Alfalfa Yield Components and Soil Potassium Depletion as Affected by Potassium Fertilization

Jaume Lloveras,* Cristina Chocarro, Lluis Torres, Denis Viladrich, Ramon Costafreda, and Francisca Santiveri

ABSTRACT

Potassium fertilization recommendations for alfalfa (*Medicago sativa* L.) vary depending on the area of production, soil levels, and crop management. The objectives of this study were to determine the impact of K fertilization on irrigated alfalfa yield, yield components, and soil exchangeable K (K_e) values in a Mediterranean climate. A field experiment was conducted during a period of 4 yr (2002–2006) in Spain, on a soil with moderate levels of K_e (161 mg K kg^{-1}). The treatments applied were five annual rates of K (0, 100, 200, 300, and 400 kg K ha^{-1}). Total 4-yr dry matter (DM) yields averaged 74.9 Mg ha^{-1} without differences between K fertilizer rates, although the unfertilized control produced the lowest DM yields. The 4-yr crop uptake of K reached 1738 kg ha^{-1} with the application of 400 kg K ha^{-1} yr^{-1}, and 756 kg K ha^{-1} for the 0 K fertilization. The removal was greater than the K applied. The results suggest that large amounts of K should not be applied to alfalfa because the crop uses excess K without increasing yield. Soil K_e concentrations decreased every year for all K rates except for the highest treatment of 400 kg K ha^{-1} yr^{-1}. Lack of K fertilization did not affect stand density but the shoot weight was the yield component most closely related to K fertilization.

Intensive agricultural cropping systems and practices require large quantities of plant nutrients, and alfalfa production generally results in a significant depletion of soil K reserves because of the extremely high crop requirements for this nutrient (Lanyon and Smith, 1985). Under these conditions, sound K fertility management is essential. Potassium is required to maximize alfalfa yields, but the manner and the yield components associated with K-induced variation in agronomic performance remains unclear. Studies have shown that increased forage yields obtained with K fertilization of alfalfa were mainly the result of increased mass per shoot (Berg et al., 2005, 2007). This fact seems to contrast with the long-held and popular belief that the increased alfalfa yields with the addition of fertilizers are associated with stand longevity (Smith, 1975).

Many K fertilization recommendations are based on K soil tests; however, exchangeable levels of soil K (K_e) vary with area and yield levels. According to Zebarth et al. (1991), crop yield response to K fertilization tends to vary dramatically between sites and years, making routine interpretation of the data difficult. For example, in different areas of the United States, K_e test levels of 60 to 125 mg kg^{-1} are considered appropriate for alfalfa depending on the soil type, whereas K_e above 125 mg kg^{-1} is considered high (Davis et al., 2005; Kelling, 2000). In the irrigated areas of the Ebro valley (Spain), the normal K_e contents for a good crop are considered to be between 125 and 250 mg kg^{-1}, whereas levels below 125 mg kg^{-1} are considered low (Piñeiro et al., 2010). According to Berrada and Westfall (2005), the response of alfalfa to K and P often varies with growing conditions, soil type, initial soil test K and P levels, irrigation, harvest management, and yield level. Havlin et al. (1984), in Colorado, reported that when soil test K levels remained high, no K fertilization was necessary unless there would be a direct economic benefit from improved alfalfa forage quality. They found that K accumulation was significantly increased by K fertilization due to a lower level of exchangeable K.

The increase in the price of fertilizers in recent years has made alfalfa producers reconsider the use of this element. Furthermore, nutrient buildup and the maintenance of high soil test levels may not be economically desirable, and drawing down soil K reserves may be economically viable in the short term (Havlin et al., 1984; Mallarino et al., 1991). Research involving applications of K for alfalfa has mainly been conducted in the northeastern and midwestern regions of the United States. These are areas in which dormant and semidormant alfalfa cultivars are grown, with typical annual DM yields ranging from 10 to 17 Mg ha^{-1}, and with three to four harvests per season (Smith, 1975; Rominger et al., 1976; Sheafler et al., 1986; Berg et al., 2005).

Data from these trials show that responses to K applications varied with production practices, growing conditions, and soil K_e levels. The observed responses ranged from no DM yield response, which was associated with the application of 300 kg K ha^{-1} and a soil test level of 75 mg K kg^{-1} (Lutz, 1973), to a maximum with the application of 448 kg K ha^{-1} to a soil with a K_e level of 55 mg K kg^{-1} (Rominger et al., 1976). These studies have also shown that applications of K tend to increase plant and soil K concentrations.

Centre Universitat de Lleida (UdL)-IRTA, Av. Rovira Roure 191, 25198 Lleida, Spain. *Corresponding author (jaume.lloveras@irta.cat).

