MULTIDISCIPLINARY JOURNAL EPISTEMOLOGY OF THE SCIENCES

Volume 3, Issue 1
January–March 2026

Quarterly publication

CROSSREF PREFIX DOI: 10.71112

ISSN: 3061-7812, www.omniscens.com

Multidisciplinary Journal Epistemology of the Sciences

Volume 3, Issue 1
January–March 2026

Quarterly publication
Made in Mexico

The Multidisciplinary Journal Epistemology of the Sciences accepts submissions from any field of knowledge, promoting an inclusive platform for the discussion and analysis of epistemological foundations across various disciplines. The journal invites researchers and professionals from fields such as the natural sciences, social sciences, humanities, technology, and health sciences, among others, to contribute with original articles, reviews, case studies, and theoretical essays. With its multidisciplinary approach, it aims to foster dialogue and reflection on the methodologies, theories, and practices that underpin the advancement of scientific knowledge in all areas.

Contact: admin@omniscens.com

9773061781003

Legal Disclaimer

Multidisciplinary Journal Epistemology of the Sciences Vol. 3, Issue 1, January-March 2026, is a quarterly publication edited by Dr. Moises Ake Uc, C. 51 #221 between 16B and 16C, Mérida, Yucatán, Mexico, C.P. 97144, Tel. 9993556027, Web: https://www.omniscens.com, admin@omniscens.com. Responsible Editor: Dr. Moises Ake Uc. Rights Reservation
No. 04-2024-121717181700-102, ISSN: 3061-7812, both granted by the Instituto Nacional del Derecho de Autor (INDAUTOR). Responsible for the last update of this issue: Dr. Moises Ake Uc, last modification date: January 1, 2026.

Multidisciplinary Journal Epistemology of the Sciences

Volume 3, Issue 1, 2026, January–March

DOI: https://doi.org/10.71112/7s3xfc80

CLASSIFICATION OF PRODUCTIVE ENVIRONMENTS FOR VARIABLE RATE FERTILIZATION IN THE PRECISION AGRICULTURE SYSTEM

CLASIFICACIÓN DE AMBIENTES PRODUCTIVOS PARA FERTILIZACIÓN A TASA VARIABLE EN EL SISTEMA DE AGRICULTURA DE PRECISION

Bladimir Fernández Orellana

Bolivia

DOI: https://doi.org/10.71112/7s3xfc80

Classification of productive environments for variable rate fertilization in the precision agriculture system

Clasificación de ambientes productivos para fertilización a tasa variable en el sistema de agricultura de precision

Bladimir Fernández Orellana

ing.fernandez.bladimir@gmail.com

https://orcid.org/0009-0005-5077-8210

Universidad Gabriel René Moreno, Faculty of Agricultural Sciences.

Santa Cruz - Bolivia.

ABSTRACT

Precision agriculture is essential in today's agricultural production. It allows fields to be classified according to the productive potential of each environment, providing personalized management, improving production costs, and increasing yields.

The methodology used in this research is descriptive and applied, classifying productive environments based on the physical and chemical attributes of soils and their geospatial availability in order to recommend variable rate fertilization prescriptions for soybean cultivation on an agricultural property in the Cuatro Cañadas Municipality in the eastern zone of Santa Cruz. Georeferenced sampling was carried out by environments, and as a result, it was determined that 54% of the study area corresponds to environment A (high potential), 22% corresponds to environment B (medium potential), and 24% comprises environment C (low potential). In addition, sustainable management measures were suggested.

Keywords: Precision agriculture; Yields; Remote sensing; Variable rate fertilization; Geographic Information Systems.

RESUMEN

La agricultura de precisión es esencial en la producción agrícola actual, permite clasificar un campo de acuerdo a la potencialidad productiva de cada ambiente brindando un manejo personalizado, mejorando los costos de producción y aumentando los rendimientos.

La metodología empleada en esta investigación es de tipo descriptivo y aplicativo donde se clasificó los ambientes productivos en base a los atributos físicos – químicos de suelos y su disponibilidad geoespacial para poder recomendar prescripciones de fertilización a tasa variable en el cultivo de soya, ubicado en una propiedad agrícola del Municipio Cuatro Cañadas Zona Este de Santa Cruz. Se realizó el tipo de muestreo georreferenciado por ambientes y como resultado se determinó que del área de estudio un 54% corresponde a un ambiente A (potencialidad Alta), el 22% corresponde a un ambiente B (potencialidad media), y el 24% comprende al ambiente C (potencialidad baja). Además, se sugirieron medidas de gestión sostenibles.

Palabras clave: Agricultura de precisión; Rendimientos; Teledetección; Fertilización a tasa variable; Sistemas de información Geográfica.

Received: December 29, 2025 | Accepted: January 21, 2026 | Published: January 22, 2026

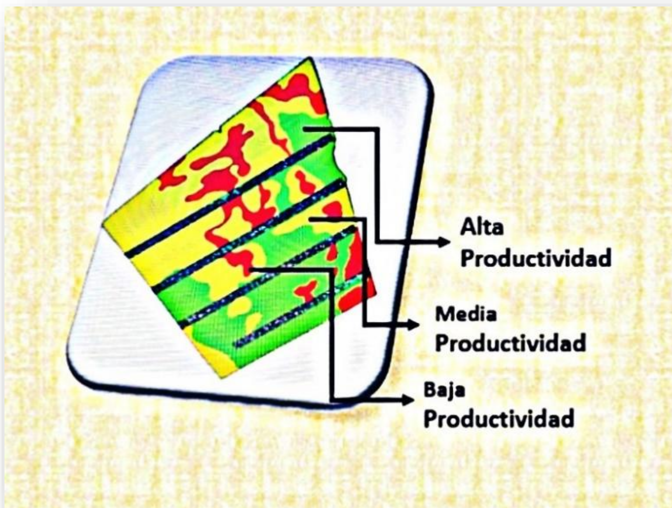
INTRODUCTION

Thanks to technological innovations, precision agriculture now allows fields to be classified according to the productive potential of each environment. The stratification of these environments is crucial for determining variable rate fertilization, setting achievable yield targets according to the productive potential of each environment and its nutritional requirements.

DOI: https://doi.org/10.71112/7s3xfc80

Figure 1

Potentially productive environments



To do this, at least three things must be acknowledged: (I) that the heterogeneity of elements and/or detect the differences that exist in a plot and, eventually, their causes and the processes affected by that heterogeneity; (II) that this heterogeneity modifies responses to management practices, that is, it interacts with them; and (III) crops can be managed within the limits of this heterogeneity; that is, units can be defined on which to make decisions and implement their management. In environment-based agriculture, unlike the plot, the management unit has similar agroecological attributes, which modulate crop performance and make it advisable to adjust a technical approach that is different from that of units belonging to another environment, both to improve yield and the efficient use of input resources, and to reduce variability and production risk. (Satorre & Bert, 2014).

Detailed knowledge of the chemical and physical variability of soils allows for the adjustment of nutrition plans to a varied rate. Its correlation with productivity can have a greater or lesser impact depending on the soil: therefore, knowing the soil type helps to complement recommendations and interpret productivity maps (Mosquera, 2012).

DOI: https://doi.org/10.71112/7s3xfc80

Santa Cruz, Bolivia, has the right conditions to develop precision agriculture technology for the benefit of producers. The adoption of variable rates in Santa Cruz will require the development of yield maps, topographic maps, satellite images, aerial photographs, real-time remote sensors, etc. (Rodríguez, 2012).

Precision agriculture (PA) allows for the management of plots based on the variability of agricultural production and the factors involved in it (Bragachini et al., 2006).

Zoning is a process of simplifying the production variability that exists in a plot, establishment, or region. The delimitation of these zones consists of dividing the plot into homogeneous subunits based on characteristics that are stable over time, others that are dynamic, and others that change over time and with management. (Bermudez, 2012).

Geographic information systems

Geographic Information Systems (GIS) play a crucial role in modern agriculture, as they provide tools for visualizing, analyzing, and managing spatial data in order to improve crop productivity and sustainability. (Astate, 2024; Esri, 2021). This technology helps farmers make informed decisions, optimize resource use, and address various challenges in agricultural practices. (Muhammad, 2023; gisnavigator, 2025).

The adoption of GIS in agriculture offers numerous advantages, resulting in more efficient, sustainable, and profitable agriculture. (Butora et al., 2022).

GIS enables farmers to create detailed maps of vegetation and productivity, allowing them to make informed decisions about seeds, nutrients, herbicides, and fertilizer amounts for each plot. This data-driven approach helps identify productive and unproductive areas, facilitating the implementation of targeted fertilization strategies.

Precision Agriculture

Precision agriculture, also known as prescription agriculture, uses GIS to optimize resource use and minimize environmental impact by focusing on site-specific management (Kumar et al., 2024).

(INTA, 2013)The National Institute of Agricultural Technology defines precision agriculture as the use of information technology to make economically and environmentally sound decisions for crop production, which has the potential to increase production efficiency and reduce environmental impact.

To this end, techniques such as remote sensing are used, which is generally defined as the measurement of energy emitted from the Earth's surface. If the source of the measured energy is the sun, then it is called passive remote sensing, and the result of this measurement can be a digital image (Richards & Jia, 2006) . This technology uses the electromagnetic spectrum as its main measurement variable, which is "the system that classifies, according to wavelength, all energy (from short cosmic to long radio) that moves harmoniously at the constant speed of light" (NASA, 2011) .

The Normalized Difference Vegetation Index (NDVI) is a widely used metric for quantifying vegetation health and density through sensor data. (projects., 2006) It is an important indicator in agricultural organizations and environmental studies, as it measures greenness, vegetation health, and predicts agricultural productivity, as well as mapping desertification. (NDVI is commonly used in remote sensing to monitor seasonal, interannual, and long-term variations in the structural, phenological, and biophysical parameters of land surface vegetation cover. (Falk, 2004) .

The results obtained through remote sensing were corroborated in situ through soil sampling. Accurate soil analyses are based on representative samples. Obtaining representative samples requires care and skill. In most cases, the sample represents a quantity of soil that is more than ten million times greater than the portion sent to the laboratory. Therefore, regardless of whether the sample represents a small or large area, it is important to take multiple samples covering the entire surface of the area, which are then combined and mixed well to obtain a sample for analysis that truly represents the entire area sampled (Jensen et al., 2013).

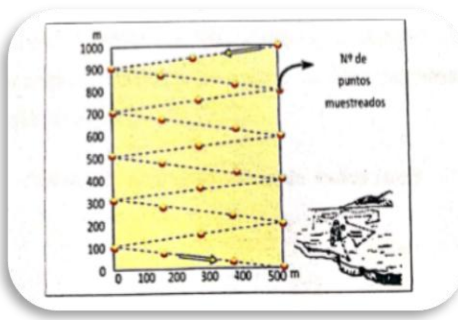
Mention three ways of taking samples, which are detailed below:

Zigzag sampling method

Subsamples will be collected in a zigzag pattern (Figure 2), at equidistant points 15 to 20 steps apart. Another way is to divide the plots into homogeneous lots, and for each division made, sampling is carried out in a zigzag pattern, with 20 to 30 subsamples of equal size considered an adequate number.

