Spatial and temporal patterns of soil available potassium on grazed permanent pastures – perspectives of differential fertilization

João Serrano, José Marques da Silva and Shakib Shahidian, ICAAM, University of Évora, P.O. Box 94, 7002-554 Évora, Portugal

Abstract

Alto Alentejo region in Southern Portugal has over 200,000ha of grazing permanent pastures. Here, the soils do not generally need potassium (K) fertilization due to the bedrock richness in K. The general objective of this study was to evaluate the specificity of the spatial and temporal soil K dynamics, over ten years, in a complex agro ecosystem (a bio-diverse pasture installed on a shallow soil, grazed by sheep, in Mediterranean conditions) and the potential for implementing site specific fertilizer management. A simplified model, based only on plant K uptake and animal return and losses was used to carry out a K field gate budget estimation. The K spatial trend and K temporal stability were evaluated by a single map of management classes. The evolution of mean soil K concentration in the experimental field over the 10-year study ranges, in relative terms, between -21% and +16% of the overall average of the period considered (96 ± 21 mg kg\(^{-1}\)). This behaviour suggests that grazed pastures, as far as the K cycle is concerned, are a “steady state” system. Significant correlation coefficients were found between the soil K concentration and altimetry (0.614), clay (0.651), sand (-0.674), phosphorus (0.749), organic matter (0.882) and pasture dry matter yield (-0.499). It can be stated that the combined effects of an undulated landscape, with sparse trees and animals that selectively graze the plant species and make a heterogeneous deposition of dung and urine, provide a notable spatial variability of soil K concentration (Spatial CV of 29.8 ± 12.3%). The K temporal stability (Temporal CV of 18.1 ± 8.6%), is confirmed by the predominance of moderately stable (56.6% of the experimental field) and of stable areas (25.0% of the experimental field). Within the classes identified as moderately stable and stable, around 45% of the experimental field shows soil K concentrations below average soil K concentration. Based on regional recommendation of 125-150 mg kg\(^{-1}\) of K in the soil to adequately promote the development of dry-land permanent pastures this study demonstrates the interest and the potential for using variable rate technology (VRT) for site-specific K management in pastures in Southern Portugal.

Keywords: Potassium, pastures, grazing animal, VRT

1. Introduction

In recent years cycling of K in grassland systems has received relatively little attention in research and practice (Kayser and Isselstein, 2005). Traditionally, four forms or pools of soil test K have been recognized: a) structural or mineral K (having an essentially geochemical origin as a consequence of weathering of primary minerals, such as mica and feldspar); b) non-exchangeable K (specific adsorption), also referred to as fixed K or interlayer K (fixed in 2:1 layer clay minerals, such as illite and montmorillonite); c) exchangeable K; and d) K in soil solution (Jalali, 2007). These fractions constitute a dynamic system in equilibrium, with
reversible K transfer between these pools (Askegaard et al., 2003). Thus, all factors that affect these equilibrium reactions will indirectly affect the size of the different K pools (Öborn et al., 2005). Exchangeable and soil solution K (measured together as available K) are readily taken up by plant roots, while both fixed and structural K are only slowly or potentially available, reserves that can be used to replenish exchangeable K (Öborn et al., 2005), and are a measure of the long-term ability of each soil type to supply K by weathering (Campkin, 1985).

Several studies have shown that release of K from the structural or the fixed fractions can contribute significantly to plant supply (Öborn et al., 2005). However, the rate of release of K from these forms is very slow and depends on the mineral weathering process. The susceptibility of different soil mineralogies to weathering and release of K represents a potentially important property (Andersson et al., 2007), and these contributions should be viewed as a valuable long-term supply of K, which increases the possibility of optimising the use of soil nutrients while at the same time minimising leaching losses from the agricultural system (Holmqvist et al., 2003). The clay and clay loam soils are most suitable for maintaining adequate soil K exchangeable where no or small applications of K fertilizer are made.

Another aspect to consider in the K balance is the texture effect on K leaching. Potassium is a soluble ion that is easily leached in soils where adsorption capacity is low (e.g. coarse-textured soils). Significant amounts can be lost by leaching in grazed areas, mainly by flow after urination or by percolation after rainfall (Alfaro et al., 2004). Leaching of K is not considered a problem in soils with high clay content, but losses of K in coarse sandy soils with little clay content and low K inputs can become a limiting factor in the development of negative K balances due to their low cation exchange capacity (Zhang et al., 2013).