Received 9 Sept. 2011.

Published in Agron. J. 104:729–734 (2012)
Posted online 9 Mar. 2012
doi:10.2134/agronj2011.0293

Abbreviations: DM, dry matter; K_e, soil exchangeable potassium.

To date, research from other geographical areas remains scarce, and limited data are available regarding K fertilization in irrigated, high-yielding, Mediterranean environments and in areas with long growing seasons. These areas typically have alfalfa dormancy ratings of 8 and 9 and crop yields of 20 to 25 Mg ha^{-1} yr^{-1} under irrigation (Dovrat, 1993; Kafkafi et al., 1977; Lloveras et al., 1998). In Mediterranean areas of southern Europe, the present recommendations of between 200 and 350 kg K ha^{-1} yr^{-1} are based normally on the amounts of K removed by the crop (Le Gall et al., 1992). Because alfalfa can remove large amounts of K in intensive production systems, there is interest in knowing more about the response of alfalfa to K fertilization in areas with high forage yields (Lanyon and Smith, 1985).

The objectives of this study were to determine the impact of K fertilization on alfalfa forage yield, yield components and their relationships, plant nutrient uptake, and soil K_e depletion in irrigated production systems with a high potential for forage production and moderate soil K_e levels under a Mediterranean climate.

MATERIALS AND METHODS

The experiment was conducted under irrigation from 2002 to 2005 at the University of Lleida (UdL)-Institut de Recerca i Tecnologia Agroalimentàries (IRTA) research station in Gimenells, Spain (41°45′ N, 0°30′ E). The average air temperature and rainfall for the area are 16.0°C and 345 mm, respectively. Mean monthly temperatures and rainfall for the 2002 to 2005 growing seasons are presented in Table 1. The climate is typically Mediterranean, with mild winters and hot, dry summers.

The soil was a Petrocalcic Calcixerept (Bellvis series) (Soil Survey Staff, 1999), which is representative of many areas of the Ebro valley. An analysis of a composite sample (depth 0–30 cm) collected from the experimental site revealed that the soil plow layer had a loam texture with 405 g kg^{-1} sand, 351 g kg^{-1} silt, 244 g kg^{-1} clay, 35 g kg^{-1} organic matter, $CaCO_3$ equivalent to 220 g kg^{-1}, a pH of 8.0, and a cation exchange capacity of 11.3 cmol kg^{-1}. The average initial K_e (NH_4OAc method), available P (Olsen method), and Mg (NH_4OAc method) were 161, 37, and 134 mg kg^{-1}, respectively. One of the reasons for selecting this site for the study was that soil tests of K_e (161 mg kg^{-1}) indicated normal to moderate concentrations of K_e for our area (Piñeiro et al., 2010). An estimation of the mineral content of the clay fraction based on x-ray data showed that illite was the dominant mineral (illite 75%, chlorite 14%, and kaolinite 11%). Soil exchangeable K and P were monitored at the beginning of each growing season (end of January), before annual fertilization, and at the end of the trial, in January 2006, by sampling the soil in 30-cm increments to a depth of 90 cm. Two core composites were taken from the central strip of each plot for each depth increment. The experimental field was seeded on February 2002 at a rate of 27 kg ha^{-1} of pure live seed and in rows 20 cm apart. The plot size was 4.5 by 7 m. The cultivar sown was Aragón (dormancy rate 8), which was chosen because it is the most common cultivar grown in Spain, being cultivated in >80% of the area under alfalfa (Alvaro and Lloveras, 2003). The previous crop was bread wheat (*Triticum aestivum* L.).

The K fertilizer treatments consisted of five annual rates of 0, 100, 200, 300, and 400 kg K ha^{-1} (K0, K100, K200, K300, and K400, respectively), without incorporation. Fertilizer treatments, applied as KCl following initial preplant applications, were topdressed in winter (end of January). The crop also received an annual application of 87 kg P ha^{-1}, topdressed in winter.

Weeds were controlled using herbicides. Benfluralin [(*N*-butyl-*N*-ethyl-2,6-dinitro-4-(trifluoromethyl) benzenamine] was applied (10 mL L^{-1}) at a rate of 1.15 kg a.i. ha^{-1} prior to alfalfa seeding, while hexazinone [(3-cyclohexyl-6-dimethylamino-1-methyl-1,3,5-triazine-2,4(1*H*,3*H*)-dione] was applied (90 mL L^{-1}) at a rate of 1 kg a.i. ha^{-1} to dormant alfalfa in January of each year. Insect control consisted of one to three sprayings per year of 0.1 kg a.i. ha^{-1} fenvalerate [cyano(3-phenoxyphenyl)methyl 4-chloro-α-(1-methylethyl) benzeneacetate] (15 mL L^{-1}) when necessary. Plots were irrigated every 10 to 15 d from April to September with a total of about 800 mm of irrigation water applied during each season.

