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Integration of precision agriculture tools for variety optimization and crop management focused on increasing productivity in sugarcane.

Carlos Mosquera[1]

[1]Agronomist Engineer, GIS Specialist, MBA. C.I. AGROAP SAS. Colombia

Abstract.

"The adoption of precision agriculture tools in sugarcane cultivation has gained popularity, addressing specific needs within the crop. However, achieving conclusive results poses challenges primarily due to the lack of integration of technological tools. The objective of this study is to present an efficient model for the utilization and operation of precision agriculture tools that consistently enhance planning and facilitate agronomic and administrative decision-making, leading to superior outcomes. The significance of this work revolves around the following key components: a) implementation of a crop monitoring system (utilizing optical and radar satellite), b) integration of precision agriculture tools such as georeferenced soil maps, production maps, variable rate fertilizer recommendation maps, irrigation telemetry systems, high-precision leveling with scrapers, and pest mapping, c) Management of operational cost monitoring system.

The model commences with georeferenced soil studies to understand the spatial variability of the soil, aiding in the development of nutrition plans, determining the intensity of preparation work, and establishing irrigation frequencies. Through the interpretation of production maps, various production scenarios are identified under different climate conditions and in areas of high, medium, and low productivity. Subsequently, areas with varying levels of productivity stability are grouped to adjust irrigation and nutrition practices based on productivity levels. During planting, precise topographical surveys and leveling (using RTK antenna) improve crop establishment conditions, while iso-productivity curves (Cenicaña – Sugarcane Research Center) assist in selecting suitable varieties for each environment.

The implementation of an operational cost monitoring system, incorporating labor standards, efficiencies, input, and service costs, enables continuous evaluation to determine agronomically necessary and administratively feasible practices. This approach has resulted in profitability under low productivity conditions and increased production at costs below the local standard. Pest mapping has facilitated an understanding of pest dynamics and spatial distribution, aiding in maintaining pest levels below the threshold of economic risk.

Throughout the crop survey, satellite image monitoring using biomass, evapotranspiration as well as variables such as vegetation indices, have supported adjustments in crop management. This has mitigated reductions in biomass production, necessitated the application of bio-stimulants, and optimized variety performance under varying water conditions. Noteworthy outcomes include a 12% reduction in fertilizers, a 10% decrease in leveling volume and costs, a 30% reduction in water consumption, and productivity increases ranging from 16% to 20% per hectare. Pest infestation levels of Aenoelamia varia were maintained below 5 adults/trap/week, and Diatrea

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levels were at 1.27%. Operational survey costs are approximately 15% lower than the local reference, while costs associated with leveling, land preparation, and planting have decreased by 20%."

Keywords.

precision agriculture, varietal location, variety management, crop monitoring, biomass production.

Introduction

Since 2005, a private company in the sugar sector of Valle del Cauca, Colombia, initiated the implementation of precision agriculture tools by adopting the model introduced by Cox Graeme et al. (1999). This model integrated various tools such as productivity mapping, land leveling, soil variability mapping, and variable rate input application. Subsequently, the University of Sao Paulo (Molin José Paulo et al., 2015) adapted the model to Brazilian conditions around 2006 and identified a set of tools that could significantly enhance crop productivity. This adapted model was later tailored to suit the conditions of sugarcane cultivation in Colombia.

The production maps of sugarcane began capturing data from sugarcane loaders and harvesters. Initially, the equipment used had 4 load cells, but by 2016, it evolved to equipment with a single load cell, and in 2020, equipment with optical sensors was introduced. In 2007, large-scale geo-referenced soil sampling commenced, covering an area exceeding 20,000 hectares. This marked the inception of the first geostatistical models to determine detailed levels, alongside the creation of fertilizer and amendment recommendation equations for application with fertilizer spreaders equipped for variable application.

By 2013, six years later, other sugar mills began adopting similar tools, although not all managed to implement the complete precision agriculture model. Around 2015, the Sugar Cane Research Center (Cenicaña) began evaluating precision agriculture equipment, primarily focusing on signal correction networks with RTK antennas. The adoption process has been gradual, with ongoing tests and trials required to aid potential adopters in understanding the concepts.

