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Effect of potassium application rate and timing on alfalfa yield and potassium concentration and removal in Tennessee

M. Pourebrahimi Foumani[1], H. Savoy[2], N. Atotey[3] and X. Yin[1,*]

[1]University of Tennessee, Department of Plant Sciences, West Tennessee Research and Education Centre, 605 Airways Blvd., Jackson, TN 38301-320, USA
[2]University of Tennessee, Department of Biosystems Engineering and Soil Science, 2506 E J. Chapman Dr, Knoxville, TN 37996, USA
[3]University of Tennessee, Department of Biosystems Engineering and Soil Science, West Tennessee Research and Education Centre, 605 Airways Blvd., Jackson, TN 38301-320, USA
[*]Correspondence: xyin2@utk.edu

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Abstract. Alfalfa (*Medicago sativa* L.) is the most important forage crop in the world and potassium plays a significant role in achieving high yields. A field experiment was conducted during the 2012–2014 growing seasons at the University of Tennessee in Springfield. The experimental design was a split-split plot that included four levels of potassium (K) application rates (0, 67.25, 134.50, and 269.00 kg K_2O ha^{-1}) as the main plots and two K application times (green-up and split) as the subplots, and harvest dates as sub-subplots. The results demonstrated that the dry matter yield (DM) increased significantly with each increment in K application rate up to 134.50 kg K_2O ha^{-1}; however, the highest K fertilizer application (269 kg K_2O ha^{-1}) did not result in a significant yield increase relative to 134.50 kg K_2O ha^{-1}, because some luxury consumption of K occurred at the highest rate due to yield leveling off while K_2O uptake continued to rise. Potassium concentration and K removal increased with K fertilizer at rates beyond those that maximized yield, indicating luxury consumption of K. The greatest K concentration and removal were recorded at 269 kg K_2O ha^{-1} in all harvest months. The split application was more beneficial than applying full K at the time of green-up due to higher dry matter, K concentration, and K removal in alfalfa. In conclusion, 134.50 kg K_2O ha^{-1} is adequate for maximizing alfalfa yield; split application of K is sometimes superior to the single dose of K fertilizer in alfalfa production.

Key words: concentration, dry matter yield, fertilizer, *Medicago sativa*, nutrient removal.

INTRODUCTION

Alfalfa (*Medicago sativa* L.), the ‘queen of forages’, is the premier legume forage and its yield depends on stand establishment, proper harvest times, and fertilization (Dordas, 2006).

Alfalfa has a deep and extensive rooting system that improves soil structure, soil fertility, and soil organic matter content (Bourgeois et al., 1990). An adequate supply of nutrients is important for maintaining high alfalfa forage quality and profitable yields (Moreira et al., 2008). A low potassium level in the soil can result in increased winterkill of alfalfa plants (Jungers et al., 2019). Potassium fertilizer application increases plant K uptake and forage yield if soil test K levels are deficient (Jungers et al., 2019). Potassium uptake by plant is affected not only by the source and application rate, time, and placement of K fertilizer, but also by soil properties (if the fertilizer is applied to soil) and weather conditions including temperature and rainfall. Most of K fertilizers are water soluble and immediately available for plant to take up (Morgan & Connolly, 2013).

Alfalfa has an extremely high requirement for K. It removes more K than any other minerals over time due to high yields or under-intensive alfalfa production (Koenig et al., 2006). Under these conditions, sound K fertility management is essential (Berg et al., 2007). The amount of K fertilizer required depends on the existing level of K in the soil, the tonnage of alfalfa removal from the previous year, and the related soil chemistry (Wolde, 2016). Potassium has a crucial role in alfalfa growth and reproduction and physiological processes within the plant (Lu et al., 2018). Adequate K nutrition increases the long-term productivity and stands longevity of alfalfa (Berg et al., 2007).

