CASE STUDY

Cashew Agroecosystems:

Processes Toward Agroecological Management in Vichada

Integrating Precision Agriculture, Regenerative Practices, and Agroecological Principles for Sustainable Cashew Production in the Colombian Orinoquia

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A project led by Kardianuts
In collaboration with Pakka Foundation
With technical support from Agrosavia

With the support of P4G – Partnering for Green Growth and the Global Goals 2030

March 2026

1. Introduction

In the heart of Vichada, a process of agroecological management is advancing for the sustainability of cashew agroecosystems in Colombia. This initiative, led by Kardianuts with the technical and scientific support of the Colombian Agricultural Research Corporation (Agrosavia) and the Pakka Foundation, represents much more than a production project: it is a rural development model to sow the future from the territory.

Through this case study, we share the acquired knowledge from implementing science-based agroecological management practices in cashew production systems. We extend a warm invitation to incorporate Science, Technology, and Innovation into agricultural management processes, with the firm purpose that these experiences may be evaluated and adapted in other territories.

2. Objective and Scope

This case study documents the transition from standardized agronomic management to a site-specific, data-driven approach in cashew agroecosystems at Kardianuts in Vichada, Colombia. Its primary objective is to present evidence-based insights on how integrating Precision Agriculture, regenerative practices, and agroecological principles can recover productivity and quality in perennial crop systems facing declining yields.

The document is intended to serve as a practical reference for cashew producers, agricultural extension services, and policymakers interested in scalable models for sustainable perennial crop management in tropical savannas. It presents the methodology, results, economic implications, and conditions for replication, aiming to contribute to the broader knowledge base on agroecological transitions in the Orinoquia region.

3. Conceptual Framework

The approach adopted by Kardianuts draws on three interconnected paradigms that together form the foundation of the agronomic transition described in this case study:

Agroecology provides the overarching vision: designing production systems that mimic natural ecosystem functions, promote biodiversity, and reduce dependence on external inputs. In this case, agroecological principles guided decisions such as the introduction of service crops (cover crops and green manures) to enhance biological nitrogen fixation, protect soil microfauna, and increase organic matter.

Regenerative Agriculture focuses on restoring degraded soils and building long-term soil health. At Kardianuts, this is expressed through mycorrhizal inoculation, the use of enriched biofertilizers, and the strategic establishment of vegetation covers (Desmodium heterocarpon) to promote carbon sequestration and rebuild soil fertility in the nutrient-poor Orinoquia savannas.

Precision Agriculture contributes the data-driven methodology: land zoning, georeferenced mapping, soil and foliar analyses by zone, and site-specific nutritional plans. Rather than applying uniform fertilization across the entire farm, precision agriculture ensures that interventions are calibrated to the specific conditions of each plot, optimizing resource use and minimizing environmental impact.

These three approaches are not in tension but rather complementary. Precision agriculture provides the diagnostic tools and data infrastructure; regenerative agriculture provides the soil-building strategies; and agroecology provides the systems-level design principles. Together, they enable a transition that is both scientifically grounded and ecologically sound.

4. Executive Summary

This case study details the transition toward an agroecological management model in the Kardianuts cashew agroecosystems in Vichada, Colombia. Facing declining yields (from 0.70 kg/tree in 2022 to 0.49 kg/tree in 2024) and low product quality resulting in a non-viable kernel yield index (<16%), it was identified that standardized nutritional management was insufficient to meet the crop's site-specific needs.

In response, a Precision Agriculture approach was implemented in 2024, based on site-specific nutrient management. The methodology included land zoning into 40 differentiated sites, soil and foliar analysis per zone, and the design of differentiated nutritional plans to correct macro and micronutrient deficiencies. Key agroecological strategies were incorporated, such as the establishment of Desmodium heterocarpon as a service crop to fix nitrogen and improve soil health, along with mycorrhizal inoculation.