Figure 2

Zigzag sampling



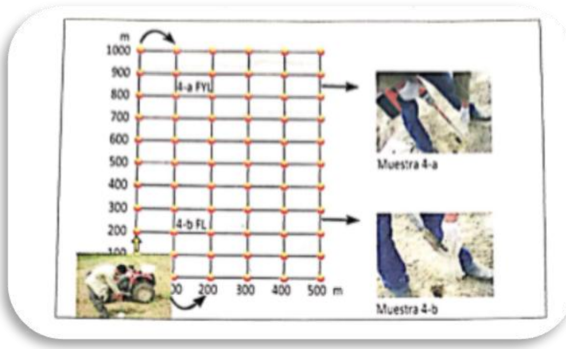
Georeferenced sampling (grid method)

This is done with the help of GPS (Global Positioning System) equipment. The methodology is more technical in nature: the plot is subdivided into grids with a distance of 50 to 100 meters between one point and another (Figure 3). Each individual sample is collected and placed in individual plastic bags. The collected samples are arranged on a table in the same way as they were found in the plot, and then touch tests are performed to determine similar textures, which are mixed and identified.

DOI: https://doi.org/10.71112/7s3xfc80

Figure 3

Zigzag sampling



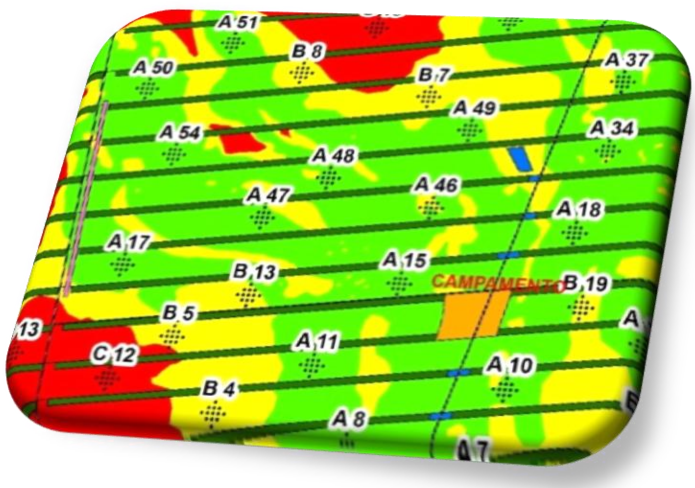
Georeferenced sampling method Potentially productive environments

Sampling is carried out with the help of GPS equipment and georeferenced data such as environment or productivity maps obtained from overlaying systems of various layers of spatial information, i.e., soil sampling is carried out based on the spatial variability detected within a productive plot. This involves the use of various technologies such as: multi-temporal satellite and drone images, GPS, yield monitors, variable rate applicators, altimetric levels, green indices, waterlogging, compaction, and the main physical, chemical, and biological characteristics of soils that affect agricultural production. (*Figure 4)*

DOI: https://doi.org/10.71112/7s3xfc80

Figure 4.

Georeferenced Sampling by Production Environments



Physical Soil Attribute

Good physical soil quality determines a suitable environment for plant root development, as well as optimal water intake and storage necessary for plant growth (Taboada & Álvarez, 2008).

Humans modify the physical quality of the soil through agricultural or livestock management. The decline in physical quality has serious consequences for chemical and biological conditions (Dexter, 2004).

Soil Profile

(Bruulsema et al., 2012) defines the soil profile as a vertical section of soil extending from the surface through all its horizons to the parent material.

Soil Texture

Texture is the relative size portion of soil particles.

The most common classification separates these sizes into sand, silt, and clay with the following limits: sand from 2 to 0.02 mm, silt from 0.02 to 0.002 mm, and clay less than 0.002

mm (Canedo, 2008) . Texture is the element that best characterizes soil from a physical-structural point of view; permeability, ease of tillage, cation exchange capacity, water retention capacity, and structure are some of the characteristics of soil that depend largely on texture. (Darwich, 2005) .

Apparent Density

Apparent density is the mass of soil per unit volume ($g.cm^{-3}$ or $t.m^{-3}$). It describes soil compaction, representing the relationship between solids and pore spaces (Keller & Hákansson, 2010)

The apparent density value is a necessary parameter in various soil-related calculations, such as: Calculating soil suitability; Calculating the weight of a given volume of soil; Calculating the amount of nutrients in kg/ha; Converting the gravimetric moisture content of the soil to volumetric content.

In addition to the above, it is an estimator of the degree of soil compaction, since if this problem is occurring, the bulk density increases; it is also an indicator of high organic matter (OM) content in the soil, since OM reduces the value of this density. In other words, the higher the bulk density, the lower the organic matter content. Apparent density is also a parameter for estimating the degree of soil deterioration, bearing in mind that as its value increases, the structure of the soil is degrading, either due to compaction or the loss of organic matter.

Chemical Attributes of Soil

pH

Canedo (2008) mentions that soil pH, directly or indirectly, can be responsible for the availability of almost all soil nutrients to plants. Phosphorus, iron, and zinc, among the main ones, are insolubilized by chemical reactions that occur at very acidic or very alkaline pH levels. pH is defined as the negative logarithm of the concentration of hydrogen ions or as the logarithm of the inverse of the activity of the hydrogen ion. Soil pH simply measures the activity of hydrogen ions and is expressed, as already mentioned, in logarithmic terms (Darwich, 2005).

Organic Matter

Canedo (2008) mentions that organic matter is an active and important part of soil, although most cultivated soils contain 1 to 5% organic matter, especially in the top 25 cm of soil. This small amount can modify the physical characteristics of the soil and strongly affect its chemical and biological properties.

Nitrogen

According to , nitrogen (N) is one of the most widely distributed elements in nature. The main reservoir of N is the atmosphere.

In the soil, it is found in three forms:

Nitrates: This is a form of N that is assimilable or available to plant roots.

Ammoniacal: This is a transitional form of N and is not abundant in the soil.

Organic: Found in organic matter and the only permanent source or reserve of N in the soil.

In addition to its role in protein formation, nitrogen is an integral part of the chlorophyll molecule, which absorbs the energy from solar radiation necessary for photosynthesis (Echeverría & Saínz Rozas, Nitrogen, 2006).

Phosphorus

Plants absorb phosphorus, preferably as an anion ($H_2PO_4^-$) and to a lesser extent ($HPO_4^=$). The first organic compounds formed with phosphorus in the plant are phosphohexoses and uridine diphosphate, the precursors of ATP. Phosphate occurs in plants in inorganic form as orthophosphate and, to a lesser extent, as pyrophosphate.

The organic forms of phosphate are compounds in which orthophosphate is esterified with hydroxyl groups of sugars and alcohols or linked by a pyrophosphate bonded to another phosphate group. The most important compound in which the phosphate group is linked by pyrophosphate bonds is ATP or adenosine triphosphate, which plays an important role in plants as a constituent of high-energy storage compounds (Mengel & Kirkby, 2012).

Phosphorus is part of enzymes, nucleic acids, and proteins and is involved in virtually all energy transfer processes. Plants with phosphorus deficiencies have less expansion and leaf area and fewer leaves. The greater effect on leaf growth than on chlorophyll growth explains the darker green colors observed in phosphorus-deficient plants (García et al., 2006).

Sulfur

The soil contains sulfur in organic matter in varying amounts, and it is only available to plants through mineralization. Sulfur is absorbed by plant roots almost exclusively in the form of sulfate ion ($SO_4^{=}$). Although small amounts are absorbed in the form of sulfur dioxide (SO_2) through the leaves of plants. A sulfur deficiency, which has a pronounced effect of slowing plant growth, is characterized by uniformly chlorotic plants and thin stems (Canedo, 2008).

Sulfur is an essential nutrient for plants with requirements similar to phosphorus. However, for a long time, it did not receive much attention because crops did not respond to its addition. This situation has changed in many crop and pasture production areas on five continents, where improvements in yields and the quality of agricultural products have been observed with the addition of sulfur. Sulfur is also a constituent of the amino acids methionine and cysteine, and its deficiency causes serious malnutrition problems in humans (Echeverría, Azufre, 2006) .

Potassium

Potassium is one of the three main inorganic mineral nutrients, along with N and P. Not only is it important quantitatively, as it is the most abundant element along with the four main components of proteins and carbohydrates (N, O, and H), but its importance also derives from its multiple functions. It is the most important cation due to its physiological and biochemical functions (Melgar et al., 2011).

Potassium is absorbed as a monovalent cation (K^+) present in the soil solution and remains without forming part of any molecule throughout the life cycle, unlike other mineral elements. (Melgar et al., 2011).

Potassium is part of organic molecules and is also involved in numerous physiological and biochemical functions in plants, which makes it an essential element. Plants require relatively large amounts of potassium, sometimes more than nitrogen. (Conti & García, 2006) .

Calcium

Calcium is an element required by all higher plants; absorbed in the form of Ca^{++} ions, it is found in abundant quantities in plant leaves and, in some species, in plant cells as calcium oxalate precipitate. It can also be present in the sap of cells in ionic form. The specific physiological functions of calcium in plants are not clearly defined. Traditionally, calcium has been considered necessary for the formation of the middle lamella of cells because of its important role in the synthesis of calcium pectate. It has also been suggested that calcium promotes the formation and increase of the protein contained in mitochondria. (Canedo, 2008).

Magnesium

Magnesium is one of the constituent elements of plant chlorophyll, so it is actively involved in photosynthesis. Most Mg is found in chlorophyll. Magnesium participates in phosphate metabolism in plant respiration, in the activation of various enzyme systems, and indirectly in protein synthesis (Darwich, 2005).

Cation exchange capacity

CEC is the property of soils to retain and exchange ions on the surface of organic and inorganic colloids in the soil. The ions retained in the exchange complex maintain a dynamic equilibrium with the ions in the soil solution (Conti and García, 2006).

Iron

Iron is absorbed by the roots as a divalent cation Fe^{2+}(ferrous iron) or as a chelate, with absorption in trivalent form being irrelevant (ferric iron) due to the low solubility of the latter at normal soil pH. The rate of iron reduction is dependent on pH, being higher at lower pH (Mengel & Kirkby, 2012; Melgar et al., 2011).

DOI: https://doi.org/10.71112/7s3xfc80

(Darwich, 2005) He mentions that iron is a catalyst that aids in the formation of chlorophyll and acts as an oxygen carrier. Iron also contributes to the formation of certain respiratory enzyme systems. Iron deficiency produces pale green leaves (interveinal chlorosis). With a marked distinction between green veins and yellow interveins, symptoms usually appear first on the green leaves at the top of the plant.

Micronutrients

Manganese

According to , the manganese present in the soil comes from oxides, carbonates, silicates, and sulfates. Due to its different degrees of oxidation (II, III, and IV) and its ability to change from one form to another, the behavior of manganese in the soil is complex.

