

Interactions between geomorphology and production chain of high-quality coffee in Costa Rica

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Abstract: High-altitude coffee has an international reputation due to its high quality, especially in countries with a long production history like Costa Rica. Specific geographical characteristics determine the regions where high-altitude coffee can be cultivated. Over the last two decades, new production conditions have promoted the growth of smallholder coffee farms in the Upper Buenavista Catchment (UBC) in the South of Costa Rica. To understand this phenomenon's process, we initially performed a detailed geomorphological mapping of the high-elevation production sites in the UBC. Then, we used remote sensing to determine the coffee land cover (2005, 2012, and 2018) to compare their landforms. Furthermore, we analyzed the production-processing-market chain that has promoted coffee plantations since 2005. Our results show that coffee farmers chose more unstable and erosive areas with short-term production prospects to cultivate premium-prices coffee. Moreover, farmers have changed their role in the coffee sector, evolving from small producers to entrepreneurs with specialized knowledge. These actions may reduce economic risks and improve the household incomes of smallholder coffee producers. However, limited research has been done along the tropics about the relationships between landforms, socioeconomic drivers, and high-altitude coffee yield. Therefore, our results are essential to present geomorphology and applied geography as baselines in land use planning for agricultural landscapes.

Keywords: high-altitude coffee; geomorphology; rural geography; production factors; Latin America

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1. Introduction

Costa Rica is recognized worldwide for its high-quality coffee production. High-quality coffee in the country is produced within certain environmental conditions to achieve the best possible yields and specific taste properties: elevation from 500 to 1700 m asl, annual precipitation between 1000 and 3000 mm, air humidity lower than 85%, high amounts of nutrients in the soil, and hillsides protected from strong winds [1]. The species *Coffea Arabica* makes up most of the production in Costa Rica, in particular, the Borbón, Centroamericano, Milenio (H10), Caturra, Geisha, and Catuaí varieties [2]. Harvesting is selective and collected by hand, with only ripe coffee fruits being chosen (at optimum maturity). Then, they are processed under wet conditions and finally dried in the sun or mechanical methods [3].

The country produces a high-quality bean, which allows for a cup with better organoleptic characteristics -fine, pleasant, and aromatic- [4, 5]. Nonetheless, the recurrent crises of coffee, manifested in low global prices and the loss of the available agricultural space, have driven the small-scale producers to innovate their production methods to obtain better market prices for a high-quality product [6].

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The coffee production sector is a keystone in the social and economic development of rural areas [7]. The supervision of this sector corresponds to the Costa Rican Coffee Institute (ICAFFE). ICAFFE stratified the industry into three main layers: (1) the coffee producers who plant, manage, and harvest the coffee; (2) coffee processor firms that transform the raw material into processed coffee to export it or consume it locally. Exporting firms (3a) and roasting firms (3b) conform the third layer, which commercializes the final product to the international or local market, respectively [2]. Among the coffee producers, the participation of many small-scale producers (i.e., less than 15 ha) is common in the eight coffee regions of the country. According to ICAFFE [2], 91.4% of the producers deliver less than 100 bushels of coffee (i.e., a bushel is the volumetric unit of coffee, equivalent to 0.4 m³). This stratification in the participation has characterized the coffee sector since its inclusion in the country's economy.

Recently, there have been relevant changes in the role of coffee producers, going from a producer-harvester to a producer that can also process with a focus on quality. This change places Costa Rica as one of the world's most excellent coffee producers [8]. Differentiated, high-quality coffee recognizes the site-specific production, processing, and commercialization of coffee with a premium price liquidation [9, 10]. In addition, high-quality coffee depends on specific geographic conditions, which must be understood to characterize the geographic and productive changes in the coffee sector.

Geomorphological maps and other environmental cartography are valuable tools for assessing geographic and socioeconomic interactions in the landscape [11]. Resource assessment and land use planning are key in developing countries since their populations depend on primary economic activities for their subsistence which provoke intense pressure on ecosystems, water, and soils [12]. Contemporary geomorphological maps are important resources for environmental approaches such as landscape analyses because of their flexibility using new technologies [13]. Alternative mapping approaches, like those that incorporate local knowledge, are helpful to understand intrinsic environmental and socioeconomic characteristics of smallholder cropping systems and land use management [14]. Since land use information can be reorganized within a GIS (Geographic Information System), subsequent analyses of the change in land cover and use are achievable because landforms endure as the elementary analytical spatial unit through time [15].

High-altitude coffee-growing regions have risen over the past few decades in Costa Rica due to its global demand. Consistently, croplands areas have been rising both in altitude and slope especially in the last years. We aim to understand the geomorphic and production chain interactions of high-quality coffee in the Upper Buenavista Catchment (UBC), part of the coffee region denominated Brunca in Southern Costa Rica. We hypothesize that specific landforms and their morphometric characteristics might have influenced the location of new coffee areas over the last twenty years. Moreover, the diversification of the coffee production chain has pushed for better quality and spread croplands into the slopes of UBC. We develop a problem-solution approach based on applied geography [16]. Our mixed approach can bring new tools for fast-changing agricultural landscapes to improve their planning. Therefore, we (i) performed a geomorphological analysis coupled with land cover change analysis, and (ii) accomplished a multi-scale assessment to identify the production conditions that drove the high-altitude coffee cropland increase between 2005 and 2018. This methodology combines local expert knowledge with environmental mapping and may be used for other developing regions with similar characteristics where information is scarce.