Potassium content in crops depends on soil type (if the fertilizer is applied to soil), crop species, doses of K fertilizer, and weather conditions (Askegaard et al., 2004; Khajbullin et al., 2020). Alfalfa can show 'luxury consumption' of K when plants are taking up more K than needed to maximize yield (Macolino et al., 2013). This can lead to a reduction in protein, Ca, Mg, and Na (Pant et al., 2004). As a result, increased K application does not always lead to higher yield (Berg et al., 2018). Split applications of K can lower the risk of alfalfa plants over-consume available K and are considered more effective than a single application of K (Kafkafi et al., 1977).

The effect of harvest time on yield, quality, and profitability of alfalfa may be more important than cultivar choice and other management practices (Orloff & Putnam, 2006). In alfalfa production, yield and quality are inversely related, so if it is harvested at the early maturity growth stages, the level of forage quality increases but the yield decreases (Lamb et al., 2006; Brink et al., 2010). The quality of alfalfa is increased by decreasing cutting intervals (Rimi et al., 2012). However, repeated harvesting of undeveloped alfalfa may lead to reduced yield and plant viability (Kallenbach et al., 2002).

There was inadequate information on K management for maximum alfalfa yield in Tennessee (TN) of the United State (the Mid-South region of the United States). The objectives of this study were to: 1) determine the sufficient and accurate K rate recommendations for alfalfa in TN, 2) evaluate the effects of splitting K applications on alfalfa yield in TN soils.

MATERIALS AND METHODS

A field experiment was conducted at the Highland Rim AgResearch and Education Center of the University of Tennessee in Springfield, Tennessee, United States (N 36° 30' 33.1632", W 86° 53' 5.9928") from 2012 through 2014. The annual average air temperature and precipitation for the area are 15.22 °C and 1,234.44 mm, respectively. Mean monthly temperatures and precipitation for 2012 to 2014 are presented in Table 1. Springfield's climate is classified as warm and temperate. The climate is classified as Cfa by the Köppen-Geiger system.

Table 1. Monthly average air temperature and precipitation and their 30-year means (1984–2014) in Springfield, TN, United States

	Precipitation (mm)				Temperature (°C)			
Months	2012	2013	2014	30-year mean	2012	2013	2014	30-year mean
January	115.3	169.4	81.0	99.8	5.2	3.7	-1.8	1.7
February	40.4	66.0	169.2	104.9	6.2	3.8	1.5	3.7
March	141.2	128.3	95.0	116.3	15.7	4.9	5.9	8.5
April	71.6	248.9	150.4	122.4	15.2	13.4	15.5	13.9
May	200.2	169.9	55.4	138.4	21.5	18.5	20.6	18.6
June	31.0	88.6	67.8	102.9	23.3	23.6	24.9	23.3
July	187.2	230.1	72.4	108.2	27.6	23.4	24.0	25.2
August	77.2	139.7	143.5	82.8	24.1	23.9	25.9	24.7
September	120.4	124.2	30.0	92.7	20.4	21.6	21.5	20.8
October	96.5	83.6	206.2	96.5	13.9	15.3	15.6	14.5
November	36.3	111.3	70.4	104.6	7.4	6.8	5.0	8.8
December	194.6	109.7	79.2	119.4	7.2	4.0	4.8	3.6

The soil series was staser loam soil (Fine-loamy, mixed, active, thermic Cumulic Hapludolls), having a loam texture. The composite soil sample was collected from 6 random locations within each sub-subplot (15.24 cm-depth) using a 1.9-cm steel soil probe for fertility assessment for three years (2012, 2013, and 2014). The samples were dried in a forced-air oven at 60 °C prior to analysis and their final values were reported on a kg ha^{-1} basis. Potassium, calcium, magnesium, and phosphorus were extracted with Mehlich-1 and determined using Inductively Coupled Argon Plasma spectroscopy (ICAP) (Mehlich, 1953) (Table 2).