The results of the 2025 harvest were significant: average production increased to 1.87 kg/tree, representing a 282% increase over the prior year. While still below the projected 2.7 kg/tree for year five, this advancement demonstrates the effectiveness of data-based, site-specific management in recovering productivity. The model not only improves productive and economic efficiency but also generates positive social impacts through knowledge transfer and environmental impacts through soil regeneration, positioning itself as a replicable benchmark for sustainable rural development in the region.

5. Background

Since 2022, Kardianuts began harvesting cashew nuts. During the first three years, a production scheme with a standard fertilization plan was implemented, focused on maintaining general practices for all plots. Over this period, actual production showed a consistent year-over-year decline, while the gap between observed and projected yields widened significantly, underscoring the need to rethink the agronomic management of the crop.

Table 1. Yields obtained per cashew plant versus projected yields

Year	Plant Age (years)	Production per Tree (kg)	Projected Production (kg)	Gap vs. Projected
2022	2	0.70	0.03	+2,233%
2023	3	0.51	0.40	+28%

2024	4	0.49	1.30	-62%

Source: Internal elaboration based on Haag et al. (1975) and Crisóstomo et al. (2004).

As Table 1 shows, actual yields in 2022 and 2023 exceeded projections for those respective tree ages, since projections for very young trees (years 2–3) are conservatively low. However, actual production declined year-over-year in absolute terms: from 0.70 kg/tree in 2022 to 0.51 kg/tree in 2023 (a 27% drop) and further to 0.49 kg/tree in 2024 (an additional 4% drop). Critically, by 2024 the expected yield for a four-year-old tree was 1.30 kg/tree, meaning actual production fell 62% below the projection. This widening gap between actual and projected yields, combined with the absolute decline in output, signaled that the standard management approach was not sustaining the crop’s growth trajectory.

In addition to the decrease in harvested volume, another critical concern was the low quality of the collected product, which did not meet the minimum standards required for entry into the processing plant. Many of the nuts did not completely fill the shell, indicating poor development of the kernel. This defect directly affects the kernel yield index—the ratio between the weight of the whole nut and the actual weight of the extracted kernel—which averaged 12.01% in processing runs conducted in 2023. According to the technical and economic guidelines established at the plant, a yield lower than 16% is not viable for processing, as it generates losses due to the high volume of empty shells and the higher cost per kilogram of recovered kernel.

Image 1: Cashew nuts with kernel growth deficiencies, 2023 harvest at Kardianuts farm.

During this period, the crop was managed under a standard fertilization plan without taking into account the particular conditions of the soil, climate, or the physiological state of the trees. Although this strategy was functional in the initial stages, over time it became evident that it did not adequately respond to the specific needs of the crop, which may have contributed significantly to the decline in production.

Together with Agrosavia, strategies were analyzed and proposed not only to mitigate the problem of low productivity but also to establish a roadmap toward agroecological management. The first key lesson was recognizing that the low yield problem was the result of a set of interactions between soil nutrient availability, the nutritional needs of the plants, and environmental constraints—rather than a simple, direct relationship with fertilizer application. External factors such as rainfall variability, which is characteristic of the Vichada region, may also play a role and should be monitored in future cycles to better isolate the effects of agronomic interventions.

For this reason, in 2024, Kardianuts decided to implement a new management model based on the detailed monitoring of key variables (soil analysis, foliar tissues, moisture levels, and the phenological response of the crop), allowing for more informed decision-making and the application of inputs in a specific, efficient, and sustainable manner.

Image 2: Application of the 2024 nutritional plan on the crop at Kardianuts.

6. Intervention Objectives

In response to the declining yields observed between 2022 and 2024, Kardianuts adopted a new agronomic management scheme in 2024 based on site-specific integrated nutrient management (Precision Agriculture), which seeks to optimize crop nutrition based on specific data for each zone. The main objectives were:

- Recover crop productivity toward projected yield benchmarks.
- Improve nut quality to achieve a kernel yield index above the 16% viability threshold.
- Build a more resilient production system through a technically grounded, site-specific management approach.

