EFFECT OF THE INCORPORATION OF SALTGRASS (*Distichlis spicata* (L.) GREENE) BURN RESIDUES ON PHOSPHORUS FIXATION IN AN ARIDISOL

Yubinza Zapata, Leonardo Figueroa, Nelson Lara, Camilo Urbina and Hugo Escobar

SUMMARY

The preferred practice for removing the natural growth of saltgrass on the soil, at the start of soil preparation for seed sowing, is the onsite combustion, a fact that introduces a change factor in the chemical properties of the soil at the moment of interaction with the irrigation water. Phosphorus (P) in the soil is one of the limiting macronutrients for the growth and development of plants; it is the element with the greatest availability problems, due to the physico-chemical fixation to which it is subjected as a consequence of the specific adsorption on allophanic minerals. Consequently, we evaluated the effect generated by the incorporation of saltgrass burn plant residue on the pH, electrical conductivity and P fixation capacity in an Aridisol. The burned plant residues were mixed with soil at rates of 0, 5, 15, 25 and 50% (w/w) and these amended soils were mixed with a P solution (100µg·ml^{-1}) in a ratio of 1:10 (soil:P solution). The addition of saltgrass combustion residues to arid soils leads to a rise of the pH from 7.47 to 8.41, an increase of EC from 14.91 to 103.62mS·cm^{-1} and an increment of the phosphorus fixation from 16.6 to 99.9%. It is essential to eliminate this practice of burning in situ *given the changes it produces in the soil's physicochemical properties.*

Introduction

The main agricultural zone of the Lluta Valley is located around 18°24'2''S and 70°14'18''W in an arid region where mean annual precipitation is less than 0.4mm; soils are characterized by being of aluvial origin, deep, highly stratified and highly saline (Espina, 1971; IREN-CORFO 1976; Torres y Acevedo, 2008). The physical and chemical characteristics of these soils are known to include low organic matter content, high porosity and low bulk density, medium to coarse textures with saline nodules in their first strata, presumably chlorides and sulphates, with subangular and coarse angular block structure, with a water table at a depth between 60 to 175cm. (NDERCO, 1980; Kosmas and Moustakas, 1990; INGENDESA, 1993, 1995; Torres and Acevedo, 2008). The total arable area of the valley is 7606ha; however, the area cultivated is ~2784ha. The principal crops include corn (1100ha), alfalfa (830ha) and onion, while the remaining 270 ha includes crops such as garlic, beets and faba beans. The reason these crops are grown and not others is mainly that they are highly tolerant to salinity and boron, which are present in the soils and in the irrigation water of the valley. Onion production is one of the most interesting activities for the valley, with optimum yields but with little profit. The corn variety used has been adapted to local conditions for many years; thus, it is a moderately profitable crop for the area (FDI-CORFO, 2000).

Due mainly to the problems of salinity and humidity in the area, the dominant vegetation is saltgrass (*Distichlis spicata* (L.) Greene), which is very common and widespread in the valley; it is resistant to drought and can grow in saline environments. It is frequently removed by controlled burning. Crop residues are generally considered a problem for the establishment of new crops in a rotation system, and the burning of these residues is a standard practice in the region (Román *et al*., 2012).

The burning of crop residues and weeds is indeed a widespread technique used to clear agricultural land; however, it carries negative consequences, including the emission of CO_2 and particulate matter to the atmosphere and, it changes physical and chemical characteristics of soils (Hepper *et al*., 2008). Some of the benefits of burning crop residues are valuable, such as the rapid and economical removal of large volumes of residues, which facilitates soil preparation and planting. However, other purported benefits such as the improvement of soil fertility, reduction of pests, weeds and diseases are debatable, since they are partial and operate only in the short term. In addition, they actually have negative consequences when an analysis is made of the mid- or long-term effects and at the scale of the entire cropping system (Díaz *et al*., 2002).

Researchers have found that burning crop residues temporarily improved the availability of nutrients including N and P, consequently improving the productivity of newly established crops (Giardina and Rhoades, 2001). However, in cropping systems which include the export of large amounts of biomass, and where residues are burned, the cycling of nutrients can be modified, or nutrient losses can be exacerbated. Indeed, the net primary productivity of such ecosystems may be reduced in subsequent rotations (Carter and Foster,

KEYWORDS / Alkaline Hydrolysis / Burning of Crop Residues / Macronutrients / pH /

Received: 07/14/2015. Modified: 08/08/2019. Accepted: 08/09/2019.