Table 2. Selected soil properties for the surface 0 to 6-inch layer at the study site in 2012, 2013, and 2014

Year	K rate (kg K_2O ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	P (kg ha^{-1})
2012	0	60.75	45.61	1,767.02	100.54
	67.25	62.20	50.10	1,748.52	91.90
	134.50	56.60	61.08	1,875.40	96.39
	269.00	64.44	113.99	1,760.52	102.55
2013	0	67.81	51.22	3,115.62	133.60
	67.25	63.88	57.38	2,967.42	124.97
	134.50	51.22	65.56	3,247.10	127.44
	269.00	50.99	97.73	2,875.54	116.23
2014	0	77	74.53	2,754.15	122.73
	67.25	61.64	61.08	3,053.19	124.41
	134.50	62.43	76.21	2,480.44	118.24
	269.00	75.65	83.16	2,578.51	121.05

The experimental area consisted of a split-split plot design with four replications. The same plots were evaluated from 2012 through 2014. The entire plot area was seeded with alfalfa (Cropland Consistency 4.10 RR) with 8 inches between rows in April of 2012. The experiment consisted of four levels of K application rates (0, 67.25, 134.50, and 269.00 kg K_2O ha^{-1}) as the main plots and two timings of K application [Green-up (this stage began when the crown buds started to grow in response to warmer temperatures during the spring) and split] as the subplots and harvest dates were the sub-sub plots. Potassium fertilizer was K oxide (K_2O, containing 83% K). The K fertilizer was broadcast applied by hand on the soil surface, and all amounts of K fertilizer were split and brodcast to each designated plot. The phosphorus (134.50 kg ha^{-1} P_2O_5) and boron (1.12 kg ha^{-1} B) were applied each spring at green-up. Sub-subplots measured 3-m ×3-m with the middle 1-m ×3-m harvested. Alfalfa yield estimates were determined from center harvest strips with a carter harvester (Carter Manufacturing Company). The crop was harvested at pre-bloom of each year (approximately 30-d between each harvest) (Table 3).

Table 3. Harvest dates at Springfield from 2012 to 2014

Year	First cut	Second cut	Third cut
2012	July	August	September
2013	May	Jun	July
2014	May	Jun	July

Crop measurements included DM, tissue K concentration, and subsequent calculation of K removal. To determine the crop measurements, grab samples of about 1.1 to 2.2 kg ha^{-1} were taken from every sub-subplot and dried in an air-forced oven at 60 °C for 72 hours then samples were ground and prepared for lab analysis. Alfalfa tissue K concentration was determined with nitric acid digestion and Inductively Coupled Plasma (ICP) spectrometry analysis of the diluted digest. For nitric acid digestion of the sample, 5 mL of 65% HNO_3 was added, and then the mixture was boiled gently over a water bath (90 °C) for 1–2 h or until a clear solution was obtained. Later, 2.5 mL of 65% HNO_3 was added, followed by further heating until total digestion (Zheljazkov & Nielson, 1996). Potassium removal by the plant was calculated by dividing the percent elemental nutrient concentration by 100 and multiplying the quotient by the DM (Murrell, 2008):

$$\text{K removal (kg } K_2O \text{ ha}^{-1}) = \text{DM (kg ha}^{-1}) \times [(\text{K concentration}(\%)) / 100] \times 1.20$$

The data were subjected to analysis of variance using the Proc Mixed Model procedure of SAS 9.4 (SAS Systems Inc., Cary, NC) to determine the effects of K rate, the timing of K application harvest time, and their interactions. In the Proc Mixed Model, K rate, the timing of K application, harvest time, and their interaction were considered as fixed effects, while the replicates were set as random effects. The means were separated with the Fisher's protected Least Significant Difference (LSD) method at the 0.05 significance level.

RESULTS AND DISCUSSION

Dry Matter Yield: The analysis of variance for DM showed significant K rate and harvest time effects for all years, but no significant timing of K application effects was observed; on the other hand, the two-way interaction between timing of K application and harvest time was found significant for DM in 2013 (Table 4). The greatest mean DM was observed for the second harvest date (3.83 ton ha^{-1}), while the third harvest resulted in the lowest mean DM yield (2.44 ton ha^{-1}) averaged across all years (Table 5). Third-cut forage generally has lesser digestibility and intake than first and second-cut forage. Under warmer conditions, greater amounts of energy are used to produce cell well components and reproductive tissue, resulting in less digestibility and lower intake potential (Atis et al., 2019).

