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Recovering Fertility of Acidic Volcanic Ash Soils in the Araucania Region (South Chile): Impacts of Liming, Grassland Composition, and P Fertilisation.

Recuperación de la fertilidad de los suelos volcánicos ácidos del sur de Chile: Impactos del encalado y fertilización fosfatada

Toneatti-Bastidas, M.[a], **Roger-Estrade, J.**[b, c]*

[a] Escuela de Agronomía, Universidad Católica de Temuco, CL-15-D Temuco, Chile.
[b] INRA, UMR 211 INRA/AgroParisTech, F-78850 Thiverval-Grignon, France.
[c] AgroParisTech, UMR 211 INRA/AgroParisTech F-78850 Thiverval-Grignon, France.

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**Corresponding author:*
Jean Roger-Estrade
E-mail address:
estrade@grignon.inra.fr

ABSTRACT

The aim of this study was to assess the effect on soil quality of a governmental program whose objective is restoring the fertility of degraded acidic volcanic ash soils. The program consisted of (i) liming, (ii) correction of the P status, and (iii) sowing forage plants. We measured soil fertility of fields after 1 to 4 years since start of the program, and compared these fields against fields under old permanent natural grasslands, used to estimate the baseline soil test values for the properties considered in this study. The survey was conducted in five localities (Lonquimay, Curacautín, Vilcún, Cunco and Villarrica) in the temperate southern part of Chile (Araucania region). The impacts of the program on acidity (pH and exchangeable aluminum) were different among localities. At Cunco, exchangeable aluminum was not affected, while pH increased initially but decreased to its initial value within four years. Instead, at Lonquimay exchangeable aluminum decreased significantly, and pH remained slightly higher than the control values through the first four years. At Lonquimay P-Olsen was initially increased, showing a positive short-term effect of the program, but gradually decreased after the first year, until it returned to the initial level. At Vilcún, an increase with time was observed during the whole period. In Curacautín, Villarrica and Cunco, the P-Olsen content increased during the first years of the experiment but began to decline at the end of the period. This study provided important results for the improvement of the program.

RESUMEN

El objetivo de este estudio, realizado en el sur de Chile, fue evaluar los efectos sobre el suelo de un programa gubernamental cuyo objetivo es la restauración y mantenimiento de la fertilidad de suelos degradados. Éste consiste en encalado, corrección de fósforo, y establecimiento de praderas. En este estudio se midió la fertilidad del suelo de praderas con 1 a 4 años desde el inicio del programa y sin fertilización de mantención, y se comparó con praderas naturalizadas de más de 4 años, estas se consideraron representantes de suelos en estado natural de baja fertilidad, y fueron la línea base en los parámetros considerados en este estudio. La investigación se realizó en Lonquimay, Curacautín, Vilcún, Cunco y Villarrica. El impacto del programa sobre la acidez (pH y aluminio intercambiable) y disponibilidad de P fue diferente entre localidades. En Cunco, el aluminio intercambiable no se vio afectado, el pH aumentó inicialmente, reduciéndose a su valor inicial en el plazo de cuatro años, el contenido de P-Olsen aumentó al inicio y comenzó a decaer a finales del período, al igual que en Curacautín y Villarrica. En Lonquimay, el aluminio intercambiable disminuyó significativamente, el pH se mantuvo ligeramente superior al control durante los primeros cuatro años y el P-Olsen se incrementó en un principio pero disminuyó después del primer año al nivel inicial. En Vilcún, se observó un aumento durante todo el periodo. Este estudio proporcionó resultados importantes para mejorar el programa apoyando la necesidad de repetir las aplicaciones de fósforo y cal.

Palabras clave: Andisoles, fósforo, toxicidad de aluminio, acidez del suelo.

INTRODUCTION

In the Southern temperate part of Chile, andisols are the dominant soil type. In this area (the region Araucania), they are called «Trumaos». Those soils exhibit a clay fraction dominated by allophane, which induces a strong retention of phosphorus, and, consequently, a low availabilty of this nutrient, essential for plant growth (Mella and Khüne, 1985; Ellena *et al*., 2014; Nelson *et al*., 2014).