Alfalfa yields were determined by harvesting a central, 1.5-m-wide strip, with a Haldrup small-plot harvester. The crop was harvested six to seven times per year, depending on the year and climatic conditions. The first harvest was done at the middle to end of April, while the last harvest was performed by mid-October. Except in the establishment year, in which the crop was harvested only three times, there was an interval of about 30 d between harvests.

The alfalfa was harvested near 100% flowering (Stage 6) (Kalu and Fick, 1983), except for the first and last cuttings, in which the alfalfa did not flower because of the temperature and photoperiod. The initial seedling density was determined by counting the number of plants at the first trifoliate leaf stage in two 0.5-m-long central rows in each plot. In the last year of the trial (2005), the stand density was evaluated in February.

The stand density was then determined by digging up the plants in one of the central rows of each plot and counting the number of plant crowns in 0.5 m. At each harvest, the number of shoots was measured by cutting all of the shoots contained in a 50-cm length of one of the central rows just before harvest. These shoots were then taken to the laboratory, where they were counted. Fifteen of these shoots were used to determine the shoot weight.

Table 1. Mean monthly air temperature (T_m) and total monthly rainfall at Gimenells from 2002 through 2005 during the alfalfa growing cycle. Long-term (30-yr) mean annual temperature and rainfall at Gimenells are 16.0°C and 345 mm, respectively.

	2002		2003		2004		2005	
Month	T_m	Rainfall	T_m	Rainfall	T_m	Rainfall	T_m	Rainfall
	°C	mm	°C	mm	°C	mm	°C	mm
Feb.	8.0	4.2	5.7	70.6	4.7	50.6	4.1	8.6
Mar.	11.6	14.7	10.9	30.5	8.3	37.4	9.3	9.2
Apr.	13.0	40.8	13.4	25.9	11.6	61.1	13.7	7.2
May	16.2	52.7	17.6	62.5	15.8	40.8	18.4	53.1
June	22.1	35.0	24.9	15.1	22.6	7.6	23.2	13.1
July	23.0	20.3	25.1	2.0	23.1	49.8	24.5	18.5
Aug.	21.7	17.7	25.9	38.0	23.7	6.0	22.4	20.9
Sept.	18.6	38.0	19.3	101.5	20.6	18.5	19.3	28.6
Oct.	14.6	41.0	13.9	71.2	16.1	31.0	15.8	82.0
Annual mean temperature or total annual rainfall	16.5	264	17.4	417	16.3	344	16.7	241

To determine the DM concentration, the whole stems were dried at 65°C for 48 h. The average number of shoots per square meter and the shoot weight per harvest, per plot, and per year were used for the statistical analyses. Another 300-g sample of green herbage was collected from each plot at each harvest to determine the DM concentration of the plot and carry out chemical analyses. The DM concentration of the herbage was calculated by drying the samples at 65°C for 48 h. Ground (1-mm screen) plant tissue samples were analyzed for nutrients.

Total N was analyzed by a conventional Kjeldahl method. Potassium was analyzed by inductively coupled argon plasma spectrophotometry (Polyscan 61E) after using HNO_3 to digest the calcinated plant ashes (Mills and Jones, 1996, p. 116–124). The annual weighted averages of the mineral concentrations were used for the statistical analyses.

The experiment was arranged in a randomized complete block design with four replications and analyzed as a split plot in time (Steel and Torrie, 1980). The results were subjected to an analysis of variance using the General Linear Model procedure of SAS (SAS Institute, 1988). Year and K application rate were the class variables, and the K treatment effects were partitioned into polynomial contrasts. The least significant differences (LSD, $P = 0.05$) were calculated to separate the means. Pearson correlation coefficients were calculated between DM yields and number of shoots per square meter and shoot weight for each year by using the Proc Corr procedure (SAS Institute, 1988).

RESULTS AND DISCUSSION

Dry Matter Yields

Potassium fertilization increased alfalfa DM yields in two (2003 and 2005) of the 4 yr (Table 2), although the total 4-yr DM yields did not show significant differences with respect to K fertilizer rates.

Annual fertilization rates of 100 kg K ha^{-1} were sufficient for producing the maximum annual and 4-yr total DM yields, suggesting that the initial (K_e) levels of 161 mg kg^{-1}, with annual maintenance levels of about 100 kg K ha^{-1}, are sufficient to maximize the 4-yr DM production.

Table 2. Alfalfa dry matter yield response to K fertilization.

