Phosphorus and Potassium Fertilizer Effects on Alfalfa and Soil in a Non-Limited Soil

Stefano Macolino, Leonard M. Lauriault, Filippo Rimi,* and Umberto Ziliotto

ABSTRACT

Fertilization strategies for high-yielding alfalfa (*Medicago sativa* L.) should take in account the increase in soil nutritional status that occurred during the last decades in areas with intensive agricultural use. A field study was conducted at the University of Padova, northeastern Italy, to determine the response of alfalfa yield and nutritive value to various combinations of P and K rates in a soil lacking nutrient deficiency. Alfalfa cultivar Delta was seeded in March 2005 on a silt loam soil having 38 mg kg^{-1} available P and 178 mg kg^{-1} exchangeable K. Nine treatments deriving from the combination of three P fertilization rates (0, 100, and 200 kg ha^{-1} P_2O_5) and three K rates (0, 300, and 600 kg ha^{-1} K_2O) were compared in a randomized complete block design. Plots were harvested at bud stage during three growing seasons (2005–2007) and dry matter (DM) yield, forage nutritive value, P and K contents, canopy height, and stem density were measured at each harvest. Soil samples were collected at the end of the research period for determination of available P and exchangeable K. The results demonstrated that P application had no impact on yield and did not interact with K in determining productivity, while K had a positive effect on yield. However, the 300 kg ha^{-1} K_2O rate appeared sufficient to maximize yield, without adverse effects on the forage nutritive value. Data from soil analyses showed that alfalfa has a high K uptake even when it is fertilized at high rates.

Modern dairy farms require high-yielding forage having sustained nutritive value and often rely on alfalfa to meet these demands. Alfalfa forage quality is improved by reducing cutting intervals (Nelson and Satter, 1992; Tabacco et al., 2002; Rimi et al., 2012); however, frequent harvests of immature alfalfa may lead to reduction in yield and stand persistence (Brink and Marten, 1989; Sheaffer et al., 2000; Kallenbach et al., 2002). It has been reported that alfalfa has high requirements for P and K, and fertilization becomes increasingly important to sustain yield and maintain stand persistence as management intensifies (Gross et al., 1953; Kafkafi et al., 1977; James et al., 1995).

A proper P nutrition is essential for alfalfa plant survival and its supply is often necessary to reach maximum stand development, productivity, and persistence (Jung and Smith, 1959; Berg et al., 2005, 2007). Phosphorus is also involved in the nitrogen fixation process since it contributes to increase both the size and number of *Rhizobia* nodules (Azcón et al., 1988). Yield responses to P are typically most evident at the first harvest of the season; however, the efficiency of P fertilization may be influenced by application timing (James et al., 1995). In northern Italy, P is commonly applied annually in early winter (December) and the current fertilization rate recommendations range from 40 to 50 kg ha^{-1} yr^{-1} of P_2O_5 (Parrini and Bonari, 2002). Moreover, alfalfa yield, forage nutritive value, and stand density are strongly affected by K nutrition (Wolf et al., 1976; Kafkafi et al., 1977; Lanyon and Smith, 1985). Nevertheless, alfalfa can absorb more K than needed for maximum growth through a behavior called "luxury" consumption, which generally leads to a reduction in protein, Ca, Mg, and Na (Lanyon and Griffith, 1988; Pant et al., 2004). High concentrations of K (e.g.,>3% dry wt.) in alfalfa may be undesirable for livestock nutrition because the reduced concentration of Ca and other nutrients impact animal utilization of alfalfa forage (Meyer and Matthews, 1995). In southern Europe, K fertilizer is typically applied once a year as a single application during the winter, at a rate of 200 to 300 kg ha^{-1} yr^{-1} of K_2O (Lloveras et al., 2001; Parrini and Bonari, 2002). However, split applications of K can reduce alfalfa plants' tendency for luxury consumption and are considered more efficient than a one-time application of a large amount of K (Kresge and Younts, 1962; Kafkafi et al., 1977). In particular, Kafkafi et al. (1977) recommended to use split applications of K in soils having low cation exchange capacity (e.g., 5.5 cmol$_c$ kg^{-1}).