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2. Materials and Methods 94

2.1. Study area 95

The case study area comprises the high-elevation coffee plantations of the UBC in the Rivas district of Pérez Zeledón's municipality, southeast Costa Rica. Most of the croplands are over 1200 m asl. The UBC belongs to the General River, which is one of the main branches of the Terraba River Catchment, the largest one in Costa Rica [17, 18]. This river drains along the Pacific facing slopes of the Cordillera de Talamanca and its source comes from the country's highest peak, Cerro Chirripó (i.e., 3810 m asl; [19]).

Dissimilar exogenic processes controlled by water, ice, temperature, and vegetation have shaped the landforms of UBC [20-23]. Seasonal and cyclonic rains activate fluvial processes that alter the landforms continually [24, 25]. The average annual precipitation is more than 2500 mm and can reach up to 5500 mm [26, 27]. The local landscape is mainly carved by intense rainfall combined with high rates of soil loss and chemical weathering [28].

Tropical premontane rainforests compose the vegetation with intense deforestation and forest fragmentation dating from the 20th century. Locally, deforestation touched its top during the 1960s and 1970s, in the interim anthropogenic changes sustained into 1980s. Several environmental policies combined with the growth of ecotourism and sustainable production changes provide an ecosystem regaining [29]. Very steep slopes with evident erosion and shallow soils, which determine its land capability mostly in class VII (i.e., inadequate soils for arable culture or permanent pasture; [30], dominate the landscape of the study area. At present, common land uses are forests, pastures, coffee, and temporary crops [31, 27].

These conditions reveal that the UBC currently presents an overuse of its lands [32, 27], which favors erosion, gravitational movements, ecological impacts through fragmentation, and deforestation due to the increase of croplands. Rivas district in Pérez Zeledón has approximately 7000 inhabitants [33]. More than half of its population is rural and mainly works in the primary sector (e.g., agriculture, cattle raising). Moreover, this district has a mean social development comparable with the national average (52.7 out of 100; [34]).

2.2. Geomorphological mapping, coffee land cover, and their interactions 124

We mapped the landforms of the study area in three stages: the pre-mapping, the fieldwork, and the post-mapping [35]. We built a morphogenetic cartography created upon aerial photo interpretation at 1:25,000 scale [36]. Then, we georeferenced the aerial photographs and aimed to achieve the geomorphological mapping [37]. The method helped map the genesis, dynamics, morphology, evolution, and age of the different landforms and their processes using manual and digital graphic techniques to perform the final cartographic product [38].

We carried out the fieldwork throughout four campaigns made between 2016 and 2017 to check or precise the diverse landform dynamics and bounds employing the preliminary morphogenetic map at 1:25,000 scale. Through the final phase of post-mapping, we created the legend for the geomorphological map of the UBC, classifying the landforms genetically into exogenic features and structures (i.e., gravitational and fluvial). These landforms have exogenic features that are mainly erosional [39]. All the maps were made using ArcGIS 10.5.

139
140 We used official coffee land coverage and digitalization to identify the historical de-
141 velopment of coffee areas in the study area. The National Forestry Financing Fund and
142 Environmental Ministry of Costa Rica, based on the CARTA aerial photos of 2005 scale
143 1:25,000 [40] was the base for 2005's coverage. For 2012, we obtained the coffee land cov-
144 erage from the Costa Rican Coffee Institute [41]. Finally, we digitalized the coffee land
145 coverage for 2018 using Google Earth and Sentinel images. We determined the match be-
146 tween coffee areas and landforms to identify growth patterns over the 13 years of study.
147 Moreover, we calculated the altitudes and slopes of the UBC using a 10-m Digital Eleva-
148 tion Model (DEM). In addition, we created a mesh with a cell size of 50 × 50 m covering
149 coffee areas for every studied year (i.e., 2005, 2012, and 2018). After that, we estimated
150 each polygon's slope, altitude, and aspect with a centroid to determine growth tendencies
151 using ArcGIS 10.5 and R Software.

2.3. Production conditions and the implication for the growth of coffee areas 152

153 To understand the production chain conditions behind the increase of high-quality coffee
154 areas in Costa Rica, we performed a multi-scale assessment in the UBC as a study case.
155 First, we reviewed secondary information related to coffee production, specifically of the
156 Pérez Zeledón's municipality at the Brunca coffee region, to characterize the regional level
157 of the production chain [2]. Second, we visited the UBC for the local level to carry out field
158 verification of areas cultivated with coffee and processing plants. Furthermore, we inter-
159 viewed producers to learn about the characteristics of high-quality coffee production in
160 the study area. Finally, we used GPS and processed the information with ArcGIS 10.5.