Table 4. Results of analysis of variance for effects of K rates, K timing, and harvest time on alfalfa DM yield, tissue K concentration, and K removal

		Yield			Tissue K concentration			K removal		
Sources	Df	2012	2013	2014	2012	2013	2014	2012	2013	2014
R	3	0.55^{**}	0.20^{**}	0.32^{**}	0.32^{**}	0.37^{ns}	0.39^{**}	$1,656.15^{**}$	$1,668.89^{**}$	$2,048.20^{**}$
H	2	1.43^{**}	4.98^{**}	13.18^{**}	7.84^{**}	1.56^{**}	0.38^{*}	$5,989.19^{**}$	$11,039.70^{**}$	$29,905.57^{**}$
Error a	6	0.03^{ns}	0.05^{ns}	0.07^{ns}	0.04^{ns}	0.13^{ns}	0.10^{ns}	90.15^{ns}	283.58^{ns}	194.76^{ns}
K	3	0.13^{**}	0.29^{**}	1.22^{**}	4.17^{**}	7.31^{**}	4.16^{**}	$2,848.25^{**}$	$19,738.57^{**}$	$15,875.96^{**}$
H × K	6	0.007^{ns}	0.04^{ns}	0.01^{ns}	0.13^{*}	0.57^{*}	0.30^{**}	132.89^{ns}	$1,385.65^{**}$	$1,479.67^{**}$
Error b	27	0.03^{**}	0.06^{*}	0.06^{ns}	0.04^{ns}	0.20^{ns}	0.05^{ns}	49.10^{ns}	494.7^{ns}	142.48^{ns}
T	1	0.04^{ns}	0.02^{ns}	0.28^{*}	0.26^{*}	0.09^{ns}	1.19^{**}	394.74^{*}	$1,005.14^{ns}$	$3,767.33^{**}$
H × T	2	0.01^{ns}	0.18^{**}	0.07^{ns}	0.009^{ns}	0.50^{ns}	0.04^{ns}	25.67^{ns}	899.07^{ns}	62.65^{ns}
K × T	3	0.02^{ns}	0.04^{ns}	0.04^{ns}	0.01^{ns}	0.28^{ns}	0.24^{*}	15.84^{ns}	64.21^{ns}	566.81^{ns}
H × K ×T	6	0.009^{ns}	0.02^{ns}	0.01^{ns}	0.007^{ns}	0.35^{ns}	0.12^{ns}	14.40^{ns}	859.78^{ns}	115.82^{ns}
Error	36	0.01	0.03	0.06	0.04	0.17	0.07	69.58	364.84	311.97

Note. Values in this table are mean squares. Replication (R), Harvest time (H), K rates (K), Timing of K application (T). * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. ns, not significant.

The DM yield of alfalfa was not significantly different between 134.50 and 269 kg K_2O ha^{-1} (Table 5). On average, fertilized plots had a higher DM yield than unfertilized plots, so that, the DM yield was about 24% higher at 269 kg K_2O ha^{-1} than the unfertilized plots (Table 5). The reduced yield in the unfertilized plots in the third year seemed to have been due to the association of no K application resulting in low K content in the soil, as often reported that alfalfa yield depends on soil K fertility (Berrada & Westfall, 2005). The results of Buskiene & Uselis (2008) studies revealed that when the rate of K fertilizers was increased from 90 to 240 kg ha^{-1}, K content in the soil increased to 33%. These yield changes provided a good opportunity to measure the effect of K fertility on alfalfa yield. Our findings confirm the results of other studies, that reported a positive influence of K on alfalfa yield (Lutz, 2008; Lioveras et al., 2001).