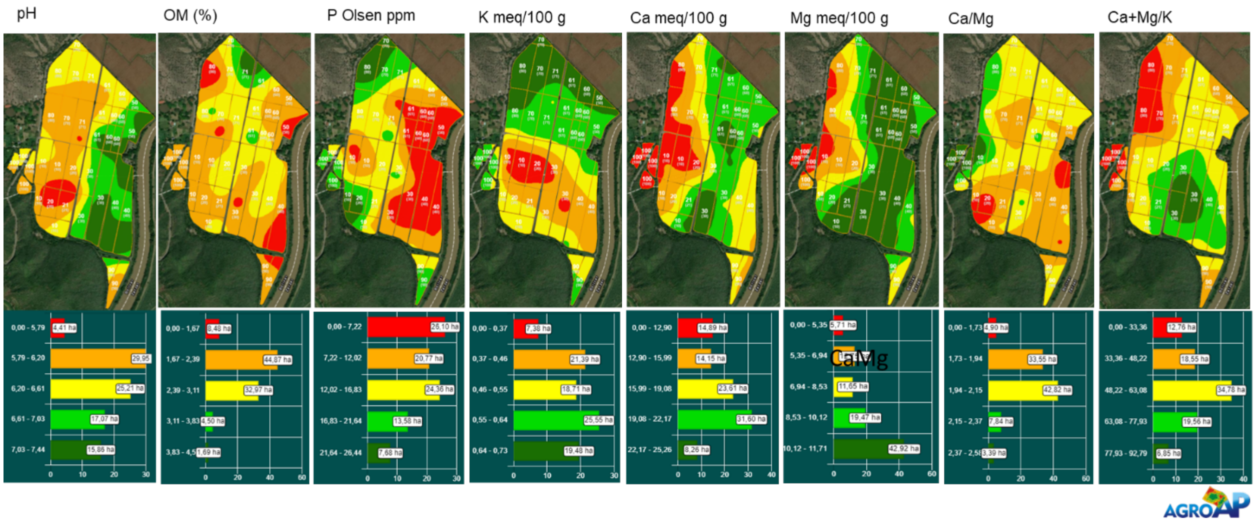
In the same year, a private company initiative led to the implementation of high precision leveling systems triangulated with RTK antennas, showcasing benefits in operational cost reduction by minimizing material movement. Additionally, the integration of software and ERP platforms in several companies has provided detailed insights into operational costs. In 2016, a new proposal for a simpler and more versatile ERP system emerged, offering adaptability to the needs of farmers and agribusinesses through a cloud-based platform and mobile applications. This facilitated detailed and controlled monitoring of operational costs, enhancing decision-making opportunities.

In 2021, a process commenced to parameterize and validate algorithms for biomass and evapotranspiration estimation following FAO guidelines (FAO 2020 and Jarmain Caren et al., 2014). Other technologies, as validated by Erickson Bruce and Lowenberg J. (2020), have proven to be stable and immensely valuable for farmers, confirming the established model for sugarcane.

Variability Maps

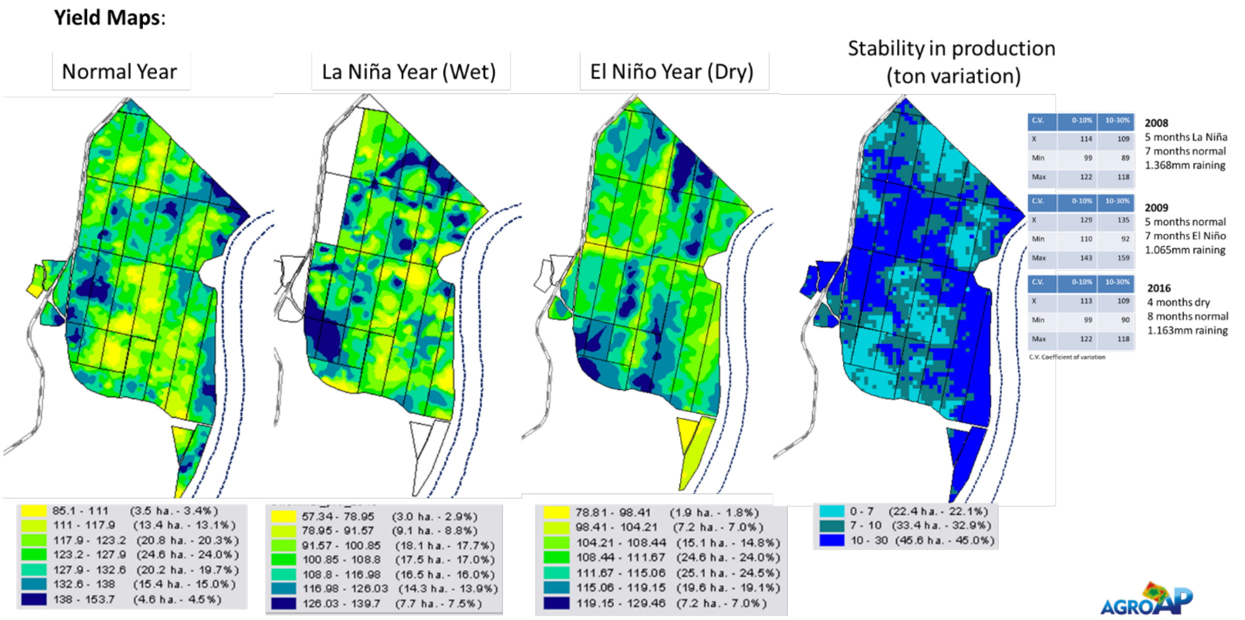
Soil variability maps were created through geo-referenced soil sampling conducted in 2007, with sampling points established at one sample per two hectares at a depth of 30 cm. The maps were generated in 2007, 2012, and 2019, with a resolution of 20x20m pixels. The **Figure 1** shows some variability maps that were created to adjust fertilizer recommendations. The nutrient contents, pH, and soil textural phase were variables used to construct the recommendation equations, adjusting maximums and minimums that are agronomically reasonable and that the variable-rate equipment can apply.

