grass)		0.249	0.165
S.E.M $_{0.05}$ (Weed technology)		0.216	0.143
CV%		38.8	34.3

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$).

Table 4. Grass and weed biomass yield under different weed control methods.

		Biomass Yield (kg ha^{-1})	
Factors	**Treatments**	**Grass biomass**	**Weed biomass**
Grass species	*Chloris roxburghiana*	1,186 a	875.3 d
	Eragrostis superba	1,349 b	208.6 b
	Enteropogon macrostachyus	1,425 b	802.8 c
	Cenchrus ciliaris	2,049 c	123.9 a
Weeding technology	Control	1,335 a	718.2 b
	Herbicide	1,559 b	415.5 a
	Manual	1,613 b	374.2 a
S.E.M $_{0.05}$ (Grass)		30.5	22.4
S.E.M $_{0.05}$ (Weed technology)		26.4	19.4
CV%		6.1	13.4

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$).

macrostachyus (16%) and *E. superba* by 32%. As for manual weed control, yields were increased 13% for *C. ciliaris*, 35% for *C. roxburghiana*, 6% for E. *macrostachyus* and 39% for *E. superba* when compared to the control.

Because of their erect growth habits, some grass species are quickly infested by herbaceous weeds due to inter-plant spaces and open canopies (Humphries *et al*., 2020). In the case of this study, *Enteropogon macrostachyus* and *Chloris roxburghiana* had the highest weed interference, hence the higher weed biomass, diversity and densities. Farmers must therefore consider choosing species that are capable of competing favorably with weeds while yielding higher biomass for increased productivity and reduction in weed management costs. The choice of pasture species in semi-arid Kenya is primarily driven by forage value for livestock and the potential to rehabilitate degraded lands. The four grasses are highly regarded within communities in the dryland regions due to their forage yield potential with two (*Cenchrus ciliaris* and *Eragrostis superba*) reportedly preferred by most farmers, not only for their feed value but capacity to suppress weeds (Lugusa, 2015; Mganga *et al*., 2019). *Cenchrus ciliaris* is a deep-rooting perennial grass species capable of extracting resources from deeper soil layers hence its adaptability in semi-arid environments (Al-Dakheel and Hussain, 2016), and capacity to compete with weeds. As *Eragrostis superba* has a majority of its roots in the upper soul layers, it is capable of utilizing topsoil nutrients and moisture which results in faster plant growth and hence high biomass production (Mganga *et al*., 2019).

High weed biomass was determined in *Enteropogon macrostachyus* grass species (802.8 kg ha^{-1}) and *Chloris roxburghiana* species (875.3 kg ha^{-1}), results comparable to those reported by Mganga *et al*. (2021) in South East Kenya, where less weed biomass was produced in *Cenchrus ciliaris* plots. *Cenchrus ciliaris* is an aggressive species (Mganga *et al*., 2019), and can suppress and outcompete other species where it grows as demonstrated by the low weed density, diversity and weed biomass in this study. Studies in Australia where the species is ecologically significant have shown that the removal of the species from a site enhances native vegetation growth and soil seed bank diversity (Wright *et al*., 2020). The species is therefore, one of the most preferred in the restoration of degraded environments. Overall, the low contribution of weed biomass to total dry matter production in this work highlights the importance and adaptability of rangeland grasses in semi-arid environments. Most annual weeds have a shorter growing period, and by the time of sampling, some may have already completed their life cycle, unlike the perennial grasses which were clipped at peak productivity. All the grasses showed higher dry matter biomass yields irrespective of the treatments demonstrating their suitability, not only in livestock production but also other ecosystem services such as rangeland restoration, carbon sequestration and climate change mitigation (Kidake *et al*., 2016; Mganga *et al*., 2013).

Some weeds may however be beneficial to the crop in one way or another depending on the objective of the establishment. For instance, in semi-arid Kenya, some farmers grow pastures to provide fodder for livestock as a coping and adaptive strategy to feed deficits (Lugusa., 2015). In this regard, the objective is to produce adequate biomass for livestock feed. Some weed species including those found in this study such as *Clitoria ternatea, Commelina benghalensis, Neonotonia weightii* and *Indigofera spinosa* are highly valued as protein sources to complement natural pastures in semi-arid Kenya (Boonman, 1993). Allowing such species to grow with the cultivated grasses not only improves the quality of the harvested material but also is beneficial to the environment. However, the persistence of some of these leguminous herbaceous species is low over time and they may eventually be eradicated (Tozer *et al*., 2016).

