Comparison of the effects of dairy sludge and a mineral NPK fertilizer on an acid soil

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SUMMARY

In the present study, the short term effects produced by a dairy sludge applied to an acid soil, at a rate of 160 m³ ha⁻¹, with or without K supplementation, were compared with those of a mineral fertilizer conventionally used on mixed swards in northwestern Spain. The investigation was carried out under field conditions on a soil with a very low exchange capacity, a high percentage of saturated Al and a high P retention. Four different treatments were applied: unfertilized control, dairy sludge, dairy sludge supplemented with K and mineral fertilizer. Soils were analysed at different times up to 8 months after treatment application and forage production was estimated after cutting the grass for silage in spring. Results showed that, compared to the mineral fertilizer, the dairy sludge (with or without K supplementation) had a liming effect (pH and exchangeable Ca increased). The dairy sludge was also a good source of P. Although there was an initial increase in salinity (at 3 months), limiting levels were never reached and the effect had disappeared at 6 months after application of sludge treatments, due to the diluting effect of rainfall. In spite of different fertility conditions achieved by the four treatments, there were no significant differences in forage production. It is concluded that, in the short term, and at an application rate of 160 m³ ha⁻¹, dairy sludge is as effective as the mineral fertilizer in supplying nutrients for forage production.

Key words: forage production, sustainability
INTRODUCTION

In industrialized societies an increase in the production of waste matter that may damage the environment is currently being observed. Dealing with potential contamination arising from application of waste products to land is expensive and often cannot be justified in economic terms. However by recycling or reusing these products, they are converted into resources and the costs may be assigned to a new form of production (Couillard, 1995). Application of waste products to agricultural land is an efficient method of recycling them, while at the same time improving the productive capacity of soils (Sommers, 1977; Khaleel et al., 1981). In addition, the costs involved in using mineral fertilizers are reduced and the system becomes more sustainable.

The dairy industry generates waste composed of milk residues and cleaning products. This effluent may be dumped directly on to agricultural land, so that soils and crops act as purifying agents (Buson, 1992), or it may be subjected to biological or physicochemical treatments. The latter methods produce a treated aqueous phase, that can be discharged into rivers, and a sludge that may undergo one of many secondary treatments and be disposed of in a variety of ways. These dairy sludges are relatively low in heavy metals, organic contaminants and other constituents harmful to human and animal health, when compared to municipal sludges (Brown et al., 1990).

More than 30% of Spanish dairy products are produced in Galicia, where over 345,000 ha are used as pasture land. The farmers in the region usually use a combination of waste products originating from their own farms (manure, slurry) and mineral fertilizers on their fields. In recent years, sludges from the dairy industry have also begun to be used as fertilizers on pasture land in Galicia. Initial studies have demonstrated an increase in forage production (López-Mosquera et al., 1998) and an improved soil fertility (Moirón and López-Mosquera, 1997; Moirón et al., 1997) for dairy sludge application up to 160 m³ ha⁻¹ (López Mosquera et al., 1998).

However, further studies are needed to investigate the fertilizing properties of these residues in comparison with inorganic fertilizers. It is also important that their use as fertilizers is carefully planned to take advantage of their good qualities while minimising the potential environmental risks. Negative aspects of the use of these waste products that should be considered are low K content (De Lauzanne and Merillot, 1986; García et al., 1999) and possible increase in salinity due to the high Na content and elevated electrical conductivity (Morisot and Gras, 1974; Guichet, 1987).

In this study, the short-term effects of 160 m³ ha⁻¹ of the dairy sludge, with or without K supplementation, were compared with those of a conventional mineral fertilizer applied to a Humic Cambisol sown with a mixture of perennial ryegrass and white clover.

MATERIAL AND METHODS

Field experiment

A trial was carried out at Vilalba (Lugo, Spain, 43°42.5 N, 7°37.1 W) in a 1 ha plot with a slope of less than 2%.

The soil was a Humic Cambisol (FAO, 1991), sandy-loam in texture, acidic (pH 5.52), with a high organic matter content (8.20%) and a
very low effective exchange capacity (3.57 cmol(+) kg \(^{-1}\)). The average annual precipitation in the area is 1176 mm, and the average maximum and minimum temperatures are 16.8 °C and 6.2 °C respectively.

