Anthropogenic Geomorphology of Costa Rica

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Abstract

Anthropogenic geomorphology examines the impact of human activities on the physical landscape. This chapter focuses on the ways in which different human actions have shaped the terrain in the country, creating landforms and modifying the pace of external geodynamic process since Pre-Columbian time (≥ 4.5 ka ago). Developing countries, including Costa Rica, face the challenge of balancing economic growth and sustainable development while addressing the impacts of anthropogenic geomorphology. Human activities such as urbanization, deforestation, and resource extraction, road building, and large-scale agriculture and tourism can cause alterations to the natural landscape and lead to soil erosion, changes in hydrologic regimes, and loss of biodiversity. Costa Rica has implemented policies to protect its natural resources and promote sustainable development, such as reforestation and low-impact tourism activities. The principal landscapes generated by anthropogenic geomorphology in Costa Rica could be classified in three classes determined by their geomorphic expression in (i) excavated, (ii) leveled, and (iii) artificial landforms. Thus, anthropogenic geomorphology is a critical issue for developing countries like Costa Rica, and effective management strategies are necessary to balance economic growth and environmental protection.

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Keywords

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12.1 Introduction

Anthropogenic geomorphology could be defined as the study of the role of humans in creating landforms (human-made landforms) and modifying the operation of geomorphological processes such as weathering, erosion, transport, and deposition. In addition, it predicts the consequences of disruptions to natural equilibria and proposes ways to prevent harmful impacts (Sherlock 1922; Szabó 2010; Goudie 2010).

In Costa Rica and globally, human activities are equally significant as other geomorphic factors in shaping the landscape. This is due to the rapid population growth and increased demand for land, natural resources, and energy, leading to widespread modifications of the environment (Hall 1984; Santillana 2008; Vargas 2014). Geologists, geomorphologists, geographers, civil engineers, biologists, and archeologists have recognized anthropogenic alterations of landforms in Costa Rica and deep-time human environmental impacts, which have occurred in Pre-Columbian time, particularly after the last glaciation (Cooke 2005; Piperno 2011), but extensively since the second half of the twentieth century (Flores 2001; Vargas 2014).

Literature review of the anthropogenic geomorphology of Costa Rica can enhance the knowledge of what happened between the Pre-Columbian, through colonial, to the present eras. The subject of this chapter is therefore, for the first time in the Costa Rican geomorphic literature, to provide description of a large and ever-widening range of surface artificial landforms, extremely diverse in origin and in purpose, created by the operation of human society.

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12.2 Brief History in Costa Rica

Slight and early anthropic landform modifications in the contemporary Costa Rican territory could have started as the first human arrive during the Paleoindian Period (~15 ka b.P.) and/or early Holocene (11.7–8.2 ka b.P.), but there is no direct evidence in Costa Rica, even though food production might had taken place propitiated by selective clearing and plant selection since the early part of the Holocene in tropical environments (Cooke, 2005; Piperno 2011). Studies on microfossils, such as pollen, phytoliths, and starch grains, indicate adaptative processes in neotropical areas of the Americas driven by food production and plant domestication along the Archaic Period (10–4 ka b.P.). A wide variety of cultigens made its way to the southern part of Central America in that period, including corn and manioc. Based on documented findings in Panamanian territory between 8.6 and 5.7 ka b.P. (Piperno 2011), the presence of cultigen can be expected for Costa Rica. In fact, early maize agriculture in Costa Rica came back at 5.5 ka b.P. (Arford and Horn, 2004).

It is likely that raise in number, size, and time of permanence in occupation sites happened during the Archaic Period. However, available data for Costa Rica have archeologist to suggest more sedentary lifestyle starting at about 4.5–4.0 ka b.P. (Hoopes 1994; Hurtado de Mendoza 2004), and intentional forest fires at least since 3 ka b.P. (Clement and Horn 2001). Those data show a tangible increase in the quantity of sites and cultural remains in the time interval 300 b.P.–300 A.D., as a reflection of population growth. Pre-Columbian villages with stone constructions, marked walking trails, causeways, and hydrologic works have been documented for later periods, from 1500 to 800 years in the past (Snarskis 1981; Sheets and McKee 1994; Hurtado de Mendoza 2004; Fernández and Alvarado 2006; Peytrequín and Aguilar 2007; Benfer 2012; Corrales 2016; Vázquez and Rosenswig 2017; Solís et al. 2019; Núñez 2020; Hurtado de Mendoza and Alvarado 2021; Salgado et al. 2021; Vázquez et al. 2022).