Moreover, acidity is high in those soils, which is also detrimental to phosphorus availability (Pinochet *et al*., 2005; Hashimoto *et al*., 2012; Meijas *et al*., 2013) and promotes a high level of aluminium (Al^{3+}), toxic for crops (Besoain, 1999; Hirzel *et al*., 2011). These characteristics strongly impede soil productivity, especially in the pastures, which are vital for small cattle breeders. Moreover, those characteristics are also detrimental to the growth of legumes (Ritchie, 1989). Therefore, native pastures of this region have a very low productivity and express a very specific flora, which consists essentially of grass, but contains also some legumes, adapted to the high acidity of the soil, and some other aluminium-tolerant species, adapted to an acidic environment (Mora *et al*., 2000).

Since they have been used for agriculture, these soils hardly received a low amount of mineral fertilizers, calcium and organic amendments. This has worsened the problems. Finally, overgrazing caused also problems of erosion. These conditions are very hard on the Mapuches farmers of this area, whose main activity is cattle breeding (ovine and bovine) and whose farms are very small.

As a response, since 1997 the State of Chile has developed a program called "Incentive System for the Recovery of Degraded Soils" (hereafter called the *SIRSD* program from the Spanish designation: Sistema de Incentivo para la Recuperación de Suelos Degradados), whose aim is to help producers improve the fertility of Trumaos soils. The program focuses on improving the availability of phosphorus through phosphate supplements and liming, in order to decrease acidity and the content of free aluminium in the soil. The program also aims at establishing a pasture (with variable compositions) to ensure a permanent coverage of the soil, thus limiting erosion and increasing productivity and quality of forages. The program also includes other actions (such as the creation of terrasses to prevent erosion, the set up of cover-crops). However, these have been seldom applied in the area object of this study, and therefore they will not be discussed in this paper.

This program has been operational for more than a decade. The aim of this study was to evaluate its effects on soil properties and on pasture productivity in the region of the Araucania, home of small producers Mapuche. In order to answer these questions, we selected a series of fields that participated in the program in four municipalities of the Precordillera and in one municipality of the Andes Cordillera. Our method was based on the comparison of native pastures with farmers' grasslands after they have received, 1 to 4 years before our survey, the program actions. We measured soil characteristics and grassland productivity, but in this paper, only the soil data are presented.

MATERIAL AND METHODS

Hypothesis on the effects of the SIRSD program on phosphorus availability

Arrows in Figure 1 shows relationships between program actions and changes expected in the soil. The liming supplied brings about an increase in the pH (Ordoñez *et al*., 2005). This, in turn, causes an increase in the mineralization of organic matter (arrow 1a) (Campillo, 1995) and, by favouring the insolubilization of aluminium, affects the quantities of exchangeable aluminium (arrow 1c). This in turn affects the P-Olsen content (arrow 3, De la Fuente and Herrera, 1999). The establishment of a pasture increases the restoration of organic matter, which leads to an increase of the amount of ions H^+ adsorbed on OM, contributing to the fixation of H^+ ions (arrow 1b). Phosphoric fertilizers affect directly phosphorus availability (Helyar, 1998). Finally, the productivity and the quality of the pasture should benefit from the decrease in pH (arrow 6), the decrease of exchangeable aluminium (arrow 5) and the increased availability of phosphorus (arrow 4).

Site description and experimental settings.

We worked in four municipalities in the precordillera zone of the Araucania region (Curacautín, Vilcún, Cunco and Villarrica) and in one municipality in the Cordillera area (Lonquimay). This area is located between the latitudes 38°27' and 39°16' south and between the longitudes 71°22' and 72°13 west. Climate is humid with an average annual precipitation amount of 2,300 mm and temperate cold: the mean temperature of the hottest month (January) is 16.1 °C and that of the coldest (July) is 7.4 °C; mean annual temperature is 11.4 °C (Gastó *et al*., 1993).