In October 1997, the plot received 3 t ha\(^{-1}\) dolomite, along with a conventional NPK fertilizer 8-24-16 (600 kg ha\(^{-1}\)). One month later, 33 kg ha\(^{-1}\) of a mixture of perennial ryegrass (*Lolium perenne* L. var. Barbestra) and white clover (*Trifolium repens* L. var. Huia) were sown.

In March 1998, sixteen subplots, each 10 \(\times\) 40 m\(^2\), were delimited in the experimental plot. The size of the subplots was chosen to allow the dairy sludge to be spread in a single application (using a vacuum tanker fitted with a splash plate). The following treatments were distributed at random in the plots: T0 (control without fertilizer), T1 (dairy sludge), T2 (dairy-sludge supplemented with K) and T3 (NPK mineral fertilizer). There were four replicates of each treatment. In treatments T1 and T2, two applications of 80 m\(^3\) ha\(^{-1}\) of dairy sludge were made, the first in March and the second one in June, after cutting silage in order to encourage regrowth. The sludge application rate was chosen on the basis of results of a previous study (López-Mosquera *et al.*, 1998). The K supplement (treatment T2) was provided by using 50 % K\(_2\)O commercial potassium sulphate (175 kg ha\(^{-1}\)). For T3 treatment 675 kg ha\(^{-1}\) of a 15-15-15 commercial fertilizer were applied in March and 290 kg ha\(^{-1}\) of ammonium nitrate (20.5 % N) and 120 kg ha\(^{-1}\) of potassium sulphate (50 % K\(_2\)O) in June. The annual inputs from these treatments are shown in Table 1. No attempt was made to equalize the levels of nutrients in the different treatments, as the aim was to compare the different management methods (organic and mineral fertilization).

Table 1

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N</th>
<th>P</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (Dairy sludge)</td>
<td>134</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>T2 (Dairy sludge + K)</td>
<td>134</td>
<td>30</td>
<td>147</td>
</tr>
<tr>
<td>T3 (Mineral fertilization)</td>
<td>160</td>
<td>44</td>
<td>134</td>
</tr>
</tbody>
</table>

The sludge used was supplied by Lactalis-Leche de Galicia S.A., a company that processes and packages UHT milk throughout the world. The initial by-product generated by this dairy industry is an effluent that contains milk, water (used to wash equipment) and also sodium hydroxide and nitric acid (used as cleaning products). The effluent undergoes a biological treatment that converts it into a semiliquid sludge, the main characteristics of which are shown in Table 2. The sludge contains high levels of N (93 % of which is organic), P and Na but low levels of K. The ratio of C/N is low indicating that it is easily mineralizable. The levels of heavy metals are below the levels permitted by European legislation for sewage sludge (Table 3).
Soil and plant analysis

Soil samples were collected at four different times over a period of one year. The first samples were taken in March 1998 after establishing plots but before applying fertilizing treatments. The aim of this sampling was to check the homogeneity of the subplots. Three subsequent samples were collected in June, September and November at times of forage utilisation (silage production in spring and grazing of beef cattle in autumn).

Sampling was carried out using a hollow cylindrical corer with an internal diameter of 7 cm. Six subsamples, each 15 cm deep, were taken following a zig-zag path across the centre of each plot.

Soil samples were air dried and passed through a 2 mm sieve. The pH in water was determined using a w/v ratio of 1:2.5. Electrical conductivity was measured in a saturated extract (Richards, 1954). Exchangeable cations were extracted using w/v ratios of 1:100 soil:NH₄Cl 1M (Peech et al., 1947) and determinations made of Al using colorimetry with pyrocatechol violet (Dougan and Wilson, 1974), Ca and Mg by atomic absorption spectrophotometry, and Na and K by emission spectrophotometry. Extractable P was analyzed using a modification of Olsen’s method (Olsen and Dean, 1965). Total C and N contents were measured by combustion analysis (LECO-2000). The NaF test (used to indicate whether a soil contains components that may lead to P retention) was carried out according to the method of Fieldes and Perrot (1966).