Figure 1. Maps of variability of some soil conditions



Sugarcane production variability (ton/ha) maps were developed for the years 2008, 2009, 2010, and 2016. (**Figure 2**). Performance assessments were conducted during dry (phenomenon El Niño), wet (phenomenon La Niña), and normal years, enabling the estimation of productivity stability levels. This analysis identified areas affected by soil compaction, high clay percentages, elevated magnesium content, and phreatic levels. The maps categorized zones into high, medium, and low productivity prevalence, crucial for varietal selection, nutritional planning, and drainage management plan.

Figure 2. Production (ton/ha) behavior under different climatic conditions



C.V.	0-10%	10-30%
X	114	109
Min	99	89
Max	122	118

2008
5 months La Niña
7 months normal
1.368mm raining

C.V.	0-10%	10-30%
X	129	135
Min	110	92
Max	143	159

2009
5 months normal
7 months El Niño
1.065mm raining

C.V.	0-10%	10-30%
X	113	109
Min	99	90
Max	122	118

2016
4 months dry
8 months normal
1.163mm raining

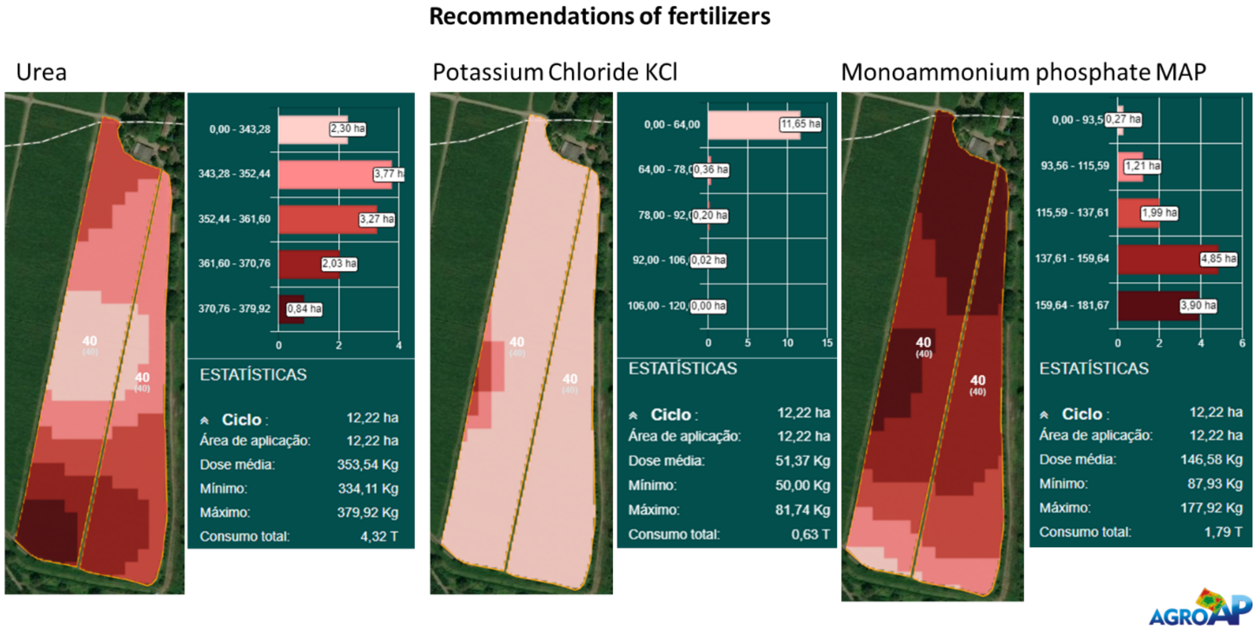
C.V. Coefficient of variation

The production maps were obtained thanks to the data captured by the productivity monitors installed in the sugar cane harvesters, which typically consist of a composite scale with 4 or 1 load cell, a processor, a storage system, a GPS, and a calibration protocol that helps reduce measurement errors. The equipment requires calibration to ensure data quality. In Colombia, more than 50% of the cultivated area in the valle del Cauca already has this type of equipment.

The number of captured points can vary between 1600-2800 points/ha, but systems with optical sensors can reach more than 4500 points/ha, providing sufficient data to obtain high-quality and reliable maps.