7. Methodology

The principle of integrated nutrient management is to provide the crop with what is necessary in the appropriate dose, timing, and method to optimize yield and quality while reducing negative impacts. The work plan formulated with Agrosavia followed five steps:

1. Characterize the plots through mapping and zoning.
2. Perform a technical diagnosis based on the characterization.
3. Make informed decisions based on the technical diagnosis.
4. Plan and execute actions oriented toward solving the identified problems.
5. Follow up on the results of the implemented plan.

The first step consisted of dividing the productive area into 40 sites, grouped according to soil characteristics, nutritional status, and crop age. To achieve this, georeferenced mapping and zoning were performed, allowing for the organization of areas and the execution of precise, spatially differentiated agronomic management.

In each zone, sampling was conducted for two types of diagnostic analysis:

- **Soil analysis:** Determines pH (which conditions nutrient availability), organic carbon content (a key indicator of soil health and fertility), and levels of available macronutrients (N, P, K) and micronutrients.
- **Foliar analysis:** Determines the nutrients that the plant has absorbed and assimilated, serving as a direct method to evaluate its nutritional status at a specific moment.

The results of the soil and foliar tissue analyses, combined with the productivity history, were used to define the nutritional status and map variations across the property. The information was systematized in Excel, enabling precise data cross-referencing and the generation of site-specific diagnoses.

Soil management constituted the main pillar of this work stage, structured around four fundamental components: (1) macronutrient correction, (2) micronutrient supplementation, (3) service crops for nutrient cycling, and (4) monitoring to measure impacts and adjust strategies. These components were applied in a differentiated manner according to the zone.

This approach represents an innovation in the department of Vichada, where experiences of precision agriculture applied to permanent crops such as cashew are still scarce. By implementing this model, Kardianuts not only seeks to improve its own productivity and sustainability but also to position itself as a technical benchmark in the region.

Image 3: Unloading of inputs for the 2024 nutritional plan.

7.1 Component 1: Macronutrient Management

The balanced management of macronutrients (N, P, K, Ca, Mg, and S) is essential for the development and productivity of cashew. Based on soil and foliar analyses, the Agrosavia technical team designed a localized fertilization program, adjustable annually according to crop age, requirements, and nutrient availability. Calcium and magnesium requirements were adjusted to correct deficiencies, based on the criterion of increasing soil base saturation to 60%. The detailed fertilization recommendations by crop age and nutrient level are provided in Annex A.

Image 4: Kardianuts tractor applying the 2024 nutritional plan.

7.2 Component 2: Micronutrient Supplementation

While macronutrients provide the basic elements for growth, micronutrients act as catalysts and cofactors that ensure the efficient functioning of the plant's metabolic and reproductive processes. In cashew, zinc and boron are usually the most limiting micronutrients due to their direct role in the reproductive phase.

The initial fertilization plan, based on organic agriculture principles, was functional during the first three years. However, a 2024 laboratory diagnosis revealed nutritional deficiencies across multiple essential elements, evidencing a nutrient imbalance. A biofertilizer enriched with minor elements was formulated to respond to the plant's needs, using sources permitted within the agroecological production system. Nutritional correction also included application of calcium and phosphorus between crop rows. The critical micronutrient thresholds used for diagnosis are provided in Annex B.

7.3 Component 3: Service Crops (Cover Crops)

The process toward agroecological management involves increasing biodiversity through service crops—species established to provide multiple benefits within the agroecosystem. A comparative analysis of four candidate species was conducted:

- **Arachis pintoi:** Good nitrogen-fixing capacity but limited biomass production in the Orinoquia region.
- **Kudzu:** Good growth but vines tend to climb crop trees, creating management challenges.
- **Urochloa decumbens:** Contributes to carbon sequestration but is highly competitive with the cashew crop.
- **Desmodium heterocarpon (Maquenque):** Selected species. Leguminous plant that fixes atmospheric nitrogen through root nodules, shows good adaptation to savanna soils, and exhibits low competition with the cashew crop.

