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 (Ke) 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 Ke (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 Ke 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 (Ke) 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, Ke test levels of 60 to 125 mg K kg⁻¹ are considered appropriate for alfalfa depending on the soil type, whereas Ke above 125 mg K kg⁻¹ is considered high (Davis et al., 2005; Kelling, 2000). In the irrigated areas of the Ebro valley (Spain), the normal Ke contents for a good crop are considered to be between 125 and 250 mg K kg⁻¹, whereas levels below 125 mg K 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; Sheafer 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 Ke 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 Ke 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.

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

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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 Kafkafi et al., 1977; Lloveras et al., 1998) are between 200 and 350 kg K ha\(^{-1}\) yr\(^{-1}\) are based normally on areas of southern Europe, the present recommendations of

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 depletion in irrigated production systems with a high potential for forage production and moderate soil K\(_c\) 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 Agroalimentaries (IRTA) research station in Gimeneells, 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 Calciexcept (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, 220 g kg\(^{-1}\) clay, 35 g kg\(^{-1}\) organic matter, CaCO\(_3\) equivalent to 35 g kg\(^{-1}\), a pH of 8.0, and a cation exchange capacity of 11.3 cmol kg\(^{-1}\).

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

<table>
<thead>
<tr>
<th>Month</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T_m) mm</td>
<td>(T_m) mm</td>
<td>(T_m) mm</td>
<td>(T_m) mm</td>
</tr>
<tr>
<td>Feb.</td>
<td>8.0</td>
<td>4.2</td>
<td>5.7</td>
<td>70.6</td>
</tr>
<tr>
<td>Mar.</td>
<td>11.6</td>
<td>14.7</td>
<td>10.9</td>
<td>34.5</td>
</tr>
<tr>
<td>Apr.</td>
<td>13.0</td>
<td>40.8</td>
<td>13.4</td>
<td>25.9</td>
</tr>
<tr>
<td>May</td>
<td>16.2</td>
<td>52.7</td>
<td>17.6</td>
<td>62.5</td>
</tr>
<tr>
<td>June</td>
<td>22.1</td>
<td>35.0</td>
<td>24.9</td>
<td>15.1</td>
</tr>
<tr>
<td>July</td>
<td>23.0</td>
<td>20.3</td>
<td>25.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Aug.</td>
<td>21.7</td>
<td>17.7</td>
<td>25.9</td>
<td>38.0</td>
</tr>
<tr>
<td>Sept.</td>
<td>18.6</td>
<td>38.0</td>
<td>19.3</td>
<td>101.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>14.6</td>
<td>41.0</td>
<td>13.9</td>
<td>71.2</td>
</tr>
<tr>
<td>Annual mean temperature or total annual rainfall</td>
<td>16.5</td>
<td>264</td>
<td>17.4</td>
<td>417</td>
</tr>
</tbody>
</table>

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-buty1-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(1H,3H)-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-methyllethyl) 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.
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 HNO₃ 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 (Ke) 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.

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 Ke contents in the upper 30 cm of the soil (Fig. 1). As frequently reported, alfalfa yields depend on the Ke 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 (Ke) 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.](image-url)

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

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<thead>
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<tbody>
<tr>
<td>0</td>
<td>9.8</td>
<td>23.4</td>
<td>19.6</td>
<td>18.6</td>
<td>71.5</td>
</tr>
<tr>
<td>100</td>
<td>11.0</td>
<td>25.4</td>
<td>19.9</td>
<td>19.9</td>
<td>76.4</td>
</tr>
<tr>
<td>200</td>
<td>10.1</td>
<td>24.7</td>
<td>19.3</td>
<td>20.7</td>
<td>74.8</td>
</tr>
<tr>
<td>300</td>
<td>9.3</td>
<td>24.8</td>
<td>20.9</td>
<td>20.9</td>
<td>75.9</td>
</tr>
<tr>
<td>400</td>
<td>10.7</td>
<td>24.3</td>
<td>20.0</td>
<td>21.0</td>
<td>76.2</td>
</tr>
<tr>
<td>Avg.</td>
<td>10.2</td>
<td>24.5</td>
<td>19.9</td>
<td>20.2</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Significance: ns, not significant. * Significant at the 0.05 level; ** Significant at the 0.01 level.

Contrasts

- Linear ns ns ns * ns
- 0 vs. others ns ** ns ** *

† 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.
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 the number of shoots. Our results are in agreement with those reported by 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 the 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).

| Table 3. Density of alfalfa shoots and alfalfa shoot weight under K fertilization treatments. |
|--------------------------------------------------|----------------|----------------|----------------|
| K rate kg ha\(^{-1}\) | Density shoots m\(^{-2}\) g shoot\(^{-1}\) | Density shoots m\(^{-2}\) g shoot\(^{-1}\) | Density 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 |

* 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.

| 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 kg ha\(^{-1}\) | K conc. g kg\(^{-1}\) K rem. kg ha\(^{-1}\) | K conc. g kg\(^{-1}\) K rem. kg ha\(^{-1}\) | K conc. g kg\(^{-1}\) K rem. kg ha\(^{-1}\) |
| 0 | 13.7 | 134 | 11.9 | 278 | 10.3 | 202 | 7.7 | 143 |
| 100 | 18.8 | 206 | 16.2 | 411 | 13.4 | 267 | 12.6 | 251 |
| 200 | 17.4 | 175 | 19.7 | 487 | 16.7 | 322 | 15.0 | 310 |
| 300 | 21.0 | 195 | 22.5 | 559 | 18.0 | 376 | 19.0 | 397 |
| 400 | 22.0 | 235 | 24.6 | 598 | 20.9 | 418 | 23.2 | 487 |
| Avg. | 18.6 | 189 | 19.0 | 467 | 15.9 | 317 | 15.5 | 318 |

* 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 K fertilization treatments.

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).
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 were 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. Barbacick (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.
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