Research investigating the effects of P and K on the agronomic performance of alfalfa suggests that the interactions between nutrients should not be underestimated. Lissbrant et al. (2010) demonstrated that, under various soil conditions, lower yields were obtained by unbalanced P and K fertilization compared to zero fertilization, confirming the interdependent nature of these nutrients. Still, Lanyon and Griffith (1988) reported that fertilizer efficiency varied across locations because the plant response to fertilization depends on many

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Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; CP, crude protein; DM, dry matter; EE, ether extract; NDF, neutral detergent fiber; NIRS, near infrared reflectance spectroscopy.

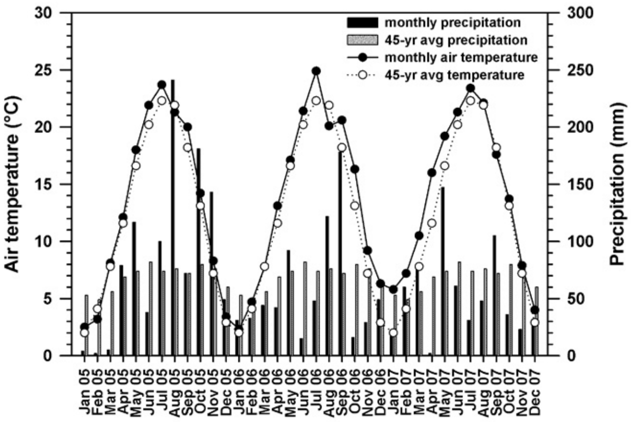

Fig. 1. Monthly mean air temperature and precipitation from January 2005 to December 2007, and 45-yr monthly averages (1963–2007) at the agricultural experimental farm of Padova University in Legnaro, Italy.

environmental factors, such as soil nutrient availability, soil status, and climate conditions. According to this, alfalfa fertilization programs should be customized on the basis of local conditions, which may also change over time.

For decades in most regions with intensive agricultural systems, producers increased fertilization inputs and especially P rates to achieve higher yields, often leading to soil nutrient accumulation (Haden et al., 2007; Delgado and Scalenghe, 2008; Pizzeghello et al., 2011). However, there is little information in the current body of scientific literature on fertilization effects from areas where soil P and/or K are not limiting. Barbarick (1985) reported that high K application to a high K soil increased irrigated alfalfa yield only after 4 yr, while no such effect was measured by Lloveras et al. (2001). To reduce production costs and to prevent further accumulation of nutrients in the soil, the alfalfa fertilization programs should be tailored on the basis of the changes in soil nutritional status. Therefore, the objective of this study was to investigate the response of alfalfa yield and nutritive value to various combinations of P and K rates in a soil lacking nutrient deficiency.

MATERIALS AND METHODS

A field trial was performed during three growing seasons (2005–2007) at the experimental farm of Padova University in Legnaro, Italy (45°20′ N, 11°58′ E; elevation 8 m). The zone is characterized by a humid subtropical climate with an average annual temperature of 12.3°C and 820 mm total rainfall. Monthly mean air temperatures and monthly precipitation during the investigation period and the 45-yr monthly averages are reported in Fig. 1. The first two growing seasons were characterized by low precipitation in June and above-average precipitation during late summer. Monthly air temperatures were generally similar to the long-term averages, with the exception of winter 2006–2007, during which temperatures were extraordinary high (Fig. 1). Soil at the site was an Oxyaquic Eutrudept, coarse-silty mixed, mesic (Morari, 2006), having a silt loam texture, high content of available P, and medium content of exchangeable K (Table 1). The total cation exchange capacity was 21.6 and 17.2 $\mathrm{cmol_c\ kg^{-1}}$ for the 0- to 46- and 46- to 73-cm depths, respectively (Giupponi and Dibona, 2004). On 30 Mar. 2005, alfalfa cultivar Delta was seeded at a rate of 29 kg seed $\mathrm{ha^{-1}}$ in rows spaced 20 cm apart. The cultivar used in this study was nondormant (fall dormancy rating = 8.5) and it was selected on the basis of its common use in the area of investigation (Rimi et al., 2010).

Table 1. Soil characteristics for the study area at Legnaro, northeastern Italy, to a depth of 20 cm from samples collected before seeding alfalfa in March 2005.