The forms in which it can occur are:

Manganous ion Mn^{2+}(divalent) in soil solution. It is interchangeable and available to plants.

Oxides and hydroxides (MnO_2 Mn(OH)) or associated with iron hydroxides. In some soils, it can occur in layers on the planes of separation of aggregates or in the form of fern leaves. In these states, manganese is neither exchangeable nor available.

Poorly soluble salts (Mn(II) and Mn(III) phosphates, Mn(II) carbonates), especially in calcareous or alkaline soils.

Zinc

Zn absorption occurs mainly as a divalent Zn^{2+}cation from the soil solution, aided by a protein with a high affinity for Zn at low pH values, and probably as $Zn(OH)_2$at high values. Transport in plants occurs both as Zn^2+ and bound to organic acids. The latter, in the form of low molecular weight compounds, are the most physiologically active fraction. It accumulates in the roots but is translocated to the shoots when necessary. It is relatively mobile, translocating from mature leaves to developing organs. (Alloway, 2008).

DOI: https://doi.org/10.71112/7s3xfc80

Copper

Copper is an immobile element that accumulates in surface horizons due to bioaccumulation and anthropogenic contamination. Most of this element is absorbed specifically by organic matter and, to a lesser extent, by silicate clay surfaces, generating forms that are not readily available. (Torri et al., 2006).

Copper is absorbed in very small quantities through a metabolically assisted process and competes strongly with Zn absorption and vice versa (Bowen, 1969) . However, copper absorption is mainly related to the levels of copper available in the soil. Nevertheless, there is debate as to whether copper is absorbed as a Cu2+ ion or as a chelate, (Graham, 1981) .

Boron

Boron is absorbed by the plant as boric acid (H_3BO_3) and perhaps as borate anion at high pH, both through the roots and through the leaves. Boron is an element with low mobility within the plant. It has also been proven that young plants absorb it more intensely than older ones, with low mobility from old to young tissues. There may even be a boron deficiency in one leaf while another on the same stem has adequate levels. (Canedo, 2008).

Variable Rate

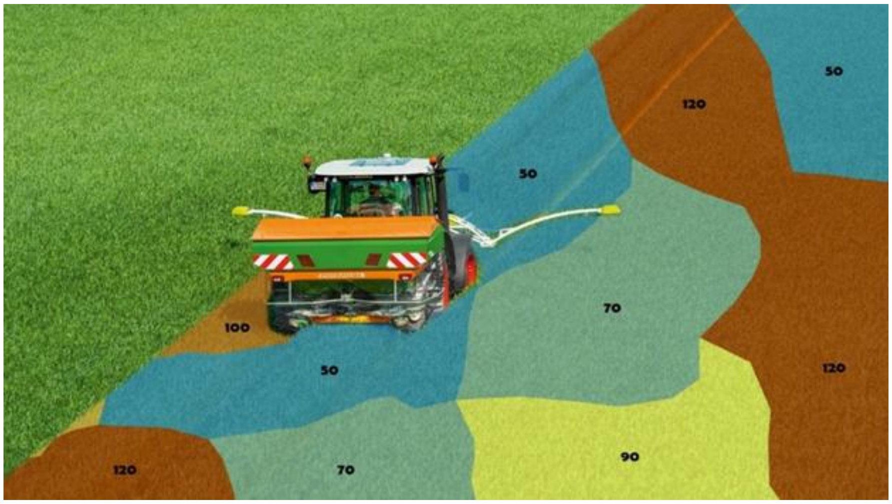
Variable rate is a technology that allows for the rationalization of input use without affecting productivity. On the contrary, by balancing the amounts of active ingredient or nutrient, lowering costs, and creating more environmentally balanced conditions, after a few crop cycles it is possible to better adjust the system and increase productivity (Mosquera, 2012).

Variable Rate Technology (VRT) allows farmers, once they know the behavior of the crop in each sector of the plot, to calculate the input requirements in each smaller homogeneous area or subunit on the ground and apply them in a site-specific manner ( ) (Bragachini, 2004 cited by Bragachini et al., 2009). See Figure 5.

DOI: https://doi.org/10.71112/7s3xfc80

Figure 5.

Variable rate fertilization



The potential for improving profitability through variable application of these inputs depends on 1) identifying areas in the field where additional inputs will increase income on a larger scale than the additional costs generated by such inputs and/or; 2) the identification of areas where reducing inputs will decrease costs on a scale that is greater than the potential reduction in income correlated with lower grain yield (Koch, 2004, cited in Bragachini et al., 2009).

Fertilization for soybean cultivation

(García & Correndo, 2013) In the FUNDACRUZ technical dissemination manual on soybeans, they mention that soybean cultivation needs to absorb a significant amount of nutrients to achieve adequate growth and grain yield. Nutrient harvest rates (the ratio between the amount of nutrients in the grain and the amount of nutrients absorbed) are high (Table 1).

DOI: https://doi.org/10.71112/7s3xfc80

Table 1.

Nutritional requirements for soybean cultivation

Nutrients	Requirements	Harvest indices	Soybean 3000 kg/ha	
			Absorption	Extraction
-	Kg/ton grain	%	kg/ha	kg/ha
N	75	0.73	225	164.25
P	7	0.88	21	18.48
K	39	0.49	117	57.33
Ca	16	0.19	48	9.12
Mg	9	0.39	27	10.53
S	4.5	0.72	13.5	9.72
B	0.025	0.31	0.075	0.02325
Cl	0.237	0.47	0.711	0.33417
Cu	0.025	0.53	0.075	0.03975
Fe	0.3	0.25	0.9	0.225
Mn	0.15	0.33	0.45	0.1485
Mo	0.005	0.85	0.015	0.01275
Zn	0.06	0.7	0.18	0.126

This research stems from the need for farmers to know the

the productive potential and fertility of their soils when making decisions, including fertilization, taking into account the unknowns: ¿How much to apply? What to apply? And where to apply it? Based on this objective, we will proceed with the classification of productive environments based on the physical and chemical attributes of the soil and its geospatial distribution, and then set achievable yield goals, recommending variable rate fertilizer prescriptions.

METHODOLOGY

The research was carried out on the San Carlos property in the Cuatro Cañadas Municipality, Ñuflo de Chávez Province, Department of Santa Cruz. Geographically located at 17°18'35.69" south latitude and 62° 0'57.00" west longitude, at an altitude of 265 meters above sea level.

The materials used are: sampling drill, sample bags, shovel, pickaxe, tape measure, metal cylinder, precision scale, oven, customized computers (16–32 GB RAM), Garmin 64S GPS, CHC i70 Centimeter GPS RTK, John Deere Axial Combine Performance Monitor, and Kacife laboratory physical-chemical analysis – Brazil.

The geographic information systems used are: ArcGIS (10.6) (ArcMap) Trial Version software, Global Mapper 18 software, Russian SAS Planet software, Google Earth Pro software, and Apex John Deere software.

The geospatial materials used are satellite and aerial images:

Landsat 5,7: Multitemporal images from 1990 > 2014.

Landsat 8: Multitemporal images from 2014 to 2017, flooding and NDVI

Sentinel 2: Multitemporal images > 2018, Flooding risk and NDVI

Aster: For the Digital Elevation Model (DEM)

Google Maps/Earth, Bing Maps (Bird's Eye), Yandex Maps, OpenStreetMap, DigitalGlobe, and eAtlas: High-precision measurement for detecting net cultivable area.

Fixed-wing drone with "Micasense" multispectral camera: Very high-precision measurement by plot and NDVI, Chlorophyll.

Classification of soils by productive environments

To classify the soils in the study area according to their productive potential, factors causing their heterogeneity were identified, which made it possible to classify them into three types of productive environments. The characteristics used for each of them are detailed below:

DOI: https://doi.org/10.71112/7s3xfc80

High Environment (A): Loamy to medium-heavy soils: Loose, predominantly loamy-silty texture, with less than 25% clay, good productive potential, high green index (NDVI), and no risk of waterlogging.

Medium Environment (B): Medium-heavy soils with acceptable productivity, clay content between 25–35%, medium green index, with slight surface unevenness and minor waterlogging problems;

Low Environment (C): Heavy soils, predominantly clayey in texture, with clay content above 35%, and other soils with high sand content >80%, low productive potential, abundant depressed areas, low green index, areas with un r waterlogging and salinity problems.

Sampling Points

On the map of productive environments, with the intention of identifying the aptitudes of each productive environment and searching for its deficits or virtues, georeferenced points (GPS – X and Y coordinates) were positioned.

Soil sampling was carried out with the help of GPS equipment, a drill, plastic bags, and labels. Twenty subsamples were taken around each georeferenced point, at a depth of 0–20 cm, which were homogenized to obtain a representative sample. To determine soil compaction, apparent density samples were taken using the cylinder method. Three replicates were taken from each layer identified at the following depths: 0–10, 10–20, and 20–30 cm, corresponding to the topsoil layer.

These samples were properly labeled and placed in an oven for drying, obtaining the dry weight of the soil. The apparent density (g/cm3) was calculated using the following formula.

$$\mathbf{DAP} = \frac{\boldsymbol{MS}}{\boldsymbol{VC}}$$

Where:

DAP: Apparent density (g/cm³); MS: Dry soil mass (g); VC: Cylinder volume (cm³).

The following parameters were used to interpret the pH. (Table 2)

DOI: https://doi.org/10.71112/7s3xfc80

Table 2.

Interpretation of active soil acidity class (pH)

Chemical classification						
Very high acidity	**High acidity**	**Medium acidity**	**Low acidity**	**Neutral**	**Weak alkalinity**	**High alkalinity**
> 4.5	4.5 - 5.0	5.1 - 6.0	6.1- 6.9	7	7.1 - 7.8	> 7.8
Agronomic assessment						
Very low		**Low**	**Good**	**High**	**Very high**	
<4.5		04.05 - 05.04	5.5 - 6.0	6.1 - 7.0	> 7.0	

With regard to the interpretation of macro- and micronutrients, soil parameters according to Kacife Laboratories were used (Table 3):

Table 3.