Yubinza Zapata. Laboratory Chemist, Universidad de Tarapacá (UTA), Chile.

Leonardo Figueroa. (Autor de corrrespondencia). Laboratory Chemist, UTA, Chile. Professor, Universidad de Tarapacá, Chile. Dirección: Departamento de Química, UTA. Av. General Velásquez 1775. Arica, Chile. e-mail: lfiguero.arica@gmail.com

Nelson Lara. Doctor in Sciences, Universidad Complutense de Madrid, España. Professor of Chemistry and Natural Sciences, Universidad Metropolitana de Ciencias de la Educación, Chile. Professor, Universidad de Tarapacá, Chile.

Camilo Urbina. Bachelor of Agronomy, Pontificia Universidad Católica, Chile. Agronomical Engineer, Pontificia Universidad Católica de Chile.

Hugo Escobar. Magister in Sciences, Colegio de Postgraduados, Chapingo, México. Doctor in Sciences, Universidad de Chile. Professor, Universidad de Tarapacá, Chile.

EFECTOS DE LA INCORPORACIÓN DE RESIDUOS DE COMBUSTIÓN DE GRAMA SALADA (*Distichlis spicata* (L.) GREENE) SOBRE LA FIJACIÓN DE FÓSFORO EN UN SUELO ÁRIDO

Yubinza Zapata, Leonardo Figueroa, Nelson Lara, Camilo Urbina y Hugo Escobar

RESUMEN

La práctica preferida de limpieza del terreno utilizada por el agricultor para retirar la grama salada arraigada al suelo, hierba de crecimiento natural, previo a la siembra es mediante la combustión in situ*, hecho que introduce un factor de cambio en las propiedades químicas del suelo al momento de la interacción con el agua de riego. El fósforo (P) en el suelo es uno de los macronutrientes que limita el crecimiento y desarrollo de las plantas; es el elemento con mayor problema de disponibilidad, debido a la fijación físico-química a la que está sujeto como consecuencia de la adsorción específica en minerales alofánicos. En consecuencia, se evaluó el efecto generado por la incorporación de residuos de combustión de la planta conocida como 'grama salada' en el pH, conductividad eléctrica y capacidad de fijación de P en un suelo árido. Los residuos de combustión de las plantas se mezclaron con suelo a tasas de 0, 5, 15, 25 y 50% (m/m), y estos suelos modificados se mezclaron con una solución de P (100mg·ml^{-1}) en proporción 1:10 (suelo:solución P). La adición de residuos de combustión de grama salada a los suelos áridos, generó una elevación del pH desde 7,47 a 8,41, una elevación de la CE desde 14,91 a 103,62mS·cm^{-1} y un aumento de la fijación de fósforo desde 16,6 a 99,9%. Es esencial eliminar esta práctica de quema en el suelo dados los cambios que produce en las propiedades físico-químicas de ellos.*

EFEITOS DA INCORPORAÇÃO DE RESÍDUOS DE COMBUSTÃO DE GRAMA-DO-LITORAL (*Distichlis spicata* (L.) GREENE) SOBRE A FIXAÇÃO DE FÓSFORO EM SOLO ÁRIDO

Yubinza Zapata, Leonardo Figueroa, Nelson Lara, Camilo Urbina e Hugo Escobar

RESUMO

A prática preferida para limpeza do terreno utilizada pelo agricultor, prévia à plantação, para retirar a grama-do-litoral enraizada no solo, erva de crescimento natural, é mediante a combustão in situ*, fato que introduz um fator de mudança nas propriedades químicas do solo no momento da interação com a água de irrigação. O fósforo (P) no solo é um dos macronutrientes que limita o crescimento e desenvolvimento das plantas; é o elemento com maior problema de disponibilidade, devido à fixação físico-química à qual está sujeito como consequência da adsorção específica em minerais alofânicos. Em consequência, se avaliou o efeito gerado pela incorporação de resíduos de combustão da planta conhecida como 'grama-do-litoral' no pH, condutividade eléctrica (CE) e capacidade de fixação de P em um solo árido. Os resíduos de combustão das plantas se misturaram com solo em taxas de 0, 5, 15, 25 e 50% (m/m), e estes solos modificados se misturaram com uma solução de P (100mg·ml^{-1}) em proporção 1:10 (solo:solução P). A adição de resíduos de combustão de grama-do-litoral aos solos áridos, gerou uma elevação do pH de 7,47 para 8,41, uma elevação da CE de 14,91 para 103,62mS·cm^{-1} e um aumento da fixação de fósforo de 16,6 para 99,9%. É essencial eliminar esta prática de queima no solo devido às mudanças que produz nas propriedades físico-químicas deles.*