To generalize these findings further, the soil mineralogical composition and its potential weathering capacity and leaching risk need to be taken into account when deciding on the fertilizer requirements of a given field (Andersson et al., 2007). Given the importance of K in the quality of crops and since traditional uniform fertilizer application in areas with spatial variation in soil properties could result in points of fertilizer application above or below the required doses (Mallarino and Wittry, 2004), it is important to evaluate the potential for implementation of Variable Rate Technology (VRT) to match fertilizer application with crop needs (Jalali, 2007). Jalali (2007) confirmed that locally variable fertilizer recommendations based on large scale maps of soil fertility can contribute to maintaining agricultural sustainability.

Variable-rate fertilizer application requires previous knowledge of soil nutrients management zones within fields. At a field scale, the main factors influencing variability are soil type, topography, and previous crop and soil management practices (Mallarino and Wittry, 2004). For grassland systems, the catalyzing component is the animal, which recycles the vegetative material and modifies the dynamics of nutrient cycling (Carvalho et al., 2010). Grazing animals play, therefore, a dominant role in soil pasture fertility, where the concentration of nutrients in urine and dung patches within the main grazing area and other areas causes a mosaic of nutrient concentrations (Kayser and Isselstein, 2005). Soil nutrient concentrations are particularly high at stock camps, i.e. sites where the animals congregate spontaneously (Dahlin et al., 2005). This flow of nutrients across different areas of the field can cause imbalances and tends to increase the possibility of nutrients loss (Alfaro et al., 2003). It also highlights the interest of VRT to restore balance and promote pasture productivity taking into account the variability of K in the soil as a result of mineral weathering and leaching processes but also as a result of animal grazing.

A number of methods have been used by different research teams to assist farm managers in defining the spatial and temporal trends found within a field (Blackmore, 2000; Blackmore et al., 2003; Xu et al., 2006; Serrano et al., 2011). Soil nutrient spatial variability and temporal stability are two conditions which may justify the differential management and are the basis for spatially variable fertilization. A spatial and temporal map trend can help to distinguish between different areas of the field in relation to their soil characteristics (Blackmore et al., 2003) and to develop site-specific management strategies for each field in subsequent seasons (Xu et al., 2006). A popular approach to managing within field variation is the use of management zones, sub-regions of a field that have a relatively homogeneous combination
of yield-limiting factors and for which a single rate of a specific crop input would be appropriate. If a spatial pattern is temporally stable within a field, then it is reasonable to suppose that it should be a good predictor of the spatial patterns in the following years. Blackmore et al. (2003) emphasised the difficulty inherent to the selection of threshold values that distinguish between temporal stability and instability. Previously, a particular threshold value for the temporal CV of 30% was used by Blackmore (2000) for cereal crops and two threshold values (15 and 25%) were used by Xu et al. (2006) for grassland. Few data are available in relation to K balances in grassland systems and little is known about their dynamics under grazed pasture ecosystem in Mediterranean conditions. The general objective of this study was to evaluate the specificity of the spatial and temporal soil test K dynamics, over ten years, in a complex agro ecosystem (a bio-diverse pasture installed on a shallow soil, grazed by sheep, in Mediterranean conditions) and the potential for implementing site specific fertilizer management.

2. Materials and Methods

2.1 Site characteristics and field management

The experimental field, with an area of about 6 ha, is located at the Revilheira farm (38°27′51.6″N and 7°25′46.2″W), about 40 km northeast of Évora in Southern Portugal, where pastureland use of soil is particularly important. The predominant soil of this field is classified as a Leptic Luvisol (FAO, 2006). The general characteristics of the soil are: clay loam texture; low organic matter concentration (< 2%); slightly acid; relatively rich in potassium; poor in nitrogen and phosphorus. A permanent bio-diverse pasture was established in this field in September 2000 and until 2003 the field was grazed by sheep and maintained by an annual homogeneous fertilization of 300 kg ha⁻¹ of super phosphate fertilizer 18% (SP18) (54 kg P ha⁻¹). Between 2004 and 2013 the field was subjected to two periods of intervention: i) field management 1 (2004–2007), the field was used for grazing by sheep and improved by an annual and variable-rate application of SP18, consisting of four differential application rates (80, 60, 30 and 0 kg P ha⁻¹) based on classes of existing soil test P concentration; ii) field management 2 (2007–2013), the field was left fallow without any animal grazing or fertilizer application. A topographic survey of the area was carried out using a Real Time Kinematic (RTK) GPS instrument (Trimble RTK/PP - 4700 GPS, Trimble Navigation Limited, USA). The elevation data were sampled in the field with an all-terrain vehicle. The bedrock depth of the experimental field was determined using a pneumatic gouge auger in twenty geo-referenced samples (56 m × 56 m grid). The depths were organized into four classes, namely: 0-0.20 m; 0.20-0.30 m; 0.30-0.50 m; and more than 0.50 m. At the lower positions and in the slope areas, the typical bedrock depths were more than 0.50 m, with a tendency for smaller depths (< 0.20 m) at the higher relative field elevations.

