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Effect of Herbicides on Forage Dry Matter Yield and Plant Density in the Old Arable Lands in Communal Area of the Eastern Cape Province, South Africa

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Abstract: With the world's population growing at an alarming rate, there is an urgent need to improve food security. This study aimed to assess forage dry matter yield and plant density under different herbicide treatments at Kubedlana arable lands. The study was carried out using eight treatments consisting of seven herbicide treatments and a control. Seed mixtures of seven legume species were broadcasted in 24 plots of 3 m $\times$ 5 m size. Herbicide treatments including Bendioxide (BEN), Glyphosate (GLY), Haloxyfop-R methyl (HAL), Haloxyfop-R methyl and Bendioxide (HBE), Paraquat (PAR), Bendioxide (BRR), and Paraquat (PRR) were applied individually in three plots. Dry matter production and plant densities were determined in five randomly distributed 0.25 m^2 quadrats per plot. The results revealed that GLY had a significantly ($p < 0.05$) higher effect on the DM yield compared with other treatments. Both BRR and HBE significantly ($p < 0.05$) decreased the DM yield. GLY and HBE significantly reduced ($p < 0.05$) the grass density in 2017 and BRR significantly affected ($p < 0.05$) the legume density in May 2017 and May 2018, respectively. These results indicate that the application of GlY and HAL resulted in the reduction of grass density. Furthermore, none of the applied chemicals negatively influenced the legume density.

Keywords: pasture legumes; herbicide; species composition; plant density

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1. Introduction

The human population is increasing at an alarming rate, increasing the necessity to strengthen food security. It is projected that global food production will increase by 70–100% to meet global food demand in 2050 [1]. Milk and meat from livestock contribute significantly to global protein and calorie consumption [2]. As a result, increasing livestock production is essential to meet imminent global food demand and curb the increasing food insecurity and poverty. Livestock in communal areas in particular are reared extensively in rangelands which are facing severe degradation, with grasses in these systems being less productive and deficient in essential nutrients, more so during the dry season [3]. This, therefore, calls for the utilization of alternative fodder reserves to supplement livestock, especially for resource-poor communal farmers. Arable lands, also referred to as abandoned croplands, have potential for use as cultivated reserve pastures to increase forage production in communal areas [4]. Crop abandonment has increased over the past two decades, owing, amongst other drivers, to climate change and largely erratic rainfall which reduces crop yields, forcing subsistence crop farmers to resort to livestock production [5]. Apart from climate change, land use changes together with human population increase led to high land consumption, which reduces grazing land capacity to produce forage [6]. This on its own has put more pressure on the remaining rangelands, as the demand for more fodder to feed large animal numbers increases [7].

The planting of improved forages, largely legumes in arable lands, has become central in government initiatives aimed at improving livestock production in communal or smallholder farming systems. In South Africa, the Eastern Cape Communal Arable Lands Initiative (ECCAL) which was launched in 2006 by the Eastern Cape Department of Agriculture in partnership with the Western Australian Government and Murdoch University is one of the notable interventions. The initiative involved planting different varieties of forage legume species including *Lespedeza cuneata* (Poor men's lucerne), *Trifollium vesiculosum* (Arrow leaf clover), and *Lotus corniculatus* (Birdsfoot trefoil)] across different agro-ecological zones of the Eastern Cape Province. Legumes were selected for their high digestibility, essential nutrients (e.g., high crude protein), and their ability to fix atmospheric N via rhizobium bacteria. A sustainable production of these legume forages depends largely on long-term monitoring and management that will ensure the prolonged persistence of these legume pastures. However, amongst other challenges, weed infestations are the greatest threat to the productivity and persistence of these cultivated legume pastures [8]. Weeds are undesirable plants that impede crop growth and productivity by competing for soil nutrients moisture, light, and space [4]. If weeds are left unchecked, they do not only reduce the yield of preferable plants but also the forage quality [9]. Hence, weed management, including herbicide application in particular, is critical for the improvement and sustainable productivity of these arable lands. However, non-selective herbicides can pose a threat to non-target plants, thereby reducing pasture establishment and production [10]. Thus, the knowledge of the efficacy of herbicides for the management of legume-overseeded abandoned croplands is limited. This, therefore, may lead to the failure of pasture establishment, negatively affecting the sustainability of livestock production, especially in communal areas.