Few Pre-Columbian interregional routes of human movement, definable by marks of pedestrian use or constructed features, have been identified in Costa Rica (Vázquez et al. 2003, 2021). Long indigenous routes interconnecting territories count with one report only, which was deduced by ethnohistorical correlation and in large part articulated to waterways (Cavallini 2011; Salgado et al. 2016). It has been hypothesized that indigenous roads were taken advantage of in Colonial times, intervened for circulation of carts and afterwords for transportation with motor vehicles (Vázquez 2014). Pathways leading to modern-day indigenous communities, particularly in regions of Talamanca (Fig. 12.1), could be related to long-lasting communication roads, used in Pre-Columbian times and with linkage to archeological sites but, to this regard, only very preliminary information is known (Vázquez, personal communication 2023).

The earliest formalized communication so far identified in Costa Rica belongs to societies on the Arenal-Tilarán area (Fig. 12.1), in the form of narrow pathways used in the bracket A.D. 500–1300 (McKee et al. 1994; Sheets and Sever 2007). Radiocarbon dating of the trails along that extended archeological trajectory was agency by stratified tephra from the Arenal volcano intercalated with paleosols. Pathways became eroded when people walked single line, in processional mode passing through villages, cemeteries, and water springs. This prehistorical behavior attests for the resilience of human communities to vulcanism, reoccupying its territory and having handy a mobilization strategy as a response to natural disasters (Sheets 2012). Investigators of the Arenal-Tilarán's archeology have proposed interactions and exchanges through the network of trails, not only within an intraregional sphere but further away with the northeastern Caribbean lowlands, the northwest territory of Guanacaste-Nicoya, and the central highlands of Costa Rica (Sheets and Sever 2007; Benfer 2012). The erosion by repetitive use resulted in paths entrenched 2 m or deeper. The cultural standard developed over centuries was that the preferred way of entering a special place was by an entrenched path. Thus, people approaching a special place would have a restricted view of their surroundings. Upon entering a site, the view would dramatically open. Through cognitive experiences like that, people created and perpetuated social memory across their landscapes after generations of processional use (Sheets 2008, 2011).

Also, beach dikes on the coast of Guanacaste (Culebra Bay) and Quepos made by Pre-Columbian inhabitants with local stones indicate that they functioned mainly as traps forming ponds for fish, crustaceans, turtles, and mollusks (Figs. 12.1 and 12.2d). In the case of Culebra Bay, the erection of these traps dates between 800 and 1350 AD (Vázquez et al. 2019).

As indicated by archeological survey, differentiated rank societies never developed in the Arenal-Tilarán area (Sheets and Sever 2007). Also, few architectural examples attributable to chiefdoms are recorded for Guanacaste-Nicoya (Creamer and Hass 1985; Lange 1992; Vázquez 2023). By contrast, a series of chiefdoms did develop in other territories of the current Costa Rica, interpreted upon remains of architectural villages and differentiation of salient features. These indicators can be traced back to about A.D. 600 (Vázquez et al. 2003; Corrales 2016; Solís et al. 2019; Salgado et al. 2021). Demonstrative infrastructure of residential centers has been identified in diverse geographic setting, among them: the slope of a volcano, foothills, alluvial