Table 5. Mean DM yield affected by K rates and harvest time

Treatments	DM yield (ton ha^{-1})			Average
Harvest date	2012	2013	2014	-
First cut	1.70 b	3.85 b	3.21 b	3.31b
Second cut	2.28a	5.02 a	5.40 a	3.83a
Third cut	1.34c	3.29 c	2.69 c	2.44c
K rate (kg K_2O ha^{-1})				
0	1.63b	3.69b	3.11c	2.80c
67.25	1.68b	4.07a	3.63b	3.11 b
134.50	1.79ab	4.23a	4.10a	3.36 a
269.00	1.99a	4.21a	4.25a	3.47 a

Note. Within a column, means followed by the same letter are not significantly different according to *LSD* (0.05).

Dry Matter yield versus K_2O uptake: Application of high rates of K fertilizer to achieve maximum yields will result in luxury consumption of potassium. The results of the present investigation revealed that some luxury consumption of K occurred at the highest K rate due to yield leveling off while K_2O uptake continued to rise (Fig. 1). The continuing rising K removal seemed to indicate that alfalfa takes up excessive K without increasing DM yield. Therefore, large amounts of K should not be applied to alfalfa as a single dose during the growing season. Our results suggest that a K rate of

134.50 kg ha^{-1} is adequate for maximizing alfalfa yield; higher K rates will not significantly increase yields (Fig. 1).

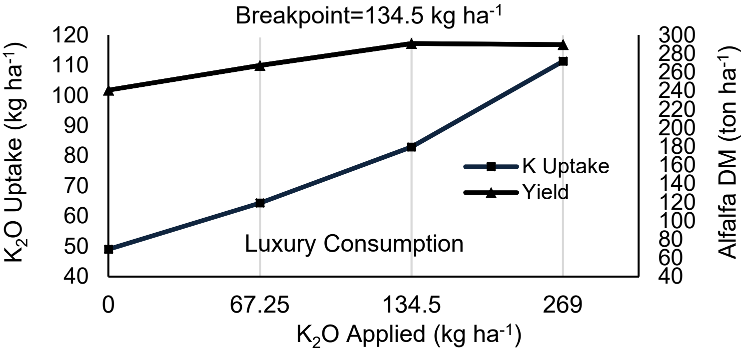

Figure 1. Impact of K rate on DM yield in Springfield, TN from 2012 through 2014.

When K concentration in the soil increases, alfalfa will take up K in proportion to the K concentration in the soil, much higher than the K amount needed for normal growth and development of the crop. This process is often referred to as luxury K consumption. Luxury K consumption often leads to excessive-high K concentration in plant tissues, increased K removal from the field, and reduced economic return (Murrell et al., 2021). Luxury consumption of K by alfalfa confirmed that the yield of alfalfa with K application is improved only to a certain point, after which yield does not increase with additional K fertilizer application (Lioveras et al., 2001; Berg et al., 2018). The result of research by Loide (2004) indicated that as the potassium content increases further, the yield of red clover and ryegrass begins to decrease.

Timing of K Application on DM Yield: The K application time had a significant effect on DM yield only in 2014 (Table 4). The results indicated that split application was more beneficial than applying full K at the time of green-up in terms of DM in one out of three years. The DM yield was around 7% higher in the split application than that under the single application (Table 6). The split application reduces the soil fixation of K and favors the uptake of K during the entire growing season, thereby increasing the yield (Annadurai et al., 2000). Consumption of K rate in split dose reduces competition between microorganisms and plants, luxury consumption, leaching losses, and K fixation processes at the critical plant growth stages (Lu et al., 2014).

Table 6. Mean DM yield, tissue K concentration, and K removal affected by the timing of K application

Timing of K application	Parameters	2012	2014	Average
Green-up	Yield (ton ha^{-1})	-	4.02 b	-
Split		-	4.29 a	-
Green-up	K concentration (%)	1.49 b	1.54 b	1.51 b
Split		1.60 a	1.76 a	1.68 a
Green-up	K removal (kg ha^{-1})	32.03 b	71.67 b	51.85 b
Split		36.58 a	85.71 a	61.01 a

Note. Within columns, means followed by the same letter are not significantly different according to *LSD* (0.05).