We analysed the soil in those fields, for two consecutive years, characterized by very different weather conditions: year 2007 was relatevely humid and hot, while year 2008 was marked by a severe drought, a cold winter and a cold beginning of spring.

We chose a synchronic approach. In each area, we selected fields that had not been subjected to the program (these old permanent grasslands were considered to represent the soils in their natural, poor fertility status, and therefore these soils were used to estimate the

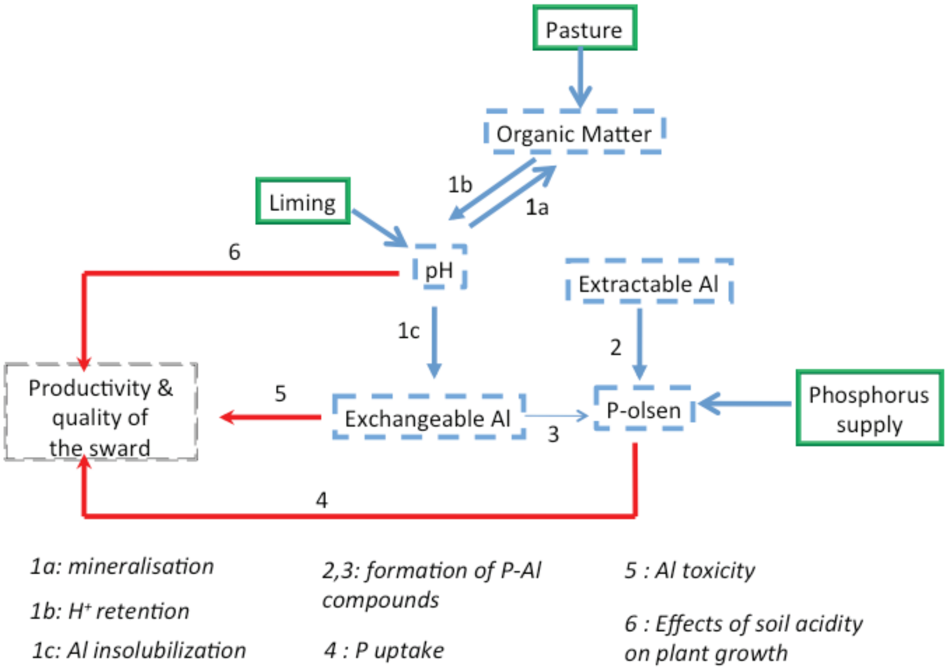

Figure 1. Hypothesis on the effects of the program SIRSD. The actions of the program (establishment of the pasture, liming, phosphoric fertilization) are boxed with continuous lines; the soil properties acted upon are boxed with thick dashed lines; the sought-after quality of the sward in thin dashed lines.

Figura 1. Hipótesis sobre los efectos del programa SIRDS. Las acciones del programa (establecimiento de praderas, encalado, fertilización fosfórica) se enmarcan con líneas continuas; las propiedades del suelo que actúan en consecuencia son enmarcadas en líneas segmentada gruesa; la calidad buscada de la pradera en líneas segmentada delgada.

baseline or "initial" soil test values for the properties considered in this study). Those fields are considered as control in the following tables. They were compared to fields that received the program one, two, three or four years earlier and were located near enough of the control plots so that the characteristics (in terms of soil condition and cultivation history) were similar. The number of fields studied is shown in table 1.

Soils of these five localities are classified as andisols (Vitric-Silandic Andosol as mentioned by Salazar *et al*., 2005 and WRB, 2006). Average clay, silt and sand contents of the 0-30 cm surface layer of these soils were respectively 30, 66 and 4 g kg^{-1} with an allophane content representing 50% of the total clay content. Average Soil Organic Carbon content was 103 g kg^{-1}.

Cultivation

Cultivation practices of the different fileds studied are presented in table 2.

The fields received calcium carbonate and superphosphate the year before the grasslands were established and during the year following this establishement. No fertilization was applied afterwards, whatever the delay between the program application and our survey (in 2007 and 2008).

