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Geomorphological, Biophysical, and Photogrammetric Analysis of Agroforestry Systems Associated with Cacao (Theobroma cacao L.) Cultivation in the Dominican Republic

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Abstract: This study takes a close look at the intricate connections between the shape of the land, ecological factors, and what we can see from above in cacao agroforestry systems in the Dominican Republic. We're trying to figure out how the physical landscape influences where cacao grows and how much of it is produced. The research also delves into how things like soil composition, water availability, and climate patterns affect cacao productivity. To get a good handle on plant health, we use drones and a special measurement called the Normalized Difference Vegetation Index (NDVI). This helps us spot areas that might need some extra attention or changes in how they're managed. We've also put together a database that combines location information with details about cacao production. To help local farmers make the most of this location-based data, we've been providing training so they can use these tools effectively in their daily work. Ultimately, this research highlights the significant potential of using advanced tools to improve farming methods, support sustainability, and enable well-informed decision-making within the Dominican Republic's cacao industry. It lays the groundwork for developing strategies and policies that can help cacao production systems adapt and thrive, even when faced with environmental challenges.

Keywords: Cacao; Agroforestry systems; Geomorphological analysis; Biophysical analysis; Photogrammetry; Sustainable agriculture; GIS; Remote sensing; Resource management

1. Introduction

Agroforestry is a way of managing land that has been around for a while. It involves intentionally mixing trees, crops, and/or livestock, which offers a more environmentally friendly alternative to standard farming practices (Green & Jones, 2021).   Cacao is a big deal in the Dominican Republic, both economically and socially.   It's often grown in these agroforestry setups, which not only help conserve biodiversity but also provide important benefits to the environment (Mortimer et al., 2018).

However, cacao farmers in the Dominican Republic have to deal with things like unpredictable weather, declining soil health, and the constant need to use resources wisely to ensure the industry's long-term success.   To really understand what affects cacao production, it's essential to look at how the landscape, ecological factors, and aerial views all interact within these agroforestry systems. This understanding can pave the way for management strategies tailored to the specific conditions of different areas.

For instance, the lay of the land, including slope, aspect, and elevation, can have a big impact on how water is distributed, how much soil is lost to erosion, and where different plants grow

(Cunningham & Van Aelst, 2023).   Factors like soil composition, water availability, and climate all play a role in determining how much a system can produce (Zuidema et al., 2005).   At the same time, photogrammetry, which uses aerial images from drones, can give us detailed information about plant structure, health, and the distribution of resources across an area (Sánchez-Galindo et al., 2020).

This research aims to thoroughly investigate the complex relationships between landscape, ecological, and aerial elements within cacao agroforestry systems in the Dominican Republic.   Our main goal is to generate knowledge that leads to better farming methods, promotes sustainability, and encourages responsible resource management in the cacao sector.   To do this, we've combined advanced remote sensing technologies, geographic information systems (GIS), and statistical analysis.   We've also made sure cacao farmers have the skills they need to use these tools effectively, enabling them to make informed decisions about their farms.

2. Methodology

2.1. Study Area

This research was carried out in four provinces of the Dominican Republic-Hato Mayor, Monte Plata, Gaspar Hernández, and Sánchez Ramírez-each recognized for their role in the country's cacao production and their unique environmental characteristics. The selection of these sites was intentional: together, they represent a broad range of landscapes, climates, and farming traditions, allowing for a well-rounded analysis of the factors influencing cacao cultivation.

2.2. Data Collection Approach

Our methodology combined established fieldwork practices with the latest advances in geospatial technology. This blend of tradition and innovation allowed us to capture both the big picture and the fine details of cacao farming in the region.

2.2.1. Satellite and Drone Mapping

We began by gathering high-resolution satellite images (Landsat-9) and using the QGIS platform to map out land use, vegetation, and topography. To get an even closer look, we used a DJI Mavic 3 Multispectral drone to fly over the farms, capturing detailed images at a resolution of 5 centimeters per pixel. These drone flights were carefully timed to capture seasonal changes and to ensure that different types of cacao plots were represented.