Sufficiency levels of soil analysis parameters (KACIFE)

Analysis parameters	Sufficiency levels				
	Very low	Low	Moderate	High	Very high
Organic matter (%)	*< 0.71*	*0.71 - 2.00*	*2.01 - 4.00*	*4.01 - 7.00*	*> 7.00*
Total, nitrogen (%)	*< 0.05*	*0.05 - 0.12*	*0.12 - 0.22*	*0.23 - 0.28*	*> 0.28*
Available nitrogen (mg/kg)	*< 12.00*	*12.40 - 29.00*	*29.10 - 53.00*	*54.00 - 70.00*	*> 70.00*
Phosphorus Resin (mg/l)	*< 6.0*	*7.00 - 15.00*	*16.00 - 40.00*	*41.00 - 80.00*	*> 80.00*
Potassium (mg/l)	*---*	*< 150*	*150 - 250*	*250 - 800*	*> 800*
Calcium ($cmol_c$/l)	*< 0.41*	*0.41 - 1.20*	*1.21 - 2.40*	*2.41 - 4.00*	*> 4.00*
Magnesium ($cmol_c$/l)	*< 0.16*	*0.16 - 0.45*	*0.46 - 0.90*	*0.91 - 1.50*	*> 1.50*
Int. Capacity Cat. Effective (cmolc/l)	*< 1.61*	*1.61 - 4.30*	*4.31 - 8.60*	*8.61 - 15.00*	*> 15.00*
Total, Int. Bases (cmolc/l)	*< 0.81*	*0.81 - 2.30*	*2.31 - 4.60*	*4.61 - 8.00*	*> 8.00*
Base saturation (%)	*< 20*	*20 - 40*	*40 - 60*	*60 - 80*	*> 80*

Remaining P (mg/l)	Analysis parameters	Sufficiency levels				
		Very low	Low	Moderate	High	Very high
0 – 4	Sulfur (mg/l)	*< 1.80*	*1.80 - 2.50*	*2.60 - 3.60*	*3.70 - 5.40*	*> 5.40*
Oct 4		*< 2.50*	*2.50 - 3.60*	*3.70 - 5.00*	*5.10 - 7.50*	*> 7.50*
Oct-19		*< 3.40*	*3.40 - 5.00*	*5.10 - 6.90*	*7.00 - 10.30*	*> 10.30*
19 – 30		*< 4.70*	*4.70 - 6.90*	*7.00 - 9.40*	*9.50 - 14.20*	*> 14.20*
30 – 44		*< 6.50*	*6.50 - 9.40*	*9.50 - 13.00*	*13.10 - 19.60*	*> 19.60*
44 – 60		*< 8.90*	*9.00 - 13.00*	*13.10 - 18.00*	*18.10 - 27.00*	*> 27.00*

Nutrient management and requirements in soybean cultivation

The nutritional balance was calculated for each georeferenced point that was sampled, considering the essential nutritional requirements and needs for soybean cultivation. Taking into account the laboratory results, these were converted to kilograms/hectare at a depth of 20 cm using the soil weight calculated from the apparent density. The difference in nutrients required to be incorporated into the soil was calculated and converted into forms of commercial products available on the market.

The following tables show the absorption and extraction values of different nutrients: For environments A and B (High and Medium Potential), yield targets of 3.5 t/ha were set. (See Table 4).

DOI: https://doi.org/10.71112/7s3xfc80

Table 4.

Nutritional Balance (Environment A and B)

Nutrients	Requirements	Harvest indices	Absorption	Extraction
-	Kg/t	%	kg/ha	kg/ha
N	75	0.73	262.5	191.625
P	7	0.88	24.5	21.56
K	39	0.49	136.5	66.885
Ca	16	0.19	56	10.64
Mg	9	0.39	31.5	12.285
S	4.5	0.72	15.75	11.34
B	0.025	0.31	0.0875	0.027125
Cl	0.237	0.47	0.8295	0.389865
Cu	0.025	0.53	0.0875	0.046375
Fe	0.3	0.25	1.05	0.2625
Mn	0.15	0.33	0.525	0.17325
Mo	0.005	0.85	0.0175	0.014875
Zn	0.06	0.7	0.21	0.147

And for environment C (low potential), a yield target of 2.5 t/ha was set (See Table 5)

Table 5.

Nutritional Balance (Environment C

Nutrients	Requirements	Harvest Indices	Absorption	Extraction
-	Kg/t	%	kg/ha	kg/ha
N	75	0.73	187.5	136.875
P	7	0.88	17.5	15.4
K	39	0.49	97.5	47.775
Ca	16	0.19	40	7.6
Mg	9	0.39	22.5	8.775
S	4.5	0.72	11.25	8.1
B	0.025	0.31	0.0625	0.019375
Cl	0.237	0.47	0.5925	0.278475
Cu	0.025	0.53	0.0625	0.033125
Fe	0.3	0.25	0.75	0.1875
Mn	0.15	0.33	0.375	0.12375
Mo	0.005	0.85	0.0125	0.010625
Zn	0.06	0.7	0.15	0.105

DOI: https://doi.org/10.71112/7s3xfc80

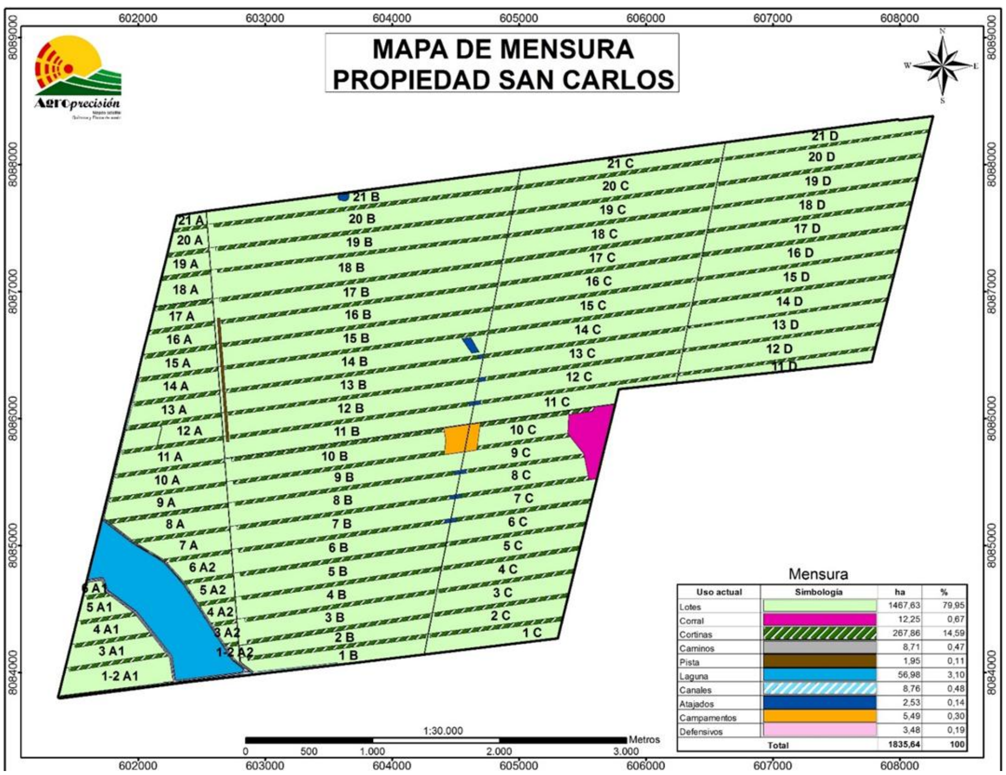
RESULTS

Survey Map

The total area under study on the San Carlos property is 1835.64 ha, of which 1467.63 ha (3626.59 acres) is usable for agricultural plots; 267.86 ha is windbreaks; 56.98 ha is water ponds; 12.25 ha are corrals; 8.76 ha are water channels; 8.71 ha are roads; 5.49 ha are campgrounds; 3.48 ha are defensive; 2.53 ha are water barriers; and 1.95 ha are for the track. (see Figure 6)

Figure 6

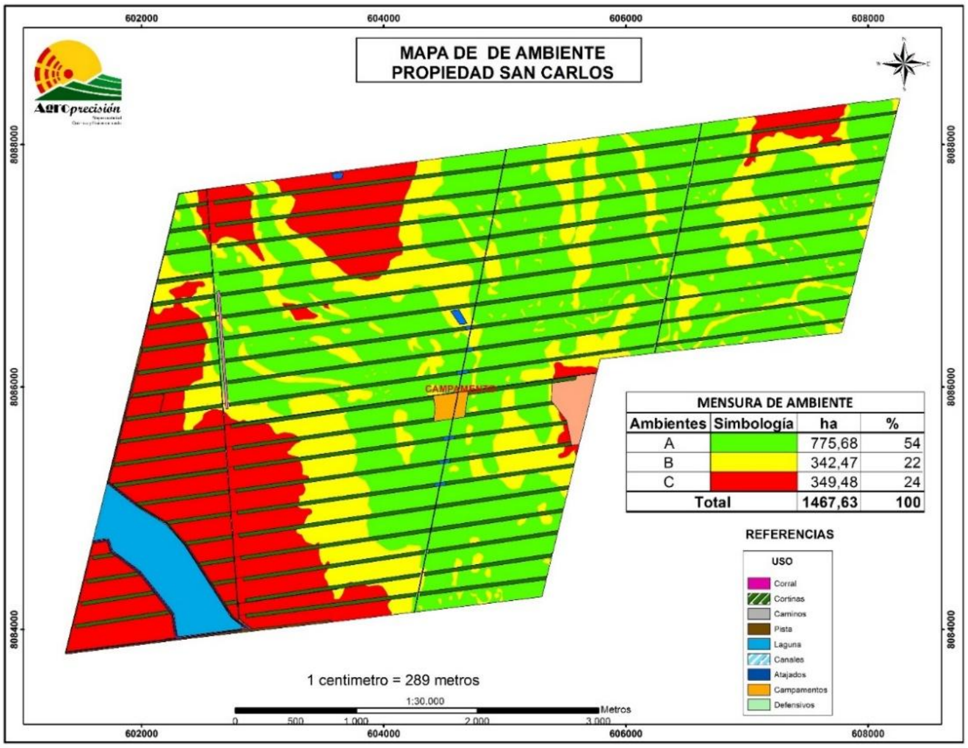
Survey map



DOI: https://doi.org/10.71112/7s3xfc80

Figure 7

Map of potentially productive environments.