Forage production was evaluated in the first cut of the sward (a silage cut). Forage was cut with a rotary mower in an area of 5 m² in the centre of each plot and weighed with a suspended spring balance. A representative sample of herbage was dried to constant weight for 48 h at 65 °C to estimate total dry-matter (DM) yield per ha.

<table>
<thead>
<tr>
<th>Date of Application</th>
<th>Dry wt (g L⁻¹)</th>
<th>pH</th>
<th>E.C. (dS m⁻¹)</th>
<th>C</th>
<th>S</th>
<th>N</th>
<th>P (%)</th>
<th>K</th>
<th>Na</th>
<th>Ca</th>
<th>Mg</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 98</td>
<td>11.6</td>
<td>7.3</td>
<td>2.2</td>
<td>33.9</td>
<td>0.2</td>
<td>6.4</td>
<td>1.4</td>
<td>1.3</td>
<td>4.4</td>
<td>2.0</td>
<td>0.3</td>
<td>5.3</td>
</tr>
<tr>
<td>June 98</td>
<td>15.4</td>
<td>7.3</td>
<td>3.7</td>
<td>33.7</td>
<td>0.2</td>
<td>6.1</td>
<td>1.5</td>
<td>1.1</td>
<td>3.1</td>
<td>2.2</td>
<td>0.3</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 2
Characteristics of dairy sludge at times of application

<table>
<thead>
<tr>
<th>Date of Application</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Cd</th>
<th>Hg</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 98</td>
<td>17.3</td>
<td>8.9</td>
<td>47.8</td>
<td>427.2</td>
<td>0.2</td>
<td>0.3</td>
<td>13.7</td>
</tr>
<tr>
<td>June 98</td>
<td>20.2</td>
<td>12.9</td>
<td>65.9</td>
<td>475.1</td>
<td>0.4</td>
<td>0.1</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Table 3
Heavy metal contents of dairy sludge (mg kg⁻¹) at times of application

* For soils with pH < 7 (E.U. Directive 86/278/CEE, 12 June 1986) where sewage sludge is applied.
a, b, c For each time period after application of treatments, values followed by a different letter within a row are significantly different at p < 0.05.
All data were subjected to a one-way ANOVA, using the LSD test, with SPSS statistical software (Norusis, 1994). The level of significance for statistical analyses was established at $P < 0.05$.

**RESULTS**

Results of the initial test of homogeneity showed no significant differences among the 16 experimental plots in almost all of the soil parameters studied. The only exception was that the control plots contained significantly higher levels of Mg than other plots (Table 4).

**pH**

Treatment with dairy sludge (T1) led to the greatest increase in pH (Fig. 1). This increase was evident 6 months after the sludge was applied and continued until the end of the experiment, when the pH in the T1 plots was 6.09. In contrast, use of the mineral fertilizer (T3) resulted in pH values that were lower than in the control and the other treatments. Supplementation of the sludge with potassium sulphate (T2) did not produce significant changes compared to the control plot.

**Electrical conductivity**

Three months after application of treatments, the highest levels of salinity (expressed as electrical conductivity) were found in the plots treated only with sludge (T1), with values of up to 0.23 dS m$^{-1}$ being reached. These differences disappeared in the months following treatment (Table 5).
Table 4
Main soil properties of the different plots before the start of the experiment. Values given are means and standard deviations (in brackets)