2004). Studies carried out in different ecosystems worldwide show that the effect of fire on soils can vary depending on fire intensity, the characteristics of the ash and the degree to which it is incorporated into the soil, and the frequency of fire events. Among the effects of fire on soil physical properties, an incomplete dispersion in clay content has been observed (Hubbert *et al*., 2006). This, combined with reductions in the amounts of organic soil components, can impact the micro aggregation and lead to the degradation of the soil's microstructure (Andreu *et al*., 2001).

Chemical changes include changes in stocks of nutrients that are essential to the long-term sustainability of production. Greater concentrations of total P and Ca were found after burning due to a physical reduction of the surface layers of soil, while reductions in total N and C contents were attributed to the volatilization of these elements (Smith *et al*., 2001). Other authors did not observe changes in the amount of total and available soil N after burning (Arocena and Opio, 2003), but did observe higher pH and greater amounts of exchangeable Ca, Mg, K and Na due to the ash produced in the fire, which contained large amounts of soluble salts, mostly carbonates and Ca, Na, K, and Mg oxides and hydroxides. Unless they are lost by wind erosion or runoff, these ashes can contribute to raise soil pH and the amounts of available Ca, Mg, Na, K, and P in soil (Arocena and Opio, 2003). Losses of nutrients in fire-affected soils can be attributed to volatilization, leaching, removal in convection currents during the fire or wind erosion after the fire (Giardina *et al*., 2000), while nutrient enrichment can result from the mineralization of organic matter and the addition of ash from burning biomass (Albanesi and Anriquez, 2003).

The importance of studying the effect of crop residue burning and the incorporation into soil of burned residues on the behavior of P in soil and soil water stems from the fact that P availability to plants may be limited by the physico-chemical absorption of the nutrient, which occurs in both acidic and basic environments. Phosphorus forms poorly soluble compounds with Ca, and consequently the amount of P in the soil solution is low and plants absorb the available P, which remains in equilibrium with P in the solid phase. Thus, each form of P in the soil contributes to increase the amount of P available to plants in its own distinct way. In Andisols and soils associated with volcanic ash P may be specifically absorbed; fixation occurs on the surface of minerals such as allophane, imogolite and humus-Al complexes. Phosphorus fixation represents one of the greatest problems in soils with high amounts of active Al. The mitigation of this problem must occur through a reduction in Al reactivity, with one practical option being the application of alkaline soil amendments leading to the precipitation of Al hydroxide, which has a low solubility (Sanchez, 2019).

The importance of this problem varies with soils and regions of the world, but where it represents a serious limitation, sufficiently high rates of P will need to be applied to saturate P fixation sites and maintain an adequate concentration of this nutrient in the soil solution. Alternatively, the use of amendments which reduce the soils' P adsorption capacity should be considered (Sadzawka *et al*., 2006). The range in soil pH where the greatest availability of P is observed is between 6.5 and 7.5, mainly due to the fact that in this range the inorganic forms of P in soil are most soluble. At pH<6.5 the solubility of Fe and Al phosphates is reduced, while the solubility of Ca phosphates is high. At pH>7.5, the availability of P decreases substantially due to the formation of poorly soluble Ca compounds. High pH can also alter the availability of micronutrients such as Cu and Fe, negatively impact the physiological processes whereby plant roots absorb soil nutrients, deteriorate the root system, lead to toxicities due to excessive absorption of phytotoxic elements and lead to the dispersion of clays, thus negatively affecting soil physical properties. Given the large number of factors which affect the properties of fire-impacted soil, the interpretation of effects in the field can be difficult if each factor is not well understood individually.

The objective of this study was to assess the impact of the incorporation of residues from the burning of saltgrass on the P fixation capacity of an Aridisol. Saltgrass is a native plant which grows and reproduces vigorously in the Lluta Valley.

Experimental

The soil used in this experiment is an Aridisol, representative of the arid and saline soils of the Lluta Valley (18°24'2"S, 70°14'18''W, 10km from the town of Arica in northern Chile. The sample was taken from a depth of 0-20cm in an area where no use of prescribed fires was recorded; the land was prepared for a future crop, with no vegetation or remains of previous burns. Soil was air dried, passed through a 2mm sieve and its physical and chemical properties were analyzed in saturation extracts (Bhargava and Raghupathi, 1993); texture was determined using the method of Bouyoucos and according to the percentage of sand, silt and clay, using the United States Department of Agriculture (USDA) classification system.