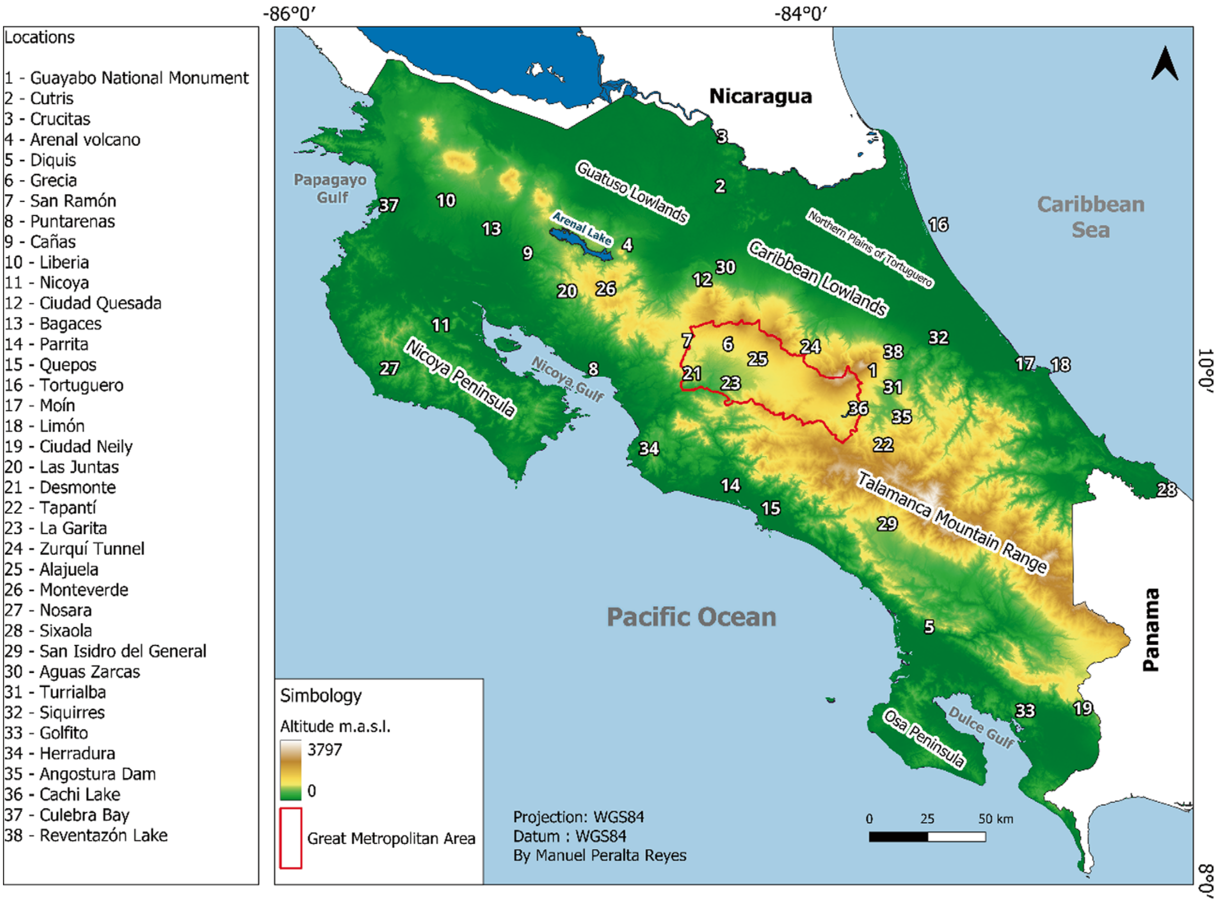


Fig. 12.1 Main locations of Costa Rica studied in this chapter

plains, intermontane valleys, and mountain ranges. The basal architectural structures of such centers were built mostly out of cobble rocks with earthen fills (Hurtado de Mendoza 2004; Hurtado de Mendoza and Alvarado 2021).

It is important to point out that, starting at around 500–300 B.C., considerable energy expenditure was dedicated by Pre-Columbian peoples of Costa Rica to funerary architecture. Archeology has shown that since those centuries, house construction demanded use of copious quantities of forest materials, together with clever skills and even the employment of cobble rocks. In addition, building of graves entailed elaborated standards in, for example, shaft-and-chamber tombs and corridors for aligning interments. Time progressed with the advent of carefully layout stone covers, which incorporated volcanic and sedimentary slabs, as well as rock mounts or tumuli. At the northwestern territory, in the Cañas-Liberia and other region, dozens of huge concentrations of rocks for protecting burial have been recorded by archeological research (Guerrero and Solís 1997; Fernández and Alvarado, 2006).

In Costa Rica, Pre-Columbian villages with monumental architecture and attributes of ceremonial centers are known. Architectural cores in these sites are from small settlement to villages, mostly from 1 to 10 ha. Some sites that come to the point are distributed in the Central Caribbean Watershed, among them: Guayabo (Aguilar 1972; Fonseca 1996; Hurtado de Mendoza 2004; Alarcón 2019), Las Mercedes (Vázquez and Chapdelaine 2008; Vázquez and Rosenswig 2017), Anita Grande (Vázquez et al. 2022), and Nuevo Corinto (Salgado et al. 2021). As an example, the Guayabo archeological site, designated National Monument in1973, shows foundations of dwellings in conjunction with spaces for social interaction, as well as the arrival, and assembly of visitors (Figs. 12.1 and 12.2). These characteristics suggest ceremonial activities linked to the residence at the village of a regional sociopolitical leader (Fonseca 1996; Hurtado de Mendoza 2004). A built road interconnects additional architectural sites, with Guayabo as a hob within a regional system of salient settlements (Acuña 1987; Vázquez et al. 2021). The cusp of construction works is dated at AD 900–1200 upon radiocarbon determinations obtained in the main site (Alarcón 2019). Guayabo includes an aqueduct, a channelized creek, water collectors, and two causeways, among other features that in sum required tons of cobble rocks. It holds the designation of Civil Engineering World Heritage, awarded in 2009 by