Parameter	Method of determination	Value
Sand, % (0,05–2 mm)	gravimetric	18.0
Silt, % (0002–0,05 mm)	gravimetric	65.9
Clay, % (<0002 mm)	gravimetric	16.0
Organic matter, %	Walkley and Black	2.28
pH	electrode (1:2)	8.1
Total N, g $\mathrm{kg^{-1}}$	Kjeldahl	0.125
Total P, ‰ P_2O_5	mineralization via HNO_3 and H_2SO_4	1.9
Available P, mg $\mathrm{kg^{-1}}$	Olsen	38.2
Exchangeable K, mg $\mathrm{kg^{-1}}$	buffered $BaCl_2$	178.0
C/N ratio	Organic C ÷ Organic N	10.7

A total of nine treatments deriving from the factorial combination of three fertilization rates of P and three of K were compared in a randomized complete block design with three replicates. The fertilization treatments included: 0, 100, or 200 kg $\mathrm{ha^{-1}}$ of P_2O_5, and 0, 300, or 600 kg $\mathrm{ha^{-1}}$ of K_2O. The first fertilization was applied according to the treatments before seeding in March 2005, and subsequent applications were made in December of 2005 and 2006. The fertilizers were distributed as a single application each year, according to the common alfalfa management in northern Italy. Irrigation was limited to the establishment phase and plot size was 8 $\mathrm{m^2}$ (1.6 by 5 m), of which 6 $\mathrm{m^2}$ were used for sampling. Plots were harvested using a sickle-bar harvester at a 5-cm height four times from June through October 2005, seven times from May through October 2006, and seven times from April through September 2007. The first harvest of each growing season was made at the appearance of new crown shoots, while the subsequent harvests were made at an early bud phenological stage (Kalu and Fick, 1981).

At each harvest, canopy height was measured at four randomly selected locations within each plot and the values were averaged to obtain one value. In addition, all stems from 30 cm of two rows of each plot were counted to determine stem density (stem $\mathrm{m^{-2}}$). After harvest, the fresh herbage was weighed in the field and 500-g subsamples were collected and dried for 36 h at 65°C to determine dry matter (DM) yield. Subsequently, samples were analyzed for crude protein (CP), ether extract (EE), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and ash concentration via calibrated near infrared reflectance spectroscopy (NIRS) (model 5000; NIRSystems, Silver Springs, MD). Calibration samples were subjected to conventional chemical analysis for CP (AOAC, 1995), NDF, ADF, ADL (Goering and Van Soest, 1970), EE (AOAC, 1990), and ash (Pearson, 1976). Spectra data analyses were performed using WinISI II software package (version 1.5; Infrasoft International, Port Matilda, PA) and calibration statistics are presented in Table 2.

In October 2007, three soil cores measuring 4.5 (diam.) by 20 cm (depth) were randomly collected on each plot, for determination of available P and exchangeable K at the end of the research period. The cores were divided into three sections representing the 0- to 5-, 5- to 10-, and 10- to 20-cm soil layers;

Table 2. Standard error of cross-validation in modified partial least square regression (SECV) and coefficient of determination (r^2) for calibration of near infrared reflectance spectroscopy analysis of forage nutritive values for alfalfa harvested at early bud during 3 yr at Legnaro, northeastern Italy.

Constituent	SECV	r^2
Crude protein	0.97	0.89
Ether extract	0.31	0.57
Neutral detergent fiber	1.90	0.88
Acid detergent fiber	1.96	0.86
Acid detergent lignin	1.01	0.66
Ash	0.41	0.91

and weighted averages were calculated for the 0- to 20-cm depth. The forage concentrations of P and K were determined using prediction equations developed by the NIRS Forage and Feed Testing Consortium (Hillsboro, WI). Calibration statistics were the following: P, standard error of cross-validation in modified partial least square regression (SECV) = 0.04 and r^2 = 0.67; K, SECV = 0.27 and r^2 = 0.88 (P. Berzaghi, personal communication, 2012). Subsequently, soil balances of P and K were calculated by subtracting the total forage uptake from the initial soil contents and the cumulative supply due to fertilization.

The data were subjected to analysis of variance using SAS Proc Mixed (version 9.2; SAS Institute, Cary, NC) to determine the main effects of P, K, and their interaction. Fertilization treatments showed little differences at individual harvests (data not shown), consequently the yield data were summarized as annual totals, whereas the nutritive values were weighted by yield values (Kallenbach et al., 2002; Rimi et al., 2012). Replicates were considered random and P, K, and their interaction were considered fixed. When appropriate, years or soil sampling depths were included in the statistical model as repeated measurements. Fisher's Protected LSD test was used at the 0.05 probability level to identify significant differences between means.