K rate	2002	2003	2004	2005	Total (2002–2005)
kg ha^{-1}			Mg ha^{-1}		
0	9.8	23.4	19.6	18.6	71.5
100	11.0	25.4	19.9	19.9	76.4
200	10.1	24.7	19.3	20.7	74.8
300	9.3	24.8	20.9	20.9	75.9
400	10.7	24.3	20.0	21.0	76.2
Avg.	10.2	24.5	19.9	20.2	75.0
Significance†	ns	*	ns	*	ns
LSD(0.05)‡	–	1.1	–	1.5	–
			Contrasts		
Linear	ns	ns	ns	*	ns
0 vs. others	ns	**	ns	**	*

* Significant at the 0.05 level; ns, not significant.

** Significant at the 0.01 level.

† Year and K rate main effects and the Year × K rate interaction for the period (2002–2005) were significant at the 0.01 level.

‡ LSD(0.05) value for the year effect is 0.55 Mg ha^{-1}.

The yield decrease in the fourth year in the 0K treatment seems to have been due to an association of the absence of K applications with low K_e contents in the upper 30 cm of the soil (Fig. 1). As frequently reported, alfalfa yields depend on the K_e content of the soils (Kafkafi et al., 1977; Havlin et al., 1984; Berrada and Westfall, 2005).

Yield Components

The stand density at the beginning of the trial was 412 plant m^{-2}, which decreased to an average of 63 plant m^{-2} in the fifth year of production, with no differences observed among K fertilization treatments. These results suggest that even if the DM yields during some years were affected by K application, it was not due to a negative effect on the alfalfa stand.

Several studies have reported that appropriate K nutrition is generally thought to promote plant persistence and stand

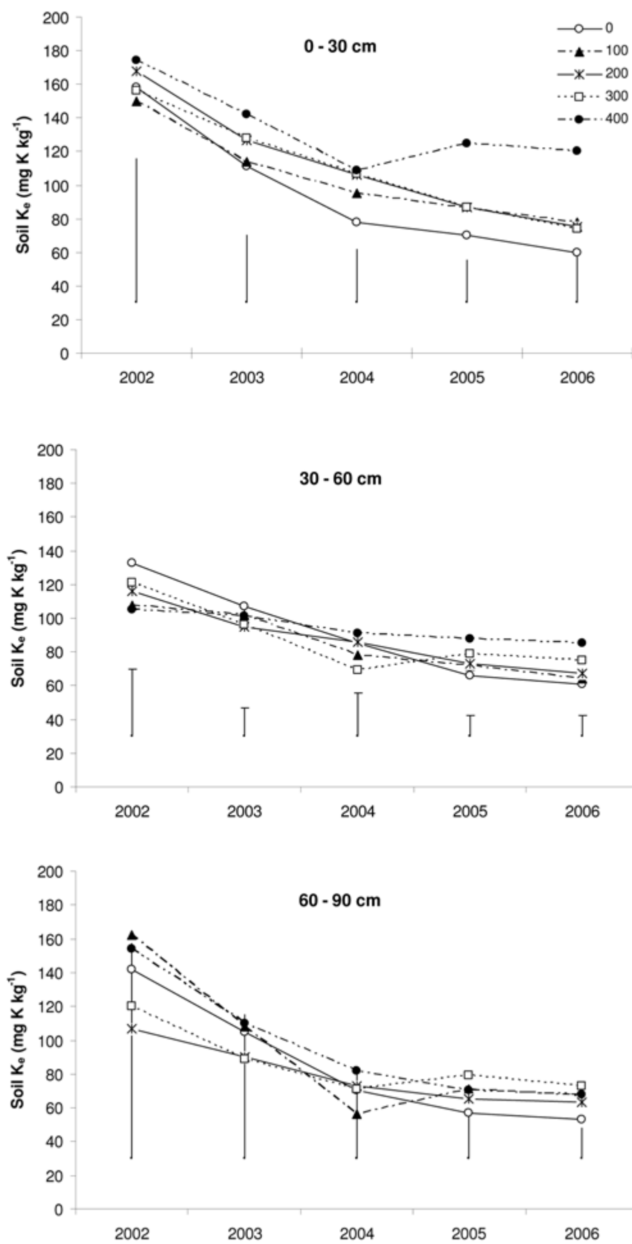

Fig. 1. Evolution of soil exchangeable K (K_e) at three soil depths from 0 to 90 cm under five annual K fertilization rates (0–400 kg K ha^{-1}). Bars present the LSD(0.05) values.

longevity (e.g., Smith, 1975; Sheafler et al., 1986); this was not the case in the present study. Berg et al. (2005) also reported that K fertilization did not influence the plant population.