Thus, time-series monitoring of the efficacy of herbicides is crucial for the sustainable production of planted forage species. Furthermore, since the establishment of the ECCAL, there have been no studies conducted to assess the effect of herbicides on the productivity and persistence of planted legumes. Therefore, this study was conducted to assess the efficacy of herbicides in controlling the plant density of the native grasses and introduced legumes as affected by the application of various herbicides.

2. Materials and Methods

2.1. Study Area

The research was conducted in arable lands of the Kubedlana communal area in Tsolo town under OR Tambo district municipality in the Eastern Cape Province of South Africa. Kubedlana is situated at 32°11′53 S and 28°14′1 E and at an altitude of 1020.8 m. The vegetation type of the study area is Foothill Moist Grassland (Mucina and Rutherford 2006). The mean rainfall of the area ranges between 630 mm and 640 mm per annum (Figure 1) and the temperatures range from a minimum of 3 °C in winter to a maximum of 28 °C in summer (Figure 2). The soil chemical properties are as follows: P (5.99 mg/kg), K (0.20 mg/kg), Ca (4.26 mg/kg), Mg (1.16 mg/kg), and Zn (6.28 mg/kg).

2.2. Experimental Procedure

An area of 0.5 ha was demarcated in which 24 plots of 3 × 5 m^2 were marked randomly in a completely randomized design. In each plot, seven forage legume species were planted in mixed stands. The experimental legume species were *Lotus corniculatus*, *Trifolium repens*, *Trifolium vesiculosum*, *Yellow serradella*, *Pitman serradella, Biserrula*, and *Lespedeza cuneata*. The choice of legume species was mainly based on adaptability to local soils, productivity, compatibility with grasses, and ability to fix nitrogen. Before planting, legume seeds were hand-mixed with the appropriate inoculant. The seeds of legumes were broadcasted at a rate of 14.3 kg/ha making for a total of 100 kg seeds/ha. Planting was done with an

Aitchison Mini seeder, which was used for the over-sowing the legumes into grazing land (grasses) (six-row no-till pasture seeder).

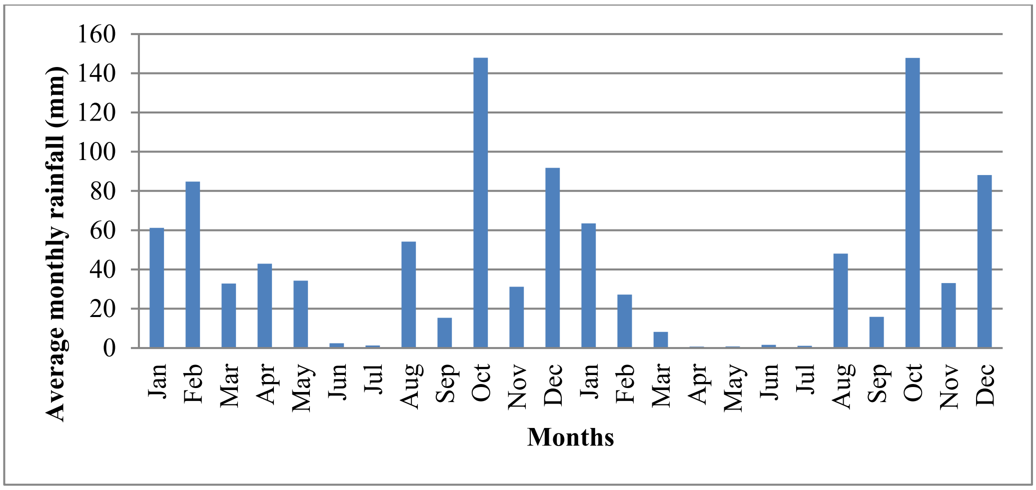

Figure 1. The average monthly rainfall (mm) from January 2017 to December 2018 in the Kubedlana communal area.