3. Results 161

3.1. Landforms and processes 162

163 The first group of landforms found were the fluvial ones (Fig. 1). Erosional fluvial
164 landforms (i.e., valley slopes: <20 m deep valleys, >20 m deep valleys) result from the riv-
165 ers' dynamics. The valleys are linked to other fluvial morphologies such as scarps, ravines,
166 and gullies. Depositional fluvial morphologies concentrate only in the floodplains, which
167 occupy the valley bottoms.

168 Gravitational landforms are the second group of landforms found, which present
169 both geneses, erosional and depositional (Fig. 1). The erosional gravitational landforms
170 constitute the volcanic slopes molded by mass movements, rotational landslide ruptures,
171 and translational landslides. In contrast, the depositional gravitational landforms include
172 talus, rotational landslides, and volcanic slopes molded by mass movements. These mor-
173 phologies are located in slopes over 15° and in poorly consolidated material with dense
174 fracturing, which can be triggered by earthquakes and extraordinary precipitation.

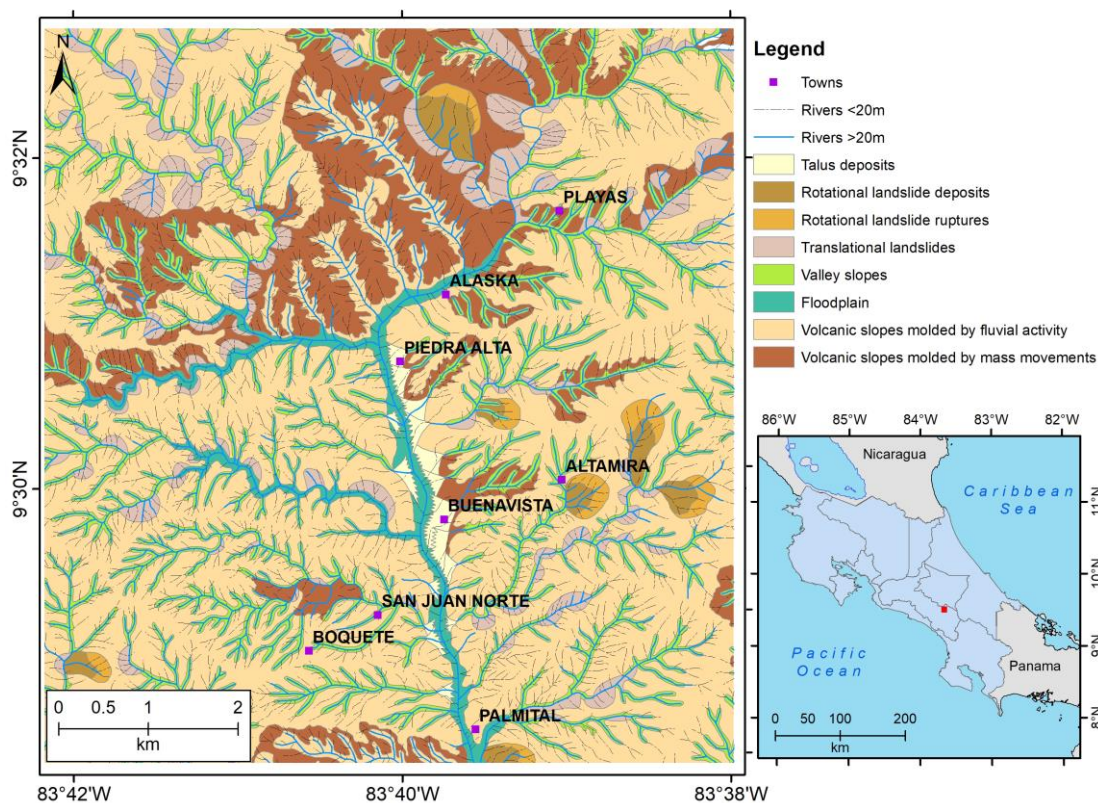


Fig. 1. Geomorphological map and location of the Upper Buenavista Catchment.

3.2. Interactions between landforms and coffee areas growth

High-altitude coffee croplands have been increasing since 2005 in the UBC. The cultivated area increased from 163.3 ha in 2005 to 235.4 ha in 2012 and 365.2 ha in 2018 (Pearson correlation, $R^2 = 0.98$, $p = 0.13$). Spatially, coffee lands grew oriented to the north towards the Cordillera de Talamanca, along the slopes of the UBC (Fig. 2). These newly cultivated lands grew in landforms. Normally, over the 13 years of analysis, coffee grew on volcanic and landslide slopes shaped by fluvial activity as well as in valley slopes, in proportion, respectively (Table 1).

Volcanic slopes shaped by fluvial processes present large and deep weathered soils that support a well-developed vegetal cover and contribute to fix eluvial debris on very sloping surfaces of sub horizontal and convex morphology. Moreover, landslide slopes shaped by fluvial dynamics usually present a high density of translational or rotational landslides that do not permit individualizing each failure. The structural control and intense rainfall normally control their formation and dynamics. Finally, valley slopes are narrow and elongated depressions that are controlled by channel erosion and local tectonics with V-shaped morphologies. Nonetheless, other landforms have constantly reported small increments in area during this period, such as the floodplain, talus deposits, and active landslides.