We think that some of the differences observed between our study and those conducted in the U.S. Midwest might be due to the milder winter temperatures of the Mediterranean compared with those of Minnesota (Sheafler et al.,1986), increasing the chance of plant winter survival.

Potassium fertilization did not affect the number of shoots per square meter in any year (Table 3). This lack of response could reflect the variability observed when counting the number of shoots. Our results agree with those reported by Berg et al. (2007), who stated that while shoots are clearly needed for forage yield, high forage yield was not associated closely with a greater number of shoots per plant, and that other yield components such shoot weight can be more determinant.

Table 3. Density of alfalfa shoots and alfalfa shoot weight under K fertilization treatments.

K rate	2003 Density	2003 Weight	2004 Density	2004 Weight	2005 Density	2005 Weight
kg ha^{-1}	shoots m^{-2}	g shoot^{-1}	shoots m^{-2}	g shoot^{-1}	shoots m^{-2}	g shoot^{-1}
0	543	0.96	386	0.84	377	0.74
100	543	0.96	399	0.91	398	0.89
200	516	1.00	371	0.88	396	0.82
300	505	1.09	390	0.88	397	0.93
400	492	1.04	392	0.90	380	1.00
Avg.	520	1.01	388	0.88	390	0.87
Significance†	ns	ns	ns	ns	ns	**
LSD(0.05)‡	–	–	–	–	–	0.16
			Contrasts			
Linear	*	ns	ns	ns	ns	**
0 vs. others	ns	ns	ns	ns	ns	**

* Significant at the 0.05 level; ns, not significant.

** Significant at the 0.01 level.

† Year was significant at the 0.01 level for the period 2003–2005; Year × K rate interaction for the period was not significant at the 0.05 level.

‡ LSD(0.05) for year effect on the number of shoots is 28 and for the weight per shoot is 0.07 g.

Shoot weight differences were observed during the last year of the experiment (Table 3). In particular, the K300 and K400 rates of K fertilization resulted in higher shoot weight than the unfertilized plots. Indeed, in the 0K plots, the alfalfa plants were of lower height than those in the K-fertilized plots (visual observations).

Significant correlations were observed between DM yield and shoot weight in all years (r = 0.592, P = 0.001 in 2003; r = 0.614, P = 0.001 in 2004; and r = 0.607, P = 0.001 in 2005), whereas significant correlations were observed between DM yields and shoots per square meter only in 2004.

Our results are in agreement with those of Berg et al. (2005, 2007), who reported that the mass per shoot was the yield component most closely associated with yield in response to K fertilization. In their study, the mass per shoot was associated positively with yield, whereas other yield components were either negatively (shoots per square meter) or not (plants per square meter) associated with forage yield. The higher shoot weight in K-fertilized plots could be explained because plants receiving K initiated new shoot growth more quickly than unfertilized plants, given that increased nutrient mobilization occurs between the roots and actively growing shoots (Li et al., 1997).

Tissue Mineral Concentrations

Potassium concentrations for the whole plant increased linearly with increasing K fertilization rates, ranging from 7.7 g K kg^{-1} for the unfertilized treatment (0K) in 2005 to 24.6 g kg^{-1} for the 400 kg K ha^{-1} treatment in 2003 (Table 4). The K concentrations in the plant decreased every year in K0 and K100 plots; even in K200 plots, K concentrations in plants decreased from the second year onward. This continuous decrease in K concentrations for the whole plant may have reflected the continuous decrease in soil K_e content (Fig. 1) due to large-scale K uptake by the alfalfa (Table 4).

Increases in alfalfa K plant concentration with increasing rates of K fertilization have been reported frequently (e.g., Havlin et al., 1984). Our values were within the range reported by others (Sheafler et al., 1986; Smith, 1975), who found

Table 4. Annual average concentrations of K in alfalfa shoots (K conc.) and K removal (K rem.) as affected by K fertilization rates.

K rate	2002 K conc.	2002 K rem.	2003 K conc.	2003 K rem.	2004 K conc.	2004 K rem.	2005 K conc.	2005 K rem.	Total K rem.
kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	kg ha^{-1}
0	13.7	134	11.9	278	10.3	202	7.7	143	757
100	18.8	206	16.2	411	13.4	267	12.6	251	1135
200	17.4	175	19.7	487	16.7	322	15.0	310	1294
300	21.0	195	22.5	559	18.0	376	19.0	397	1527
400	22.0	235	24.6	598	20.9	418	23.2	487	1738
Avg.	18.6	189	19.0	467	15.9	317	15.5	318	1290
Significance†	**	ns	**	**	**	**	**	**	**
LSD(0.05)‡	4.7	–	1.9	135	1.9	62	1.5	88	223
					Contrasts				
Linear	*	ns	**	**	**	**	**	**	**
0 vs. others	ns	ns	**	**	**	**	**	**	**

* Significant at the 0.05 level; ns, not significant.