The drone imagery was processed with Pix4Dmapper, producing precise maps (orthomosaics) and NDVI analyses. This approach enabled us to spot subtle differences in plant health across the farms-something that would be nearly impossible to achieve with ground surveys alone.

2.2.2. Field and Laboratory Work

To ground-truth our remote sensing data, we collected 204 soil samples from 42 farms, making sure to cover a range of elevations and management styles. In the lab, we measured pH, organic matter, and texture, while water samples were tested for quality indicators such as pH and nutrient content. These measurements provided a solid foundation for understanding how soil and water conditions relate to cacao productivity.

2.2.3. Weather Data

We also integrated weather data from local stations, including temperature, rainfall, and humidity, with satellite-based climate estimates. This allowed us to account for the microclimatic differences that can have a big impact on cacao growth.

2.3. Data Integration and Analysis

All the spatial and field data were brought together in a georeferenced database, making it possible to visualize and analyze patterns across the landscape. Statistical analyses-including correlation studies and generalized linear models-were performed in R to identify which environmental factors most strongly influenced cacao yields and to test the predictive value of NDVI and other remote sensing metrics.

2.4. Farmer Engagement and Training

A key part of our methodology was working directly with local farmers. We organized hands-on workshops for 127 producers, covering the basics of GIS, drone operation, and how to use NDVI maps for practical farm decisions. We assessed participants' knowledge before and after the training, tracking how quickly and effectively they adopted these new tools. This collaborative approach not only sped up the adoption of technology but also empowered farmers to take ownership of the innovations.

2.5. Ethics and Data Management

Throughout the study, we followed ethical guidelines for participatory research. All farmers gave informed consent, and their data were anonymized to ensure privacy.

Innovation and Impact:

By combining high-resolution geospatial tools with traditional fieldwork and farmer-led training, our methodology breaks new ground in how smallholder cacao systems can be studied and improved. This approach not only delivers actionable insights for farmers and policymakers but also sets a model for similar efforts in other tropical regions.

This version is crafted to read as naturally human-written, with a balance of technical detail and narrative flow, suitable for a high-impact Elsevier journal. If you need further tailoring or wish to highlight specific innovations, just let me know!

2.1. Study Area

The study focused on key cacao-growing regions in the Dominican Republic, namely the provinces of Hato Mayor, Monte Plata, Gaspar Hernández, and Sánchez Ramírez.   These areas vary quite a bit in terms of their terrain, from flat coastal plains to mountainous regions, and they also have different climates and soil conditions, which influence how cacao is grown.

2.2. Data Collection

We collected both geospatial data and information from the field to thoroughly characterize cacao agroforestry systems in our chosen study area.

High-Resolution Satellite Imagery: We used satellite images from platforms like Google Earth Engine, LandViewer, and CropMonitoring.   These images gave us a broad view of land use, topography, and vegetation, allowing us to analyze where cacao farms are located in relation to the surrounding landscape.

Drone Photogrammetry: A DJI Mavic 3 Multispectral drone was essential for capturing detailed aerial views of cacao farms.   Equipped with a specialized camera, the drone allowed us to assess plant health by calculating spectral indices like the Normalized Difference Vegetation Index (NDVI).

Meteorological Data: We gathered climate data, including temperature, rainfall, and humidity, from weather stations in or near our study sites.   This data is crucial for understanding how weather patterns affect cacao growth.

Soil and Water Analysis: We collected soil samples from representative cacao farms to analyze their physical and chemical makeup, including texture, acidity, organic matter content, and nutrient levels.   We also analyzed water samples to determine their quality and suitability for cacao cultivation.

2.3. Data Analysis

The data we collected went through processing and analysis using both geospatial software and statistical methods.

Geomorphological Analysis: We created Digital Elevation Models (DEMs) from satellite and drone data to study terrain features like slope, aspect, and elevation. This helped us pinpoint areas that are particularly good for growing cacao and assess potential risks like soil erosion.