The pastures were sown with a mix of red clover (*Trifolium pratense* L.) and ryegrass (*Lolium perenne* L.) in the Precordillera area, and with Alfalfa alone at Lonquimay, in the Cordillera. All fields that did not receive the SIRSD program (the controls) supported very old native pastures. Each value in tables 3-5 is the average of 4 to 8 measured values.

Soil analysis

The 0-20 cm layer was sampled in October 2007 and in October 2008, using a gauge. The 0-20 cm layer was sampled. We mixed the soil of eight sub-samples in each field. Each sample was analyzed at the soil laboratory of the Catholic University of Temuco. All samples were prepared and analysed according to the Commission for Normalisation and Accreditation of the Chilean Society of Soil Science rules (Sadzawka *et al*., 2004).

To determine the pH value, 20 g of soil were suspended in water (ratio soil/solution = 1/2.5); the pH of the solution was measured after 2 hours. For the analysis of exchangeable aluminium, 10 g of dry soil were added to a solution of KCl 1M, then shaken for 30 minutes at room temperature. After filtering, measurements were taken using an atomic absorbtion spectrophotometer. For the analysis of exchangeable aluminium, 5 g of dry

Table 1. Subdivision of the 32 fields sampled in each municipality, with reference to the application of the program at the time of measurement.

Tabla 1. Subdivisión de 32 campos muestreados en cada municipio, con referencia a la aplicación del programa en el momento de la medición.

Year of observation	Controls	Age of the pasture			
		1 year	2 years	3 years	4 years
2007	4	4	4	4	0
2008	4	0	4	4	4
Total	8	4	8	8	4

Table 2. Cultivation practices in the five localities studied.

Tabla 2. Prácticas de cultivo en las cinco localidades estudiadas.

Cultivation practices	**Locality**				
	Lonquimay	Curacautín	Vilcún	Cunco	Villarrica
Grassland installation	November	March	March	March	March
Grassland composition	Alfalfa	Mixed forages*	Mixed forages *	Mixed forages *	Mixed forages *
Liming period dose (t ha^{-1} $CaCO_3$)	March 2.0	Spring after the sowing date 2.0	Spring after the sowing date 2.0	Spring after the sowing date 2.0	Spring after the sowing date 2.0
P supply the year before the grassland was installed	253 kg P_20_5	253 kg P_20_5	253 kg P_20_5	253 kg P_20_5	253 kg P_20_5
Mineral fertilizer supplied the year after grassland installation	0 kg N 115 kg P_20_5 100 kg K_2O	50 kg N 115 kg P_20_5 60 kg K_2O	50 kg N 115 kg P_20_5 60 kg K_2O	50 kg N 115 kg P_20_5 60 kg K_2O	50 kg N 115 kg P_20_5 60 kg K_2O
Soil tillage	Traditional**	Traditional**	Traditional**	Traditional**	Traditional**

* Mix of red clover (*T. pratense*) and prennial ryegrass (*L. perenne*)

** Variable depending on soil conditions: generally, two passages of disc chisel followed by a deep disc ploughing and again two disc chiseling.

Table 3. pH (water) measured in different localities of the precordillera and the cordillera, Araucania Region south of Chile.

Tabla 3. pH (agua) medido en diferentes localidades de la precordillera y la cordillera, Región de la Araucanía al sur de Chile.

Number of years after the treatment	Lonquimay	Cunco	Vilcún	Villarrica	Curacautín
Control	5.83b	5.31b	5.38a	5.51a	5.82a
1	5.71b	5.31b	5.27a	5.34a	5.82a
2	5.83b	5.44ab	5.27a	5.42a	5.59b
3	6.18ab	5.55a	5.35a	5.34a	5.59b
4	6.35a	5.31b	5.25a	5.51a	5.47c

Within a same column, different letters beside the figures correspond to significant differences ($p \le 0.05$).

Table 4. Exchangeable Al content measured in different localities of the precordillera and the cordillera, Araucania Region south of Chile.