Timing of K Application on K Concentration and Removal: The tissue K concentration and removal were significantly affected by the timing of K application in 2012 and 2014 (Table 4). The split application recorded 11% and 18% higher K concentration and K removal than the green-up single application, respectively (Table 6). The continuous supply of K through split application results in higher availability of applied K to the plant (Anji et al., 2018, Sharma & Singh, 2021). The K use efficiency in the split application of K fertilizer is higher than its single application due to the reduction in leaching losses and luxury consumption of K (Tandon & Sekhon, 1988). The benefits of the split application may also be contributed to higher soil buffering capacity with less K fixation (Römheld & Kirkby, 2010; Wani et al., 2014). Split application of K has improved K availability during the growing season, which contributes to better plant metabolic activities, resulting in K uptake and higher yield (Tariq & Shah, 2002; Sheng et al., 2004).

Interactions of K Rates and Harvest Time on Tissue K Concentration and Removal: The interactive effects of K rates and harvest time were significant on both tissue K content and K removal in all three years except K removal in 2012 (Table 4). Potassium concentration for the whole plant increased with increasing K fertilization rates, ranging from 0.71% for the unfertilized treatment in 2012 to 3.46% for the 269 kg K_2O ha^{-1} treatment in 2013 (Fig. 2). Higher application rates of K increased K concentration in forage (Fig. 2).

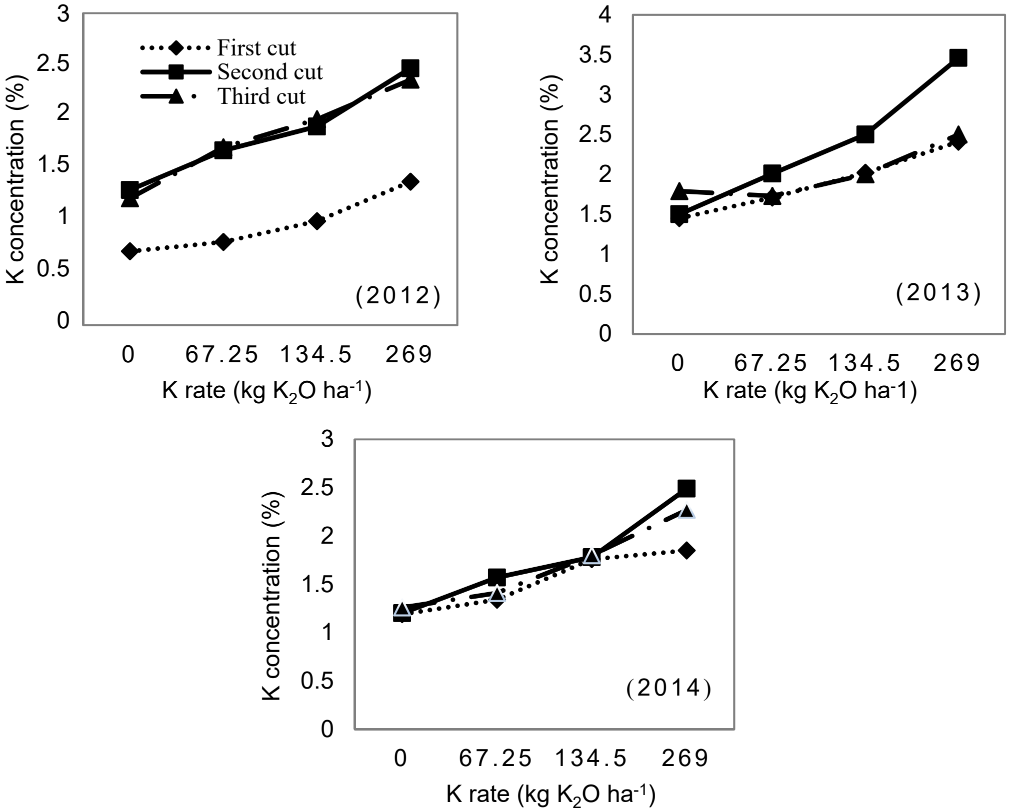

Figure 2. Effects of K rates and harvest time on tissue K concentration in 2012, 2013, and 2014.