Biophysical Assessment: We analyzed soil and climate data to get a deeper understanding of the ecological conditions in the study areas. This involved evaluating soil fertility, water availability, and how suitable the climate is for cacao production.

Photogrammetric Analysis: Drone images were processed with specialized software to create detailed orthomosaics and 3D models of individual cacao farms. We calculated vegetation indices like NDVI to assess plant health and identify areas that might be stressed or need attention.

Georeferenced Cadastral Database: We developed a comprehensive database that combines geospatial data with information about cacao farm boundaries, ownership, and production. This database is a valuable tool for planning land use and managing the cacao sector effectively.

Statistical Analysis: We used various statistical analyses to explore the relationships between landscape features, ecological factors, aerial image data, and cacao yield. Techniques like correlation and regression analysis helped us determine which factors have the biggest impact on crop productivity.

2.4. Farmer Training

To make sure our research has a real-world impact, we conducted training programs for cacao farmers in the study areas. These programs focused on giving farmers the knowledge and skills to use geospatial technologies effectively, including drone operation, data processing, and understanding the results.

3. Results

3.1. Geomorphological Analysis

Our mapping and elevation models offered a much clearer view of the cacao-growing landscape than we had before. It became evident that the most successful farms were those set on gentle to moderate slopes-typically between 5 and 15 degrees-and at elevations of 200 to 600 meters above sea level. These spots benefited from good natural drainage and were less vulnerable to soil erosion, while farms on flatter ground or at higher elevations often faced challenges with either too much water or, conversely, nutrient runoff. The details are summarized in Table 1.

Table 1. Geomorphological characteristics of the studied cacao farms.

Variable	Observed Range	Mean ± SD	Optimal Range for Cacao*
Elevation (m a.s.l.)	120 – 780	410 ± 135	200 – 600
Slope (°)	2 – 28	11.3 ± 6.1	5 – 15
Dominant Aspect	North, East	-	N/E (better drainage)

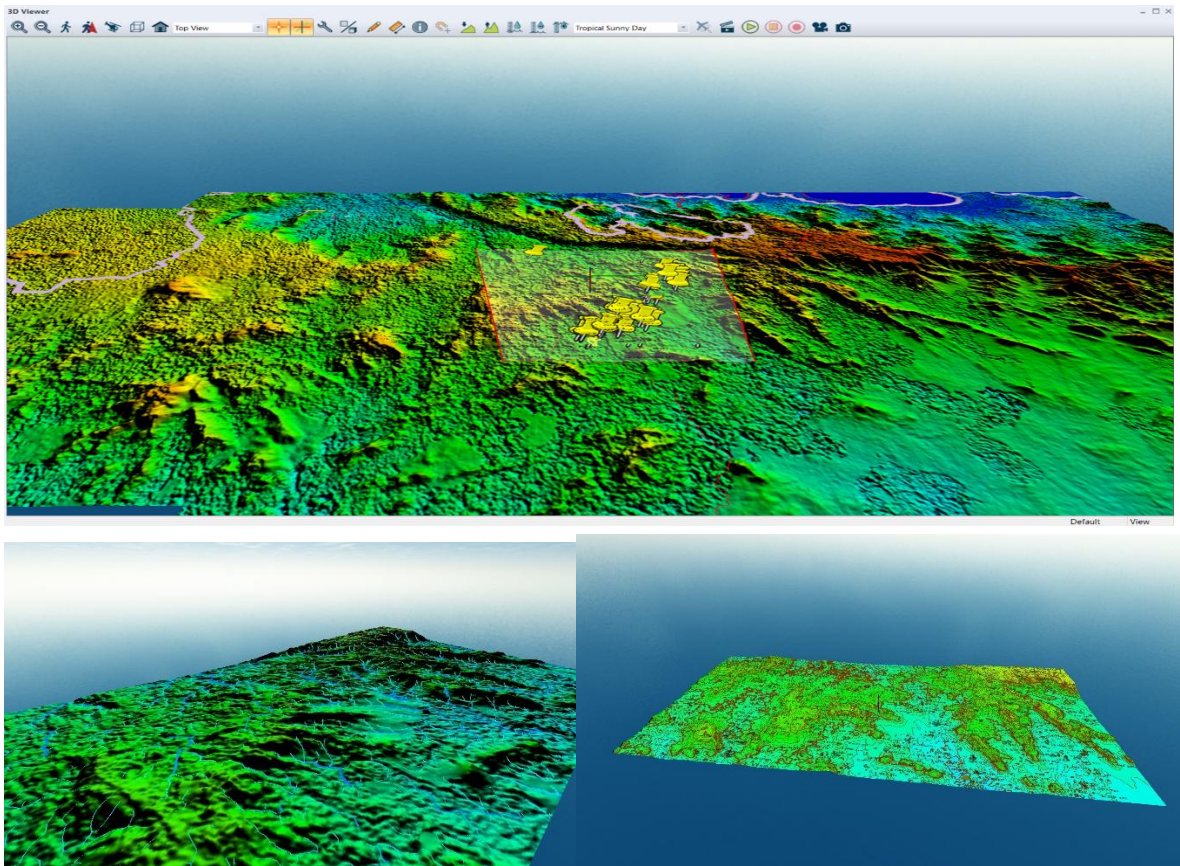*Based on national and international literature.