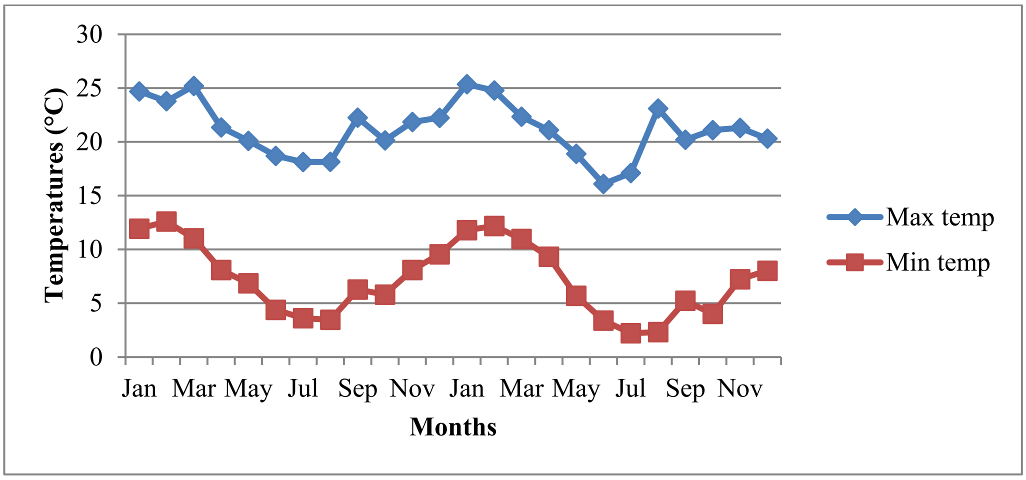

Figure 2. The monthly maximum and minimum temperatures (°C) from January 2017 to December 2018 at Kubedlala communal area.

2.3. Herbicide Treatments

Seven different herbicides as shown in Table 1 (i.e., Glyphosate; Ha-loxyfop-R methyl; Bendioxide low dosage; Paraquat low dosage; Bendioxide at 50% recommended rate; Paraquat at the recommended rate; Haloxyfop-R methyl and Bendioxide and Control were applied in three replicate plots). The mode of herbicide application was aerial using knapsack sprayers. A 2 m border was left between plots to avoid spillover effects of one treatment to another.

Table 1. Rate of herbicide treatment applications and their expected effects.

Treatment No.	Treatments	Description	RR Rate as per Label	Rate/ha in 300 L Water/ha	Expected Effect
1	Control	No Herbicide	No RR	No water	Control treatment
2	Round up LD	Glyphosate	6 L/ha	3 L/ha (50% recommended rate)	Retard growth of grasses and broadleaved plants
3	Gallant Super RR	Haloxyfop-R methyl	1 L/ha	1 L/ha (recommended rate)	Control of grasses
4	Bassagran LD	Bendioxide	3 L/ha	1.5 L/ha (low dosage)	Retard growth of broadleaved plants
5	Gramoxone LD	Paraquat	4 L/ha	2 L/ha (50% recommended rate)	Retard growth of grasses and broadleaved plants
6	Basagran RR	Bendioxide	3 L/ha	3 L/ha (recommended rate)	Control of broadleaved plants
7	Gramoxone RR	Paraquat	4 L/ha	4 L/ha (recommended rate)	Control of grasses and broadleaved plants
8	Gallant Super RR and Basagran LD	Haloxyfop-R methyl & Bendioxide.	4 L/ha	1 L/ha+ 1.5 L/ha (low dosage)	Control of grasses & retard the growth of broadleaved plants

LD = Lower dosage, RR = Recommended rate.

2.4. Data Collection

2.4.1. Plant Density

Plant counting was conducted to determine plant density. This was achieved by randomly throwing five 0.25 m^2 quadrats in each 3 m $\times$ 5 m plot and counting the number of plants for each identified plant species. Counting was conducted before herbicide application in 2016 and after application at the beginning and end of the planting seasons (i.e., November and May) of 2017 and 2018, respectively.