Coffee croplands increased mostly on landslide slopes (347.28 %) and volcanic slopes (154.36 %) molded by fluvial activity. Because of their dynamics, landslide slopes naturally have less dense vegetation and facilitate the cropping processes while volcanic slopes are very close to the limit of reported andisols, so they possess higher soil fertility levels. Other minor areal landforms conditioning coffee growth were the floodplain, active landslides (even with an acute decrease), and talus deposits. There is a clear trend of increasing coffee cropland, with both slope and altitude, during 2012 and especially in 2018 (Fig. 3).

Considering the 50 x 50 m coffee cropland analysis from 2005 to 2018, the cultivated areas in 2012 were growing in hillsides higher than 1400 m asl and 20° slope while, for 2018, coffee areas even surpass 1800 m asl and 40° inclination slopes. There is a statistical growth in both the slope and altitude (Pearson correlation, $R^2 = 0.37$, $p < 0.05$) over the 13 years of analysis. Slope aspect did not show a significant pattern, but it had higher values oriented to the West (16.5%), South (16.1%), SW (15.2%), SE (14.6%), and East (13.7%). Generally, slopes have a general southern orientation, West or East according to the side of the UBC valley disposition.

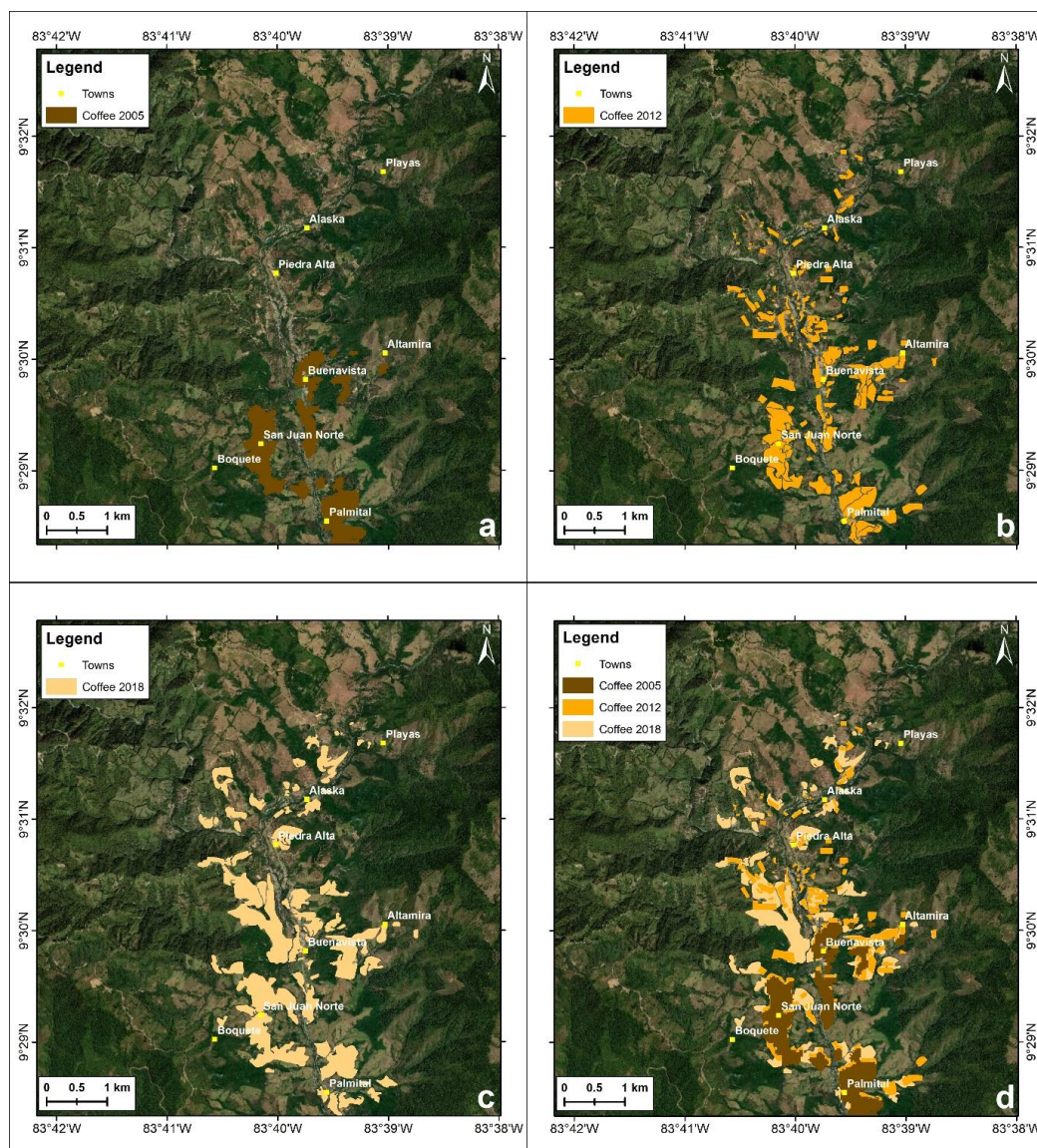


Fig. 2. Coffee areas' growth in 2005 (a), 2012 (b), 2018 (c), and combined (d).