Tabla 4. Al intercambiable medido en diferentes localidades de la precordillera y la cordillera, Región de la Araucanía al sur de Chile.

Number of years after the treatment	Lonquimay	Cunco	Vilcún	Villarrica	Curacautín
	------------------------		Cmol$^+$ kg^{-1}	---------------------------	
Control	0.15a	0.73a	0.24c	0.17ab	0.13b
1	0.10b	0.32b	1.10a	0.12c	0.14b
2	0.06c	0.28b	0.78b	0.17ab	0.10b
3	0.03d	0.42ab	0.42bc	0.20a	0.28a
4	0.02d	0.77a	0.67b	0.14b	0.24a

Within a same column, different letters beside the figures correspond to significant differences ($p \leq 0.05$).

Table 5. P-Olsen measured in different localities of the precordillera and the cordillera, Araucania Region south of Chile.

Tabla 5. P-Olsen medido en diferentes localidades de la precordillera y la cordillera, Región de la Araucanía al sur de Chile.

Number of years after the treatment	Lonquimay	Cunco	Vilcún	Villarrica	Curacautín
	--------------------------		mg kg^{-1}	---------------------------	
Control	8.00c	3.62c	4.12c	4.25c	3.50b
1	15.36a	4.81b	5.15b	5.05b	5.90a
2	13.60b	4.60bc	5.31b	6.29a	5.18a
3	8.72c	6.40a	7.37ab	6.12a	5.25a
4	8.32c	4.67a	10.50a	4.71bc	6.40a

Within a same column, different letters beside the figures correspond to significant differences ($p \leq 0.05$).

soil were added to a solution of ammonium acetate 1M, and shaken for 30 minutes, before filtering. 1 mL of filtrate was then mixed with 9 mL of a potassium chloride solution. Then the concentration of aluminium was measured with an atomic absorbtion spectrophotometer.

To determine the P content, we chose the Olsen method. A sample of 2.5 g of dry soil was taken; we added 0.3 g of active carbon and 50 mL of sodium bicabonate 0.5M. The solution was shaked for 30 minutes and filtered. The phosphorus was determined by colorimetry with the blue of molybdene method, using ascorbic acid as a reducing agent.

Data were analysed using the GLM procedure of SAS, and the Tukey multiple comparison test, with a 0.95 level of confidence.

RESULTS AND DISCUSSION

Soil acidity

Application of the program had different effects on the pH of the soil in the different locations studied (Table 3). At Vilcún and Villarrica, the program had no effect, and the pH remained unchanged. The increase in pH was temporary at Curacautín and Cunco, where the pH returned to its initial value four years after the program was applied. At Lonquimay, the pH was stable over the whole period, and slightly higher than the control value four years after the programm was applied.

These changes show poor effectiveness of the program to recover soil acidity in the area investigated. Liming in the precordillera was insufficient (2 t ha^{-1} of

$CaCO_3$); this is probably the case for Vilcún and Villarrica, where the pH was not altered and at Curacautín, where liming did not prevent soil acidification. Second, liming had a temporary effect: within three to four years, the pH value returned to the same level as before the program, like in Cunco. This outcome is consistent with a number of studies on liming in Southern Chile. It is usually explained by the high rainfall amount in this region, causing significant leaching of bases and release of H^+ ions (Verde *et al*., 2010).

Exchangeable Al

The program had also contrasted effects on the exchangeable Aluminium (Alex) content (Table 4). Alex decreased significantly at Lonquimay, while it increased at Vilcún and Curacautín between the first and the fourth year after the program was applied. The findings are not similar to those of Verde *et al*. (2010). They could be explained by the above-mentioned changes in the pH. Alex values were not significantly different between the first and the fourth year, but exhibiting a slight decrease during the period at Cunco. Those fluctuations in Alex values could be linked to the fluctuations in pH observed at Cunco. At Villarrica Alex remained stable (statistically) except the value in the first year, as well as the pH values. The results at Vilcún are difficult to interpret, a burst of Alex the second year being followed by a decrease in Alex values afterwards, while pH remained constant during the whole period.