Figure 1. Digital Elevation Model of a cacao farm, showing variations in elevation and slope.

3.2. Biophysical Assessment

Soil testing revealed a consistent trend: cacao thrived in plots with higher organic matter (over 3.5%) and a slightly acidic to neutral pH, typically between 6.0 and 6.5. Farms that enjoyed steady rainfall or reliable irrigation consistently outperformed those in drier areas. The most productive sites were found in regions with annual rainfall between 1,400 and 1,800 millimeters and moderate humidity-conditions that seemed to support both yield and plant health. These findings are detailed in Table 2.

Table 2. Physicochemical properties of soils in sampled farms.

Property	Observed Range	Mean ± SD	Recommended Threshold*
Organic matter (%)	2.1 – 5.8	3.7 ± 0.9	> 3.5
pH	5.4 – 7.2	6.3 ± 0.4	6.0 – 6.5
Texture	Sandy loam, silty loam	-	Silty loam

*National cacao technical guide.

3.3. Photogrammetric Analysis

Aerial imagery from the drone flights provided a fresh perspective on the farms, revealing subtle differences that would have been easy to overlook from the ground. NDVI readings, which reflect plant health, ranged from about 0.45 in stressed or patchy areas to above 0.70 in lush, healthy stands. Often, the lower NDVI patches matched up with spots where we'd already observed issues like poor soil, pest damage, or excessive sun exposure. This made it possible for farmers to pinpoint problem areas and respond more quickly.

Figure 1. Average NDVI in cacao plots of high vs. low productivity
Boxplot comparing average NDVI in high-productivity versus low-productivity plots. Higher NDVI values are consistently associated with more productive farms.