Fertilizer recommendation maps were created using modeled equations for each nutrient. Nitrogen recommendations were based on organic matter content, clay content, and productivity levels, considering source, fractionation, and variety development behavior adjustments. (**Figure 3**).

Figure 3. Recommendations of fertilizers (variable rate)



The application of variable-rate fertilizers is carried out with a 165HP tractor capable of working in heavy soil conditions (>60% clay). The variable-rate equipment has 3 compartments for NKP, in a 4:3:3 ratio, with a total loading capacity of 1000kg. The hydraulic system allows working with the implement on a 3-point hitch. The equipment has four outlets with an application error between 3-5% in discharge and operates at a speed between 6-8 km/h.

Once the work is completed, it is possible to generate an application map to verify the quantities of product applied and the quality of distribution in the field.

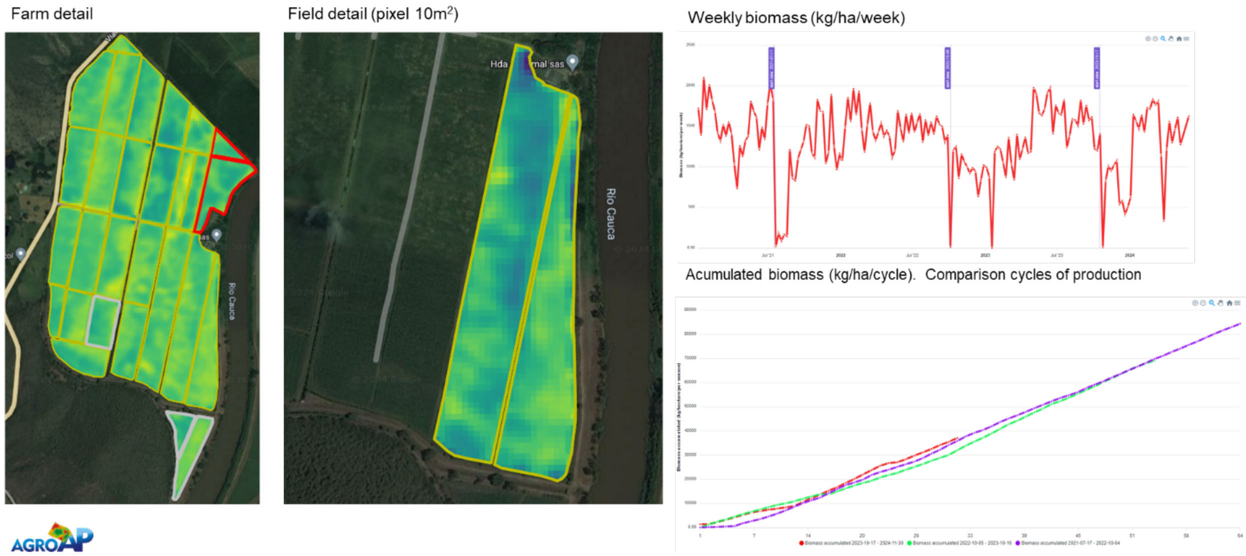
In terms of crop health, to address the risk of pest populations, weekly sampling and mapping were conducted during the initial five months to predict and prevent outbreaks that could lead to economic damage. Data processing was facilitated through the precision agriculture platform.

Mapping insects is a challenge to understand their mobility habits and propagation capacity. Previous semivariogram analyses involve a high number of samples; however, the sample level has been adjusted to a reasonable and practical amount since the sampling is manual through traps. Undoubtedly, these maps are a more robust parameter than traditional sampling methodology and allow decisions to be made to mitigate or control populations.