Fig. 12.2 Guayabo National Monument. **a** Aerial view of the Turrialba volcano in the top of the image, **b** ceremonial monuments, **c** stony Pre-Columbian road (almost 7 m wide) and extending for at least 7 km, **d** fish trap in Papagayo, Guanacaste

the American Society of Civil Engineers (ASCE), a most prestigious institution (Fig. 12.2).

Another case to mention is the Cutris site, a monumental site hub of the largest network of Pre-Columbian villages known for the northeastern territory of Costa Rica (Fig. 12.1). Cutris is composed of over 70 stone architectural structures, most of them interpreted as elevated dwelling foundations. Four sunken roads constructed with side embankments from the artificial earth movements, some of them huge, radiate out of Cutris toward satellite sites at 6–9 km away. The occupational history of Cutris, from 1500 B.C. to A.D. 900, is similar in extended trajectory when compared to other monumental sites of the country. However, Cutris gave ceramic clues of a rise in high infrastructural proportion at A.D. 600–900 years, earlier to the analogical development in remarkable villages as Guayabo and Las Mercedes of the Central Caribbean (Vázquez et al. 2003). A similar panorama is interpreted for the southern territory of Costa Rica, where the early monumental complexity of Cutris together with its road infrastructure does not have documented correlates. That territory has rendered the stone spheres sculpted out of cobble rocks, usually taken from the riverbeds (Corrales 2016).

Also, beach dikes made by cobbles are consistent with pond traps for catching fish, crustaceans, turtles, and mollusks. These costal features have been documented in

Guanacaste, at Bahía Culebra, and the Central Pacific seashore in Quepos (Figs. 12.1 and 12.2d). The dikes were made by Pre-Columbian inhabitants with rocks readily available scoured from costal cliffs. They were placed in backwaters influenced by tidal flow with low energy of the surf. In the case of Culebra Bay, the erection of raps is dated to between 800 and 1350 A.D., in view of large seafood meadows absent in previous archeological phases of that region (Vázquez et al. 2019).

During the Colonial Period, the Spanish colonizers used these same patterns of movement for their own transportation and communication (Hurtado de Mendoza 2004; Benfer 2012; Salgado et al. 2016). As the Costa Rican population rose after the Conquest in the sixteenth century, but particularly after the Independence process (1821–1823), new lands and resources were exploited. In addition, new technologies were gradually adopted, which increased the impact of humans. At that time, the first landforms were produced by direct anthropogenic actions, associated with extensive farming (cultivation, grazing, and horticulture), human-made wildfire clearing, quarrying of volcanic and sedimentary rocks, building of several new roads, and gold mining. Moreover, in the twentieth and twenty-first centuries, hydrological interference (e.g., the building of dams, reservoirs, and channels), garbage deposition mountains, touristic complexes, including recreation lakes and gulf camps, and open mines were developed. On the marine littoral, for example, the construction of breakwaters, protection walls, and dikes were common (Hall 1984; Santillana 2008; Vargas 2014).

These landform modifications have produced indirect anthropogenic impact involving acceleration (or deceleration) of natural processes of erosion and sediment transport. One of the main environmental changes are land cover/use modification (e.g., cutting, bulldozing, burning, and grazing) that have accelerated rates of soil erosion in some regions and sedimentation in others. Moreover, other related processes include landslides triggered by human actions, the change of hydraulic regimes, and sediment concentration in rivers. These can affect the rate of erosion and sedimentation in the fluvial systems which, in turn, changes the dynamics of sand beaches and coral reefs.