Desmodium was sown at a dose of 333 g of seed per effective hectare (41% of total area per plot). The vegetation cover objectives include providing organic matter to the soil, facilitating biological nitrogen fixation, controlling erosion, regulating soil temperature, protecting soil microfauna, and contributing to carbon sequestration.

The covers were complemented with mycorrhizal inoculation (Acaulospora colombiana, Rhizophagus intraradices, Rhizophagus manihotis, and Glomus albidum), which strengthened the root system, improved nutrient absorption, and increased crop resilience to water and nutritional stress.

Key management considerations for service crops include fire risk management (dry biomass accumulation requires preventive cutting) and maintenance costs (circle weeding and inter-row brush cutting). These are ongoing operational costs that must be factored into adoption decisions.

Image 5: Established cover crops at Kardianuts.

7.4 Component 4: Monitoring and Control

Kardianuts has defined four key monitoring moments:

1. **Flowering:** Sampling inspections on selected trees to assess panicle and flower status and identify fruit formation trends per zone.
2. **Productivity Monitoring:** Recording kilograms collected per plot and per producer during harvest to evaluate yield, identify zone variations, and project future productivity.
3. **Soil and Foliar Analysis:** Conducted post-harvest to identify nutrient availability and recalculate needs for the next production cycle.
4. **Management Plan Feedback:** Based on analyses and monitoring, identify weak points, adjust the nutritional plan, and recalculate requirements for continuous improvement.

8. Results and Conclusions

The results of the implemented nutritional plan are directly reflected in the 2025 harvest, in both quantity and quality.

In 5-year-old trees, the average production per tree increased from 0.49 kg in 2024 to 1.87 kg in 2025, representing a 282% increase and a significant recovery in crop performance.

Table 2. Complete yield trajectory including post-intervention results

Year	Age (yrs)	Actual (kg/tree)	Projected (kg/tree)	Gap	YoY Change
2022	2	0.70	0.03	+2,233%	—
2023	3	0.51	0.40	+28%	-27%
2024	4	0.49	1.30	-62%	-4%
2025	5	**1.87**	2.70	-31%	**+282%**

Image 6: 2025 Kardianuts harvest stored in the warehouse.

While this result highlights the positive impact of incorporating site-specific management practices during its first year of implementation, actual production remains below the estimate for 2025 (2.7 kg per tree). This confirms the key lesson that low yield is a consequence of a complex set of interactions between agroecosystem components, and continuous improvement is necessary. It is also important to note that isolating the precise contribution of the nutritional intervention from other variables (such as rainfall patterns, tree maturation, and cumulative soil health improvements) would require multi-year controlled comparisons, which Kardianuts intends to develop in future cycles.

Image 8: Developed cashew nut ready for harvest. Photo by Diego Solano, Field Director at Kardianuts.

9. Economic Implications

While a full cost–benefit analysis is beyond the scope of this initial case study, the productivity gains achieved have direct economic significance that merits preliminary assessment:

9.1 Revenue Impact

The increase from 0.49 kg/tree to 1.87 kg/tree represents a 282% increase in harvestable volume. For a commercial operation, this translates directly into higher raw material throughput for the processing plant. Critically, the improvement in kernel yield index (from below 16% to viable processing levels) means that a greater proportion of the harvest can be processed into saleable product, rather than being discarded or redirected to lower-value uses.

9.2 Cost Structure

The transition to precision agriculture involves additional costs compared to standard fertilization, including: soil and foliar laboratory analyses per zone (40 zones), differentiated input procurement and application, service crop establishment and maintenance (seed, sowing, periodic cutting), and mycorrhizal inoculants. However, these costs are partially offset by more efficient input use (applying only what each zone requires rather than blanket application) and higher revenue per hectare from improved yields.

9.3 Processing Plant Utilization

With higher yield per hectare and improved kernel quality, the processing plant's capacity utilization improves. Given that fixed costs (labor, equipment, facility maintenance) remain relatively constant, higher throughput directly improves EBITDA margins. Kardianuts intends to develop a detailed financial model in subsequent cycles as multi-year data becomes available.