2.4.2. Dry Matter Yield

Data on herbage production (grasses, legumes, and forbs) was collected in November 2017 and 2018. This was achieved by cutting plants at a stubble height of 5 cm in three randomly placed 1 m^2 quadrats per plot. Plants were harvested according to plant functional groups including legumes, forbs, and grasses. The harvested plant material was placed into paper bags, oven-dried for 72 h at 65 °C and weighed to determine the dry matter (DM) production.

2.5. Data Analysis

The repeated measures analysis of variance (RMANOVA) was conducted using Statistical Analysis System (SAS) 2016, version 9.4 where herbage biomass and plant density were dependent variables and herbicide treatments and years were between-subject and within-subject factors, respectively. The General Linear Model (GLM) procedure of SAS (2016) was used to determine the effect of herbicides on plant density and biomass yield. Fisher's LSD test was used to determine the significance of differences between means at the 95% significance level.

3. Results

3.1. Dry Matter Yield in Response to Herbicide Application

Herbicides had a significant effect on DM yield ($p < 0.05$), with HAL, KHC, BEN, and PAR having higher DM yield than other treatments during the first year of planting. However, the DM yield was not significantly different ($p > 0.05$) for BRR and HBE herbicide applications. In the second year, the response trends changed significantly ($p < 0.05$), as DM yield responded similarly, across all the herbicide treatments. However, there was an interannual variability in the DM yield, with herbicides increasing DM yield three to four-fold higher in the second year compared to the first year of herbicide applications (Table 2).

Table 2. Mean dry matter yield (kg ha^{-1}) of plots treated with herbicide treatments over two-year periods.

Treatments	Mean DM (kg/ha)	
	Year 1 (2017)	**Year 2 (2018)**
GLY	2497 ^{a}	10,191 ^{a}
HAL	4259 ^{b}	10,010 ^{a}
KHC	4123 ^{b}	9755 ^{a}
BEN	4309 ^{b}	11,391 ^{a}
PAR	4029 ^{b}	10,061 ^{a}
BRR	3646 ^{ab}	9294 ^{a}
PRR	3833 ^{b}	11,297 ^{a}
HBE	3282 ^{ab}	9870 ^{a}
LSD	1276	2993

KHC = Kubedlana herbicide control plot; BEN = Bendioxide at 50% of the recommended rate; GLY = Glyphosate at 50% of the recommended rate; HAL = Haloxyfop-R methyl at 50% recommended rate; HBE = Haloxyfop-R methyl at recommended rate & bendioxide at 50% recommended rate; PAR = Paraquat at 50% recommended rate; BRR = Bendioxide at the recommended rate, PRR = Paraquat at recommended rate, Year 1 = 2017 and Year 2 = 2018. Values in the same column with the same superscript letters do not differ significantly ($p > 0.05$).

3.2. Plant Density in Response to Herbicide Application

The density of forbs and legumes showed a significant difference ($p < 0.05$) while grasses were not significantly different ($p > 0.05$) before herbicide application (Table 3). Results indicate that the total plant density was significantly different between HAL, KHC, and BEN treatments. The legume density was highest under PAR and HBE while HAL and BRR showed the lowest legume density (Table 3). During May 2017, GLY and HBE significantly reduced ($p < 0.05$) the grass density compared to the control treatment (Table 4). Only BRR had a significant effect ($p < 0.05$) on legume density. The total plant density was significantly affected ($p < 0.05$) by GLY herbicide during the first year (2017). In November 2017, none of the treatments had any significant effect on plant densities of all plant functional groups when compared to the control treatment KHC. In May 2018, only BRR significantly affected ($p < 0.05$) the legume density when compared to November 2018, GLY and PRR significantly ($p < 0.05$) reduced grass density. Legume density showed a significant decline ($p < 0.05$) when treated with GLY herbicide (Table 4).

Table 3. Baseline plant density before the application of herbicide in 2016.