12.3 Landforms and Processes

The effects of human activity on geomorphic processes, particularly those related to denudation/sedimentation, have been investigated at a global scale covering the past few centuries (Goudie 2020). There is evidence from different parts of the world showing that certain geomorphic processes are experiencing acceleration, especially since the mid-twentieth century (Goudie 2022). This suggests that a global geomorphic change is taking place, largely caused by anthropogenic landscape changes (Tarolli et al. 2019). Sedimentation has increased considerably in most regions and in all kinds of sedimentation environments (Moragoda and Cohen 2020). Although the link between denudation and sedimentation is not direct and unequivocal, it is safe to assume that if sedimentation rates increase in different regions during a given period, denudation must have increased too, even though their magnitudes could be different (Owens 2020). This augmentation, particularly marked from the second half of the last century onwards, appears to be determined mainly by land surface changes, in conjunction with climate change. Cendrero et al. (2022) suggested that the changes are clear because:

(a) There is evidence at a global scale of a growing response of geomorphic systems to socioeconomic drivers, such as Gross Domestic Product density, which is a good indicator of the human potential to cause such impacts.
(b) Land-use/cover changes enhance effects of climate change on global denudation/sedimentation and landslide/flood frequency and appear to be a stronger controlling factor.
(c) There is a global geomorphic change which is especially evident since the “great geomorphic acceleration” that began in the middle of the twentieth century and constitutes one of the characteristics of the proposed and informal most recent geologic time period, the Anthropocene.

The principal landscapes generated by anthropogenic geomorphology in Costa Rica could be classified, following Szabó (2010) and Castro et al. (2021), in three classes determined by their geomorphic expression: (i) excavated, (ii) leveled, and (iii) artificial landforms.

12.3.1 Excavation Landforms

Direct human-driven denudation (through activities involving excavation, transport, and accumulation of geologic materials) has increased worldwide by a factor of 30 between 1950 and 2015, representing a tenfold increase of per capita effect. Human-induced denudation, indirectly caused by alterations of the land surface, is currently at least ten times greater than denudation resulting from natural processes alone. Mass movement have also shown a clear intensification representing an important contribution to denudation, sediment generation, and landscape evolution (Cendrero et al. 2022). The frequency of hazardous events and disasters caused by intense rainstorm events has increased significantly in Costa Rica since the mid-twentieth century, often triggering more and frequent slope movements.

12.3.1.1 Quarries and Open-Pit Mines

The Bellavista gold mine has a quarry, mining lakes, and flumes. Most recently, there has been chaotic and illegal open-mining development in Crucitas (north of Costa Rica), which encourages manual extraction that is scattered and irregular (Ching 2014). The intensity of this mining produces several small holes, tunnels, and triggers deforestation, whose dimensions are relatively small, but with a strong environmental impact. The most evident landscape modifications are quarries of volcanic rocks (mainly lava and pyroclastic deposits) that are modified through excavations, blasting, and piling of waste material (Fig. 12.3). The result is a mosaic of excavated land represented by artificial cliffs, small lakes, terraces, and pits of sterile rocks, which increase the roughness of the terrain. There are also hundreds of quarries and open-pit mines in Costa Rica with legal authorization (Fig. 12.4).

12.3.1.2 Road Cuts

Anthropogenic slopes, such as cuttings and embankments for transportation and irrigation systems, can greatly impact regional slope–area relationships. These slopes often have a rectilinear shape and limited gradient range, particularly for embankments (26–32 °) (Tarolli et al. 2013; Brown et al. 2017). The first rural roads connecting villages and towns in the Valle Central were established in the sixteenth century. However, acceleration of international trade between 1844 and 1846 led to the construction of new roads for ox carts between Cartago, Valle Central, and the Puntarenas harbor. Additionally, secondary trails were established in coffee regions like Grecia and San Ramón. This road expansion continued through the end of the nineteenth century and early twentieth century, reaching places like Cañas, Liberia, Nicoya, and Quesada. The Interamerican road was built after World War II (Hall 1984; Flores 2001). Most roads in the country are concentrated in the Greater Metropolitan Area (GAM), but there are several critical highways that connect other regions, such as the Interamerican Highway stretching from Nicaragua to Panama, Route 32 connecting to the Caribbean coast, and Route 27 linking to the Central and South Pacific. Their building involved excavation of deep trenches into bedrock (Fig. 12.5).

Road cuts in Costa Rica are characterized by local but frequent slides (rock falls, rocks slides, and landslides) because of the recent volcanic and sedimentary geologic history, which also involved hydrothermal alteration weakening the rock, and the occurrence of thick soils which become unstable under heavy tropical conditions in the rainy season (May–December). The roads located on unstable slopes and in areas with high rainfall annual rates are commonly affected by mass movement processes (Fig. 12.6), as are old roads which are used by four-wheel drive vehicles, mules, ATVs, and motorcycles. There are also particular tracks used for four-wheel drive vehicles competitions, which also present a problem. Costa Rica is the number two in roads density in Central America (Fig. 12.7). The country is very well connected although it is divided by a mountain system that cross Costa Rica from NW to SE and hilly landscapes are more common than flatlands.