RESULTS AND DISCUSSION

For DM yield, P and all interaction terms including P were not significant (Table 3), which was probably due to the high level of available P in the soil at seeding (Table 1). Therefore, the application of P did not interact with K and appeared basically needless to improve yield; however, an increase of fertilization from 100 to 200 kg ha^{-1} of P_2O_5 was not detrimental to yield. The analysis of variance for DM yield showed significant K and year main effects, and their interaction (Table 3). Observing the interaction between K and years, there were differences among K rates only in the second and third year of investigation (Table 4). In 2006, the unfertilized plots had lower DM yield compared to those that received K_2O, which showed no differences between each other. In 2007, the difference in DM yield between unfertilized plots and fertilized plots further increased, and a significant difference was observed between the 300 and 600 kg ha^{-1} K_2O treatments (Table 4). These findings corroborated the results of other studies that reported a positive influence of K on alfalfa yield even in soils with high exchangeable K levels (Markus and Battle, 1965; Kafkafi et al., 1977; Barbarick, 1985). In the average of 3 yr, the increase of K_2O from 300 to 600 kg ha^{-1} did not provide any increment of DM yield (Table 4), suggesting that the application of 300 kg ha^{-1} was sufficient to maximize yield. These recommendations appeared in disagreement with previous studies from Indiana, where maximum levels of K fertilization increased alfalfa yields on each year during a 5-yr investigative period (Berg et al., 2005, 2007). The different responses observed between the studies could be attributed to contrasting initial soil nutritional status for the two sites and/or the levels of P and K fertilization imposed.

Similarly to DM yield, the canopy height was not affected by P, while it was influenced by K, years, and their interaction (Table 3). The canopy height responded to K treatments and was related to the environmental differences that occurred between years consistently to DM yield (Table 4). The stem density was not influenced by P or K (Table 3), but a decrease in stem density was observed over the three experimental years, with stem m^{-2} diminishing from ≈1100 to ≈550 (data not shown). This could be attributed to stand thinning and a natural physiological reduction in the number of stems per plant over time (Hall et al., 2004). Therefore, additional K application possibly affected DM yield through stem elongation rather than stem density.

While the effect of years was significant for all forage nutritive values, changes in consequence of fertilization treatments were limited to CP, EE, ash, P, and K (Table 3). The analysis of variance for CP revealed a significant three-way interaction among P, K, and years (Table 3). In the establishment year (2005), all plots had similar CP, with the exception of those

Table 3. Analysis of variance for forage yield, canopy height, stem density, and forage nutritive values (crude protein [CP], ether extract [EE], neutral detergent fiber [NDF], acid detergent fiber [ADF], and acid detergent lignin [ADL], ash, P, and K), of alfalfa subjected to three fertilization rates of P and three of K from 2005 to 2007 at Legnaro, northeastern Italy.

Source	Yield	Canopy height	Stem density	Forage nutritive values							
				CP	EE	NDF	ADF	ADL	Ash	P	K
P	ns†	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K	**	***	ns	*	ns	ns	ns	ns	***	**	***
P × K	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Yr	**	***	***	***	***	***	***	***	***	***	**
P × yr	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	*
K × yr	***	***	ns	***	ns	ns	ns	ns	***	ns	**
P × K × yr	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Not significant at the 0.05 probability level.

Table 4. Dry matter yield, canopy height, ash, and K content of alfalfa under the influence of three K fertilization rates at Legnaro, Italy, from 2005 to 2007. The data were averaged over three P fertilization rates and three replicates.

K_2O	2005	2006	2007	Average
kg ha^{-1} yr^{-1}				
	Dry matter yield, Mg ha^{-1}			
0	14.9a†	22.9b	18.3c	18.7b
300	15.0a	23.9a	20.3b	19.7a
600	14.9a	24.1a	21.3a	20.1a
	Canopy height, cm			
0	66.3a	71.0b	60.0c	65.8c
300	66.9a	72.6ab	65.0a	68.1b
600	67.7a	72.9a	67.7a	69.4a
	Ash, g kg^{-1} dry wt.			
0	101a	96c	98c	99c
300	102a	101b	104b	102b
600	101a	105a	110a	105a
	K, g kg^{-1} dry wt.			
0	22.6c	22.0c	20.8c	21.8c
300	23.3b	24.5b	24.1b	24.0b
600	24.5a	25.9a	26.9a	25.8a

† Within a column and measurement parameter, values followed by the same letter are not significantly different at 0.05 level of probability (Fisher's protected LSD).