Biomass, Evapotranspiration and Vegetation Indices Maps

Artificial intelligence algorithms combining optical and radar satellite images with climate information were employed to quantify weekly and cumulative biomass values, measured in kg/ha/week or per cycle, and weekly evapotranspiration in mm/week (Fieldlook platform by eLEAF). These tools facilitate the monitoring of growth and varietal performance, enabling adjustments to the water balance. By tracking growth patterns, decisions regarding bio stimulation timing can be made, allowing for production monitoring and verification of the crop's physiological activity to maximize biomass accumulation. The recommendation of nitrogen and ripener can be complemented with biomass data too (pixels $10m^2$.)

Figure 4. Biomass monitoring



Farm detail

Field detail (pixel $10m^2$)

Weekly biomass (kg/ha/week)

Acumulated biomass (kg/ha/cycle). Comparison cycles of production

Satellite image processing platforms enable the acquisition of various vegetation indices such as NDVI, RECI chlorophyll index, and NDMI crop moisture index. These indices aid in monitoring development and detecting water stress. However, they are constrained by cloud cover and do not directly quantify the growth of biomass in the fields. Nonetheless, they serve as early warning indicators for making timely management and control decisions.

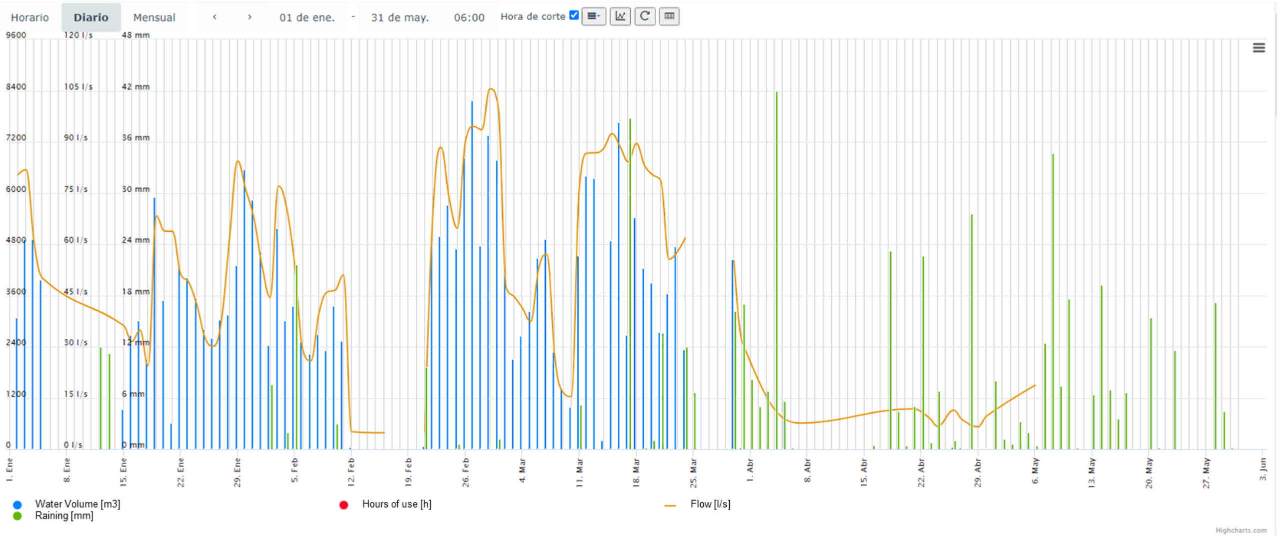
After using quantifiable biomass information, it is a more robust data than the traditional vegetation index, achieving objectivity in field observations. However, the behavior of the varieties may have nuances regarding the proportion of leaf percentage to stem. This situation requires good calibration and adjustment to better understand the impact on growth due to the influence of climate and field management actions.

Operational Costs and Irrigation Telemetry

The utilization of the operational cost platform (SimpleAgri) has enabled the structured organization of operational costs, allowing for the display of operation details and crucial management indicators for companies or farmers. The key of this tools is the parameterization and standardization of efficiencies to ensure accurate quantification and valuation of field activities. The platform is continuously updated with operation costs captured through computer systems and a mobile field application. This has positively influenced administrative decisions, facilitating adjustments to budgets based on productivity and cost per ton.