2.2 Soil and pasture sample collection and analysis

Soil and pasture spatial variability of the experimental field were characterized by 76 samples, geo-referenced with GPS, from the whole field (one from each 28 × 28 m square). The soil was characterized in terms of texture, pH, organic matter content and macronutrients (N, P and K). The soil samples were collected using a gouge auger and a hammer, in a depth range of 0–0.30 m. Each composite sample was the result of five sub-samples, one taken from the center of the square, and the other four taken near the corners of the square. The K soil content was extracted by the Egner-Riehm method (Egner and Riehm, 1955). The pasture samples of 1 m² areas were collected using manual shears where the pasture had been protected from grazing, using pre-installed boxes (exclusion-cage) at the southeast corner of each square in the grid. Sampling was carried out each year from March to May, depending on the vegetative growth stage of the pasture. The collected samples were stored
in marked plastic bags and taken to the Pasture and Forage Laboratory of the University of Évora. These samples were stored in bags and weighed to determine the green matter production per hectare, and subsamples in small paper bags were placed in a 65°C oven for 48h to determine the pasture forage moisture content, which was used to calculate pasture dry matter yield (DM).

### 2.3 Statistical treatment

The surface maps of soil parameters and DM were developed in ArcGIS 9.3, using a 5 m grid inverse-squared-distance interpolator.

The linear correlation coefficients between K and altimetry, soil and pasture parameters were calculated, for the set of sampling years. A statistical significance level of $p<0.05$ was used.

The spatial trend in soil test K concentration was calculated as the mean value ($\bar{y}_i$, Eq. 1) at the $i^{th}$ sampling point over the 10-year period (Blackmore, 2000; Xu et al., 2006; Serrano et al., 2011):

$$\bar{y}_i = \frac{1}{n} \sum_{t=1}^{n} y_{it}$$

where $y_{it}$ is the soil test K concentration (mg kg$^{-1}$) at the sampling point $i$ at time $t$ and $n$ is the number of sampling years.

The average K spatial coefficient of variation (Spatial CV) was calculated as the average value of CV obtained in all the soil sampling years (Eq. 2):

$$\text{Spatial CV} = \frac{1}{n} \left( \sum_{i=1}^{n} CV_i \right)$$

where $n$ is the number of soil sampling years.

The temporal stability of soil test K concentration was determined by calculating the CV at each sampling point over time (or Temporal CV, Eq. 3) using the method presented previously by Blackmore (2000), Xu et al. (2006) and Serrano et al. (2011) to assess the temporal stability of crop yields, cereals, grassland and pasture, respectively and phosphorus soil concentration.

$$\text{Temporal CV}_i = \left( \frac{\left( \frac{1}{n} \sum_{t=1}^{n} y_{it}^2 - \left( \frac{1}{n} \sum_{t=1}^{n} y_{it} \right)^2 \right)^{0.5}}{y_i} \right) \times 100$$

where Temporal CV$_i$ is the coefficient of variation over time at sampling point $i$.

The average K temporal coefficient of variation (Temporal CV) for each year for all sampling points was calculated as follows (Eq. 4) (Xu et al., 2006):

$$\text{Temporal CV} = \frac{1}{m} \sum_{i=1}^{m} CV_i$$

where $m$ is the number of soil sampling points.
Although the two techniques described above quantify the K spatial trend and K temporal stability, they can be combined further into a single map of management classes, which can be used for future decision making (Serrano et al., 2011). This classified management map is a synopsis of the important features found in the spatial trend and temporal stability maps (Blackmore, 2000). Five different classes were considered in this study and already used by Xu et al. (2006) and Serrano et al. (2011): 1- greater than mean soil test K concentration and stable in time; 2- greater than mean soil test K concentration and moderately stable in time; 3- smaller than mean soil test K concentration and stable in time; 4- smaller than mean soil test K concentration and moderately stable in time; and 5- unstable in time. Each sampling point was represented by a coded value. The sampling points were classified by applying combinational logic statements to the spatial variation and temporal stability data sets, considering the following conditions: condition 1 (relative soil test K concentration) identifies whether the value is greater or smaller than the mean of all sampling points for all the years; condition 2 (temporal stability) identifies the stability of soil test K concentration (mg kg\(^{-1}\)) at a particular point by comparing the CV to two arbitrary thresholds (15 and 25%). A point was considered to belong to a particular class if both conditions were true, and it was then assigned a class code shown in brackets.

3. Results and Discussion

Table 1 presents the significant correlation coefficients between average soil test K concentration and other soil parameters, altimetry and DM.

Table 1: Significant correlation coefficients between average soil test K concentration and other soil parameters, altimetry and pasture dry matter yield.