Table 5. Crude protein of alfalfa forage as affected by various combinations of P and K fertilization rates during three growing seasons (2005– 2007) in Legnaro, northeastern Italy. Data are the means of three replicates.

P_2O_5	K_2O	2005	2006	2007
—— kg ha^{-1} yr^{-1} ——		———— g kg^{-1} dry wt. ————		
0	0	186a†	194a	195a
0	300	185a	188c	194a
0	600	186a	188c	196a
100	0	185a	192abc	199a
100	300	183a	193ab	197a
100	600	187a	189bc	185b
200	0	178b	191abc	196a
200	300	185a	193ab	195a
200	600	184a	188c	187b

† Within a column, values followed by the same letter are not significantly different at 0.05 level of probability (Fisher's protected LSD).

Table 6. Forage concentration of K as affected by three P fertilization rates in combination with three K fertilization rates and during 3 yr (2005–2007) at Legnaro, northeastern Italy. Potassium rate data are the means of 3 yr and three replicates; and annual data are the means of three K fertilization rates and three replicates.

	K_2O, kg ha^{-1} yr^{-1}					
P_2O_5	0	300	600	2005	2006	2007
kg ha^{-1} yr^{-1}	————————		mg kg^{-1} dry wt.	————————		
0	226a†	246a	257a	235a	248a	244a
100	219ab	237a	256a	238a	236b	240a
200	211b	237a	263a	232a	241ab	237a

† Within a column, values followed by the same letter are not significantly different at 0.05 level of probability (Fisher's protected LSD).

receiving 200 kg ha^{-1} P_2O_5 and 0 kg ha^{-1} K_2O, which had lowest content of CP (Table 5). In the subsequent year, the plants unfertilized with K were in the top statistical group, while those receiving 600 kg ha^{-1} K_2O had lowest CP, regardless of P fertilization (Table 5). In 2007, plots fertilized with 600 kg ha^{-1} K_2O had again lowest content of CP when combined with the 100 and 200 kg ha^{-1} P_2O_5 rates (Table 5). In general, the negative effect of high K applications on CP could be ascribed to a decrease of leaf/stem ratio, possibly due to increased stem length as suggested by canopy height (Table 4). Also, lower CP could be explained by a diminution of N content per leaf area as the result of higher competition for light in consequence of the greater plant height and yield (Sheafler et al., 1986; Lemaire et al., 1991). Moreover, there was a significant interaction between P fertilization rates and year on EE (Table 3), however the differences among treatments were of little biological importance (data not shown). There were significant differences in ash content among K fertilization rates and a significant K × year interaction (Table 3), due to a continued increment of ash over years with the increase of K rate (Table 4).

The accumulation of K in the tissues was promoted by K fertilization rates and was also influenced by the two-way interactions P × K, P × year, and K × year (Table 3). The forage concentrations of K increased as K_2O fertilization passed from 0 to 300 and from 300 to 600 kg ha^{-1}, although there was a difference in magnitude between years (Table 4). The increase of K concentration in the forage in response to high levels of K_2O may be explained by a luxury consumption of this nutrient (Pant et al., 2004; Snyder and Leep, 2007). These results indicated that luxury consumption of K can occur even in soils having high cation exchange capacity. The forage content of K was positively correlated with ash ($r = 0.761$; $P < 0.0001$; $n = 81$), suggesting that high ash content in alfalfa grown on soils rich in K is due to luxury consumption. The forage content of K was influenced by P fertilization only in plants that had not received K_2O, with forage K decreasing when P_2O_5 passed from 0 to 200 kg ha^{-1} (Table 6). The impact of P fertilization on the forage concentrations of K across years appeared unclear, with statistical differences among treatments noticeable only in 2006 (Table 6). Interestingly, P fertilization had no effect on the concentration of P in the forage, which was influenced only by the main effects of K and years (Table 3). In fact, the forage concentrations of P were lower for plots unfertilized (29 mg kg^{-1} dry wt.) compared to those fertilized with 300 and 600 kg ha^{-1} K_2O (30 mg kg^{-1} dry wt.) (data not shown). These results reflected the lack of response of DM yield in consequence of P application and are likely due to the high availability of P in the soil at seeding.