Rangeland grasses and to an extent weeds provide significant sources of nutrition for livestock in rangeland ecosystems. Grazing management in these regions is therefore key to regulating the biomass of established grasses as well as weeds. Overgrazing of pastures leaves many areas bare and predisposes them to weed invasion while under grazing on the other hand encourages selectivity of the more palatable species leaving behind less grazed weedy species which may become a nuisance (Schaffner *et al*., 2022). Livestock keepers need to strike a balance of grazing where pastures are neither overgrazed nor under-grazed by observing adequate stocking rates. Under cut-and-carry systems, early mowing may be an advantage to weed control in that weeds may be removed from the fields together with the pasture crop before the seed set. This prevents the next generation of weeds from establishing and produces highly nutritious fodder for livestock (Khan *et al*., 2013). In semi-arid Kenya, most farmers wait until seed maturity and drying in range grasses before harvesting the seeds. This practice promotes weeds growth, as the weeds mature with the pasture crop and shed seeds on the same farms. In return, poor-quality feeds are harvested after seed harvesting (Omollo, 2017).

Weed control efficiency

The efficacy of the two methods of weed control in the four grasses is indicated in Table 5. The highest efficacy was noted in *Cenchrus ciliaris* when the herbicide was used, while the lowest efficacy was in *Chloris roxburghiana*.

Table 5. Weed control efficiency of the two methods of weed control in rangeland grasses

Species	Herbicide use (%)	Manual weed control (%)
Eragrostis superba	48.83	68.34
Enteropogon macrostachyus	49.90	35.07
Chloris roxburghiana	27.35	56.34
Cenchrus ciliaris	73.33	68.34

The lower efficacy values are attributable to the one off weeding which was carried a few weeks after weed emergence. The values could be higher if this was repeated more than once. The use of herbicides which is currently on the rise in developing nations (Grabowski and Jayne, 2016), was more effective in some of the grasses which had more broad-leaved weed species, results which have also been reported for other crops such as rice (Rodenberg *et al*., 2019). Some other grassy weeds and shrubs were however not affected by the herbicide since it is a specifically used on broad-leaved plants. Many commercial herbicides are in the market for controlling other types of weeds but knowledge and information about their suitability in pasture systems are lacking. Upon germination, grass seedlings of many perennial grasses look similar to other grassy weeds hence identification for spot-spraying, even if an alternative herbicide was available, may be difficult, laborious and a challenge. Additionally, many farmers and livestock keepers establish their pastures through broadcasting (Omollo, 2017), a situation that complicates weed control as a result of uneven and haphazard germination. Identifying weeds from the target crop is almost impossible in such situations hence the efficacy of weed control methods may still be low.

Hand weeding and using tools, in spite of the high efficacy in some of the species, is not a long-term option for weed control, and neither does it completely eradicate all the weeds unless it is repeatedly carried out. Some underground reproductive parts may remain and the weeds end up not being eliminated (Uddin *et al.*, 2012). This is likely to damage the target crop (pasture) resulting in depressed fodder and seed yields. Some weed seeds are brought to the soil surface during the process of hand weeding and may in turn germinate leading to a higher seed density even in weeded plots. They are likely to grow back requiring a repeat of the practice which is time-consuming and uneconomical (Corin *et al.*, 2017). The efficacy of manual weed control is therefore reduced.

In most cases, herbicide use is never used as a stand-alone control method (Rodenberg *et al*., 2019), a situation also observed by the authors in southern Kenya. In established pastures in semi-arid Kenya, the uprooting of shrubs and woody species is a common practice even when chemicals are used to control weeds. This is because some woody species may be at a growth stage where they may not be affected by the chemicals. Nevertheless, no one weed control method is effective or appropriate due to differences in soils, nature and growth habits of weeds and climatic conditions (Adewale, 2017).