We took samples of saltgrass from a neighboring area, which were weighed and burned in the field to determine the percentage of saltgrass burn residue (SBR) generated from the original material. Residues from the burning of saltgrass (*Distichlis spicata* (L.) Greene), were collected from the soil surface at several locations in the field. These samples were pooled in order to generate a single SBR sample which is representative of the physicochemical characteristics of this material as it is generated in the field, and this composite sample was sieved to 0.25mm. The ash percentage was determined by pyrolysis at 550ºC for 8h, and the main physiochemical properties of the SBR in a 1:2.5 SBR-water extract. In order to study the effect of incorporating SBR on P fixation by the soil, SBR was added to soil in various proportions by weight (0, 5, 15, 25 and 50%), with five replicates of each addition rate.

Each of these mixtures was reacted with distilled water in a 1:1 ratio and stirred at 250rpm for 30min. Subsequently, the pH was measured and the electrical conductivity (EC) of the extract determined (Sadzawka *et al*., 2006). Each sample was also reacted with a phosphorus solution (KH_2PO_4 stock with 100µg P·ml^{-1}) in a 1:10 soil-SBR mixture: P solution ratio. The mixtures were stirred for 2h at 250rpm at room temperature (~25 ±2ºC). The resulting extract was analyzed for pH, EC, and P (remnant or non-absorbed phosphorus content) using the vanado-molybdophosphate method with spectroscopic determination at 430nm (Bhargava and Raghupathi, 1993).

The amount of P fixed by each soil-SBR mixture was determined as the difference between the amount of P applied in the solution (100µg P·ml^{-1}; Fox and Kamprath, 1970) and the amount of P detected in the solution after reaction with the mixture. The statistical analysis of the results was carried out using one-way ANOVA (Origin 8.0) at a significance level of 0.05, and the correlation between the different treatments and variables was also assessed. The fresh saltgrass biomass is not incorporated to the soil, given that what is pursued by the practice of burning it is its removal by burning in situ, as it hinders the soil preparation process, and is also a weed that is very hard to control.

Results and Discussion

The physical and chemical characteristics of the studied soil are shown in Table I. The soil is classified in the Aridisol order according to Soil Taxonomy (Soil Survey Staff, 2010).

The physical and chemical properties of the soil are characteristic of the Aridisol of the northernmost region of Chile, with a high salt content and a sandy loam texture. This coarse texture makes the soil more vulnerable to losses of nutrients and the leaching of salts during irrigation.

Table II shows the main physico-chemical and chemical characteristics of the SBR determined in a 1:2.5 SBR:water mixture. Due to the plant origin of this residue and its formation process, which includes partial and complete combustion, it is composed of a black solid that corresponds to char and a white to gray solid that corresponds to ash or combustion residues. The latter is capable of hydrolysis with a marked alkaline character; thus, aqueous solutions of this material have high EC and elevated pH, with greater Na and K content compared to Ca and Mg.

TABLE I
MAIN CHEMICAL AND PHYSICO-CHEMICAL PROPERTIES OF THE STUDIED SOIL, DETERMINED IN SATURATED EXTRACTS

	Soil
pH	7.53
EC, mS·cm^{-1}, 25ºC	15.58
Sodium, mmol·l^{-1}	72.46
Potassium, mmol·l^{-1}	4.26
Calcium, mmol·l-1	39.86
Magnesium, mmol·l^{-1}	30.04
SAR, %	12.3
ESP, %	14.4
% Clay	6.4
% Sand	73.6
% Loam	20.0
Texture (USDA)	Sandy loam
Apparent density, kg·m^{-3}	1.25
Organic matter, %	1.22

EC: electrical conductivity, USDA: United States Department of Agriculture.

TABLE II
MAIN PROPERTIES OF THE SALTGRASS BURN RESIDUE DETERMINED IN A 1:2.5 EXTRACT. ASH IN SBR AND SALTGRASS

Burn Residue	
pH	9.1
EC, mS·cm^{-1}, 25° C	99.9
Sodium, mmol·l^{-1}	1143.0
Potassium, mmol·l^{-1}	276.2
Calcium, mmol·l^{-1}	76.7
Magnesium, mmol·l^{-1}	67.2
Ash SBR, %	80.0
Ash saltgrass, %	30.7

SBR: saltgrass burn residue. EC: electrical conductivity.