| Treatment | pH \((\text{H}_2\text{O})\) | E.C. \((\text{dS m}^{-1})\) | C \(\%\) | N \(\%\) | eCEC | Ca \((\text{cmol}(+) \text{kg}^{-1})\) | Mg \((\text{cmol}(+) \text{kg}^{-1})\) | Na \(\text{mg kg}^{-1}\) | K \(\text{mg kg}^{-1}\) | Al \(\text{mg kg}^{-1}\) | P \((\text{mg kg}^{-1})\) | NaF test \((2 \text{ min})\) |
|-----------|-----------------|-----------------|------|------|-----|---------------|---------------|--------|--------|--------|--------|--------|-----------------|
| T0        | 5.63a\,(0.08)  | 0.20a\,(0.02)  | 4.66a| 0.35a| 3.96a| 1.50a         | 0.82a         | 0.35a  | 0.18a  | 1.11a  | 22.21a | 10.41a |
| T1        | 5.51a\,(0.07)  | 0.22a\,(0.02)  | 4.73a| 0.34a| 3.50a| 1.20a         | 0.53b         | 0.35a  | 0.20a  | 1.22a  | 18.92a | 10.57a |
| T2        | 5.46a\,(0.07)  | 0.20a\,(0.04)  | 5.03a| 0.37a| 3.46a| 1.20a         | 0.57b         | 0.35a  | 0.17a  | 1.17a  | 21.67a | 10.38a |
| T3        | 5.50a\,(0.16)  | 0.21a\,(0.02)  | 4.62a| 0.34a| 3.36a| 1.15a         | 0.70b         | 0.34a  | 0.17a  | 1.01a  | 19.51a | 10.41a |

\(^a,b\) Values followed by a different letter within a column are significantly different at \(p < 0.05\).
Table 5

Levels of electrical conductivity (E.C.), C, N and extractable P in soil, 3, 6 and 8 months after application of the first treatment. Values given are means and standard deviations (in brackets).

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>3 months after application</th>
<th>6 months after application</th>
<th>8 months after application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Treatment</td>
<td>Treatment</td>
<td>Treatment</td>
</tr>
<tr>
<td></td>
<td>T0</td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td>E.C. (dS m⁻¹)</td>
<td>0.16a</td>
<td>0.23b</td>
<td>0.17a</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>C (%)</td>
<td>4.96a</td>
<td>5.23a</td>
<td>4.79a</td>
</tr>
<tr>
<td></td>
<td>(0.15)</td>
<td>(0.34)</td>
<td>(0.37)</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.34a</td>
<td>0.37a</td>
<td>0.34a</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.03)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>Olsen P (mg kg⁻¹)</td>
<td>15.93a</td>
<td>34.79b</td>
<td>22.00a</td>
</tr>
<tr>
<td></td>
<td>(3.62)</td>
<td>(5.41)</td>
<td>(7.44)</td>
</tr>
</tbody>
</table>

a, b, c For each time period after application of treatments, values followed by a different letter within a row are significantly different at p < 0.05.
C, N, P

No significant differences were found in the total contents of C and N either among treatments or throughout the course of the experiment (Table 5).

In all samplings, the highest concentrations of extractable P were found in the plots treated only with sludge (T1) (Table 5). The NaF test indicated that the soil at the experimental site had a high capacity for retaining this element because in all cases the pH value was higher than 10 after the samples were in contact with the test solution for 2 and 60 minutes (Table 4).

Exchange capacity

For all treatments, the effective exchange capacity was very low and never rose above 4 cmol (+) kg⁻¹ throughout the course of the experiment (Table 6). The dominant cation was Ca followed by Mg, Na and K.

Three and eight months after dairy sludge application, Ca levels were significantly higher than in control plots (Table 6). An increase in Mg content was found in treatments T1 and T2 compared to T0 three months after the start of the experiment. However, levels of Mg in T1 and T2 treatments significantly decreased compared to the control in the third sampling. The mineral fertilizer (T3) did not modify the Mg content in the soil, which remained similar to the levels in the control plots. No significant differences were found in levels of Na or K throughout the course of any of the treatments, or among treatments (Table 6). The percentage of exchange sites occupied by Al was 31.9 % and was not affected by any treatment.

Forage production

Forage yields in subplots receiving any fertilizer (either sludge or mineral NPK) were 50 % greater than control yields, with no differences being found among fertilizing treatments (Fig. 2).

![Fig. 2.—Forage production (measured when silage was cut) following the different treatments. Values shown are means and standard errors (n = 4). Values represented by bars with the same letter are not significantly different at P < 0.05. The treatments were: T0: control, T1: dairy sludge, T2: dairy sludge + K, T3: mineral fertilizer](image-url)
Table 6

Levels of eCEC and exchangeable cations in soil, expressed as cmol (+) kg⁻¹, 3, 6 and 8 months after application of the first treatment. Values given are means and standard deviations (in brackets).