** Significant at the 0.01 level.

† Year and K rate main effects and the Year × K rate interaction for the period 2003–2005 were significant at the 0.01 level.

‡ LSD(0.05) for year effect on K concentration is 1.0 g kg^{-1} and for K removal is 23 kg ha^{-1}.

that K tissue content ranged from 8.9 to 25.3 g kg^{-1} when K fertilization rates increased.

In our study, we observed plant K concentrations below or near deficiency values (i.e., 10 g kg^{-1}, Kelling and Matocha, 1990) only in unfertilized plots in the last 2 yr (2004 and 2005). In 2003, the second year of production, K deficiencies were observed visually in some plants, even when average plant K concentrations where above deficiency values and initial annual K_e levels exceeded 111 mg kg^{-1}.

Potassium Accumulation

Potassium accumulation depended on the year of production and on the DM alfalfa yields, but in the 4-yr average, K accumulation rose from an average of 189 kg K ha^{-1} yr^{-1} for the K0 treatment to 434 kg K ha^{-1} yr^{-1} for the K400 treatment (Table 4).

The amounts of K extracted were always greater than the K rates applied (excluding the first year because it was the seeding year) even at the highest rates of K application. The total 4-yr amount of K removed with herbage increased with increasing K rates (Table 4). The 4-yr removal of K varied between 757 kg ha^{-1} for K0 fertilization treatments to 1738 kg ha^{-1} with the application of 400 kg K ha^{-1} yr^{-1}. The highest value of K removed was quite similar to the 1728 kg ha^{-1} recorded with the application of 332 kg K ha^{-1} yr^{-1} reported in a previous study (Lloveras et al., 2001). Although high, however, these values are still lower than the accumulations of 540 kg K ha^{-1} yr^{-1} previously reported by Kafkafi et al. (1977) in Mediterranean areas. The high amounts of K extracted, greater than the K rates applied, shows the luxury consumption and probably the importance of limiting K fertilizer applications to amounts lower than the extractions, given that no yield reduction was detected.

Soil Exchangeable Potassium

Soil K_e concentrations decreased every year for all K fertilization rates (Fig. 1) as a consequence of the high rates of K extraction reported above. In the unfertilized plots, there was a continual decline in K_e in the upper 30 cm of the soil profile, with values falling from 161 mg K kg^{-1} at the beginning of the trial to 60 mg K kg^{-1} after 4 yr of alfalfa. In contrast, on K400 plots, the K_e concentration in the upper 30 cm of the soil profile decreased only from 174 mg K kg^{-1} at the beginning of the trial to 120 mg K kg^{-1} after 4 yr. Alfalfa is a crop with a high demand for K and in our study, even the highest application of rate of K (400 kg K ha^{-1} yr^{-1}) increased the subsoil K_e values only in the last 2 yr, when the alfalfa DM production decreased.

The K_e concentrations in the soil from the 30- to 60- and 60- to 90-cm depths also decreased with time for all K treatments (Fig. 1). At a depth of 60 to 90 cm, some decrease in K_e was also evident for all rates of K fertilization except for the K300 and K400 treatments in the last 2 yr of the experiment. These results seem to confirm that alfalfa is a crop with a high potential for subsoil exploitation (De Nobili et al., 1990), although the upper 30 cm was the depth most affected by K removal. At the end of the trial, we dug a 2-m-deep pit and observed that some roots reached a depth of 1 m until the hardpan layer was reached. In contrast, in areas where annual alfalfa yields are lower than the Mediterranean, K_e has been reported to increase with increasing rates of K application. Barbarick (1985), working in soils with high K_e in Colorado, also found that K_e increased with increasing rates of K.

Matching the annual DM yields with the soil K_e levels from our study, we think that it is possible to determine critical K_e levels. The effects of K fertilization on alfalfa yields were significant in 2003 and 2005; 2003 was the second year of production, which is normally the year with the highest production under our conditions, and 2005 was the fourth year of production.