As seen above, the actions taken in the program were unable to correct consistently the pH in all localities but Lonquimay. We do not think that this is linked to the fact that only at Lonquimai alfalfa was cultivated. It is more likely due to the unsufficient amount of lime added to the soil: the program consisted of only one lime addition and lime amount applied was too limited. Therefore, it was not sufficient to achieve the results observed by Pérez (1986) or by Pinochet *et al*. (2005), who showed pronounced effects on the levels of exchangeable aluminium (and on the saturation rate of the complex by aluminium). A second possible explanation of these results can be given by the generalized use of urea for nitrogen fertilization (in this area, it is the cheapest nitrogen fertilizer source). Urea acidifies soils and can cause an increase in the amount of exchangeable aluminium (Zejiang *et al*., 2014).

P availability

Finally, the impact of the program on phosphorus availability (P-Olsen) was also different between municipalities (Table 5). At Lonquimay, P-Olsen initially significantly increased, showing a positive short-term effect of the program. However, P-Olsen gradually decreased after the first year, until it returned to its initial level. In this location, the decrease of P-Olsen probably results from phosphorus consumption by alfalfa (Nichols *et al*., 2012).

This explanation is more likely than the fixation by the soil, as the content of extractable aluminium is less than 500 mg kg^{-1}. In this area phosphoric fertilizer was first applied (253 kg ha^{-1} of P_2O_5), just before the alfalfa was sown. During the first year of alfalfa cropping, a second fertilization was performed (115 kg ha^{-1} of P_2O_5). These two fertilizations were not sufficient to guarantee the maintenance of available phosphorus levels in the years after the application of the program. Moreover, Alfalfa is able to absorb significant quantities of phosphorus, thanks to its well-developed root system (Nichols *et al*., 2012). This plant also produces more biomass, thus increasing the exportation compared to native pastures. Finally, afalfa was only harvested as hay, without any return of P to the soil, which probably impeded the P balance sheet.

At Vilcún, an increase with time of the P-Olsen content was observed during the whole period. In this locality, exchangeable Al content was the highest among all the samples, which caused high toxicity and a poor growth in the grassland; this, in turn, strongly limited phosphorus uptake, which probably explains the observed imbalance. At Vilcún, the untreated control field was a pasture whose flora is adapted to the particular conditions of the soil. That flora consisted mainly of grasses (*Agrostis capillaris, Holcus lanatus*) and some naturalized legumes plants (e.g. *Medicago hispida* or *Lotus uliginosus*). Establishing perennial ryegrass and red clover, species which are not well adapted to acid soils, caused also poor productivity of the pastures and, consequently, very low phosphorus uptake.

At Curacautín, Villarrica and Cunco, the P-Olsen content increased during the first years after the application of the program, but began to decline at the end of the period. In those locations, phosphorus uptake by grasses was hampered by the presence of free aluminium. Moreover, grasslands in those municipalities are grazed, as opposed to Lonquimay, where only hay is harvested. It is likely that the presence of livestock implies phosphorus return to the soil *via* the animal manure.

CONCLUSIONS

This analysis led us to propose several possible ways to improve the program's effectiveness.

1. The quantities of lime provided initially must be reconsidered and, most of all, it is necessary to repeat the liming (every 3-4 years) in order to have more lasting effects on the pH and, consequently on the exchangeable Al content.
2. In a similar way to liming, the phosphoric fertilization must be part of a global strategy for impro-

ving P availability. Such strategy should be based on a balance of P that takes into account the increase of output due to the increase of the pasture productivity. P supply should be repeated in time. Lastly, this strategy must also integrate phosphurus recycling through cattle manure. This whole strategy is essential to keep a sufficient proportion of legume species in the pastures.

3. The program should also integrate some actions relative to pasture management. For example, new methods of nitrogen fertilization, based on a nitrogen balance, should be spread and the use of urea should be avoided.

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