The apparent soil density (Table I) implies that in order to reach the lowest rate (5%) used in this experiment, 31.3t of SBR would be needed per hectare with a soil layer of 5cm. Saltgrass is the most abundant weed in the valley and its complete combustion produced a residue of 30.73% (Table II) of the original material. Thus, for a mean annual yield of saltgrass of 30t·ha^{-1} the biomass required to reach the lowest rate would take no more than five years.

The incorporation of this SBR at different doses modified the parameters observed in the soil. The pH of 1:1 soil-SBR:water mixtures (Table III) increased linearly with SBR addition rate (r= 0.997, $p<0.01$) from 7.47 with 0% addition to 8.41 at the 50% addition rate (Figure 1), with a significant pH dependence in terms of SBR content in the soil, a condition that is of great importance in P behavior, since an alkaline pH of 7.5 substantially decreases its availability due to the formation of poorly soluble compounds with Ca; this increases to a maximum between pH 8 and 9. This effect of SBR on soil pH is of great importance for the behavior of P in soil because the optimal range of soil pH for greatest soil P availability is between 6.5 and 7.5, since in this range the maximum solubility of inorganic P forms of soil occurs, while acid pH up to 6.5 reduces the solubility of Fe and Al phosphates and increases solubility of the Ca-bound forms (Jackson, 2005).

However, the influence of alkaline pH not only affects macronutrient availability of soil P; it may also alter the availability of micronutrients such as Cu, Fe, etc. It may alter and impede the physiological process of nutrient absorption by roots, damage the root system and induce toxic effects due to excessive absorption, damaging the root system; toxicity can occur due to excessive absorption of phytotoxic elements; alkalinity can cause the dispersion of the clay fraction and lead to poor conditions from the physical point of view of the ground (Arocena and Opio, 2003). The increase in pH may be due to the ash present in the SBR of saltgrass obtained after burning, which is rich in soluble salts that consist mainly of carbonates, oxides and hydroxides of Na, K, Ca and Mg. If these ashes are not lost by wind and runoff, they may contribute to raise the pH and the content of the assimilable elements Ca, Mg, Na, and K soil (Arocena and Opio, 2003).

The existence of a shallow water table in Lluta Valley soils generates very high salinity levels near the soil surface, severely limiting agricultural crops that can withstand such conditions, but with a reduced production potential (Torres y Acevedo, 2008). Since the EC (Table I) as reference salinity classifies the soil as extremely saline, where very few crops that are tolerant have a satisfactory performance, this behavior is even more pronounced with the addition of SBR, characterized by high EC, to the ground (Table II). The EC of the unamended soil was 14.91mS·cm^{-1}, characteristic of highly saline soils. In the 1:1 extract of the various treatments, EC rose from 14.91 in unamended soil to 103.6mS·cm^{-1} when 50% SBR was applied (Table III), an almost seven-fold increase. EC was positively correlated with SBR addition rate (r= 0.996, $p<0.02$).

Given that the EC of the unamended soil and the sodium adsorption ratio (SAR) classify this soil as saline (Kwari and Batey, 1991), where very few tolerant crops would produce satisfactory yields, the incorporation of SBR aggravates the salinity problem. The soil's P fixation capacity was impacted by the incorporation of SBR (Figure 2). Indeed, unamended soil fixed 16.6% of the applied P and this value went up to 99.9% when soil had been amended with 50% SBR. The treatment in which the soil contained 5% SBR fixed 36% of the applied P, almost double the fixation capacity of unamended soil. This was associated with a pH of 7.55, at which P fixation is theoretically increased due to the formation of poorly soluble Ca compounds (Jackson, 2005). Phosphorus fixation increased linearly with SBR addition rate (r= 0.999, $p<0.02$) up to the addition rate of 15% (Figure 3), where 81.2% of the applied P was fixed. This high significance at different pH leads to the conclusion that the main mechanism of fixation of P is the precipitation of phosphates. The increase in P adsorption

TABLE III
pH AND ELECTRICAL CONDUCTIVITY OF 1:1 EXTRACTS OF SOIL AMENDED WITH VARIOUS RATES OF SBR

Burn residue in soil (%)	1:1 soil-SBR: water extract			
	pH	SD	EC (mS·cm^{-1})	SD
0	7.47	± 0.03	14.91	± 0.50
5	7.55	± 0.14	24.14	± 2.15
15	7.73	± 0.15	46.22	± 2.10
25	7.87	± 0.37	64.92	± 3.15
50	8.41	± 0.04	103.62	± 0.53

SBR: saltgrass burn residue. SD: standard deviation, EC: electrical conductivity. Mean of five replicates.