12.3.1.3 Artificial Channels

In the Caribbean lowlands near the homonymous coastline, artificial channels were constructed between the mouth of the Parismina River and Moín beach to connect the estuaries of five rivers: Pacuare, Madre de Dios, Matina, Vueltas, and Moín. These channels span a distance of 82 km, with a width of 1.5 km, and reach a length of 30 km from Tortuguero to Moín (Quesada-Román and Pérez-Briceño 2019). In the Northern Pacific region, near Cañas and Bagaces municipalities, there are about 255 km of artificial channels supplied by waters of Lake Arenal (Fig. 12.8a). In the Central Pacific, near the municipalities of Parrita

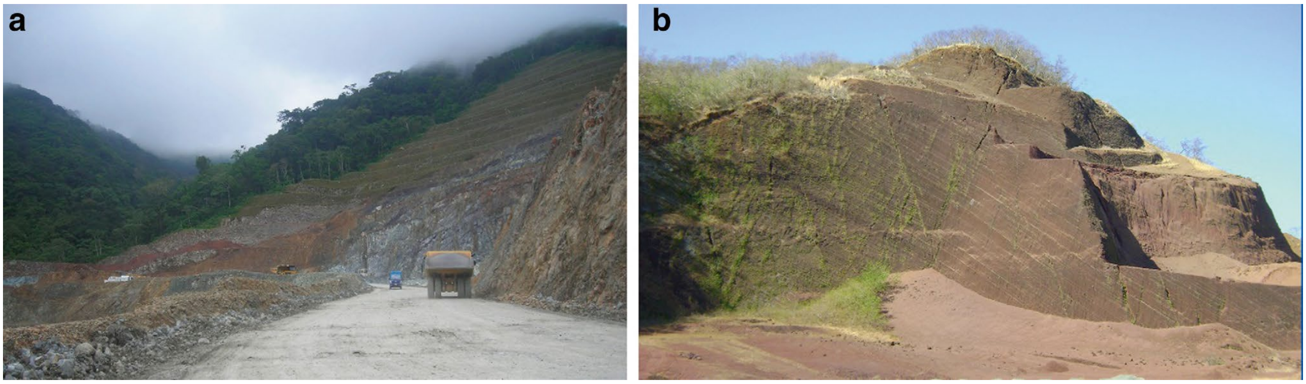


Fig. 12.3 Quarries and open-pit mines. **a** Miramar gold mine and **b** Cerro Chopo quarry in Cañas