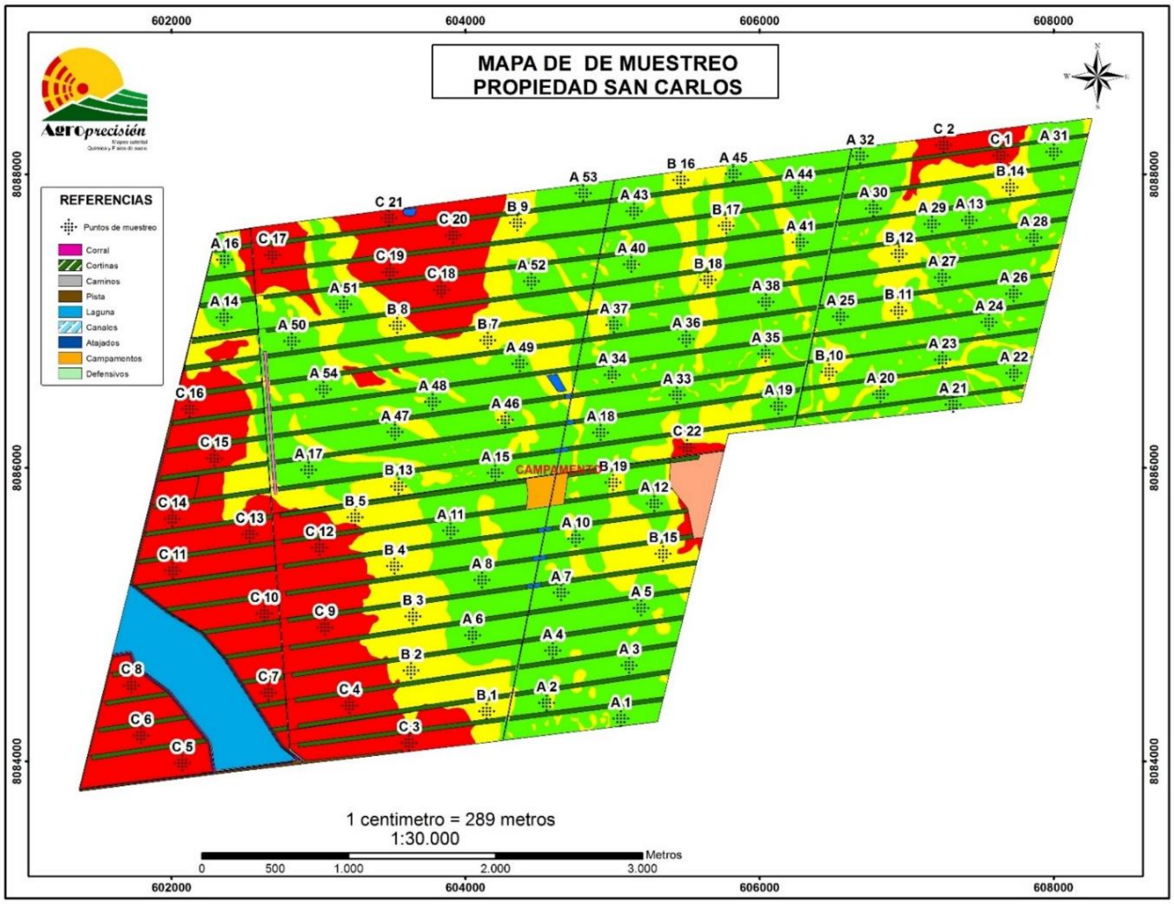


Note: This is directly related to the distribution of clay. (Figure 11)

DOI: https://doi.org/10.71112/7s3xfc80

Figure 8

Georeferenced sampling points placed on the map of potentially productive environments.

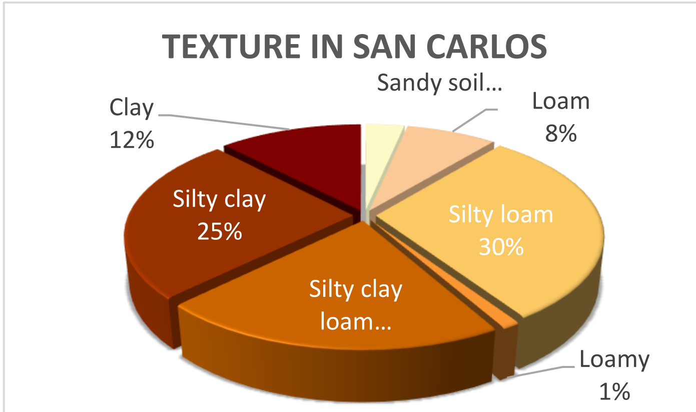


Soil texture according to the texture of the soils of San Carlos, presents textural contrast, they can be grouped as follows (Figure 9).

DOI: https://doi.org/10.71112/7s3xfc80

Figure 9

Soil texture percentage.



Intermediate soils predominate at 52% (loamy, silty, and silty loam), followed by heavy soils at 37% (silty clay and clay), and finally sandy soils at 11% (sandy loam and loam).

The Textural Number-"Y+(0.5)L" is the combined representation of the clay and silt content of a given soil in a given production environment and ranges from 24 to 82%.

Soils in environment A have complex textures, with an average clay content of 23%, but with values up to 40%, being predominantly silty loam soils, with an average of 61% silt and 18% sand.

The high silt content gives the soil a weak structure, it flattens very quickly, and tends to form a crust after rain, so it needs to be managed with a lot of stubble cover to minimize its negative effect. It also causes a reduction in water infiltration into the soil, so there must be permanent soil cover.

In environment B, clay increases to an average of 45% with ranges up to 56%. These are soils where silt particles predominate, with an average of 52% and values between 40% and 68%. In environment C, the soils are heavier, with an average of 57% clay.

Clay correlates with the textural number and ranges from 4 to 74%. There is a noticeable increase in clay in environments B and C. (see Figure 10).

DOI: https://doi.org/10.71112/7s3xfc80

Figure 10

Relationship between clay and textural number

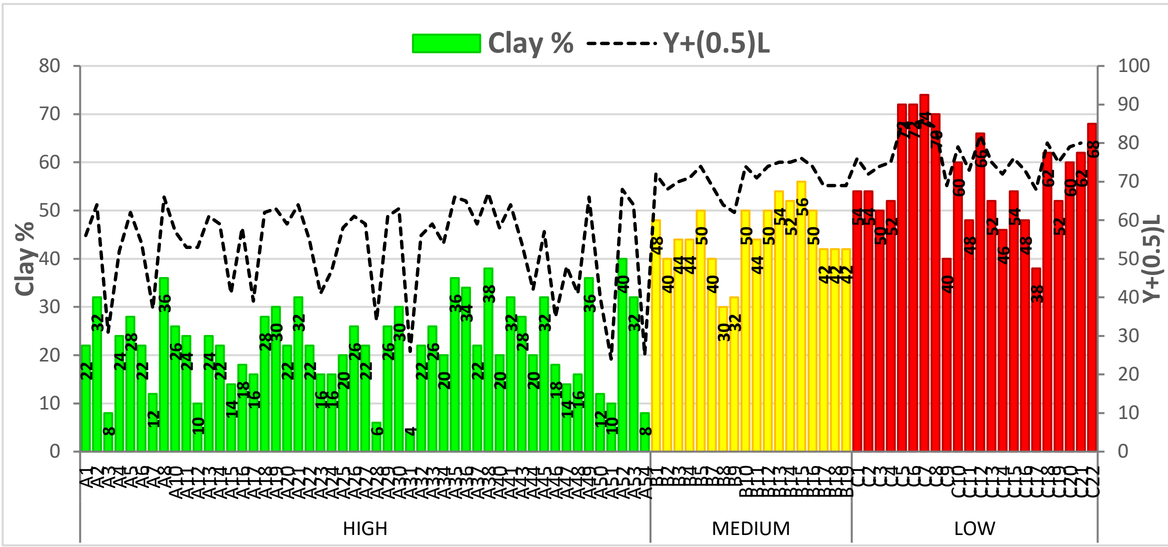
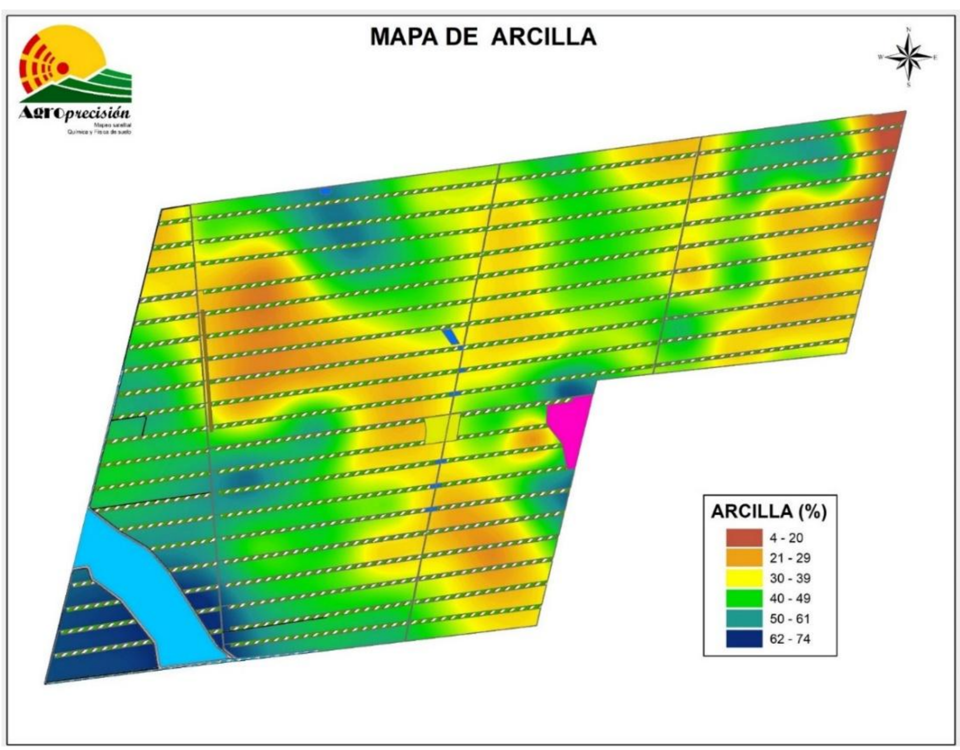


Figure 11

Clay map

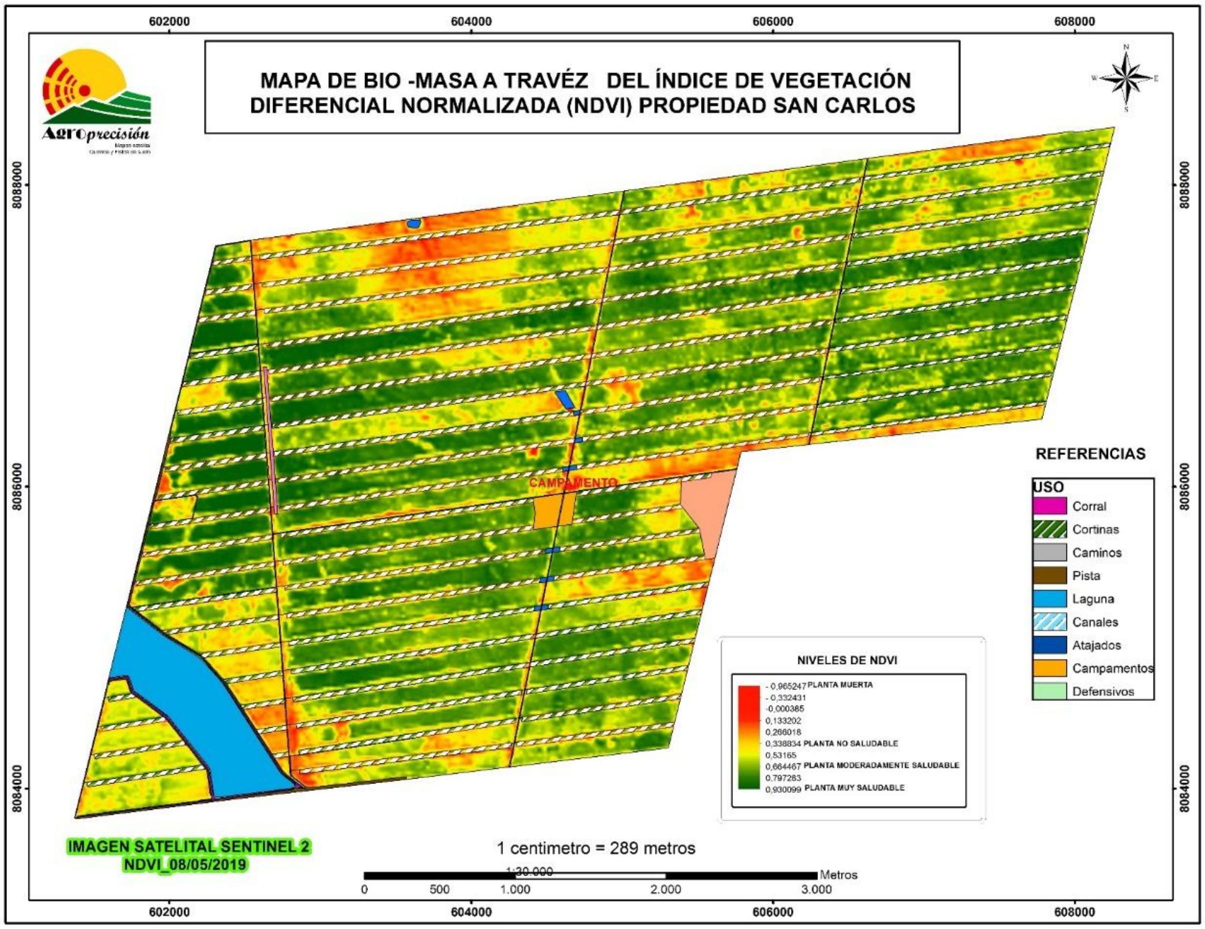


Note: This is directly related to the NDVI index. (Figure 12)