In 2003, at the initiation of the growing season, the K_e levels in the upper 30 cm of the soil profile were 111 mg kg^{-1} for the K0 treatments. These K_e values are considered medium or optimum in several U.S. states (Kelling, 2000; Davis et al., 2005), which generally have lower DM yields than the irrigated Mediterranean areas, but they do not seem sufficient to meet the requirements under our conditions. In 2005, the initial K_{e}, of all K treatments (except K400) were below 100 mg kg^{-1} of soil, and the application of K increased yields compared with the K0 treatment. At the beginning of 2004 (the third year of production), however, the soil K_e value for the unfertilized control plots was 94 mg kg^{-1}, but in this year there were no differences in alfalfa DM yields among treatments, although soil K_e levels decreased to 70 mg kg^{-1} (February 2005). These results are not easy to interpret and it seems to indicate that the critical soil K_e levels might depend on the year and on the DM production and that under our conditions and soil type, they are about 70 to 120 mg kg^{-1} of soil, which are the values at which DM yield decreases.

CONCLUSIONS

Under high-yielding irrigated conditions, such as the Ebro valley of Spain, with medium initial K_e levels, the amounts of K extracted from the soil by alfalfa were always higher than the quantities of K applied through fertilization, even at the highest rates of 400 kg K ha^{-1} yr^{-1}. The 4-yr averages for K removal ranged from 189 kg K ha^{-1} yr^{-1} for the unfertilized treatment to 434 kg K ha^{-1} yr^{-1} for the 400 kg K ha^{-1} treatment. As far as the effect of K rates on yield components, shoot weight was the component most affected by K fertilization, whereas the stand density was not affected.

The high level of K removal for all fertilization rates seems to indicate that large amounts of K should not be applied to alfalfa because the crop takes up K without additional DM yield increases. An increase in soil K_e levels, if desired, should be done after the alfalfa crop is terminated, in accordance with Lissbrant et al. (2009), who stated that high K rates do not always result in higher yields.

The initial soil K_e concentrations averaged 161 mg kg^{-1}, which could be considered adequate or high for alfalfa but did not seem sufficient to maintain the alfalfa DM yields for 4 yr because of the annual decline in K_e. Our results also indicated that, under our conditions, at least for alfalfa, irrespective of the initial level of K_e (but not below about 90 mg kg^{-1}), applications of 100 kg K ha^{-1} yr^{-1} should be sufficient to maintain good yields for a 4-yr growing period.

ACKNOWLEDGMENTS

We would like to thank J.A. Betbesé, J.L. Millera, A. López, M. Bagà, S. Martí, C. Cortes, P. Berenguer, S. Cela, and C. Herrero for their technical assistance and Dr. Jordi Voltas for his assistance in statistics. This research was financed by INIA (Spanish Institute for Agricultural Research).

REFERENCES

Alvaro, J., and J. Lloveras. 2003. Methodology of alfalfa production in Spain. (In Spanish.) Asociación Interprofesional de Forrajes Españoles y Ministerio de Agricultura, Pesca y Alimentación, Lleida, Spain.

Barbarick, K.A. 1985. Potassium fertilization of alfalfa on a soil high in potassium. Agron. J. 77:442–445. doi:10.2134/agronj1985.00021962007700030020x

Berg, W.K., S.M. Cunningham, S.M. Brouder, B.C. Joern, K.D. Johnson, J. Santini, and J.J. Volenec. 2005. Influence of phosphorus and potassium on alfalfa yield and yield components. Crop Sci. 45:297–304. doi:10.2135/cropsci2005.0297

Berg, W.K., S.M. Cunningham, S.M. Brouder, B.C. Joern, K.D. Johnson, J. Santini, and J.J. Volenec. 2007. The long-term impact of phosphorus and potassium fertilization on alfalfa yield and yield components. Crop Sci. 47:2198–2209. doi:10.2135/cropsci2006.09.0576

Berrada, A., and D.G. Westfall. 2005. Irrigated alfalfa response to phosphorus and potassium in a calcareous soil. Commun. Soil Sci. Plant Anal. 36:1213–1227. doi:10.1081/CSS-200056912

Davis, J.G., D.H. Smith, and R.L. Croissant. 2005. Fertilizing alfalfa and grasses. Crop Ser. no. 0.537. Colorado State Univ. Coop. Ext., Fort Collins.

De Nobili, M., L.V. Antisari, and P. Sequi. 1990. K-uptake from subsoil. In: IPI, editor, Development of K-fertilizer recommendations: 22th Colloquium of the International Potash Institute, Soligorsk, USSR. 18–23 June 1990. Int. Potash Inst., Bern, Switzerland. p. 133–144.

Dovrat, A. 1993. Irrigated forage production. Dev. Crop Sci. 24. Elsevier Sci. Publ., Amsterdam.