At the end of the investigative period, the available P in the upper 20 cm of soil was still sustained, although differences occurred among P fertilization treatments (Tables 7 and 8). Moreover, P fertilization affected the P balance such that only the plots that received 200 kg ha^{-1} yr^{-1} offset the P removed by the canopy over the 3-yr period (Table 8). In addition, differences in P balances were noticed among the K fertilization treatments (Table 8), indicating that K nutrition may interact with P in determining P sorption and utilization. Soil exchangeable K measured at the end of 2007 on plots fertilized with 600 kg ha^{-1} K_2O was significantly higher compared to plots that received 0 and 300 kg ha^{-1} K_2O (Table 8). However, no biologically significant increases in soil K were noticed when the values measured after the final harvest (Table 8) were compared to the soil concentrations at seeding (178 mg kg^{-1}; Table 1). These results indicated a high use of K by alfalfa even when it is supplied at high fertilization rates. The decrease of exchangeable soil K

Table 7. Analysis of variance for soil P and K at various soil depths (0–5, 5–10, and 10–20 cm) and soil balances for P and K after 3 yr of alfalfa subjected to three rates of P fertilization in combination to three K fertilization at Legnaro, northeastern Italy.

Source	Soil P		Soil K		Soil balance	
		0–20 cm		0–20 cm	P	K
P	***	**	ns	ns	***	ns
K	ns†	ns	***	***	***	**
P × K	ns	ns	ns	ns	ns	ns
Depth (D)	***	–	***	–	–	–
P × D	***	–	ns	–	–	–
K × D	ns	–	***	–	–	–
P × K × D	ns	–	ns	–	–	–

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Not significant at the 0.05 probability level.

Table 8. Concentration of P and K in 0 to 20 cm of soil (weighted mean of 0–5-, 5–10-, and 10–20-cm depths), and soil balance of K and P after 3 yr of alfalfa subjected to three rates of P fertilization in combination to three K fertilization at Legnaro, northeastern Italy. Data are the means of three replicates.

Fertilization treatment	Soil P	Soil K	Soil balance† P	Soil balance† K
	kg ha^{-1}‡			
P_2O_5, kg ha^{-1}				
0	32.1c§	–	−142c	–
100	43.7b	–	−9b	–
200	53.7a	–	122a	–
K_2O, kg ha^{-1}				
0	–	139b	−2a	−1013c
300	–	168b	−13b	−482b
600	–	246a	−19c	862a

† Calculated as: Crop exportation – (Initial soil content + Fertilization supplies).

‡ Results of soil analyses are reported assuming a soil bulk density of 1.3 g cm^{-3}.

§ Within a column and measurement parameter, values followed by the same letters are not significantly different at 0.05 level of probability (Fisher's protected LSD).

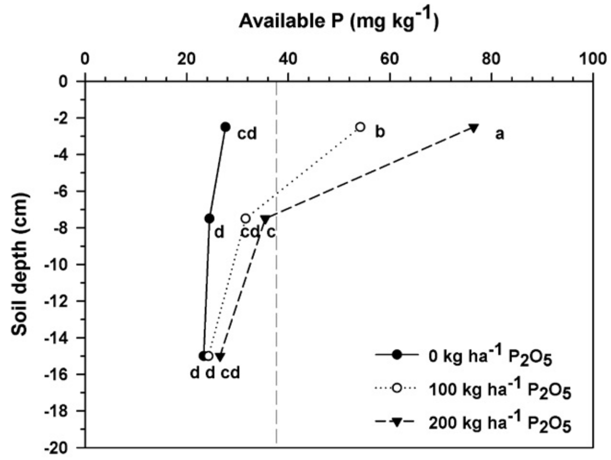

Fig. 2. Available P content at different soil depths (0–5, 5–10, and 10–20 cm) after 3 yr of alfalfa management at Legnaro, Italy. Data points with the same letters are not significantly different at the 0.05 level of probability (Fisher's protected LSD). The vertical dashed line indicates soil P content at seeding (April 2005) for the 0- to 20-cm depth.