Table 1. Historical growth of high-altitude coffee areas in hectares according to their landforms.

Name	2005	2012	2018
Floodplain	14.21	12.05	20.91
Landslides slopes	10.52	19.15	47.05
Rotational deposits	8.50	2.68	0.00
Rotational ruptures	2.85	0.95	0.00
Talus	14.16	15.32	14.33
Translational landslides	0.00	4.09	3.86
Valley slopes	18.05	27.96	32.66
Volcanic slopes	96.91	153.20	246.50
Total	165.20	235.41	365.30

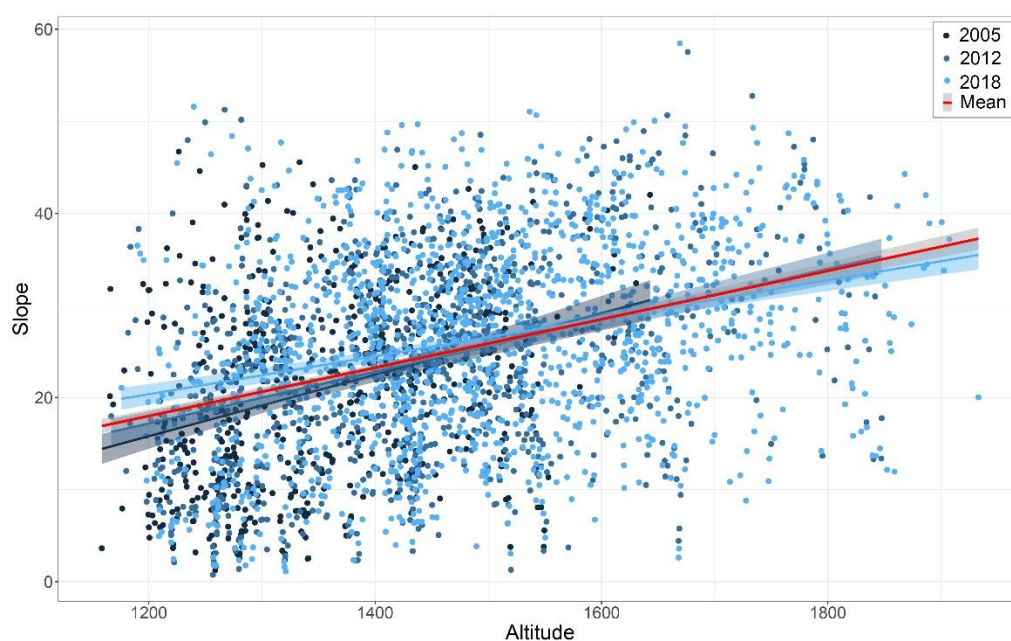


Fig. 3. Relation between slope (degrees) and altitude (m asl) depending on the coffee areas and year ($R^2=0.37$).

3.3. Interactions in the coffee production chain for high-altitude coffee growth

By the year 2019, 93,697 ha were cultivated with coffee in Costa Rica, representing a decrease of 18% compared to 2005. In addition, we also found fewer coffee producers in the same period (-25%; Figure 4). Nonetheless, the number of firms that process raw coffee has increased steadily in the same period by 129% as well as the exporting and local roasting firms, but they have grown at a slower pace (54% and 23%, respectively).

Among the number of processing firms, the micro-processing plants (i.e., plants that process less than 1000 bushels) are the only group with a constant increase (from 17 to 152). The medium-scale (i.e., plants that process between 1000 and 70,000 bushels) and

large-scale processing firms (i.e., process more than 70,000 bushels) remain somehow stable (88 ± 3 and 6 ± 2 firms, respectively). The industry dynamics and the finding that, on average, 80% of the coffee production in the country is destined to the international market indicate that the coffee sector in Costa Rica is evolving towards a specialized coffee strategy. That evolution implies innovation in the production process linked to commerce in specialized markets.