DOI: https://doi.org/10.71112/7s3xfc80

Figure 12

Normalized Difference Vegetation Index (NDVI) Map

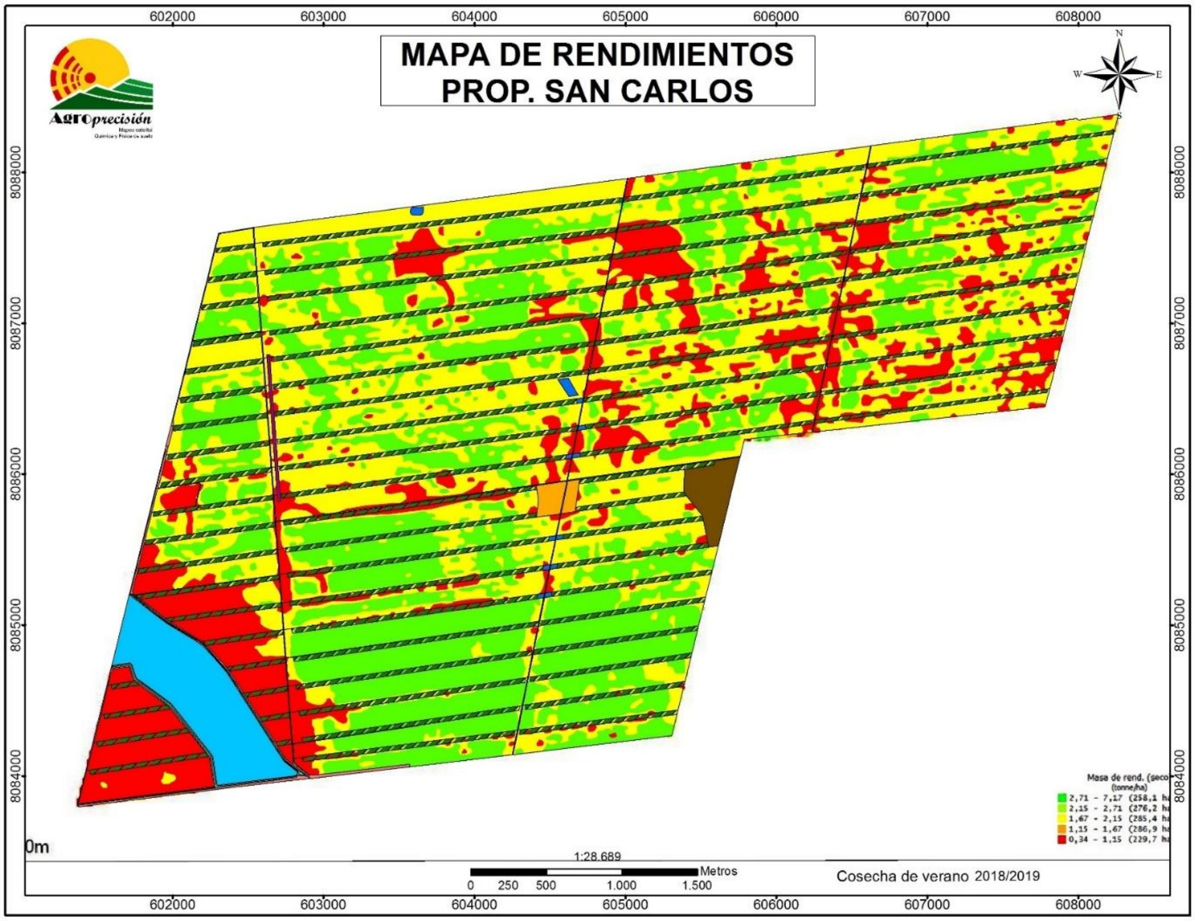


Note: This is directly related to the Yield map. (Figure 13)

DOI: https://doi.org/10.71112/7s3xfc80

Figure 13

Yield Map for the 2018/2019 Summer Harvest, San Carlos Property.



(John Deere Axial Combine Yield Monitor, Dry Matter Yield T/ha.)

Nutritional Management

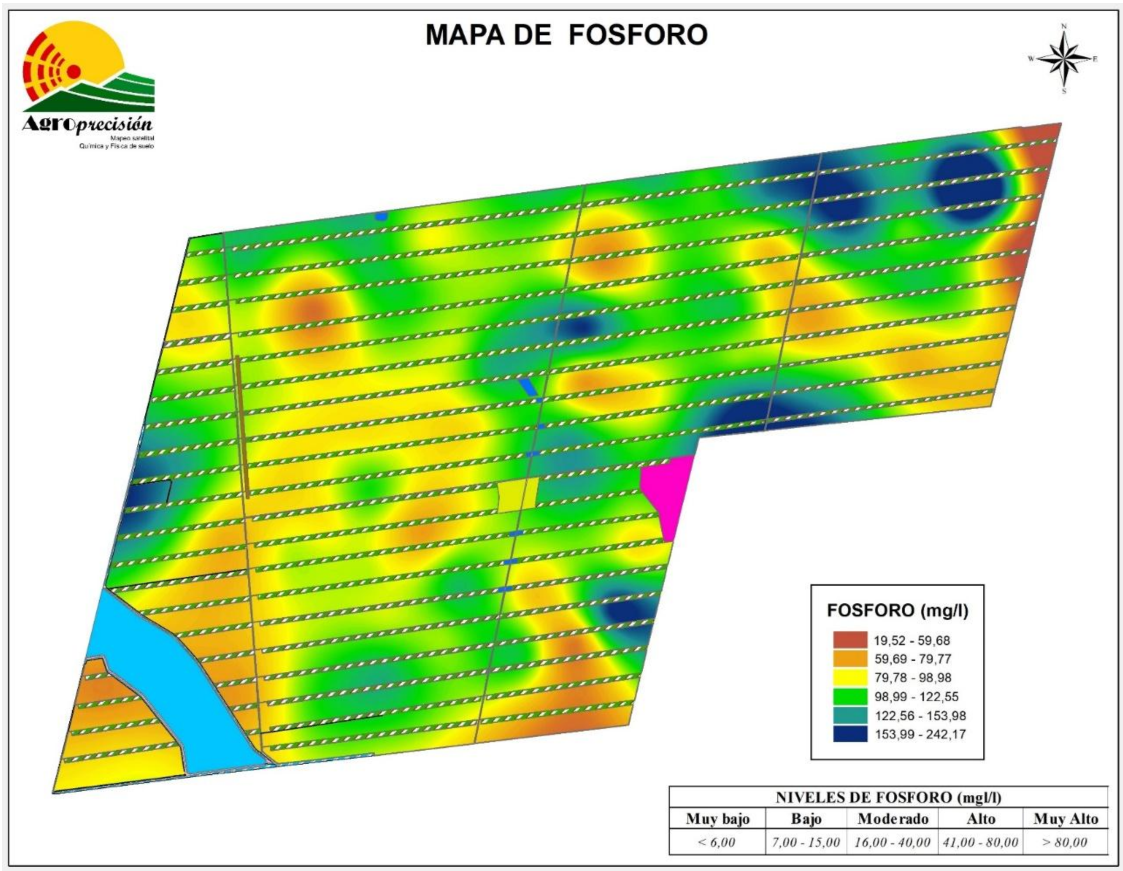
Fertilization for soybean cultivation

A productivity level for soybean cultivation has been considered with a yield target of 3.5 t/ha in environments A and B, while for environment C it is 2.5 t/ha and, based on the demand for macronutrients through a nutritional balance, only phosphorus and sulfur fertilization is required. The following maps detail the fertilizer doses that need to be applied at variable rates and their relationship to the geospatial distribution of these nutrients.

DOI: https://doi.org/10.71112/7s3xfc80

Figure 14

Phosphorus Map

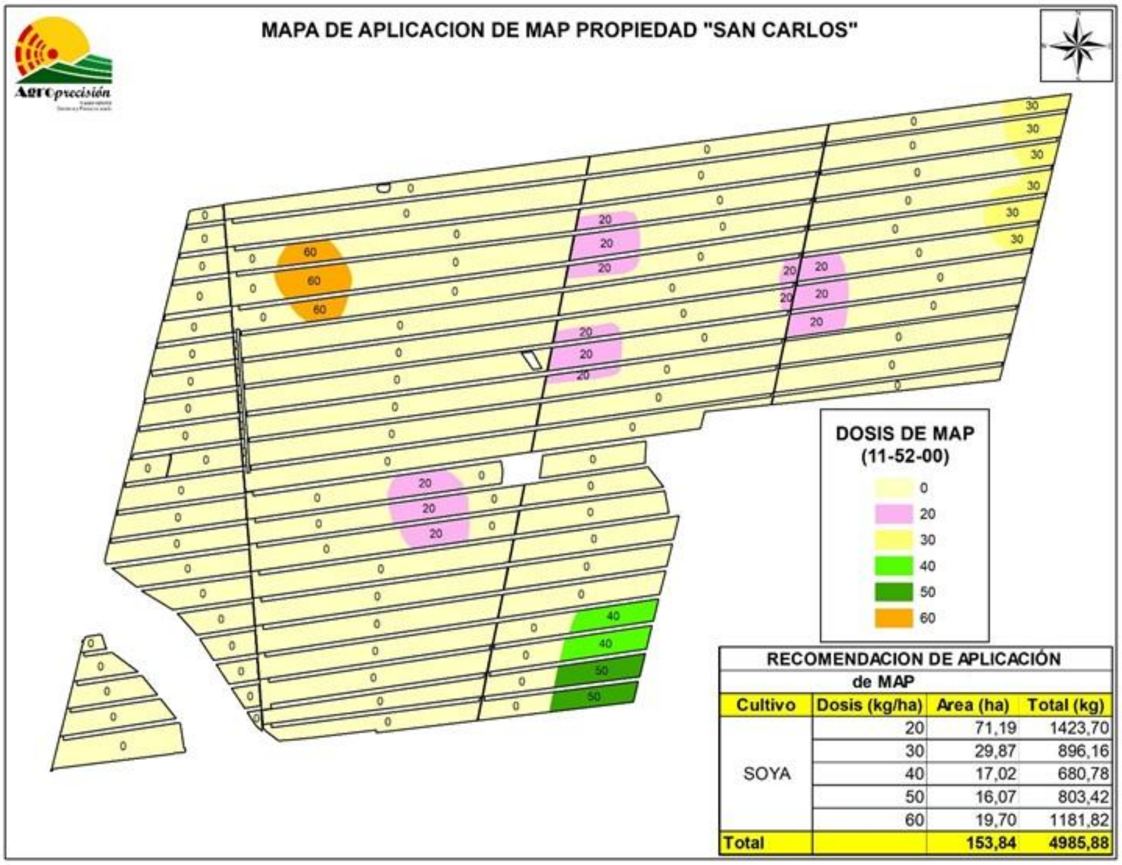


Note: The variable MAP dose was calculated taking into account the spatial distribution of phosphorus. (see Figure 15).