9.4 Investment Readiness

The demonstrated ability to recover productivity through science-based management strengthens the investment case for cashew agroforestry in the Orinoquia. Investors and development finance institutions seeking evidence of viable models for sustainable agriculture in frontier regions can draw on these results as an early proof of concept.

10. Broader Impacts

10.1 Economic

- **Productivity Increase:** The precision agriculture approach increased production per tree, reducing relative costs per kilogram of harvested kernel.
- **Financial Viability:** Higher yield per hectare improves cash flow, enabling strategic reinvestment in the nutrition cycle and maximizing processing plant utilization.
- **Rural Employment:** Higher production and technical tasks (monitoring, differentiated application, cover crop control) sustain and increase local hiring.
- **Local Economy Revitalization:** Productivity improvements generate indirect effects on transporters, local marketers, and organic input suppliers.

10.2 Social

- **Knowledge Transfer:** Kardianuts positions itself as a regional leader, transferring validated processes and supporting other producers in their development.
- **Rural Productive Fabric:** Precision agriculture methodologies stimulate professionalization and promote a culture of innovation and continuous improvement.
- **Social Stability:** More stable income for workers and rural families, improving quality of life and reducing migration caused by lack of opportunities.

10.3 Environmental

- **Soil Regeneration:** Desmodium covers and enriched biofertilizers stimulate soil microbial life, increase organic matter, and promote carbon sequestration.
- **Ecosystem Conservation:** By avoiding synthetic agrochemicals and maintaining ground covers, the biodiversity of nearby morichales (palm swamps) and gallery forests is protected.
- **Low-Impact System:** Only 20% of the soil is directly intervened, with up to 40% managed with vegetation covers, creating an integrated productive-ecological system.

11. Scalability and Conditions for Replication

For other cashew producers or organizations interested in adopting this model, the following conditions and requirements should be considered:

11.1 Biophysical Conditions

The Kardianuts farm is located in the Orinoquia savanna, characterized by acidic, nutrient-poor Oxisol soils with low organic matter content. The tropical wet-dry climate features a pronounced dry season (December–March) and high rainfall variability. Producers in similar savanna environments with comparable soil types are most likely to benefit from this approach. Those in different agroecological zones should adapt the specific crop species, fertilization rates, and cover crop selections to their local conditions.

11.2 Technical Capacity Requirements

- Access to soil and foliar analysis laboratory services (either on-site or through regional laboratories).
- Capacity for georeferenced mapping and zoning (basic GPS and GIS skills or external support).
- Data management skills for systematizing analysis results and designing zone-specific nutritional plans.
- Access to agronomic expertise (either in-house or through partnerships with research institutions such as Agrosavia).

11.3 Investment Requirements

The transition to precision agriculture involves upfront costs that are higher than standard fertilization but are expected to be recovered through improved yields. Key cost categories include: laboratory analysis fees (soil and foliar, per zone, annually), differentiated input procurement, service crop seed and establishment costs, mycorrhizal inoculants, and monitoring labor. A detailed cost breakdown per hectare will be developed as multi-year data becomes available. Smaller producers may consider collective approaches to laboratory analysis and technical assistance to reduce per-farm costs.

11.4 Institutional Support

The Kardianuts experience benefited from partnerships with Agrosavia (research institution), Pakka Foundation (project management and coordination), and P4G (financing). Replication by other producers is more feasible where similar institutional support networks exist, particularly for the initial diagnostic and planning phases.

12. Recommendations for Cashew Producers

12.1 Strategic Recommendations

Do not replicate models without adaptation: Every farm has unique conditions. Establish a baseline that includes zoning, soil and foliar tissue analysis, historical production records by plot, and calculation of the kernel yield index per plot.

Continuous technical training: The adoption of precision agriculture requires farmers to professionalize their crop management, strengthening capacities in data analysis and nutritional planning. Reach out to government entities and research centers for guidance.

Integrate the community of practice: Sharing experiences in a collaborative learning space within the cashew value chain will contribute to mitigating risks within the territory.