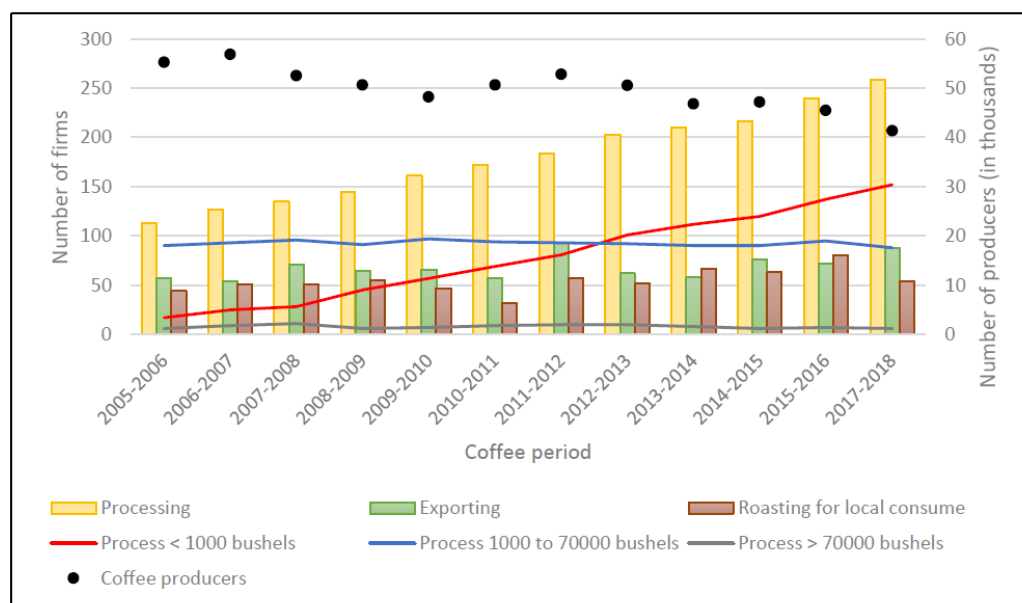


Fig. 4. Historical development of the coffee sector structure in Costa Rica from 2005 to 2018. The number of firms that process coffee (orange bar), export coffee (green bar), and roast coffee for the local market is represented on the left axis. The coffee processing firms are separated by their volume capacity (i.e., less than 1000 bushels in the red line, between 1000 and 70,000 bushels in the blue line, and more than 70,000 bushels in the gray line). The total number of coffee producers is represented as black points.

In the UBC, 13 different micro-processing plants have been established since 2003. The "Café Rivense del Chirripó" was the first plant settled in 2003 to process its coffee and the coffee of some neighboring farms. Later on, other producers became independent and established their micro-processing plants; some were established very recently, ranging from 2015 to 2018.

The owners of micro-processing plants are groups of small families that distribute the tasks of the productive process (i.e., planting, coffee processing, and commercializing) among the family members (four members per family on average). In addition to these permanent job positions for family members, there are temporary jobs to maintain the coffee lots and reap the fruits generated during the year. The volume of fruit manually harvested determines the payment to the temporary workers during the harvest season.

Unlike conventional coffee, micro-processing plants offer an attractive monetary incentive to the harvesters of high-quality coffee, who earn in situ USD ~ 2 instead of USD ~ 1 by cajuela (the volumetric unit of coffee in Costa Rica, it is equivalent to 0.02 m³). As a result, in the coffee period of 2018-2019 only, the price of high-quality coffee was 25% higher than traditional coffee on the international market. Given the low prices of traditional coffee in previous years, the highest price of high-quality coffee encourages the expansion of new high-quality coffee croplands in the UBC.

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We also discovered that differentiated and high-quality coffee production in the UBC involves new management strategies for the entire production chain (Table 2). First, the complete coffee area is divided into micro-lots, which are small patches (e.g., patches between 0.1 ha and 1 ha) with a high density of coffee plants that allow for differentiated management of the production process. The objective of the micro-lots is to maximize the relationship between the management of specific coffee varieties (e.g., planting, pruning, thinning, and harvesting) and specific environmental factors to each micro-lot. This optimization allows farmers to adapt the production to changes in the market and weather or pests' impacts. Second, the micro-processing of the coffee in which, through product traceability, the producer can be innovative in the coffee processing according to the local quality characteristics of the coffee-related to each micro-lot. Finally, in the marketing of high-quality coffee, producers can adjust their production according to a learning process about the consumer market. The differentiation of this chain of production-processing-market is based on coffee quality, and it has been incorporating producers into this new way of producing.

The micro-processing strategy is suitable for the sustainable management of the coffee plantation of smallholder producers. We observed that coffee was planted on hillsides in rows managed at level, which allows for water retention and thus provokes less erosion. Also, it promotes the use of fruit trees and other crops to provide shade to the coffee, which means additional income for the families. In addition, it reduces/decreases the use of pesticides and promotes the recycling of residues of the activity like the coffee brose that is transformed into organic fertilizer. Moreover, the producer learns to produce high-quality coffee through the traceability processes necessary. The technological innovation in the production unit is fundamental to producing high-quality coffee, improving the yield and the use of resources, and at the same time, establishing alternative technologies that allow independence from traditional technologies. In the UBC, the support of national authorities (e.g., ICAFE) was suggested as a primary factor for producers to be motivated to deepen the knowledge of the coffee activity.

4. Discussion

4.1. Local and management factors related to increasing high-altitude coffee zones

Our historical study identified a 124% increase of coffee croplands in the UBC in southern Costa Rica, mostly towards upper and steeper soils along volcanic, landslide, and valley slopes. Historically, coffee from Pérez Zeledón has not been related to high quality due to its elevation. In addition, the production of coffee was primarily located in Ultisols, which has chemical limitations affecting cultivation due to the high acidity and deficiencies of Ca and Mg [42]. Soils of the newly cultivated coffee areas are in the boundary of the reported Miocene-origin Andisols of the Cordillera de Talamanca and Ultisols from General Valley [43]. This preference happens due to the high porosity, low density, and high fertility of Andisols [44].