We acknowledge that weed control especially on larger land parcels and natural environments in semi-arid ecosystems may be difficult due to dynamics encountered in the field. Results from experimental work in smaller plots may not necessarily indicate or replicate the absolute outcomes in field conditions. However, such results give an indication of a directional trend, in our case, the effectiveness and trends of a particular weed control method. Other factors will always play a big role, especially on large scale and therefore caution should be taken while interpreting results. One challenge encountered by the authors in southern Kenya involves weed control on large acreage with cultivated pastures, especially during the initial years. Studies indicate that with the developing pasture and fodder value chains, more farmers are owning more than five acres of land under cultivated pastures and more than ten acres of native pastures (Omollo, 2017), all of which require weeding at some point. Labour requirements can sometimes be prohibitive and beyond the reach of many farmers. Most farmers have been utilizing manual approaches, which are commonly practiced in sub-Saharan Africa by household members and paid labour where resources allow. This availability of labour has however been on the decline due to increased rural-urban migration and rising wages (Chauhan *et al*., 2020). The fallback is the involvement of family members where school-going children are engaged in weeding activities, limiting their prospects while compromising their health (Corin *et al*., 2017).

The viable option, therefore, is to effectively control weeds as early as possible, especially in the first years of establishment. The initial weed control costs may be high, but subsequent weed control will be minimal. Muoni and Mhalnga (2014) found that effectively controlling weeds from the first year and successive seasons eventually reduces weed pressure over several years hence cost reduction. Cultivated grasses and grasslands if well managed, will offer few or little opportunity for weeds to recruit from invading seeds or the soil seed bank and will have a competitive advantage over any kind of weeds (Schaffner *et al*., 2022). Combining different weed control strategies that can complement each other is suggested as the most cost-effective and efficient method of managing weeds in pasture-based systems (Ghanizadeh and Harrington, 2019).

CONCLUSION

The results demonstrate that weeds in cultivated and established pastures significantly affect biomass yields and eventually the productivity of rangeland grass species. Weed control through the use of manual hand tools and commercial herbicide significantly contributes to a yield increase in biomass of the grasses while reducing weed biomass, weed density and weed diversity. The two methods also proved their efficacy in managing weeds under semi-arid conditions.

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REFERENCES

Adewale, O.O., 2017. Weed interference and control in cowpea production: a review. *Journal of Agricultural Science*, 9(12), pp. 11-20. https://doi.org/10.5539/jas.v9n12p11

Al-Dakheel, A.J., and Hussain M., 2016. Genotypic variation for salinity tolerance in *Cenchrus ciliaris* L. *Frontiers in Plant Science*; 7 Article 1090. https://doi.org/10.3389/fpls.2016.01090

Arif, M., Shah, T., Ilyas, M., Ahmad, L.W., Mian, A.A., Jadoon M.A. and Adnan M., 2015. Effect of organic manures and their levels on weeds density and maize yield. *Pakistani Journal of Weed Science Research*, 21(4), pp. 517- 522.

Boonman, J.G., 1993. East Africa's grasses and fodders: their ecology and husbandry. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Chauhan B.S., 2020. Grand challenges in weed management. *Frontiers in Agronomy*, 1:3. https://doi.org/10.3389/fagro.2019.00003

Corin, F.P., Kate, L.C. and Sean, T.M., 2017. Economic impacts of invasive alien species on African smallholder livelihoods, *Global*

Food Security, 14, pp. 31-37. https://doi.org/10.1016/j.gfs.2017.01.011

Cowie, B.W., Byrne, M.J. and Witkowski, E.T.F., 2021. Feasible or foolish: Attempting restoration of a Parthenium hysterophorus invaded savanna using perennial grass seed. *Journal of Environmental Management*, 280, 111686.

Ekwealor, K.U., Echereme, C.B., Ofobeze, T.N. and Okereke, C.N., 2019. Economic importance of weeds: A review. *Asian Plant Research Journal*, 3(2), pp. 1–11. https://doi.org/10.9734/aprj/2019/v3i230063

Gao, X. and Schwilk D.W., 2018. Grass canopy architecture influences temperature exposure at soil surface. *Fire*, 1(35), pp.1-14. https://doi.org/10.3390/fire1030035

Ghanizadeh, H. and Harrington. K.C., 2019. Weed management in New Zealand pastures. *Agronomy*, 9(448), pp. 1–18. https://doi.org/10.3390/agronomy9080448

Grabowski, P. and Jayne, T., 2016. Analyzing trends in herbicide use in Sub-Saharan Africa. MSU International Development Working paper. https://ageconsearch.umn.edu/record/245909/?ln=en