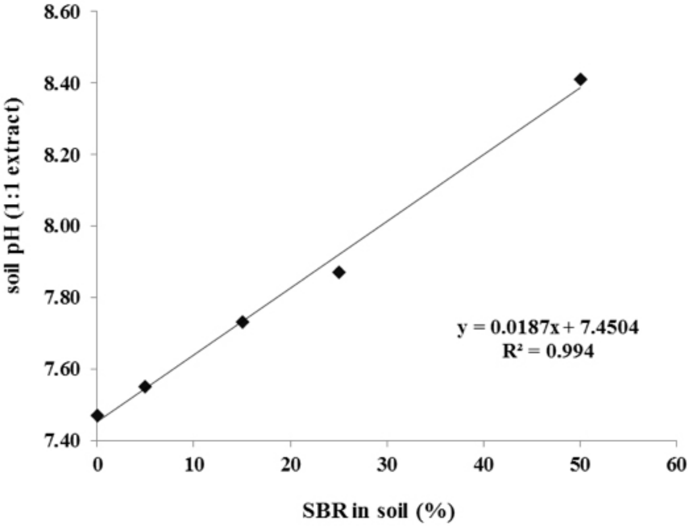

Figure 1. Behavior of soil pH with different addition rates of SBR, in 1:1 extracts. $p<0.01$.

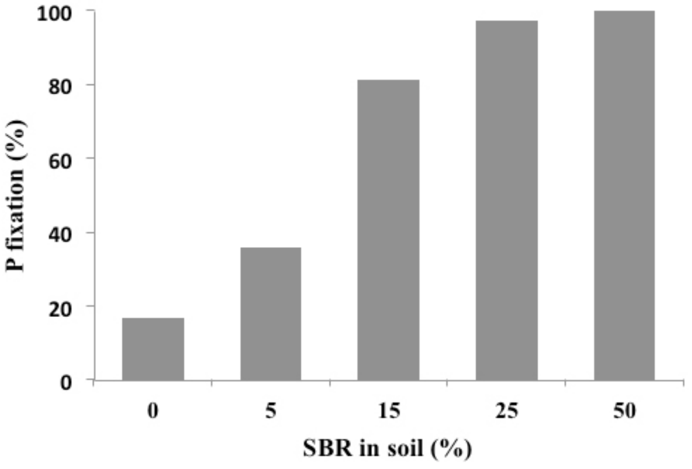

Figure 2. Phosphorus fixation capacity of soil- SBR mixtures.

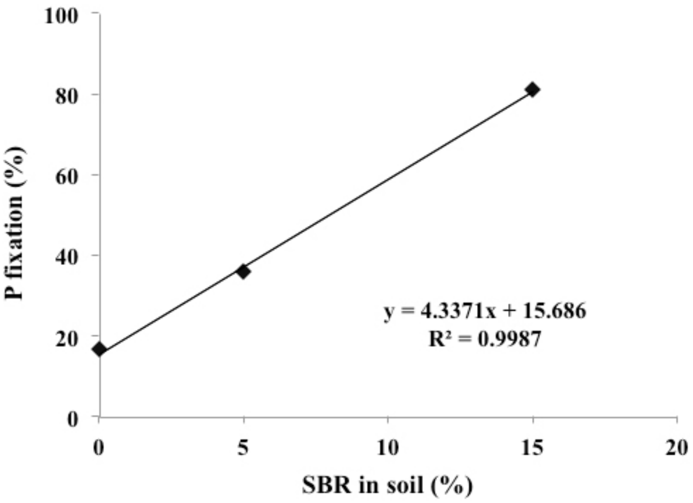

Figure 3. Phosphorous fixation behavior of soils receiving up to 15% SBR and $p < 0.02$.