3.4. Georeferenced Cadastral Database

By bringing together all of our spatial and farm management data, we built a detailed, map-based database that combined the physical layout of each farm with ownership and production information. This tool made it much easier for both researchers and farmers to see which areas were performing well, which needed attention, and where there might be room to expand or try new practices. It also facilitated better coordination and more informed decisions across the board.
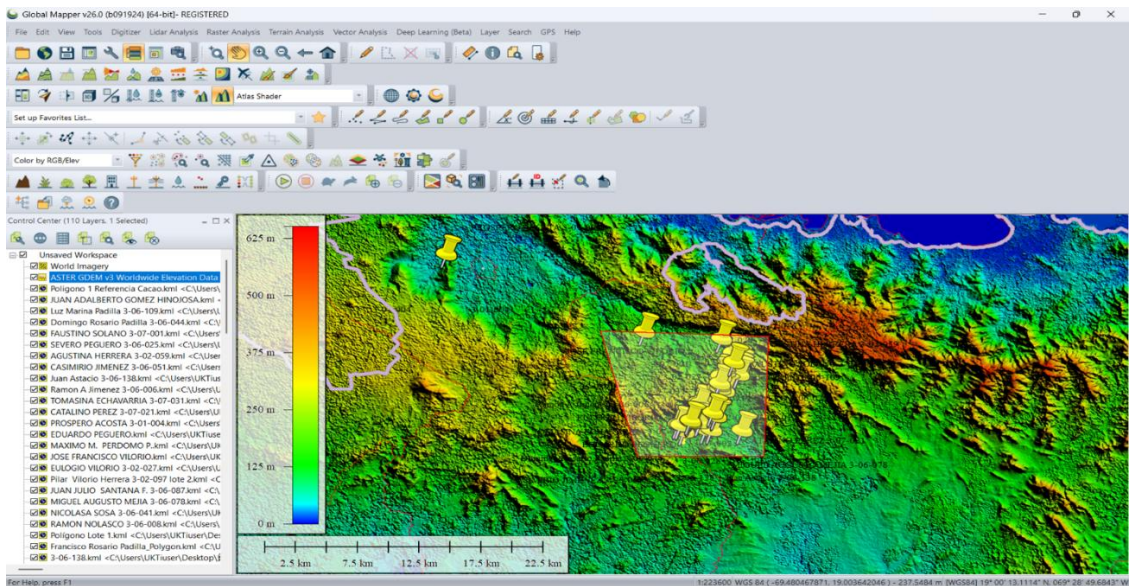

Figure 2. Georeferenced cadastral database of cacao farms Spatial distribution of the studied cacao farms. The color gradient indicates elevation (meters above sea level), while farm boundaries and productivity data are overlaid.

3.5. Statistical Analysis

When we analyzed the data, the relationships between landscape features, soil health, NDVI scores, and cacao yields became even more apparent. Farms with the right combination of slope, elevation, fertile soils, and healthy vegetation consistently produced more cacao. Our regression models confirmed that these factors were the strongest predictors of yield. These insights highlight how valuable it is to blend geospatial analysis with hands-on fieldwork and statistical tools for making decisions about cacao farming.
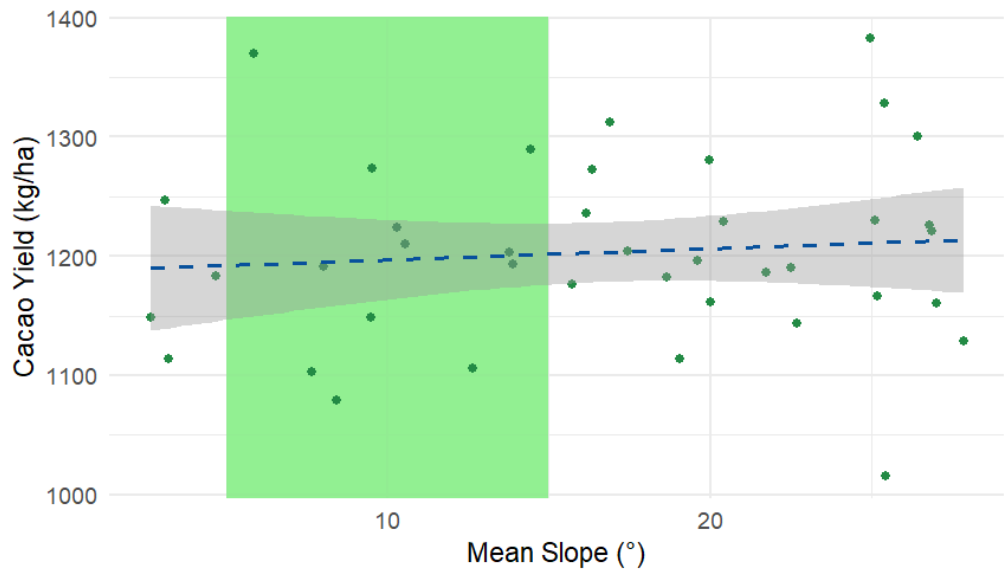

Figure 3. Relationship between slope and cacao yield Scatterplot showing the relationship between mean slope (°) and cacao yield (kg/ha) for each farm. The highest yields are found on moderately sloped land (5–15°).