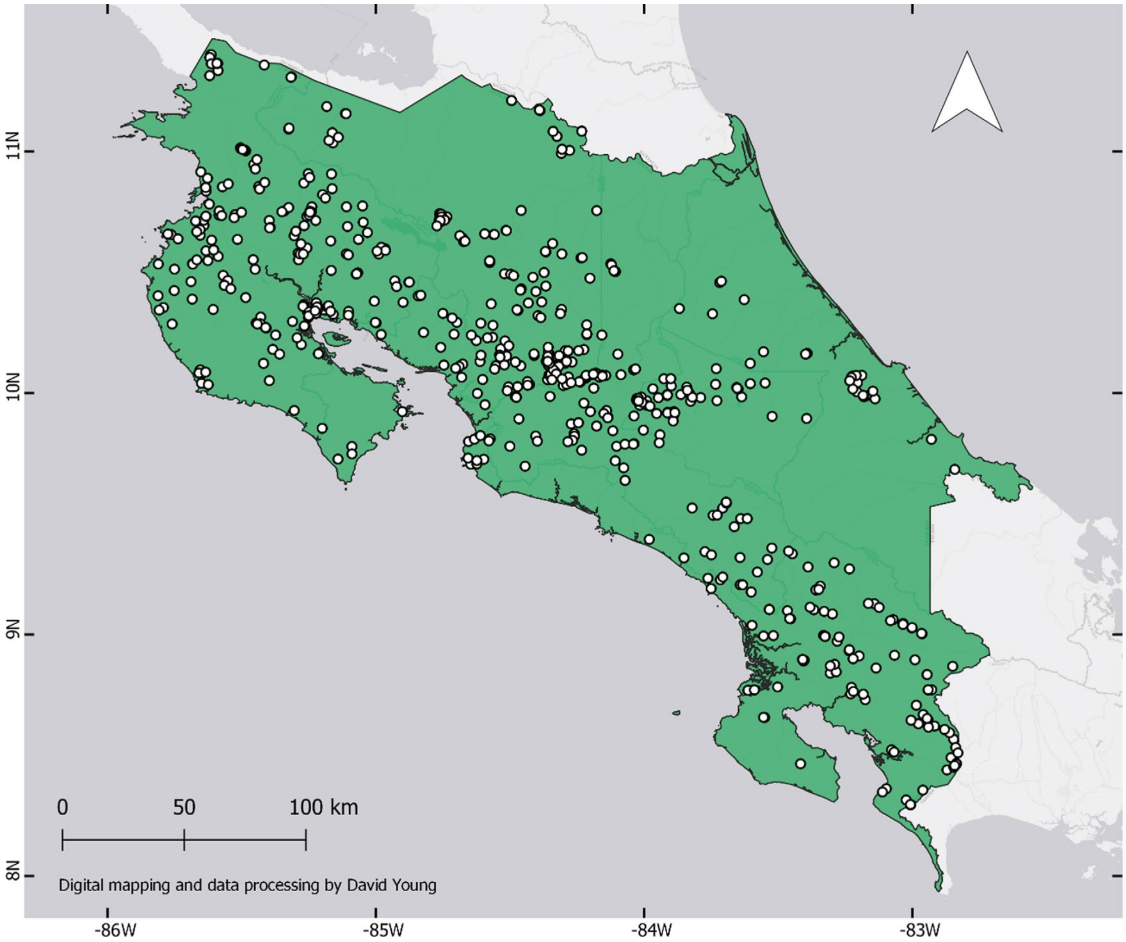


Fig. 12.4 Quarries and open-pit mines with legal authorization in Costa Rica. *Source* Dirección General de Geología y Minas. It is observed that in the Talamanca Mountain Range, Osa Peninsula, and the Northern Plains and Tortuguero, there are very few quarries and open-pit mines

and Quepos (Fig. 12.8b), the development of banana fields during the 1940s and following decades created extensive areas of lineal riverscapes (Royo 2004). In the municipality of Corredores in the Southern Pacific region, artificial channels have been built to modify the 380 km^2 of fluvial plains for the purpose of creating banana fields for the United Fruit Company (Zúñiga-Arias 2014). These modified riverscapes today are used mostly for rice, cattle, and oil palm croplands (Quesada-Román et al. 2023).

12.3.1.4 Recreational Excavated Lakes

Costa Rica is renowned for its stunning natural landscapes, which include many recreational small lakes that are perfect for various outdoor activities (Haberyan et al. 2003). These lakes boast magnificent views of their surroundings, making them ideal for picnics, fishing, kayaking, and swimming (Marcouiller and Prey 2005). Urban areas, like Parque de la Paz and La Sabana, also boast several such lakes. Recreational lakes offer numerous benefits to both local communities and visitors. These include water supply, economic development, environmental protection, outdoor recreation, scenic beauty, and flood control (Horn and Haberyan 2016). They provide vital resources for local communities, including irrigation, supply of drinking water, and hydroelectric power.

12.3.1.5 Treatment Ponds

Treatment ponds in Costa Rica are artificial water bodies used for wastewater treatment. The geomorphology of these ponds is largely influenced by the type of wastewater treatment process used, water chemistry, and the rate of sediment deposition (Vietz et al. 2016). For example, anaerobic ponds are shallower and tend to have a more complex bottom profile than aerobic ponds, which are deeper and have a more uniform bottom (Alfaro-Chinchilla et al. 2019). The environmental implications of treatment ponds can be both positive and negative. On the positive side, these ponds can improve water quality and help to prevent pollution of nearby rivers and lakes, thereby preserving the health of aquatic ecosystems. Additionally, they can serve as a source of irrigation water for agriculture, reducing the need for pumping water from rivers and other sources.