Irrigation telemetry involves the use of a magnetic flow sensor and a rain gauge to collect data, which is then transmitted to a datalogger and subsequently sent via GPRS to the web platform Lynks (**Figure 5**). Lynks provides dashboards and databases that can be integrated with the ERP system or accessed directly on the web. This telemetry system records operating hours, on/off times, captured volume, extracted flow, and daily rainfall. This data has enabled the optimization of water consumption, complemented by information on evapotranspiration and soil clay content.

Figure 5. Water pumping telemetry.



Location

Precision agriculture tools were integrated into the Churimal farm, situated in the municipality of Roldanillo at an elevation of 913 meters above sea level. The region experiences annual rainfall ranging from 760-1100mm/year, clay levels between 50-70%, magnesium levels between 8-11meq/100g of soil, pH levels between 6.0-7.5, organic matter content between 1.5-3.5%, phosphorus levels (Olsen) between 6-21ppm, potassium levels between 0.36-0.75 meq/100g of soil, potassium availability Ca+Mg/K between 19-74, micropore proportions between 30-50%, and macropores between 6-13%. The farm has a water availability of 100 liters per second for gravity window irrigation. Varieties such as CC011940, CC09066, CC10450, and CC05430 are cultivated, with infrastructure including piped drainage (1.20m), central drainage channels, and a water evacuation station.

Methods

Artificial neural networks were employed to identify variables with the most significant impact on productivity, integrating data on soil physics, chemistry, and productivity through spatial correlation analysis at the pixel level to determine crop-limiting factors. Data mining techniques were utilized to identify trends and perform clustering. Geographic Information Systems (GIS) facilitated zoning by limiting factors, while productivity stability zones were estimated based on averages and standard deviations from four crop cycles at the pixel level. Operational costs were analyzed through benchmarking across fields to optimize investments based on field potential, variety, and soil conditions.

The use of growth monitoring data through biomass measurement allowed us to establish growth benchmarks per variety, enabling us to identify growth delays and correct them through various agronomic actions.

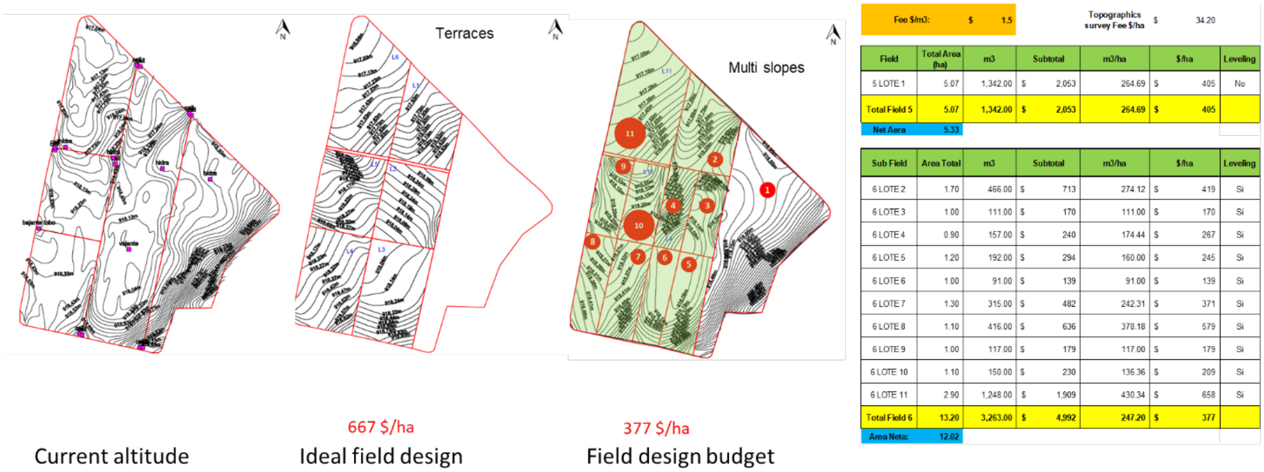
Results and Discussion

The most significant outcome was a 12% reduction in fertilizers. Soil variability maps revealed areas with higher sand content that required less nitrogen and higher clays content require more nitrogen as the low percentage of organic matter. In these sandy conditions, nutrient fractionation based on specific varieties was determined. Potassium application was limited to maintenance doses in areas with sufficient content and acceptable availability. Phosphorus optimization was tailored to pH levels and specific field requirements. Minor elements were adequately present, eliminating the need for additional application.