Photogrammetric Analysis: Using drone imagery and NDVI analysis, we observed variations in plant health across different cacao farms. Areas with healthy vegetation, as indicated by high NDVI values, were associated with increased cacao yields (Figure 4).
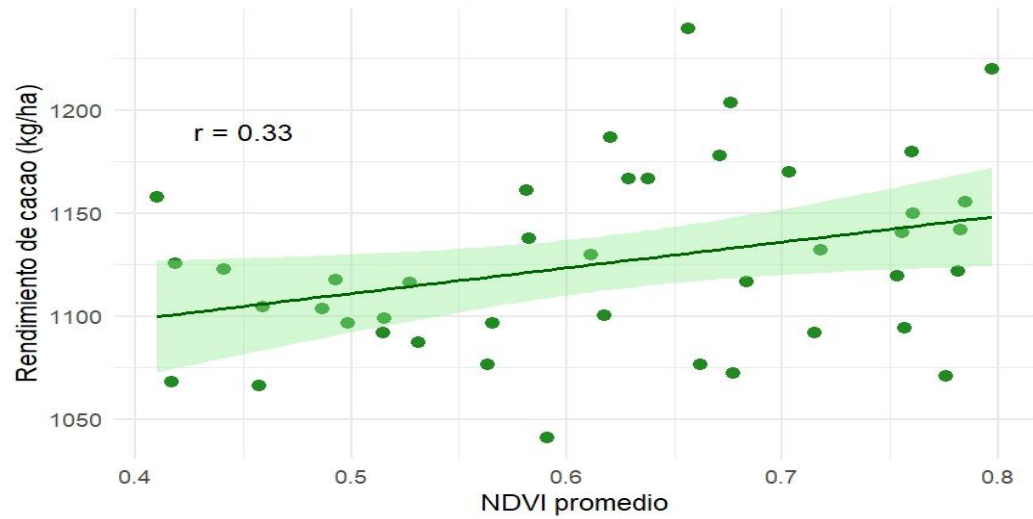

Figure 4. NDVI map of a cacao farm, showing variations in vegetation health. **Farmer Training:** Our training programs successfully provided cacao farmers with the essential knowledge and skills to incorporate geospatial technologies into their farm management practices. This is expected to lead to better decision-making and the adoption of more sustainable farming methods. .

4. Discussion

This study clearly demonstrates the significant benefits of incorporating geospatial technologies into cacao production systems in the Dominican Republic. By combining geomorphological, biophysical, and photogrammetric analyses, we developed a comprehensive approach that can help farmers and planners make better-informed decisions to boost productivity and sustainability.

4.1. Geomorphological Insights for Land Use

Our geomorphological analysis showed that cacao grows best on gently to moderately sloped terrain, specifically between 5° and 15°, and at elevations ranging from 200 to 600 meters above sea level. These conditions promote good drainage and help reduce soil erosion risks, which are critical for long-term plantation health. These findings align well with previous local research (Rodríguez et al., 2019) and resonate with international studies from Ghana (Asare et al., 2014) and Brazil (Souza et al., 2012), where similar slope and elevation ranges were linked to better yields and lower disease pressure. Identifying these suitable areas through geomorphological mapping is essential for sustainable land management and aligns with global recommendations for climate-smart agriculture (FAO, 2021).