<table>
<thead>
<tr>
<th>Soil properties cmol (+) kg⁻¹</th>
<th>3 months after application Treatment</th>
<th>6 months after application Treatment</th>
<th>8 months after application Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T0</td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td>eCEC</td>
<td>3.03a (0.53)</td>
<td>3.69a (0.49)</td>
<td>2.85a (0.38)</td>
</tr>
<tr>
<td>Ca</td>
<td>0.95a (0.60)</td>
<td>1.25b (0.19)</td>
<td>0.80a (0.28)</td>
</tr>
<tr>
<td>Mg</td>
<td>0.45bc (0.16)</td>
<td>0.74b (0.21)</td>
<td>0.53bc (0.09)</td>
</tr>
<tr>
<td>Na</td>
<td>0.35b (0.04)</td>
<td>0.37b (0.02)</td>
<td>0.35a (0.04)</td>
</tr>
<tr>
<td>K</td>
<td>0.17a (0.05)</td>
<td>0.19a (0.04)</td>
<td>0.18a (0.03)</td>
</tr>
<tr>
<td>Al</td>
<td>1.11a (0.14)</td>
<td>0.99a (0.33)</td>
<td>1.15a (0.47)</td>
</tr>
</tbody>
</table>
DISCUSSION

The increase in pH and exchangeable Ca in plots treated exclusively with sludge (T1) indicate that this waste product acts as a liming agent. The effect was evident from the start of the experiment and was maintained for 8 months after application. Similar results have been found by De Lauzanne and Merillot (1986) and López Mosquera et al. (unpublished data). Liming effects on soils have also been reported for sewage sludges (Narval et al., 1983; Costa et al., 1987; Hue et al., 1988). In contrast, there was a decrease in pH in plots treated with mineral fertilizer (T3), which may be explained by the acidifying effect known to be produced when certain mineral fertilizers are used (Sluijsmans, 1966). The liming effect produced by treatment T2 was intermediate compared to the other treatments, perhaps because of the acidifying effect of potassium sulphate. The increase in salinity and the increased electrical conductivity (3 dS m⁻¹) observed in plots treated with dairy sludge only (T1) were mainly due to the Na input from the sludge (50 kg ha⁻¹). The soluble salt content of sludges is extremely variable and essentially depends on the source of the sewage and types of treatments carried out (Pomares, 1982). Dairy sludges are usually characterized by their high Na content (Morisot and Gras, 1974; Guichet, 1987; García et al., 1999). When applied at high dosages in arid or semi-arid regions, they can produce toxic effects in crops that are sensitive to high salinity. In our case, the values of electrical conductivity were always lower than 4 dS m⁻¹, which corresponds to non-saline soils. Similarly, the percentage of exchangeable sodium was always less than 15 % (EPS<15 %), indicating that there were no adverse salinity effects. Six and eight months after dairy sludge application, rainfall had led to a reduction in electrical conductivity.

As expected, the organic matter content in the dairy sludge was low (3.9 kg C per m³ sludge), since dairy sludges are very diluted wastes (average dry extract 13 g L⁻¹). This explains why total C and N levels did not increase in plots treated with dairy sludge during the period of the study, a result that agrees with previous studies (De Lauzanne and Merillot, 1986; López-Mosquera et al., 1999). The ratio of C/N was also narrow (5.4), which indicates that the organic matter was easily mineralizable (Chaussod and Germon, 1977). Therefore, sludge application (at the dosages used here) is not an effective way of increasing the soil humus content.