For soils with clay conditions between 55-70% and organic matter levels of 1.5-3.5%, nitrogen requirements can range between 150-160 kg of nitrogen per hectare. In areas with pH levels above 7.2, nitrogen sources such as ammonium sulfate and phosphorus sources like monoammonium phosphate are used. Before using variable rate application and soil mapping, nitrogen doses were in the range of 175-183 kg of nitrogen per hectare.

A 25% reduction in leveling volume and up to 10% cost savings were achieved through precise GPS RTK antenna surveys with 10m line coverage. This data learnt leveling software design, allowing for multiple slope designs. Soil-moving volume decreased from approximately 260 to 200 m^3/ha (**Figure 6**), with leveling conducted at plank level and areas with marked slopes left untouched. (rounded data for the farm evaluated).

Figure 6. To optimize the leveling of fields 5 and 6 at the Churimal farm.



Fee $/m3: $ 1.5

Topographics survey Fee $/ha $ 34.20

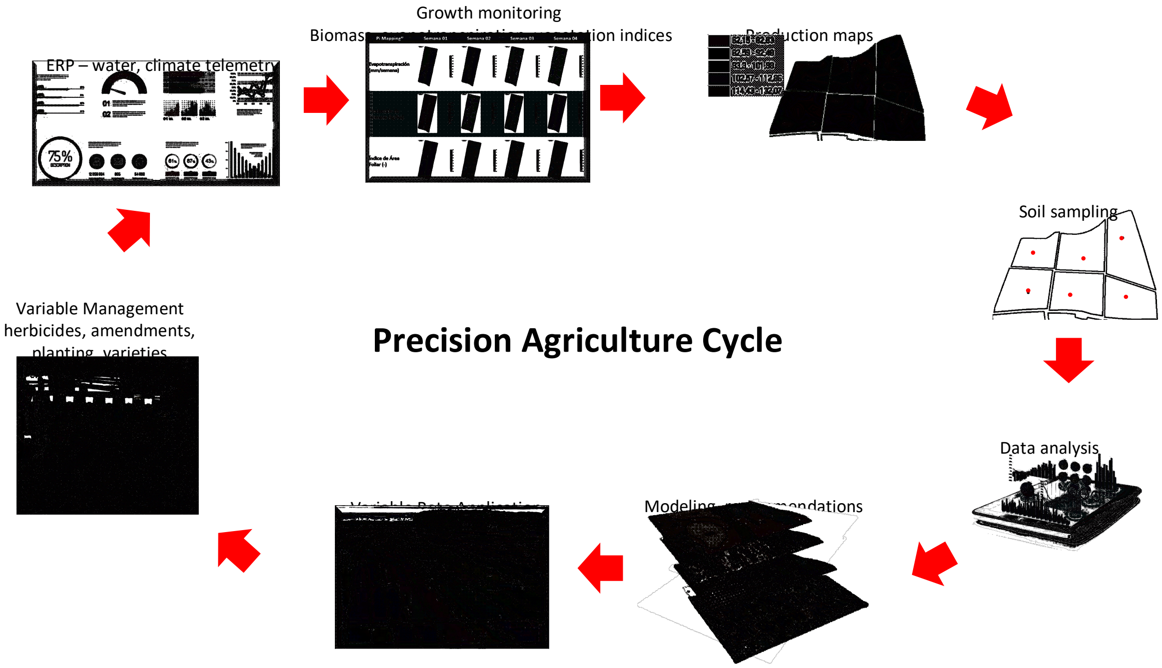
Field	Total Area (ha)	m3	Subtotal	m3/ha	$/ha	Leveling
5 LOTE 1	5.07	1,342.00	$ 2,053	264.69	$ 405	No
Total Field 5	5.07	1,342.00	$ 2,053	264.69	$ 405	
Net Aera	5.33					

Sub Field	Area Total	m3	Subtotal	m3/ha	$/ha	Leveling
6 LOTE 2	1.70	466.00	$ 713	274.12	$ 419	Si
6 LOTE 3	1.00	111.00	$ 170	111.00	$ 170	Si
6 LOTE 4	0.90	157.00	$ 240	174.44	$ 267	Si
6 LOTE 5	1.20	192.00	$ 294	160.00	$ 245	Si
6 LOTE 6	1.00	91.00	$ 139	91.00	$ 139	Si
6 LOTE 7	1.30	315.00	$ 482	242.31	$ 371	Si
6 LOTE 8	1.10	416.00	$ 636	378.18	$ 579	Si
6 LOTE 9	1.00	117.00	$ 179	117.00	$ 179	Si
6 LOTE 10	1.10	150.00	$ 230	136.36	$ 209	Si
6 LOTE 11	2.90	1,248.00	$ 1,909	430.34	$ 658	Si
Total Field 6	13.20	3,263.00	$ 4,992	247.20	$ 377	
Area Neta:	12.02					

Tools such as precision topographic surveying and leveling with scrapers guided by RTK antennas support the development of an efficient field design for gravity irrigation and surface drainage during rainy seasons. The goal is to ensure a successful emergence of the seed, to guarantee superior populations ranging between 9-10 buds per linear meter.