The increase in altitude has also been related to improving the quality production. Previous studies in Costa Rica have pointed out similar results where the quality of coffee depends on altitude and slope exposure. For example, Orosi's coffee is categorized by a floral flavor and is conditioned by its slope exposure, while Santa Maria de Dota's coffee presents a stronger chocolate taste at high altitudes [45].

Land-use intensification can affect the provisioning of ecosystem services (such as pollination), driving modifications in ecosystem functions and biodiversity loss that compromise human wellbeing [46]. The UBC has a VII class that hosts only forest protection [30]. In addition, erosion of soils is projected to increase under future climate change [47].

Future climatic scenarios predict higher temperatures, droughts in the north, and more intense precipitation in the south of Central America [48]. Significant losses in coffee aptness areas are probable for the region due to its sensitiveness to extreme weather events [49]. Higher temperatures boost the ripening of coffee berries, giving a poorer cup quality. Furthermore, high-value Arabica coffee requires lower temperatures than the less valuable Robusta coffee. Changes in temperature and precipitation are projected to affect the suitable area for coffee plantations and eventually move production up the altitudinal gradient to cooler climates [50] as we found in the UBC in the last two decades. Moreover, the coffee production cycle relies on rainfall patterns [51].

Table 2. Strategies and new forms of coffee production organization found in the UBC.

Differentiated cultivation through microlots	Process of benefitting through micro-benefits	Marketing of high quality coffee
Planting different varieties	The producer changes from a coffee supplier to a processor	The producer relates to the buyer
Different harvesting periods	Employs multiple methods of coffee processing	The producer knows about the characteristics of the coffee he is processing and for whom he is processing
Collects, stores and processes separately	Innovates in fruit processing with various processing methods	The producer takes the necessary actions to improve it until the desired quality is achieved
Maximum use of environmental conditions: altitude, soil, humidity, solar radiation, position with respect to the winds, cloudiness, etc	The beneficiary rescues the origin of the coffee; the local area and the producer	The producer is trying out new ways to process the coffee depending on the buyer's preferences
	The producer learns from tasting, becomes the producer's ally to improve quality.	

Diversifying management strategies to produce high-quality coffee can positively affect the production chain. In other important coffee regions of Costa Rica, like Los Santos, coffee productivity and quality were also associated with local and management factors [52]. Local factors include the rate of lime routine, soil exchangeable calcium and soil acidity concentration, clay contents of soils, and elevation of the terrain. Management factors include the amount of fungicide used, the average quantity of stems per plant, and the

mean number of pruned stems per plant. Furthermore, in other coffee regions of the country and worldwide, local and management factors were identified as keystone for the coffee production as well provision of multiple ecosystem services [53, 54].

Crop pests and pathogens tend to move poleward (and probably higher in altitude) in a warming world [55, 56]. The occurrence of pests and diseases can also be transformed by variations in the seasonal patterns of rainfall [57]. Different pests such as the American leaf spot [58], coffee rust [57], coffee berry borer [59], or coffee root-knot nematodes [60] commonly affect coffee production yields. To that effect, the inclusion of trees as a shade cover for the coffee may attract natural pest control services on coffee plantations (e.g., [61, 62]. Nearby non-crop habitats, like forest patches, may improve pest control but not consistently [63]. Moreover, to reduce the effects of diseases and their consequent economic losses around coffee production, management measures based on plant diversity, percentage of shade cover, and soil fertility can be explored (e.g., [64]. For instance, producers need to manage the tradeoff between conservation and production objectives carefully.

5.2. Production-processing-market chain related to coffee croplands growth

Coffee production is susceptible to the international market, especially during coffee price crises. Between 2005 and 2018, coffee production had increased worldwide (42% \pm 7%), mainly by country producers Brazil, Vietnam, and Colombia [65]. Although the coffee consumption shows an increase in the same period (34% \pm 1%), producing an oversupply of the product led to a drop in the coffee prices [66]. From 1990 to 2016, the global coffee consumption in thousands of 60-kg bags and per capita (kg) has increased exponentially [67].

In Central America, market unpredictability, the blowout of coffee pests and diseases, extraordinary weather events, and undefined support of government initiatives provoke increasing vulnerability for the coffee sector [68]. During and after the coffee crisis (i.e., 2003), the necessity of coffee-producing countries to concentrate on quality, opportunities in niche markets, and diversification has been emphasized. International development agencies, such as the World Bank, USAID, and the International Development Bank, recommend it especially for coffee in areas where natural conditions do not sustain high-quality coffee production [69, 70].

Costa Rica's coffee sector has demonstrated its sensitivity by reorganizing its production chain, emphasizing specialized production by micro-processing coffee plants [2]. This highlights the new production structure, which entails a reconceptualization and valorization of the territory, emphasizing the origin, integration with the environment, production and handmade elaboration, aromatic distinctions, and exclusive flavors [10].