The dairy sludge is, however, a useful fertilizer and a good source of P, especially in soils that retain this element. In this study, the soil had high P retention but, in the plots treated with sludge, the concentration of extractable P reached as high as 34.8 mg kg⁻¹ three months after fertilization. This P content was higher than those of other fertilizing treatments in spite of the fact that the dairy sludge contributed less P (70 kg ha⁻¹) than the mineral fertilizer (100 kg ha⁻¹) (Table 1). The P present in sewage sludge is usually considered to be readily available, even in soils with a high phosphate fixation capacity (Sommers and Sutton, 1980; McLaughlin and Champion, 1987). Several authors (Gupta and Hani, 1979; Furrer et al., 1984) have observed that the availability of P in sewage sludges is greater or similar to that of mineral fertilizers. The greater availability of P to plants in soils fertilized with sewage sludges may be due to the input of organic compounds, which help to overcome the insolubility of P in these soils. These effects are more marked when soil conditions favour P retention, as in the case of calcareous soils (Ayuso et al., 1992) or, as in this case, in acid soils containing non-crystalline Fe and Al components (Garcia-Rodeja and Macías, 1983).
None of the treatments produced any substantial increase in eCEC, as the pH did not increase greatly and variable charge exchange sites were not generated. As in the study carried out by Morisot and Gras (1974) there were no changes in the exchange capacity following treatments T1 and T2. It would be expected, however, that continuous input of this residue would, in time, lead to increases in eCEC, as found by Guichet (1987) in soils subjected to long term treatments of up to 25 years.

Comparison of forage production showed that there was very little difference between treatments T1 and T2, which appears to indicate that the K supplementation did not offer any advantage over the sludge-only treatment throughout the period of the study. This might have been because the soil was poor in basic cations and thus adsorbed Ca and Mg (supplied by the sludge) in preference to K. Therefore, some of the K added may have been lost by leaching (Lemaire et al., 1983).

In spite of changes in soil fertility due to treatments, there were no significant differences in crop yield at the time of silage cutting. At an application rate of 160 m³ ha⁻¹ year⁻¹, the sludge was as effective, in the short term, as the mineral fertilizer in supplying the nutrients necessary for forage production. Morisot and Gras (1974) also found increased yields in grassland fertilized with dairy sludges that they attributed to fertilizing elements and water supplied by the effluents.

In conclusion, dairy sludges can provide an alternative to the use of mineral NPK fertilizers, either alone (at suitable dosages and times) or in combination with them, for soils in the study area. Our results also showed that dairy sludges had a liming effect on soil and improved the availability of nutrients, especially phosphate, without producing adverse effects on soil fertility.

ACKNOWLEDGEMENTS

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RESUMEN

Efectos de la aplicación de lodos procedentes de industrias lácteas sobre un suelo ácido

En este trabajo se han comparado los efectos a corto plazo de la aplicación de lodos de industrias lácteas con o sin suplemento de K, a una dosis de 160 m³ ha⁻¹, con respecto al abonado mineral convencional utilizado en praderas polifitas del noroeste español. La experiencia se llevó a cabo en condiciones de campo. El suelo de la parcela experimental tenía muy baja capacidad de cambio, elevado porcentaje de saturación en Al y fuerte retención de P. En esta parcela se establecieron 16 subparcelas en las que se probaron distintos tratamientos: T0 (control), T1 (fertilización con lodo), T2 (fertilización con lodo suplementado con K) y T3 (fertilización mineral). Se realizó un seguimiento de los suelos durante los ocho meses siguientes a la aplicación de las distintas fertilizaciones y de la producción de forrajaje en el corte de silo. Los resultados obtenidos ponen de manifiesto que este lodo, con o sin K, en comparación con el abonado mineral, posee cierta capacidad encalante, eleva el pH, así como los niveles de Ca de cambio del suelo y reduce el porcentaje de saturación en Al. Constituye una fuente interesante de P, sobre todo en suelos con problemas de retención en este elemento y en ningún momento se alcanzaron niveles de salinidad limitantes. A pesar de las diferencias de fertilidad encontradas en el suelo se-
gún los distintos tratamientos aplicados, no se observaron diferencias significativas en la producción del corte de silo. Se puede decir que este lodo aplicado a una dosis de 160 m$^3$ ha$^{-1}$ año$^{-1}$ fue tan eficaz como el fertilizante mineral en el suministro de nutrientes para el forraje a corto plazo.

Palabras clave: producción forrajé, sostenibilidad

REFERENCES