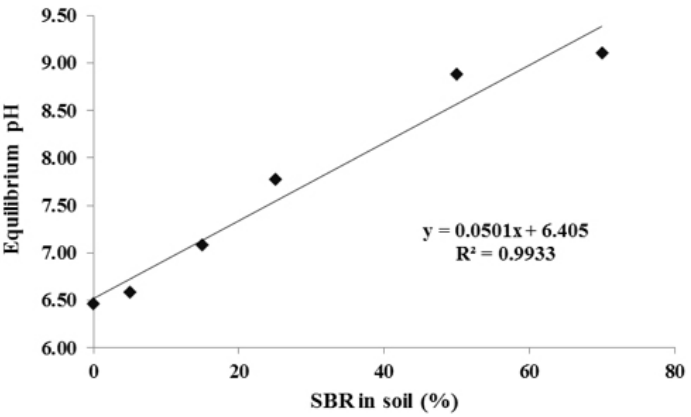

Figure 4. Equilibrium pH of soil in P solution (100 µg mL^{-1}) as a function of the addition rate of SBR and $p < 0.01$.

after addition of stubble burn is believed to be caused by an increase in free Fe oxides and Al, while the high content of exchangeable Ca and possibly carbonates and hydroxyl ions in the ashes are likely responsible for the increased adsorption of phosphate observed after burning (Kwari and Batey, 1991).

The lowest P fixation (36%) was obtained in soil treated with 5% SBR, nearly twice the natural soil fixation. This was associated with a pH 7.55, slightly alkaline, where theoretically fixing formation of sparingly soluble compounds with Ca begins. At higher addition rates the rise in fixed P was no longer proportional to the amount of SBR added, and almost all applied P (99.9%) was fixed when 50% SBR was added, with a resulting solution pH of 8.88, pH at which carbonates precipitate, hence a part of the phosphates can also precipitate (Figure 4). It is important to note that 97.4% of the added P was fixed in the presence of 25% SBR and greater addition rates did not substantially increase the rate of P fixation; it was necessary to add 70% more SBR to fix the 2.6% P remaining in solution and, at higher doses the increase was not significant; adding 25% SBR fixed 2.5% of the remaining P. In this case the maximum amount of P may be fixed by precipitation as Ca phosphates, since this reaction peaks between pH values of 8 and 9.

It is thus of fundamental importance to reconsider the burning of crop residues and weeds and the incorporation into soil of burn residues, since this practice leads to the need to carefully monitor the loss of nutrients and the efficiency of the applied nutrients. This implies that where plant burn residues are incorporated into soil, P applications must be high enough to saturate P fixation sites and maintain an adequate P concentration in the soil solution. Apart from the ability to predict crop nutrient needs and make adequate fertilizer recommendations, it is important, both from the economical and the sustainability points of view, to reduce the negative environmental impacts linked to the excessive use of fertilizers. The burning of crop residues and weeds can be justified to improve acidic soils, but it can never be considered a beneficial practice, given the environmental impacts of particulate matter and greenhouse gases which contribute to the greenhouse effect. In this situation, as an alternative to burning we suggest the transformation of crop residues to a material known as Biochar, a solid obtained by pyrolysis of the biomass and incorporated into the soil, in order to improve soil properties and mitigate climate change by sequestering carbon.

Conclusion

The addition of the combustion residue of saltgrass to an Aridisol generated a rise of the pH from 7.47 to 8,41, an increase of EC from 14.91 to 103.62mS·cm^{-1}, and an increment of the phosphorus fixation from 16.6 to 99.9%. It is essential to eliminate the practice of burning in situ, given the changes it produces in the soil's physicochemical properties.

ACKNOWLEDGEMENTS

Our interdisciplinary study inThe authors are grateful for funding from the Convenio de Desempeño UTA-MINEDUC. Leonardo Figueroa thanks UTA Mayor 4741-14, and Nelson Lara thanks UTA Mayor 4752-19.

REFERENCES

Albanesi A, Anriquez A (2003) El fuego y el suelo. In Kunst C, Bravo S, Panigatti JL (Eds.) *Fuego en los Ecosistemas Argentinos*. INTA. Santiago del Estero, Argentina. pp. 47-59.

Andreu V, Imeson AC, Rubio JL (2001) Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest. *Catena 44*: 69-84.

Arocena JM, Opio C (2003) Prescribed fire-induced changes in properties of sub-boreal forest soils. *Geoderma 113*: 1-16.

Bhargava BS, Raghupathi HB (1993) Analysis of plant materials for macro and micronutrients. In Tandon HLS (Ed.) *Methods of Analysis of Soil, Plant, Water and Fertilizers*. Fertilizers Development and Consultation Organization. New Delhi, India. pp. 49-82.

Carter MC, Foster CD (2004) Prescribed burning and productivity in southern pine forest: a review. *Forest Ecol. Manag. 191*: 93-109.