Treatment	Grass	Forbs	Legumes	Total
GLY	72 ^{a}	35 ^{a}	19 ^{ab}	126 ^{ab}
HAL	62 ^{a}	37 ^{ab}	15 ^{a}	114 ^{a}
KHC	75 ^{a}	38 ^{ab}	24 ^{bc}	137 ^{b}
BEN	74 ^{a}	46 ^{b}	19 ^{ab}	139 ^{b}
PAR	69 ^{a}	33 ^{a}	27 ^{bc}	129 ^{ab}
BRR	73 ^{a}	39 ^{ab}	15 ^{a}	128 ^{ab}
PRR	68 ^{a}	37 ^{ab}	18 ^{ab}	123 ^{ab}
HBE	66 ^{a}	36 ^{a}	22 ^{abc}	124 ^{ab}
LSD	9.8	9.6	7.6	17.3

Nov 16 = November 2016. Values in the same column with the same superscript letters do not differ significantly according to ($p > 0.05$).

Table 4. Mean plant density (plants m^{-2}) of different plant functional groups across different herbicide treatments over a two-year period.

Treatment	MAY 2017				NOV 2017				MAY 2018				NOV 2018			
	Grass	**Forbs**	**Legumes**	**Total**	**Grass**	**Forbs**	**Legumes**	**Total**	**Grass**	**Forbs**	**Legumes**	**Total**	**Grass**	**Forbs**	**Legumes**	**Total**
GLY	66 ^{a}	35 ^{a}	7 ^{ab}	108 ^{a}	64 ^{a}	27 ^{a}	9 ^{a}	101 ^{ab}	64 ^{a}	23 ^{a}	17 ^{ab}	105 ^{a}	62 ^{a}	69 ^{a}	10 ^{a}	140 ^{a}
HAL	80 ^{b}	28 ^{a}	7 ^{ab}	115 ^{ab}	61 ^{a}	29 ^{a}	7 ^{a}	97 ^{a}	71 ^{a}	23 ^{a}	18 ^{ab}	113 ^{a}	70 ^{abc}	75 ^{a}	12 ^{ab}	157 ^{ab}
KHC	87 ^{b}	33 ^{a}	10 ^{b}	129 ^{b}	70 ^{ab}	30 ^{a}	19 ^{a}	119 ^{ab}	78 ^{a}	23 ^{a}	22 ^{b}	123 ^{a}	80 ^{c}	68 ^{a}	25 ^{b}	173 ^{b}
BEN	87^{b}	34 ^{a}	9 ^{ab}	130 ^{b}	59 ^{a}	31 ^{a}	12 ^{a}	102 ^{ab}	71 ^{a}	28 ^{a}	25 ^{b}	124 ^{a}	68 ^{abc}	73 ^{a}	16 ^{ab}	157 ^{ab}
PAR	87 ^{b}	34 ^{a}	8 ^{ab}	129 ^{b}	65 ^{a}	25 ^{a}	11 ^{a}	101 ^{ab}	78 ^{a}	24 ^{a}	17 ^{ab}	119 ^{a}	72 ^{abc}	72 ^{a}	17 ^{ab}	161 ^{ab}
BRR	83 ^{b}	33 ^{a}	3 ^{a}	119 ^{ab}	82 ^{b}	25 ^{a}	15 ^{a}	122 ^{b}	81 ^{a}	31 ^{a}	12 ^{a}	124 ^{a}	79 ^{bc}	83 ^{a}	19 ^{ab}	180 ^{b}
PRR	83 ^{b}	36 ^{a}	8 ^{ab}	128 ^{b}	71 ^{ab}	30 ^{a}	12 ^{a}	113 ^{ab}	74 ^{a}	25 ^{a}	22 ^{b}	121 ^{a}	67 ^{ab}	65 ^{a}	22 ^{ab}	154 ^{ab}
HBE	73 ^{a}	31 ^{a}	10 ^{b}	115 ^{ab}	68 ^{ab}	25 ^{a}	14 ^{a}	108 ^{ab}	80 ^{a}	27 ^{a}	17 ^{ab}	124 ^{a}	76 ^{bc}	71 ^{a}	18 ^{ab}	165 ^{ab}
LSD	13.7	12.5	6.7	16.7	13.5	9.9	6.4	22.8	18.6	8.6	10.2	23.5	11.7	19.9	13.0	26.8

Nov stands for November. Values in the same column with the same superscript letters do not differ significantly ($p > 0.05$).