<table>
<thead>
<tr>
<th>Properties Altimetry</th>
<th>P</th>
<th>O.M.</th>
<th>Clay</th>
<th>Sand</th>
<th>SMC</th>
<th>D.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m] [[mg kg(^{-1})]</td>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
<td>[kg ha(^{-1})]</td>
</tr>
<tr>
<td>K [mg kg(^{-1})]</td>
<td>0.614**</td>
<td>0.749**</td>
<td>0.882**</td>
<td>0.651**</td>
<td>-0.674**</td>
<td>0.455*</td>
</tr>
</tbody>
</table>

O.M.- Organic matter; SMC- Soil moisture content; D.M.- Pasture dry matter yield; **Correlation significant at the 0.01 level; * Correlation significant at the 0.05 level;

Figure 1 shows, the soil test K concentration maps: i) at the beginning of the pasture evaluation (September of 2004); ii) after removal of the animals from pasture (May of 2007); and iii) at end of study (February of 2013).

The idea of apparent equilibrium with respect to the K cycling shared by the farmers in this region, who base their K fertilization on one or two soil analyzes, not taking into account the spatial soil variability, can be questioned when detailed soil sampling is performed.

The synopsis of the important features identified in the K spatial variation and K temporal stability of the experimental field is shown in Figure 2. The purpose of the resulting map of K management classes is to help to identify homogenous areas for research or treatment (Blackmore, 2000; Serrano et al., 2011). Maps showing the spatial patterns of soil and pasture variables within the individual fields are the basic components of new site-specific approach to crop management. Assessments of temporal stability are equally important, because if the spatial patterns of the crop yields vary significantly from year to year and if they are unpredictable, site specific management would not be feasible (Xu et al., 2006).

With the arbitrary 15 and 25% threshold for the K temporal CV and contrary to what was identified in the same field regarding soil test P concentration, in which the unstable class represents 83% of the total area (Serrano et al., 2011), the unstable areas of soil test K concentration (class 5, 18.4%) mean that it is possible to implement site-specific management. Xu et al. (2006) confirm that high degree of temporal stability coupled with well-defined spatial patterns suggest that there is a real opportunity for site-specific management. As a practical implication of the trend maps, these results justify a reassessment of this unstable area to identify the mechanisms that may underlie the
temporal instability of K concentration, because it is not possible to make management decisions on temporarily unstable information.

Figure 1: Potassium (K) of the experimental field in 2004, 2007 and 2013.

Figure 2: Map of K management classes of the experimental field.
(1- Greater than field mean concentration and stable; 2- Greater than field mean concentration and moderately stable; 3- Less than field mean concentration and stable; 4- Less than field mean concentration and moderately stable; 5-Unstable)

An aspect that affects the K temporal stability relates to the presence of free grazing animals (sheep) in the experimental field: their faeces, which are rich in K, tend to concentrate (heterogeneous excreta deposition) in the rest areas, which correspond to the higher areas of the field (hill top areas in the west), locations where soil test K concentrations were > 125 mg kg\(^{-1}\) and where the temporal CV was higher (unstable areas, Figure 2). A practical and effective site-specific management strategy can be developed in this field to create two or three separate management sub-units for differential K fertilizer application, optimizing fertilizer use and minimizing the spatial variation in pasture yield. It can be stated that the classified management map gives the field manager an indication whether to focus on spatial or temporal management (Blackmore, 2000).
4. Conclusions

The evolution of mean soil test K concentration in the experimental field over the 10-year study suggests that grazed pastures, as far as the K cycle is concerned, are a system in equilibrium. This study, however, shows that the experimental field is dominated by a large spatially anisotropic trend. Significant correlation coefficients were found between the soil test K concentration and altimetry (0.614), clay (0.651), sand (-0.674), P (0.749), organic matter (0.882), SMC (0.455) and DM (-0.499). It can be stated that, among other factors (such as soil erosion and deposition), the long-term combined effects of an undulated landscape, with sparse trees and animals that selectively graze the plant species and make a heterogeneous deposition of dung and urine, originates spatial redistribution of nutrients and provides a notable spatial variability of soil test K concentration. The K temporal stability is confirmed by the predominance of the moderately stable (56.6% of the experimental field) and of stable areas (25.0% of the experimental field). Within the classes identified as moderately stable and stable, around 45% of the experimental field shows soil test K concentrations below average soil test K concentration. Based on the regional recommendation of 125-150 mg kg$^{-1}$ of K in the soil to adequately promote the development of dry-land permanent pastures, this study demonstrates the interest and the potential for using VRT for differential K management in pastures in Southern Portugal. Progress towards more efficient use of K also requires that site-specific recommendations be based on the understanding of the processes regulating K dynamics and their spatial and temporal variability.

5. Acknowledgements

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6. References