DOI: https://doi.org/10.71112/7s3xfc80

Figure15

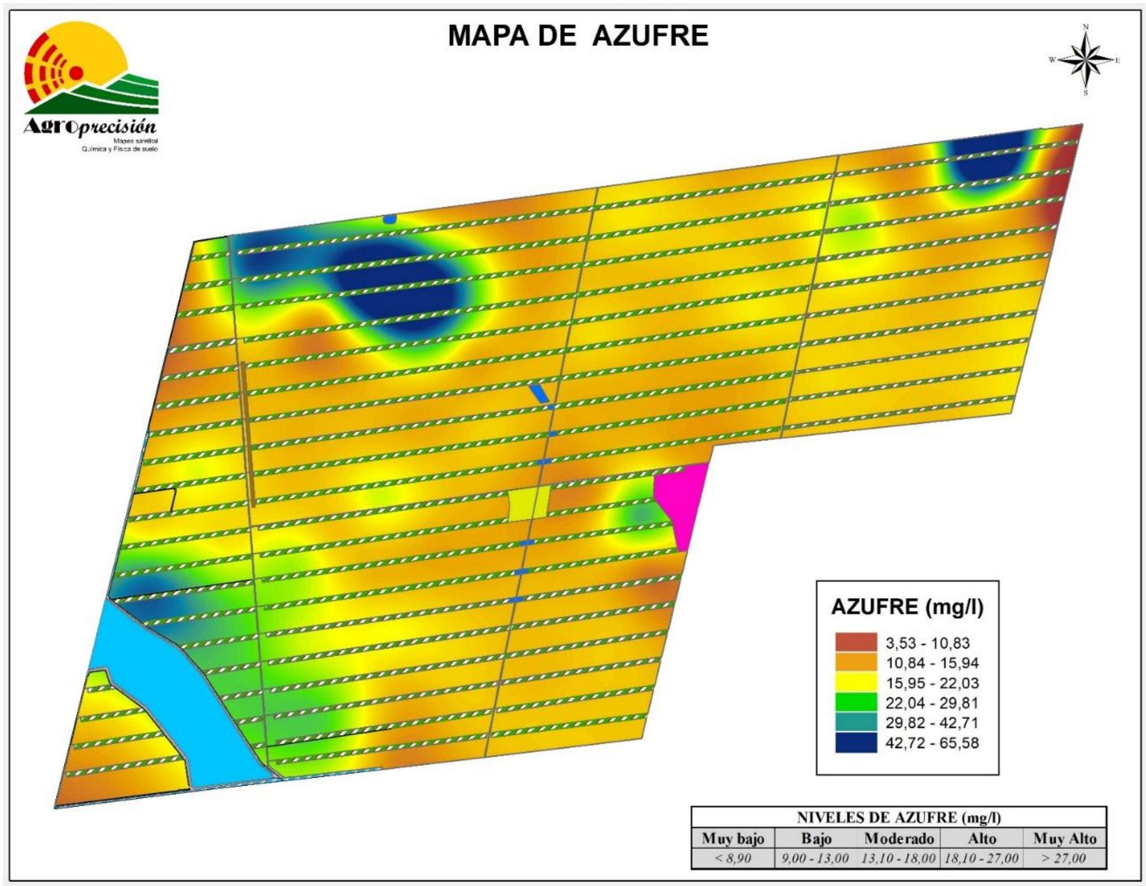
Variable MAP (monoammonium phosphate) dose map.



DOI: https://doi.org/10.71112/7s3xfc80

Figure 16

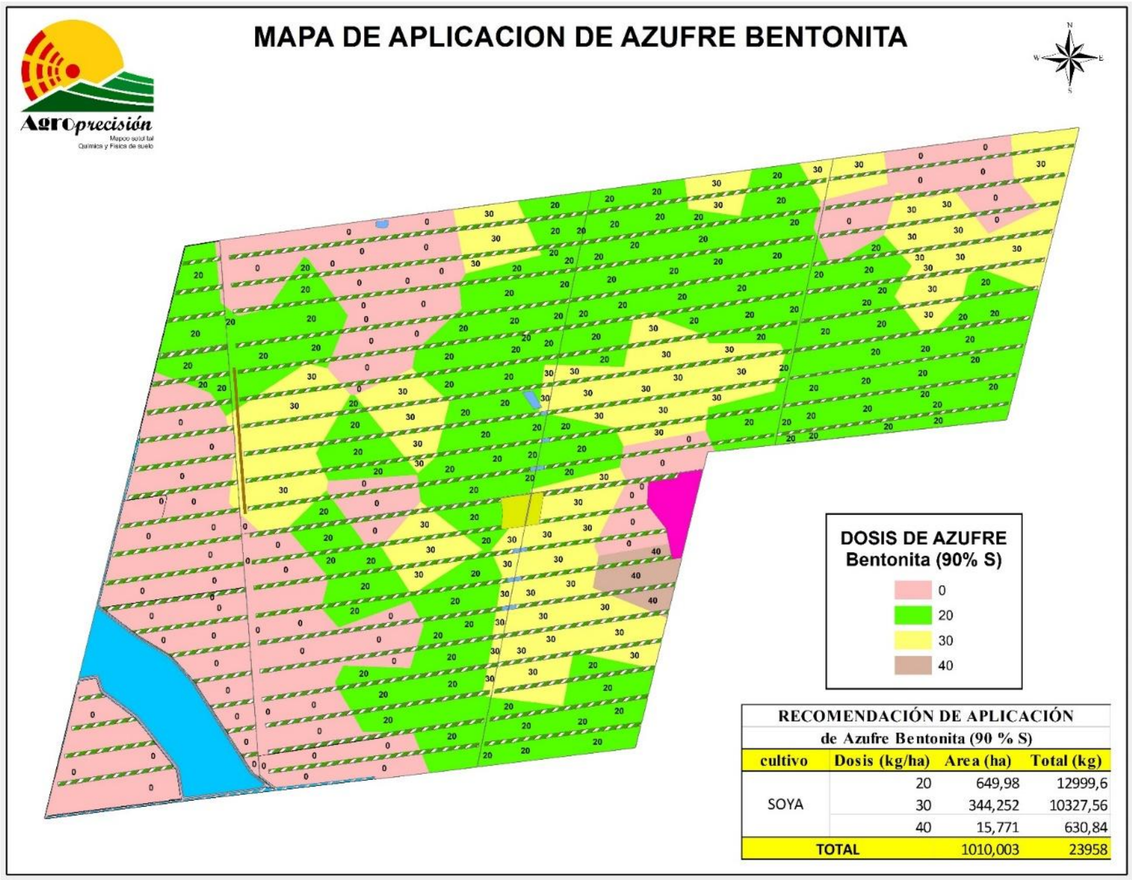
Sulfur Map



DOI: https://doi.org/10.71112/7s3xfc80

Figure 17

Variable Dosage Map for Sulfur Bentonite



DISCUSSION

In the classification of potentially productive environments, according to the total usable area of agricultural plots in San Carlos, which is 1467.63 ha, 54% corresponds to an environment A, with high productivity (775.68 ha); 22% corresponds to an environment B, with moderate productive potential (342.47 ha), and 24% comprises environment C, with low potential (349.48 ha).

The soil profile of environment A indicates that these are intermediate to semi-heavy soils with high productive potential, high-altitude soils without waterlogging problems. The soils of environment B have a higher clay content, especially the soils of environment C, which are clay soils with waterlogging problems during rainy seasons, the presence of oxidation spots, and low productive potential.

The apparent density indicates that approximately 40% of the property has compaction problems (mild and severe), which occur at a depth of 20 cm or in the second layer of the soil profile in the test pits.

According to the texture of the soils in San Carlos, there is a textural contrast, and they can be grouped as follows: 3% of the soils are sandy loam (FA), 8% are loam (F), 30% are silty loam (FL), 1% are silty (L), 21% are loamy clay loam (FYL), 25% are clay loam (YL), and 12% are clay loam (Y).

Soils with low acidity, with an average pH of 6.59, the three productive environments have values between 4.12 (very high acidity) and 8.75 (weak alkalinity).

The organic matter in the soils studied is generally at an average of 2.42%, considered a moderate level, with ranges between 1.26% and 4.10%, with the highest values in the low-productivity environment (C) and the lowest values in the high-productivity environment (A).

Total, nitrogen is generally at an average of 0.12% (moderate). The highest concentration is found in environment C and the lowest in environment A.

Phosphorus availability averages 90.00 mg/l (very high), with slight variations: in the high environment, the average is 83.89 mg/l; in environment B, it is 103.80 mg/l; and in environment C, it is 92.86 mg/l.

Sulfur averages 12.89 mg/l (moderate), but its concentration is highly variable, ranging from 3.53 mg/l to 65.67 mg/l, which is common in Santa Cruz soils.

The effective cation exchange capacity in these soils ranges from 7.86 cmolc/l (moderate) to 22.42 cmolc/l (very high) and averages 14.63 cmolc/l, which is considered high.

Soils with very high total exchangeable bases. Potassium averages 504.42 mg/l, which is considered a high level. Calcium and magnesium are at very high levels.

The soils of San Carlos have a predominantly low potential acidity, with an average of 2.34 cmol/l classified as low acidity. However, there are ranges from 0.98 cmol/l (very low acidity) to 6.32 cmol/l (high acidity).

The soils under study have an overall average base saturation of 83%, which is considered very high saturation, meaning that they will provide sufficient cations to the plant.