Illustrates the sequence of processes in the information sources integration model of the precision agriculture cycle (**Figure 7**), encompassing the nutrition plan with recommendations and variable fertilizer applications.

Figure 7. Precision farming cycle model integrated with crop development monitoring and operational cost ERP platforms.



Irrigation telemetry and rainfall data facilitated the assessment of plots with the highest water consumption and challenges in irrigation distribution. Flow rates were adjusted based on the dynamic heads corresponding to the slope of each field. Fields with the highest water consumption, considering clay and sand textures, were evaluated, resulting in a 30% reduction in water usage from 1600-1800m^3/ha to levels between 800-1000m^3/ha. Irrigation sequencing was modified based on these variables, with frequency aligned with biomass production levels and weekly evapotranspiration variations.

Soil studies informed the selection of suitable crop varieties based on soil texture and moisture content, guiding decisions on preparation work depth and passes. Detection of vulnerability in certain varieties to spittlebug infestation prompted the use of weekly traps (yellow traps with adhesive) to create variability maps of spittlebug populations per trap during the initial five months. Monitoring aimed to keep spittlebug infestation levels of *Aeneolamia varia* below 5 adults/trap/week; repellent practices were implemented in case of an increase (entomopathogenic fungi and products based on garlic and chili pepper solution) *Diatrea* infestation levels were maintained at 1.27%, thanks to the established biological control plan.

Subsequently, after the standard crop management (more than four months), biomass and evapotranspiration were monitored weekly to detect low biomass accumulations, as depicted in Figure 2 of the monitoring model. This allowed for adjusting the irrigation frequency or intensifying efforts to enhance surface drainage, channels, and piped drains. Additionally, the performance in biomass accumulation, earliness, and vulnerability of the varieties in different environments was validated.

The outcome was a productivity increase ranging between 16%-20% in tons per hectare, marking the highest productivity at the farm level in the first plant compared to the year 1998 and 2008. The first plant of 2010 and 2021 surpassed a 25% increase in total productivity at the farm level, when compared to previous ratoons harvests between 2008-2019 as can be seen in **Table 1**.

Table 1. Production analysis.

Period	Average production (ton/ha) ratoon	Average Production (ton/ha) first plant	Observation
1998-2008	121	138	
2008-2019	115	131	
2019-2021	134	153	New Varieties and PA tools

Operational costs are approximately 15% lower than the local benchmark (1.310us$/ha Farm Churimal vs 1.552us$/ha mills), and the costs of leveling, land preparation, and planting were 20% lower (1.180 us$/ha Farm Churimal vs 1.474us$/ha mills). as shown in **Table 2**.

The source of this data is the costs reported in the SimpleAgri system, and the comparison data consists of the average costs from neighboring sugar mills. Average data can sometimes mask specific cases where there are fields with better performance than others due to soil conditions and moisture levels.

Table 2. Comparison of cost parameters and water use efficiency

when implementing precision agriculture tools at the Churimal farm.

Process	Traditional Agriculture	Precision Agriculture	Var.
Production (pest control, weed control, irrigation, fertilization, tillage etc) (us$/ha)	1,553	1,310	15.6%
Fertilization (us$/ha)	500	421	15.8%
Irrigation volume (m3 water)	1600-1800	800-1000	
LPP (leveling + land prepation + planting) (us$/ha)	1,474	1,180	19.9%
Leveling (us$/ha)	473	377	20.3%

Conclusions

- The integration of precision agriculture tools and a disciplined approach to data monitoring and analysis facilitates decision-making that supports increased production at a reasonable cost.
- Crop monitoring through quantifying biomass, evapotranspiration, vegetation indices, yield maps, and pest surveillance validates the effectiveness of decisions and helps alleviate stress situations affecting biomass formation.
- Resource optimization, including fertilizers, bio-stimulants, water, and tillage intensity, benefits from applying inputs only as needed, where and when required.
- Monitoring operational costs in alignment with decision evaluations enables cost adjustments and optimization based on productivity levels.

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