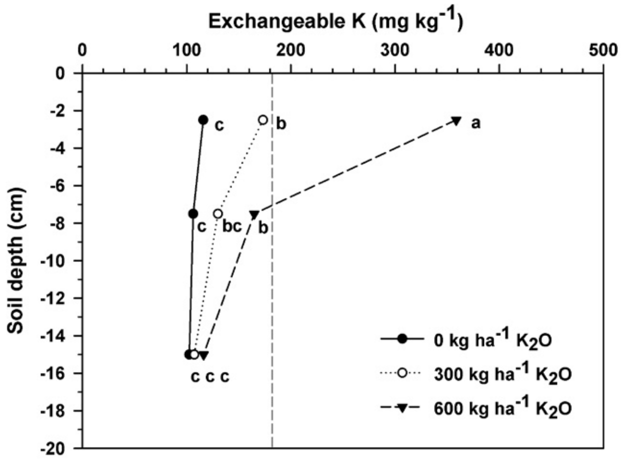

Fig. 3. Exchangeable K content at different soil depths (0–5, 5–10, and 10–20 cm) after 3 yr of alfalfa management at Legnaro, Italy. Data points with the same letters are not significantly different at the 0.05 level of probability (Fisher's protected LSD). The vertical dashed line indicates soil K content at seeding (April 2005) for the 0- to 20-cm depth.

content observed in plots receiving 0 and 300 kg ha^{-1} K_2O was substantiated by a negative soil balance for K (Table 8). Among the fertilization treatments, only the 600 kg ha^{-1} K_2O rate was sufficient to offset the K removed by alfalfa over the 3 yr. The lack of yield differences between 300 and 600 kg ha^{-1} K_2O until the third year (Table 4) suggested that 300 kg ha^{-1} yr^{-1} K_2O can be applied for the first 2 yr in high K soils. As such, soil nutritional status should be monitored in the following year, to adjust the application rate and sustain alfalfa yields.

At the end of the investigative period, soil concentrations of available P at different soil depths were influenced by P, soil sampling depths, and their interaction, while K had no effect (Table 7). A depletion of P at each soil layer was observed in unfertilized plots, while in plots receiving 100 and 200 kg ha^{-1} P_2O_5 depletion occurred at 5- to 10- and 10- to 20-cm layers (Fig. 2). However, the final P content at each soil layer, and for each P rate, was equal or higher than the amount of ≈22 mg kg^{-1}, which is considered adequate to sustain 3-yr yield in a silt loam soil (Lanyon and Griffith, 1988). The high levels of available P observed in the upper layer for the 100 and 200 kg ha^{-1} P_2O_5 treatments (Fig. 2) were likely related to the scarce mobility of P in the soil (Havlin et al., 1999).

As with P, final soil concentrations of exchangeable K at different soil depths were influenced by K, soil sampling depths, and their interaction, while P had no effects (Table 7). Differences in soil K content among K rates occurred only in the upper soil layer, where the plots fertilized with 600 kg ha^{-1} K_2O had higher K than other treatments (Fig. 3). The lack of differences in the deeper soil layers (5–10 and 10–20 cm) indicated that yield differences were most likely related to the K content of the upper soil layer. These results also suggested that the efficiency of alfalfa to remove K from the lower soil profiles was not affected by the amount of K available in the 0- to 5-cm depth. Still, it was interesting that soil exchangeable K of unfertilized control plots at each soil depths were lower than 150 kg ha^{-1}, which is recognized as a limit to sustain alfalfa yield (Snyder and Leep, 2007). However, the results of this study contradicted the previous recommendations of Snyder and Leep (2007), since the initial soil K content of 178 mg kg^{-1} (≈ 230 kg ha^{-1}) limited alfalfa performance in unfertilized plots.

CONCLUSIONS

In a soil lacking P and K deficiencies, an annual application of 300 kg ha^{-1} of K_2O was more efficient in comparison with 600 kg ha^{-1} of K_2O and no K fertilization. In fact, this fertilization schedule allowed to maximize yield and to preserve forage nutritive value over a period of three growing seasons. In contrast, the P fertilization had no impact on yield or forage nutritive value and it caused additional accumulation of this element in the soil over time, increasing potential environmental impacts. Although alfalfa plants evidenced a sustained K uptake during the growing season, high K application rates led to excessive accumulation of K in the upper soil layer. The results of this study suggest that the traditional fertilization practices for high-yielding alfalfa growing in soils having a high nutritional status should be judiciously reconsidered. To prevent excessive applications of P and K and possible luxury consumption of K, alfalfa producers are encouraged to perform soil tests on a regular basis and to schedule annual applications according to soil nutritional status.

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