The Ca/Mg ratio is predominantly below equilibrium and also at equilibrium in some areas, while the K/Mg ratio is predominantly above equilibrium, with som t equilibrium and below equilibrium.

In terms of micronutrients, iron and copper are present in high concentrations throughout; zinc is predominantly at moderate levels, with some low and high values; manganese and boron are present at low to high levels.

Physiographically, the soils of San Carlos are deep soils in the elevated areas and depressions of the fluvial-lacustrine plains, with medium to slightly heavy textures, slightly acidic to slightly alkaline pH, and moderate fertility.

CONCLUSIONS

Given that areas of the San Carlos property show a certain degree of compaction in the top 30 cm of soil, where root development occurs, it is recommended to establish a natural soil rotation scheme or, failing that, using a subsoiler to a depth of 30 cm to improve root development and rainwater infiltration, and then establishing grasses that maintain macroporosity in the soil.

Subsoiling is not recommended for soils with greater clay contraction (expansive), as they crack in the dry season.

Avoid soybean monoculture, which, due to its poor root exploration, will increase the problem of compaction, in addition to the low supply of stubble it offers, both in quantity and quality.

In loamy soils, avoid conventional tillage, thus avoiding a negative effect on the physical properties of the soil, since these soils are easily compacted and their structure is quickly destroyed.

Avoid bringing machinery onto the land when the soil profile is very wet to prevent compaction, especially in light to medium soils, as they are more susceptible to compaction. Practice direct seeding with permanent stubble cover. Use a production system based on no-till farming with surface residue management and crop rotation.

In areas with alkaline pH, it is possible to lower the pH by applying calcium sulfate in combination with a good supply of organic matter and the elimination of alkalizing fertilizers (urea, DAP, etc.). It is preferable to use ammonium sulfate and MAP, which have an acidic reaction, as well as to rotate soils and provide coverage and fix N2. Black velvet bean also provides a lot of green material that decomposes to produce organic acids, which neutralize alkaline soils.

In soils with sodicity problems, correction with the application of large amounts of gypsum is recommended, as this is the most commonly used method to minimize the effect of soil sodicity. This amendment is used as a source of Ca2+ to displace Na+ from the soil exchange complex, allowing the soil to recover its structure, improve its porosity, and allow water to flow through the soil horizons again.

In specific sites with nitrogen deficiencies for soybean cultivation, ensure good seed inoculation before planting. It is possible to double inoculate the seed to ensure nodulation and N2 fixation.

Likewise, green manure, especially legumes such as winter pigeon peas, can be used to fix N and improve crop residue input, applying conservation techniques.

In nutritionally deficient soils, correction with mineral fertilizers at variable rates is recommended, based on nutritional balance criteria, as described in the preceding chapters.

mineral fertilizers, at variable rates, based on nutritional balance criteria, as described in the preceding chapters.

Monitor yields obtained under variable rate fertilization criteria to obtain higher yields, according to each productive environment.

Conflict of interest statement

The authors declare that they have no conflicts of interest related to this research.

Declaration of contribution to authorship

Author Bladimir Fernandez Orellana: conceptualization, data curation, formal analysis, fund acquisition, research, methodology, project management, resources, free and trial software, supervision, validation, visualization, writing of the original draft, revision, and editing of the manuscript.

Declaration of use of artificial intelligence

No artificial intelligence was used in any part of the manuscript.

REFERENCES

Abdusamea, R. M. (2024). The Importance of the Normalized Difference Vegetation Index (NDVI) and the Use of the ArcGIS to create NDVI Maps. Revista de Ciencias y Estudios Humanísticos - Facultad de Letras y Ciencias - Al-Marj. https://www.semanticscholar.org/paper/4a92a36f61fa2bf90494199c8acf1d4327ebcafd

Alloway, B. J. (2008). Zinc in Soils and Crop Nutrition. IFA. Paris.

Astate. (2024). B.S.A. in GIS and Precisión Agriculture Online at A-state. https://degree.astate.edu/online-programs/undergraduate/agriculture-studies/bachelors-gis-precision-agriculture/

Bermudez, M. (2012). Nitrógeno. En A. Quiroga, & A. Bonos, Manual de Fertilidad y evaluacion de suelos (págs. 101-105). La Pampa, Argentina: Editorial INTA.

Bono, A., & Romano, N. (2012). Nitrógeno. En A. Quiroga, & A. Bono, Manual de fertilidad y evaluación de suelos. (págs. 101-105). La Pampa, Argentina: Editorial INTA.

Bowen, J. E. (1969). Absorption of Copper, Zinc, and Manganese by Sugarcane Leaf Tissue. En Plant Physiology (Vol. 44, págs. 255-261). https://doi.org/ https://doi.org/10.1104/pp.44.2.255

Bragachini, M., Méndez, A., Scaramuzza, F., & Prioetti, F. (2006). Sistema de Posicionamiento Global y su Aplicación en Agricultura. En R. Bongiovanni, E. Chartuni Mantovani, S. Best, & A. Roel, Agricultura de Precision: Programa Cooperativo para el desarrollo Técnológico Agroalimentario y Agroindustrial del Cono Sur (págs. 45-54). PROCISUR.

Bruulsema, T. W., Fixen, P. E., & Sulewski, G. D. (2012). 4R plant nutrition manual: A manual for improving the management of plant nutrition. Georgia, USA: International Plant Nutrition Institute (IPNI), Norcross.

Butora, A., Soloniewicz, B., Schwartz, C., Su, S., & Mahmoud, M. (2022). The Practical use of GIS in Agriculture. International Conference on Computational Science and Computational Intelligence (CSCI). https://www.semanticscholar.org/paper/ce04b652be1145e4c86cd10e6516213a187ef47e

Canedo, E. (2008). Edafología y Fertilidad de Suelo. Texto Guía, 228. Santa Cruz.

Conti, M. E., & García, F. O. (2006). Potasio. En H. E. Echeverría, & F. O. García, Fertilidad de suelo y fertilización de cultivos. (págs. 123-137). Buenos Aires, Argentina: Ediciones INTA.

Darwich, N. (2005). Manual de Fertilidad de Suelos y uso de fertilizantes. 2°edición, p.289.

Dexter, A. R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma, 120((3-4)), 201-214.

Echeverría, H. E., & Saínz Rozas, H. R. (2006). Nitrógeno. En H. E. Echeverría, & F. O. García, Fertilidad de suelo y Fertilización de cultivos. (págs. 69-97). Buenos Aires, Argentina: Ediciones INTA.

Echeverría, H. E. (2006). Azufre. En H. E. Echeverría, & F. O. García, Fertilidad de suelo y fertilización de cultivos. (págs. 139-160). Buenos Aires, Argentina: Ediciones INTA.

Esri. (2021). GIS for Agriculture | Precision Agriculture & Farm Management - Esri. https://www.esri.com/en-us/industries/agriculture/overview

Falk, M. (2004). Seasonal course of a normalized differential vegetation index 'NDVI' derived from tower data. Semantic Scholar. https://www.semanticscholar.org/paper/fd3c447466546c11b0fe625dddbd2154732a2feb

García, F. O., Picone, L. I., & Berardo, A. (2006). Fósforo. En H. E. Echeverría , & F. O. García, Fertilidad de suelo y fertilización de cultivos. (págs. 99-121). Buenos Aires, Argentina: Ediciones INTA.

García, F., & Correndo, A. (2013). Cálculo de requerimientos nutricionales. Acassuso , Argentina: Instituto Internacional de nutrición vegetal - IPNI Cono Sur. .

gisnavigator. (2025). GIS in Agriculture - Everything You Need to Know. . https://gisnavigator.co.uk/gis-in-agriculture/

Graham, R. D. (1981). Abosorption of copper by plant roots. (J. F. Loneragan, A. D. Robson, & R. D. Graham, Edits.) Sídney, Australia: Academic Press.

Guaygua, G., & Espinoza, D. (2013). Muestreo e interpretación de análisis de suelo. En R. Nakasato, & R. Sandoval, Manual de Difusión Técnica de Soya (págs. 171-183). Fundación de Desarollo Agrícola Santa Cruz - Fundacruz.

INTA. (2013). Curso Internacional de Agricultura de Precision. Expo de Maquinas Precisas, recopilación de presentaciones técnicas. Argentina.

Jensen, T., Norton, R., & Singh, H. (2013). Prácticas de Apoyo. En T. Brusselma , P. Fixen, & G. Sulewski, Manual de Nutrición de Plantas 4R (págs. 8-1 a 8-12). EE.UU.: International Plant Nutrition Institute - IPNI.

Keller, T., & Hákansson, I. (2010). Estimation of reference bulk density from soil particle size distribution and soil organic matter content. (Vol. 154). Geoderma.

Kumar, P., Sangeetha, C., Damor, J. S., S, K. P., & J. S., M., R. G., M., R. G., Moond, V., Moond, V. (2024). Remote Sensing and Geographic Information Systems for Precision Agriculture: A Review. International Journal of Environment and Climate Change. https://doi.org/https://doi.org/10.9734/ijecc/2024/v14i23945

Melgar, R., Vitti, G., & Benites, V. M. (2011). Fertilizando para los altos rendimientos - Soja en Latinoamérica. Instituto Nacional de la Potasa - IIP Boletín N° 20 Suiza.

Mengel, K., & Kirkby, E. A. (2012). Principles of plant nutrition. Springer Science & Business Media.

Mosquera, C. (2012). Fertilización en tasa variada. Revista Tecnicaña N°28: https://www.siiba.conadesuca.gob.mx/siiaca/Consulta/verDoc.aspx?num=654

Muhammad, F. (2023). Applications of (GIS) Geoinformatics in Agriculture. https://geopard.tech/blog/applications-of-gis-geoinformatics-in-agriculture/

NASA. (2011). Landsat 7 Science Data users Handbook Lnadsat Project Science Office at NASA´s Goddard Space Flight Center in Grebelt.

projects., C. t. (2006). Normalized difference vegetation index. https://en.wikipedia.org/wiki/Normalized_difference_vegetation_index

Richards, J., & Jia, X. (2006). An Introduction. Remote Sensing Digital Image Analysis. Germany: Springer.

Rodríguez, F. (2012). Agricultura de Precisión. En N. R. R., Manual de difusión técnica de soya (págs. 157-161). Fundación de Desarollo Agrícola -FUNDACRUZ.

Satorre, E. H., & Bert, F. E. (2014). Agricultura por ambientes: Conceptos para su incorporación eficaz al manejo de nuestros campos. Revista Cultivar decisiones, 13(5).

Taboada, M., & Álvarez, C. (2008). Fertilidad Física de Suelos 2da Edición. 2 Ed. Editorial Facultad de Agronomía. Universidad de Buenos Aires.

Torri, S. I., Urricariet, S., & Lavado, S. (2006). Micronutrientes y otros elementos traza. En H. E. Echeverría, & F. O. García, Fertilidad de suelo y fertilización de cultivos (págs. 189-205). Buenos Aires, Argentina: Ediciones INTA.