Díaz, K, Ortega R, Luppichini L (2002) Medidores de clorofila. Usos y potenciales. In Díaz K (Ed.) *Mejores Prácticas de Manejo. Cultivos Tradicionales de la Zona Centro Sur de Chile.* Boletín INIA N° 75. Instituto de Investigaciones Agropecuarias. Chillán, Chile. pp. 97- 111.

Espina L (1971) *Estudio Agroeconómico del Valle de Azapa*. Universidad de Chile. Santiago, Chile. 155 pp.

FDI-CORFO (2000) *Validación de nuevas alternativas Hortofrutícolas para la Primera Región*. Fundación Chile. Santiago, Chile. 120 pp.

Fox RL, Kamprath EJ (1970) Phosphate sorption isotherms for evaluating the phosphate requirements of soils. *Soil Sc. Soc. Am. Proc. 34*: 902-907.

Giardina CP, Sanford RL, Døckersmith IC (2000) Changes in soil phosphorus and nitrogen during slash burning of a dry tropical forest. *Soil Sc. Soc. Am. J. 64*: 399-405.

Giardina CP, Rhoades CC (2001) Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodge pole pine forest. *Forest Ecol. Manag. 140*: 19-28.

Hepper E, Urioste A, Belmonte V, Buschiazzo V (2008) Temperaturas de quema y propiedades físicas y químicas de suelos de la región semiárida pampeana central. *Cienc. Suelo 26*, 29-34.

Honorato R (1994) *Manual de Edafología*. 2ª ed. Universitaria. Santiago, Chile. 196 pp.

Hubbert KR, Preisler HK, Wohlgemuth PM, Graham RC, Narog MG (2006) Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, USA. *Geoderma 130*: 284-298.

INDERCO (1980) *Estudio de la Red de Drenaje del Valle del Río Lluta*. Dirección General de Aguas, Ministerio de Obras Públicas Departamento de Estudios y Racionalización, Ingeniería de Riego-Consultores. Santiago, Chile. 125 pp.

INGENDESA (1993) *Consultoría Dep-012, Análisis de Descontaminación y Embalse en Río Lluta*. Vol. 4/4. Dirección de Riego, Ministerio de Obras Públicas. Santiago, Chile. 111 pp.

INGENDESA (1995) *Consultoría Dep-012, Análisis de Descontaminación y Embalse en Río Lluta*. Parte II. Dirección de Riego, Ministerio de Obras Públicas. Santiago, Chile. 45 pp.

IREN-CORFO (1976) *Inventario de Recursos Naturales por Métodos de Percepción del Satélite LANDSAT. I Región de Tarapacá*. Convenio IREN-SERPLAC. Santiago, Chile. pp. 50-110.

Jackson ML (2005) *Soil Chemical Analysis. Advanced Course*. 2nd ed. University of Wisconsin-Madison Libraries. Madison, WI, USA. 933 pp.

Kosmas C, Moustakas N (1990) Hydraulic conductivity and leaching of an organic saline-sodic soil. *Geoderma 46*: 363-370.

Kwari JD, Batey T (1991) Effect of heating on phosphate sorption and availability in some north-east Nigerian soils. *Eur. J. Soil Sc. 42*: 381-388.

Román LF, Potter WH, Dionizis N, Sepúlveda R, Allende M (2012) *Implicancias de las Buenas Prácticas Agrícolas*. Informativo 65. Instituto de Investigaciones Agropecuarias. Ministerio de Agricultura. Chile.

Sadzawka A, Carrasco M, Grez R, Mora M, Flores H, Neaman A (2006) Métodos de análisis recomendados para los suelos de Chile. Serie *Actas INIA 34*: 10-69.

Sanchez PA (2019) *Properties and Management of Soils in the Tropics*. 2nd ed. Cambridge University Press. Cambridge, UK. 665 pp.

Smith SM, Newman S, Garret PB, Leeds JA (2001) Differential effects of surface and peat fire on soil constituents in a degraded wetland of the Northern Florida Everglades. *J. Environ. Qual. 30*: 1998-2005.

Soil Survey Staff (2010) *Keys to Soil Taxonomy*. 11th ed. USDA-Natural Resources Conservation Service. Washington, DC, USA. p. 33.

Torres A, Acevedo E (2008) El problema de salinidad en los recursos suelo y agua que afectan el riego y cultivos en los valles de Lluta y Azapa en el norte de chile. *Idesia 26*: 31-44.