12.2 Operational Recommendations

Perform soil and foliar analysis annually: Divide the farm into homogeneous zones, collect soil sub-samples per zone at 0–30 cm depth, and send 500 g to the laboratory. Foliar analysis should be done during peak vegetative growth, taking 100 healthy leaves from 20–30 representative trees per zone.

Design zone-specific nutritional plans: Identify nutrient deficiencies and excesses in each plot and adjust fertilization doses in a differentiated manner, selecting the most appropriate sources and application timing.

Sow strategic vegetation covers: Select species adapted to local conditions, establish them between crop rows, and use seeds inoculated with mycorrhizae. Include periodic pruning to avoid excessive competition with the main crop.

Prepare efficient bio-inputs: Standardize manufacturing processes, control raw materials and fermentation conditions, and validate batches with quality analyses whenever possible.

12.3 Key Sustainability Recommendations

Efficient soil and nutrient management: Conduct annual analyses to adjust fertilization by zone. Supplement with technically validated bio-inputs.

Biodiversity strengthening: Establish strategic vegetation covers (e.g., Desmodium ovalifolium) and diversify the system with complementary species. Manage agricultural residues as biochar or compost to close nutrient cycles.

Monitoring and continuous improvement: Monitor environmental and social indicators (soil organic matter, vegetation cover, biodiversity, rural employment) to evaluate progress. Provide permanent training in good agricultural practices and fire prevention.

13. Key Lessons Learned

1. **Low yield is systemic, not simple:** Declining productivity was not caused by a single factor but by the interaction between soil nutrient availability, plant needs, and environmental constraints. A systems approach is essential.
2. **Data changes everything:** The shift from standardized to site-specific management was only possible because of systematic data collection (zoning, soil analysis, foliar analysis). Without data infrastructure, precision agriculture cannot function.
3. **Agroecological transition is iterative:** Results improved dramatically in the first year, but the gap between actual and projected yields shows that continuous improvement is needed. Each cycle provides new data for further refinement.
4. **Cover crops require active management:** While service crops provide significant ecological benefits, they also introduce fire risk and maintenance costs that must be planned for.
5. **Institutional partnerships amplify impact:** The collaboration with Agrosavia, Pakka Foundation, and P4G was critical for accessing research expertise, project coordination, and financing. Isolated producers would face greater barriers to adoption.

Credits

A project led by: **Kardianuts** – www.kardianuts.com
In collaboration with: **Pakka Foundation** – www.pakkafoundation.org
With technical support from: **Agrosavia** – www.agrosavia.co
With the support of: **P4G – Partnering for Green Growth and the Global Goals 2030** – www.p4gpartnerships.org

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Annex A: Macronutrient Recommendations by Crop Age

The following table presents the initial macronutrient recommendations for cashew cultivation according to age, as adapted from Crisóstomo et al. (2003). These recommendations are subject to variations as new analyses are performed and production data are obtained.

Stage / Year	N (g/tree)	P_2O_5 (g/tree)	K_2O (g/tree)	Notes
Planting (Year 0)	0	100–200	0	P adjusted by soil level
Growth (Year 1)	60	0	20–60	K adjusted by soil level
Growth (Year 2)	80	100–200	40–100	P & K adjusted by soil level
Growth (Year 3)	150	120–250	60–140	P & K adjusted by soil level
Growth (Year 4–5)	200–300	150–300	80–180	Full range per soil analysis

Source: Adapted from Crisóstomo et al. (2003). Ca and Mg adjusted to reach 60% base saturation.

Annex B: Critical Micronutrient Levels for Cashew

Element	Unit	Low	Medium	High
Fe	mg/kg	< 10.0	10.0–20.0	> 20.0
Mn	mg/kg	< 5.0	5.0–10.0	> 10.0
Zn	mg/kg	< 0.5	0.5–1.2	> 1.2
Cu	mg/kg	< 0.3	0.3–0.8	> 0.8
B	mg/kg	< 0.2	0.2–0.6	> 0.6

Source: Based on Crisóstomo et al. (2007).