For many smallholder producers, modernizing the production-processing chain poses challenges related to the management of agricultural units and access to technical support and credit. The producers have access to resources at the institutional and local levels to tackle those challenges. At the institutional level, ICAFE established differentiated liquidations, which determined a higher price for the high-quality coffee than the conventional one. In addition, the action has supported and encouraged the production, processing, registration, verification, control, and follow-up of the commercialization process of the grain with differentiated characteristics.

At the local level, coffee cooperatives can support smallholder producers to comply with international requirements of high-quality coffee markets by gaining technical information and assistance (e.g., coffee certifications; [71]). Accordingly, increasing the local

knowledge may promote appropriate assessments and improvements of the coffee sector (i.e., adaptive capacity to overcome environmental or market shocks) [72, 14].

Adequate land-use decisions are vital for scheming strategies to improve the production chain of high-quality coffee. Castro et al. [73] indicate that the growth and application of different technologies may reduce environmental impacts of agroforestry systems, like coffee, and reduce monetary costs to the farmer, consequently affording a market-based incentive for conservation. They also suggest that considering the farmers' time preferences is necessary to understand their decisions.

Conventionally intensive agriculture is favored when producers place little value on the future, even if land degradation and environmental contamination are related [74]. Agroforestry systems may return considerable profits in the long term, but they also acquire high establishment and maintenance costs and generate net losses in the first few years [75]. In that sense, initial financial incentives (e.g., payment for ecosystem services provision) may compensate for these losses. Tools that support land use planning (i.e., geomorphologic mapping) can promote agroforestry adoption in coffee regions as a measure to reduce impacts on the environment.

We found that UBC producers principally use fruit trees as shade for the coffee. We recommend incorporating harvestable trees apart from coffee to increase the profits. In coffee agroforestry systems in Nicaragua and Honduras, de Sousa et al. [76] found that smallholder wood production is profitable in parallel with coffee plantations. The net value from timber sales signifies 11–49 % of the total profits from agroforestry systems. Nevertheless, this quantity might be 58 % higher if farmers could improve administration practices. Under different management intensities in agroforestry systems, coffee production can increase according to specific environmental and socioeconomic conditions [77]. This diversification in management may also benefit the delivery of ecosystem services such as erosion control, warming, and pest control. In the south of Costa Rica, profitable species like *Cedrela odorata* L. are commonly used as shade in agroforestry systems of coffee, and they show likely volumetric growth [78].

Training and self-learning is constant task to produce high-quality coffee, which becomes a challenge and an incentive for producers. In this study, we found that physical geography is linked to the coffee production-processing-market chain in the coffee region of Pérez Zeledón. However, more comparative areas need to be deeply investigated to understand better why and how the coffee sector is changing in Costa Rica. For instance, we suggest that studies similar to ours should be developed in other regions of Costa Rica and other coffee-producing countries. That will help to gain knowledge about the new market of high-quality coffee and its implications to geomorphology, land use, management, and planning.

5. Conclusions

Despite the limited research throughout the tropics regarding the interactions between landforms, socioeconomic drivers, and high-altitude coffee yield we provided an applied geography study case of the interactions of geomorphic characteristics and production-processing-market chain of high altitude/quality coffee in Costa Rica with the Pérez Zeledón region as an analysis example. From 2005 to 2018, coffee croplands in the Upper Buenavista Catchment (UBC) in southern Costa Rica have increased by 124%. Moreover, new coffee areas are in altitudes over even 1800 m asl and slopes above 40°, on south-facing, volcanic, landslides, and valley slopes. The combination of geomorphological maps and land use assessments proved helpful to understand the environmental factors related to coffee land-use changes in mountain regions such as local soil and climate. We recommend considering geomorphic mapping for future coffee entrepreneurships to

ensure croplands stability, better locations, reduce erosion, and coupled with soil analysis, superior production yields. Our analysis did not consider key factors such as fertilization, cultivation techniques, harvest season, and ripening stage at harvest. These variables must be considered in future studies involving high-quality coffee and geomorphology.

Differentiated liquidations and varieties that are more profitable have allowed the producers to place their coffee directly in the international market, receiving higher income. This modality also permitted the creation and identification of micro-lots, differentiated delivery of coffee, and commercialization with flexible and agile mechanisms that will be an incentive for small, new producers to join the production of differentiated coffee in the future. Coffee producers have changed their role in the Costa Rican coffee sector, which signifies new opportunities and challenges for smallholder coffee producers' socio-economic development. Moreover, smallholder coffee producers can increase their profits by diversifying activities.

Our expected results presented several limitations. First, there is no complete soil baseline information to accomplish a detailed assessment of growing coffee croplands over the years related to their landforms. Second, we had limited access to local producers' data from 2005 to 2018. Hence, we had to use ICAFE general information to analyze production chain of high-quality coffee. These limitations should be considered in future assessments integrating coffee and its producing chains in the future.

Environmental implications such as erosion, ecological impacts, and forest fragmentation should be surveyed soon to understand the effects of high-quality coffee growth in higher altitudes by the academia and public institutions focused on agriculture. The potential use of geomorphic assessments coupled with agriculture production-processing-market chains can be key for future landscape management plans for agricultural frontiers expanding processes to achieve sustainable development based on the local ecosystem's functioning and cultural background.

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