4. Discussion

4.1. Dry Matter Yield Response to Herbicide Application

The results of this study revealed interannual variation in DM production, with the highest production noticeable in year 2 relative to year 1 in all herbicide treatments. This suggests that the biomass was severely affected by the herbicide during the year 2017 and quickly recovered after the rainy season of the year 2018. In the current research, GLY herbicide significantly decreased the DM yield in comparison to the control treatment during the first year of herbicide application, while in year 2, there was no significant change observed. Glyphosate distracts the plant's shikimic acid pathway vital for amino acid synthesis, thereby negatively affecting plant growth. By inhibiting this pathway, glyphosate prevents amino acid production, necessary for building proteins. According to the findings of field studies conducted in Virginia to determine the most effective herbicide between glyphosate and paraquat herbicide on a range of grass species, glyphosate alone controlled 94 to 98% of grass species 4 weeks after application [11]. Increased DM is consistent with the findings of [12] who found a substantial increase in forage biomass yield when herbicide was applied to switchgrass pastureland in the Central and Northern Great Plains. Similarly, ref. [13] reported that GLY and PAR herbicide application increased the dry matter yield of broadleaved plants and grasses. Furthermore, ref. [14] claimed that despite the fact that not all herbicides are capable of inducing a reaction, minimal amounts of herbicide chemicals may promote plant vegetative growth. However, ref. [15] discovered a reduction in forage dry matter on Turfgrass.

In this study, greater DM yield increases were recorded in the GLY treatment even though it was applied at a 50% recommendation rate, highlighting that the herbicide is efficient and economically viable for weed control. When treated at levels equal to a 5–10% field recommended rate, the herbicide GLY can provide a genuine boost in biomass growth of roughly 25% [16]. Generally, GLY is a post-emergence herbicide that gains an advantage for plants with delayed germination and growth. Also, the results indicated that Bendioxide decreased the DM yield during year 1 of herbicide application. It is worth noting that Bendioxide was applied at a 50% recommended rate for this treatment. Thus, the efficacy of this herbicide at this rate confers an economic advantage to farmers, as this means a decline in herbicide quantities to purchase. Bendioxide disrupts the plant's growth hormone regulation causing stunted growth and impairing photosynthesis and energy generation [17]. This ultimately compromises the plant's health, leading to mortality and a subsequent decline in dry matter yield. These results concur with [17] who showed that Bendioxide reduced Soyabean leaf area and leaf mass two weeks after the application. In addition, during the early growth stages, soybeans typically presented some injuries after two weeks of application of Bendioxide, but the crop managed to recover [18].

Likewise, HBE significantly reduced the DM yield during the first year. In agreement, [19] found that HBE controls a broad range of annual grasses. Furthermore, contrary to other broadleaf herbicides, HBE herbicides also control grassy weeds and have a direct effect on pasture legumes [20]. Comparing years, the second-year post-herbicide application produced the highest significant DM yield compared to the first year in all treatments. This could be attributed to the fact that herbicides reduced plant competition in the first-year post-herbicide application, allowing herbicide survivors or non-target plants to flourish and produce more seeds which contributed to the recruitment of new plants. Ref. [21] reported that weed control in pastures might even assist in enhancing pasture efficiency, which significantly increases productivity. These results could be ascribed to the fact that herbicides tended to reduce plant density, thereby reducing the number of plants that could contribute to overall yield.

4.2. Plant Density in Response to Herbicide Application

With regard to plant density, GLY and HAL herbicide application resulted in a significant decrease in grass density in May 2017. Grasses, forbs, and legumes were all affected by Glyphosate and Paraquat because they rely on the shikimic acid pathway for growth.