Havlin, J.L., D.G. Westfall, and H.M. Golus. 1984. Six years of phosphorus and potassium fertilization of irrigated alfalfa on calcareous soils. Soil Sci. Soc. Am. J. 48:331–336. doi:10.2136/sssaj1984.03615995004800020022x

Kafkafi, U., R. Gilat, D. Yoles, and Y. Noy. 1977. Studies on fertilization of field-grown irrigated alfalfa. Plant Soil 46:165–173. doi:10.1007/BF00693123

Kalu, B.A., and G.W. Fick. 1983. Morphological stage of development as a predictor of alfalfa herbage quality. Crop Sci. 23:1167–1172. doi:10.2135/cropsci1983.0011183X002300060033x

Kelling, K.A. 2000. Alfalfa fertilization. Publ. A2448. Univ. of Wisconsin Coop. Ext. Serv., Madison.

Kelling, K.A., and J.E. Matocha. 1990. Plant analysis as an aid in fertilizing forage crops. In: R.L. Westerman, editor, Soil testing and plant analysis. SSSA Book Ser. 3. SSSA, Madison, WI. p. 603–644.

Lanyon, L.E., and F.W. Smith. 1985. Potassium nutrition of alfalfa and other forage legumes: Temperate and tropical. In: R.D. Munson, editor, Potassium in agriculture. ASA, Madison, WI. p. 861–893.

Le Gall, A., J.D. Arnaud, P. Guy, H. Bousquet, A. Pflimlin, and P. Planquaert. 1992. Alfalfa cultivation and uses. (In French.) Groupement National Interprofessionel des Semences-Institut Tecnique de l'Elevage Bovin-Institut Tecnique des Cereals et des Fourrages, Paris.

Li, R., J.J. Volenec, B.C. Joern, and S.M. Cunningham. 1997. Potassium and nitrogen effects on carbohydrate and protein metabolism in alfalfa roots. J. Plant Nutr. 20:511–529. doi:10.1080/01904169709365271

Lissbrant, S., S. Stratton, S.M. Cunningham, S.M. Brouder, and J.J. Volenec. 2009. Impact of long-term phosphorus and potassium fertilization on alfalfa nutritive value–yield relationships. Crop Sci. 49:1116–1124. doi:10.2135/cropsci2008.06.0333

Lloveras, J., J. Ferran, A. Alvarez, and L. Torres. 1998. Harvest management effects on alfalfa (*Medicago sativa* L.) production and quality in Mediterranean areas. Grass Forage Sci. 53:88–92. doi:10.1046/j.1365-2494.1998.00100.x

Lloveras, J., J. Ferran, J. Boixadera, and J. Bonet. 2001. Potassium fertilization effects on alfalfa in a Mediterranean climate. Agron. J. 93:139–143. doi:10.2134/agronj2001.931139x

Lutz, J.A. 1973. Effects of potassium fertilization on yield and K content of alfalfa and on available subsoil K. Commun. Soil Sci. Plant Anal. 4:57–65. doi:10.1080/00103627309366418

Mallarino, A.P., J.R. Webb, and A.M. Blackmer. 1991. Soil test values and grain yields during 14 years of potassium fertilization of corn and soybean. J. Prod. Agric. 4:562–566.

Mills, H.A., and J.B. Jones, Jr.. 1996. Plant analysis handbook II: A practical sampling preparation, analysis and interpretation guide. Revised ed. Micro Macro Publ., Athens, GA.

Piñeiro, J., J. Castro, and R. Blázquez. 2010. Fertilization of the forage crops. (In Spanish.) In: MMARM, editor, Guía práctica de la fertilización racional de los cultivos en España. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid. p. 173–180.

Rominger, R.S., D. Smith, and L.A. Peterson. 1976. Yield and chemical composition of alfalfa as influenced by high rates of K topdressed as KCl and K_2SO_4. Agron. J. 68:573–577. doi:10.2134/agronj1976.00021962006800040010x

SAS Institute. 1988. SAS/STAT user's guide. Version 6.03. SAS Inst., Cary, NC.

Sheafler, C.C., M.P. Russelle, O.B. Hesterman, and R.E. Stucker. 1986. Alfalfa response to potassium, irrigation, and harvest management. Agron. J. 78:464–468. doi:10.2134/agronj1986.00021962007800030014x

Smith, D. 1975. Effects of potassium topdressing a low fertility silt loam soil on alfalfa herbage yields and composition and on soil K values. Agron. J. 67:60–64. doi:10.2134/agronj1975.00021962006700010016x

Soil Survey Staff. 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. Agric. Handbk. 436. U.S. Gov. Print. Office, Washington, DC.

Steel, R.D., and J.H. Torrie. 1980. Principles and procedures of statistics: A biometrical approach. McGraw-Hill, New York.

Zebarth, B.J., R.W. Sheard, and W.E. Curnoe. 1991. A soil test calibration method for potassium on alfalfa which allows for variation in crop value and fertilizer cost. J. Prod. Agric. 4:317–322.