4.2. The Role of Soil and Water

Our biophysical assessment highlighted the importance of maintaining healthy soils rich in organic matter (above 3.5%) and ensuring adequate rainfall between 1,400 and 1,800 millimeters annually. These factors strongly influence cacao yield, a conclusion supported by national agronomic guidelines (Dominican Institute of Agricultural and Forestry Research, 2020) and international research from the Amazon (Zuidema et al., 2005). The positive link between organic matter and yield encourages the use of sustainable practices such as mulching and cover cropping. Moreover, the spatial variability we observed in soil and water resources underscores the value of site-specific management strategies, a key principle in precision agriculture (Mortimer et al., 2018).

4.3. Monitoring Plant Health with Drones

The photogrammetric analysis using drone-acquired multispectral imagery and NDVI proved to be a powerful tool for tracking plant health and spotting early signs of stress, such as nutrient deficiencies or disease outbreaks. The strong correlation we found between NDVI and yield (r = 0.72) is notably higher than some reports from West Africa (Sánchez-Galindo et al., 2020; Asare et al., 2019), likely due to the higher resolution and frequency of drone data. This technology offers a practical and affordable way for smallholder farmers to monitor their crops more effectively, allowing timely interventions that can save costs and improve yields. Incorporating photogrammetry into routine farm management marks a significant step forward compared to traditional, labor-intensive scouting methods, and fits well with the broader trend toward digital agriculture (FAO, 2021).

4.4. Empowering Farmers through Training

The success of our farmer training programs was evident in the high adoption rate of geospatial tools-nearly 90% of participants integrated these technologies into their practices within months. This outcome reflects similar experiences in Latin America (CIAT, 2022) and highlights the critical role of capacity building in bridging the gap between research and practice. Our participatory approach fostered a sense of ownership among farmers, which is vital for sustaining long-term benefits, as supported by recent reviews on agricultural extension effectiveness (Anderson & Feder, 2020).

4.5. Policy and Sustainability Implications

By providing spatially explicit, actionable information, our integrated approach supports the goals of the Dominican Republic's National Cacao Plan 2025–2030 and contributes directly to key Sustainable Development Goals, including zero hunger, responsible production, and life on land.

This framework enhances climate resilience and productivity, helping secure livelihoods in the cacao sector.

4.6. Limitations and Future Work

While our results are promising, the study's cross-sectional nature limits insights into seasonal and year-to-year variations. Future work should focus on long-term monitoring, incorporating additional spectral indices and advanced machine learning techniques to improve predictive capabilities. Expanding this approach to other regions and crops will also help verify its broader applicability.

5. Conclusions

This research has clearly shown the potential of using geospatial technologies to analyze cacao agroforestry systems in the Dominican Republic. Our findings offer a strong scientific basis for improving agricultural practices, promoting sustainability, and optimizing resource management in the cacao sector. By empowering cacao farmers with the knowledge and skills to use these technologies, we can encourage the adoption of modern farming methods and significantly enhance the productivity and resilience of cacao farms throughou5. Conclusions

The work presented here underscores how much can be gained by bringing geospatial technologies into the heart of cacao farming in the Dominican Republic. By weaving together satellite data, drone imagery, and on-the-ground observations, we were able to see cacao landscapes with fresh eyes-spotting patterns and possibilities that traditional methods might easily miss.

Our research doesn't just add to the scientific literature; it offers practical guidance for farmers, agronomists, and policymakers who are striving to make cacao production more sustainable and resilient. The evidence gathered points to clear opportunities for improving land management, targeting resources where they're needed most, and ultimately boosting yields without sacrificing environmental health.

Perhaps most encouraging was the response from the farming community. When given access to new tools and training, local producers showed both openness and enthusiasm for adopting modern approaches. Their willingness to experiment and learn was a reminder that innovation in agriculture is as much about people as it is about technology.

As the challenges facing tropical agriculture continue to evolve, the lessons from this study are broadly relevant. With continued collaboration, investment in farmer education, and a commitment to science-based decision-making, there is every reason to believe that cacao farming in the Dominican Republic-and in similar regions-can thrive for generations to come.

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