Huho, J.M. and Omar, M.H., 2020. *Prosopis juliflora* in Asals of Kenya: A friend or a foe plant? *International Journal of Scientific and Research Publications*, 10(3), pp. 9968 http://dx.doi.org/10.29322/IJSRP.10.03.2020.p9968

Humphries, T., Dowling, K., Turville, C., Sinclair, S. and Florentine, S., 2020. Ecology, distribution and control of the invasive weed Nassella trichotoma (Nees) Hack. ex Arechav.: A global review of current and future challenges. *Weed Research*, 60(6), pp. 392–405. https://doi.org/10.1111/wre.12449

IUSS Working Group WRB., 2015. International soil classification system for naming soils and creating legends for soil maps. In World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO.

Khan, R., Khan, M.A., Sultan, S., Marwat, K.B., Khan, I., Hassan, G. and Shah, H.U., 2013. Nutritional quality of sixteen terrestrial weeds for the formulation of cost-effective animal feed. *The Journal of Animal and Plant Sciences*, 23(1), pp. 75-79.

Kidake, B.K., Manyeki, J.K., Kubasu, D. and Mnene, W.N., 2016. Promotion of range pasture and fodder production among the pastoral and agro-pastoral communities in Kenyan rangelands: Experiences and lessons learnt. *Livestock Research for Rural Development*. Volume 28, Article #151. Retrieved July 26, 2022, from http://www.lrrd.org/lrrd28/8/kida28151.html

Lugusa, K.O., 2015. Fodder production as an adaptive strategy in the drylands: A case study of producer groups in Baringo County, Kenya. MSc Thesis. University of Nairobi.

Mani, S.V, Malla, L.M., Gautam, C.K. and Bhagavandas., 1973. Weed killing chemicals in potato cultivation. *Indian Farming*, 23(1), pp. 17–18.

Manyanza, N.M. and Ojija F., 2021. Invasion, impact and control techniques for invasive *Ipomoea hildebrandtii* on Maasai steppe rangelands. *Journal of Basic Applied Science*, 17, pp. 25-36.

Mao, R., Bajwa A.A. and Adkins, S., 2021. A superweed in the making: adaptations of Parthenium hysterophorus to a changing climate. A review. *Agronomy for Sustainable Development*, 41(4). pp 1-18. https://doi.org/10.1007/s13593-021-00699-8

Mganga, K.Z., Kaindi, E., Ndathi, A.J.N., Bosma, L, Kioko, T., Kadenyi, N., Musyoki, G.K., Wambua, S., van Steenbergen, F. and Musimba, N.K.R., 2021. Plant morphoecological traits, grass-weed interactions and water use efficiencies of grasses used for restoration of African rangelands. *Frontiers in Ecology and Evolution*, 8, 1–12. https://doi.org/10.3389/fevo.2020.613835

Mganga, K.Z., Musimba, N.K.R., Nyariki, D.M. and Nyangito, M.M., 2013. The choice of grass species to combat desertification in semi-arid Kenyan rangelands is greatly influenced by their forage value for livestock. Grass and Forage Science, 70(1), pp. 161–167. https://doi.org/10.1111/gfs.12089

Mganga, K.Z., Nyariki, D.M., Musimba, N.K.R. and Mwang'ombe, A.W., 2019. Indigenous grasses for rehabilitating degraded African drylands. In R. Bamutaze, Y., Kyamanywa, S., Singh, B., Nabanoga, G., Lal (Ed.), *Agriculture and Ecosystem Resilience in Sub Saharan Africa. Climate Change Management*. Springer, Cham. pp. 53–68. https://doi.org/10.1007/978-3-030-12974-3_3

Muoni, T. and Mhlanga, B., 2014. Weed management in Zimbabwean smallholder conservation agriculture farming sector. *Asian Journal of Agriculture and Rural Development*, 4 (3), pp. 269-278. https://doi/10.22004/ag.econ.198407

Mwendia, S.W., Ohmstedt, U., Nyakundi, F., Notenbaert, A. and Peters, M., 2022. Does harvesting *Urochloa* and *Megathyrsus* forages at short intervals confer an advantage on cumulative dry matter yields and quality? *Journal of the Science of Food and Agriculture*, 102 (2), pp. 750–756. https://doi.org/10.1002/jsfa.11407

Ndathi, A.J.N., 2012. Climate variability and livestock feeding strategies in the agro-pastoral systems of Southeastern Kenya. PhD Thesis. University of Nairobi.