Increases in the concentration of alfalfa K with increasing K fertilization have been reported frequently (Snyder & Leep, 2007; Jungers et al., 2019). The increase of K concentration in alfalfa in response to high K_2O application levels may be explained by the luxury consumption of this nutrient (Pant et al., 2004; Snyder & Leep, 2007).

The highest and lowest concentrations of K in plants were observed in the second and third cut in all years, respectively. In 2012, 2013, and 2014, the tissue concentration of K in third cut was 90%, 130%, and 107% higher at the rate of 269 kg K_2O ha^{-1} than those with the unfertilized plots, respectively (Fig. 2). Generally, second cut harvesting resulted in greater K concentration in the biomass than first cut harvesting (Fig. 2). The total 2-yr amount of K removal by harvest increased with increasing K rates (Fig. 3).

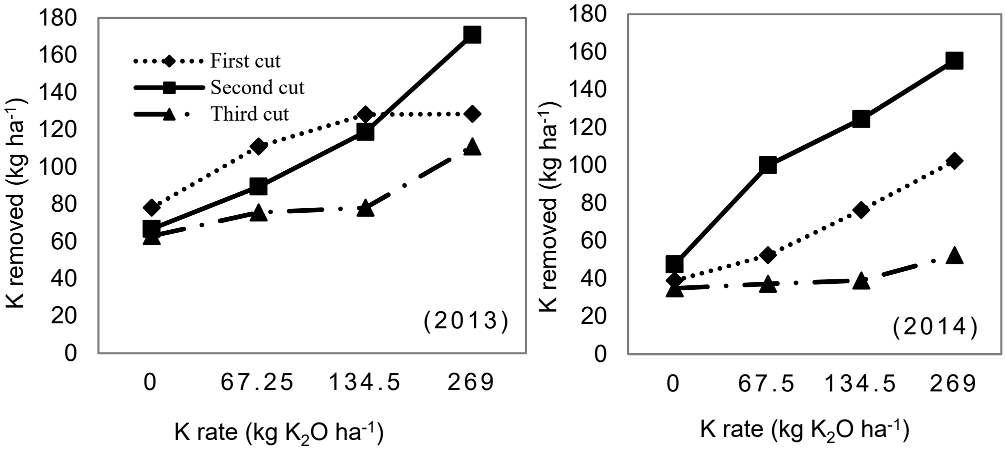

Figure 3. Effects of K rates and harvest time on K removal in 2013 and 2014.

The 2-yr removal of K varied between 34.83 kg ha^{-1} for the unfertilized treatment to 174.11 kg ha^{-1} with the application of 269 kg K_2O ha^{-1} in 2014. The highest value of K removal was recorded with 269 kg K_2O ha^{-1}in the second cut in 2013 and 2014, respectively (Fig. 3).

CONCLUSIONS

The forage concentrations of K were lower from plots unfertilized than those fertilized with 134.50 and 269 kg K_2O ha^{-1}. Meanwhile, in the K-applied plots, K concentration in the forage depended on harvest time and was much higher in the second cutting than in the first cutting. Potassium positively influenced alfalfa yield but should not over-apply K, because plants could engage in luxury consumption, leading to increased tissue K concentrations. The split application of K significantly affected dry matter yield, tissue K concentration, and K removal. The results of the three-year experiment suggest that 134.50 kg K_2O ha^{-1} is adequate for maximizing alfalfa yield; split application of K is sometimes superior to the single dose of K fertilizer in alfalfa production.

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