With the pathway disrupted by these herbicides, the plants cannot synthesize the necessary amino acids, leading to stunted growth, reduced photosynthesis, and ultimate mortality, leading to decreased plant density [21]. Essentially, glyphosate interferes with plants, e.g., photosynthesis hindering their nutrient and water uptake, thereby impairing their growth and development [22]. Consequently, reduced grass density might alter grazing patterns as animals may concentrate in areas with denser vegetation, leading to uneven utilization of pastures [23]. During November 2018, herbicide application caused a decline in grass density except for PAR and HAL. This finding could be attributed to the fact that the main function of herbicides is species–specific for many grasses and broadleaved forbs recorded in this study. Moreover, land recovery following cultivation abandonment is a slow process whose early successional stages, e.g., pioneers are vulnerable to herbicides [24]. For instance, ref. [25] reported that herbicide application early following abandonment reduces biomass and enhances grass mortality. In agreement with our findings, ref. [26] also found that GLY application resulted in a lethal effect on the growth and competitiveness of perennial grass species in semi-natural grasslands. Ref. [27] reported a decrease in Western Wheatgrass after Glyphosate herbicide was introduced to native grasses.

In a study conducted by [28], HAL reduced total grassy weed density by up to 85% after 30 days of planting and forb density was not significantly affected by the herbicide treatments. In this study also, the forb density was resistant to the applied herbicide throughout the experiment, whereas the legume density was adversely affected by the application of herbicide except HBE during May 2017. The resistance to herbicides is the greatest proof of forbs' exceptional ability to adapt under adverse circumstances [29,30]. Furthermore, herbicide-resistance genes are caused by arbitrary DNA mutations that confer an outstanding advantage in survival and reproduction and are thus swiftly chosen for and enriched in herbicide-treated weed populations [30,31]. A similar trend was noticeable in May 2018, except for BEN and PAR, and in November 2018, where herbicide application significantly reduced the legume density. This can be attributed to the fact that the morphological structure of legumes is more likely the same as that of weeds and most herbicides are manufactured to be weed-specific. All the herbicides used have the expected effect to control broadleaf plants and retard growth, respectively. In agreement, ref. [32] reported that herbicide treatments reduced the density of planted red clover, alfalfa, and white clover by more than 86% compared with control plots. Moreover, based on the herbicide and forage species used, spring planting after fall herbicide application can lead to decreased establishment and production efficiency [33]. Furthermore, ref. [34] reported that annual forage legumes were significantly injured by the application of herbicide. In May 2017, GLY, HBE, BEN, and HAL all significantly influenced the total density of plants. In November 2017, only HAL resulted in a significant decrease and BEN resulted in a significant increase in total density. In November 2018, all treatments yielded a significant increase in the total density of plants harvested during that period except the BEN treatment, respectively. Plant species have distinct responses to herbicide exposure, varying from no effect to finish growth inhibition, either permanently or temporarily [26,35]. Consequently, herbicide offset is anticipated to have an effect on competition between species by preventing some plant species from growing more than others [36]. Glyphosate spray drift had harmless but major implications, such as flower inhibition and damage to plants, and it was suggested that spray drift might have had long-term repercussions for ecosystems [37]. Conversely, the consequences of herbicide condensation on species composition are affected not only by the method of action of the compound, management, species pool, and specific traits but also by the range of the cropland field [38]. Furthermore, the small percentage of herbicide at a given distance from an arable field is affected by the herbicide-specific application method, wind direction and intensity, and distance to the last nozzle.

5. Conclusions

The research conducted found that applying herbicides to old lands established with pasture legumes affected plant density and forage production. The dry matter (DM) reaction to the various herbicide applications was positive, highlighting that herbicides are beneficial for the management of legume over-seeded pastures. However, the responses of plant density were not consistent across the herbicides applied. This highlights the importance of herbicide selection, and that herbicide selection should be weed-specific. Specifically, our results indicate that the application of Glyphosate and Haloxyfop-R methyl reduces grass density. Furthermore, none of the applied chemicals negatively influenced the legume density. Also, since the inception of the trial, plant densities continued to increase, this could be caused by the fact that plants may have established self-defense mechanisms to combat herbicide chemicals in order to survive, and treatment was carried out during the experiment's starting phase. Future studies need to be conducted on the effect of herbicide usage on soil mechanical and chemical properties and the quality of the forage produced. In addition, studies can focus on understanding the specific mechanisms through which herbicide treatments affect forage production. The findings could encourage a shift towards integrated weed management strategies.

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