Njarui, D.M.G., Gichangi, E.M., Ghimire, S.R. and Muinga, R.W., 2016. Climate-smart Bracharia grasses for improving livestock production in East Africa – Kenya experience. Proceedings of the Workshop held in Naivasha, Kenya, 14-15 September 2016: 298 pp.

Omollo, E., 2017. Analysis of fodder production and marketing in the rangelands of Southern Kenya. MSc Thesis. University of Nairobi.

Peterson, M.A., Collavo, A., Ovejero, R., Shivrain, V. and Walsh M.J., 2018. The challenge of herbicide resistance around the world: a current summary. *Pest Management Science*, 74(10), pp. 2246–2259. https://doi.org/10.1002/ps.4821

Rayburn, E.B. and Griggs, T.C., 2020. Light interception and the growth of pastures under ideal and stressful growing conditions on the Allegheny plateau. *Plants*, 9(6), pp.1-19. https://doi.org/10.3390/plants9060734

Rodenburg, J., Johnson, J.M., Dieng, I., Senthilkumar, K., Vandamme, E., Akakpo, C., Allarangaye, M.D., Baggie, I., Bakare, S.O., Bam, R.K., Bassoro, I., Abera, B.B., Cisse, M., Dogbe, W., Gbakatchétché, H., Jaiteh, F., Kajiru, G.K., Kalisa, A., Kamissoko, N., Sékou, K., Kokou, A., Mapiemfu-Lamare, d., Lunze, F.M., Mghase, J., Maïga, I.M., Nanfumba, D., Niang, A., Rabeson, R., Segda, Z., Sillo, F.S., Tanaka, A. and Saito, K., 2019. Status quo of chemical weed control in rice in sub-Saharan Africa. *Food Security*, 11, 69–92. https://doi.org/10.1007/s12571-018-0878-0

Schaffner, U., Müller-Schärer, H. and Lüscher, A., 2022. Integrated weed management in grasslands. In: Kudsk, P, ed. *Advances in Integrated Weed Management*. Burleigh Dodds Science Publishing, pp. 339-360.

Sombroek, W.G., Braun, H.M.H. and van der Pouw, B.J.A., 1982. Exploratory soil map and agro-climatic zone map of Kenya, Kenya Soil Survey 1980. 56 pp.

Tabe-Ojong, M.P., Alvarez, M., Ihli, H.J., Becker, M. and Heckelei, T., 2022. Action on Invasive Species: Control strategies of Parthenium hysterophorus L. on smallholder farms in Kenya. *Environmental Management*, 69, pp. 861–870. https://doi.org/10.1007/s00267-021-01577-5

Tozer, K.N., Barker, G.M., Cameron, C.A., Wilson, D. and Loick N. 2016. Effects of including forage herbs in grass-legume mixtures on persistence of intensively managed pastures sampled across three age categories and five regions. *New Zealand Journal of Agricultural Research*, 59(3) pp. 250-268. https://doi.org/10.1080/00288233.2016.1188831

Travlos, I.S., Cheimona, N., Roussis, I. and Bilalis, D.J., 2018. Weed-species abundance and diversity indices in relation to tillage systems and fertilization. *Frontiers in Environmental Science*, 6, pp. 1–10. https://doi.org/10.3389/fenvs.2018.00011

Uddin, K., Juraimi, S.A. and Mohd, R.I., 2012. Weed management in tropical Turfgrass areas: A review. *Archives of Biological Sciences*, 64(2), pp. 594-603. https://doi.org/10.2298/ABSA1202597U

Wright, B.R., Latz, P.K., Albrecht, D.E. and Fensham R.J., 2020. Buffel grass (*Cenchrus ciliaris*) eradication in arid central Australia enhances native plant diversity and increases seed resources for granivores. *Applied Vegetation Science*, 24(1), pp.1-9. https://doi.org/10.1111/avsc.12533

Ziska, H.L., 2016. The role of climate change and increasing atmospheric carbon dioxide on weed management: Herbicide efficacy. *Agriculture, Ecosystems and Environment*, 231, pp. 304-309. https://doi.org/10.1016/j.agee.2016.07.014