Fig. 12.5 Road cut in Route 27, km 47. Intense hydrothermal alteration and terracing to stabilize the slope are observed

However, treatment ponds can also have negative environmental impacts. For example, they can emit pollutants, such as nitrogen and phosphorus, which can contribute to eutrophication and the growth of toxic algae blooms (Gołdyn et al. 2015). They can also release pathogens and heavy metals, posing risks to human health and the environment. Furthermore, accumulation of sediment in these ponds can reduce the volume of water available for treatment, leading to the need for regular maintenance and cleaning. Therefore, it is crucial to implement effective management strategies for treatment ponds to minimize their negative impacts and maximize their positive impacts (Shilton 2006). This can include regular monitoring of water quality, proper maintenance and cleaning, and the use of appropriate treatment processes to minimize the release of pollutants. Additionally, the use of constructed wetlands and other sustainable wastewater treatment technologies can help to minimize environmental impacts of treatment ponds (Varma et al. 2022).

12.3.1.6 Tunnels, Galleries, and Ventilation Shafts

In Costa Rica, underground human-made structures such as mines, street and train tunnels, and ventilation shafts (Fig. 12.9) are in a way equivalents of caves and cave passages, subterranean rivers, lava tubes, sinkholes, vertical shafts, and volcanic pipes in natural geomorphology. Extensive mining activities in Costa Rica started about 1821 with the exploitation of gold and silver, but initial landscape modification was negligible, including only tunnels and subterranean galleries. However, this activity favored the settlement of sparsely populated towns and villages such as Desmonte, Las Juntas de Abangares, and Líbano. Las Juntas de Abangares grew through mining over time (1890-present), giving this town a particular cultural and geoheritage value (García 1984; Bundschuh et al. 2007; Castillo 2009).

The born economy generated first by gold mining and later by coffee production promoted the construction of railroads, including several train tunnels to the Pacific

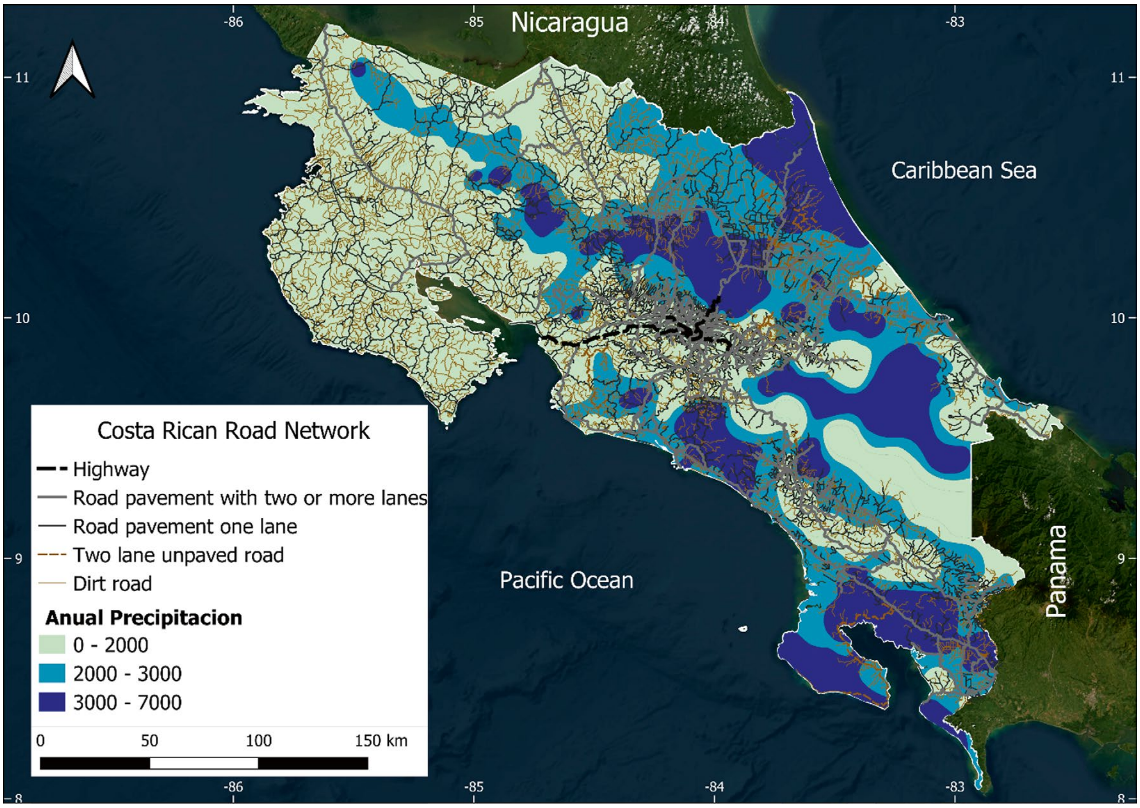
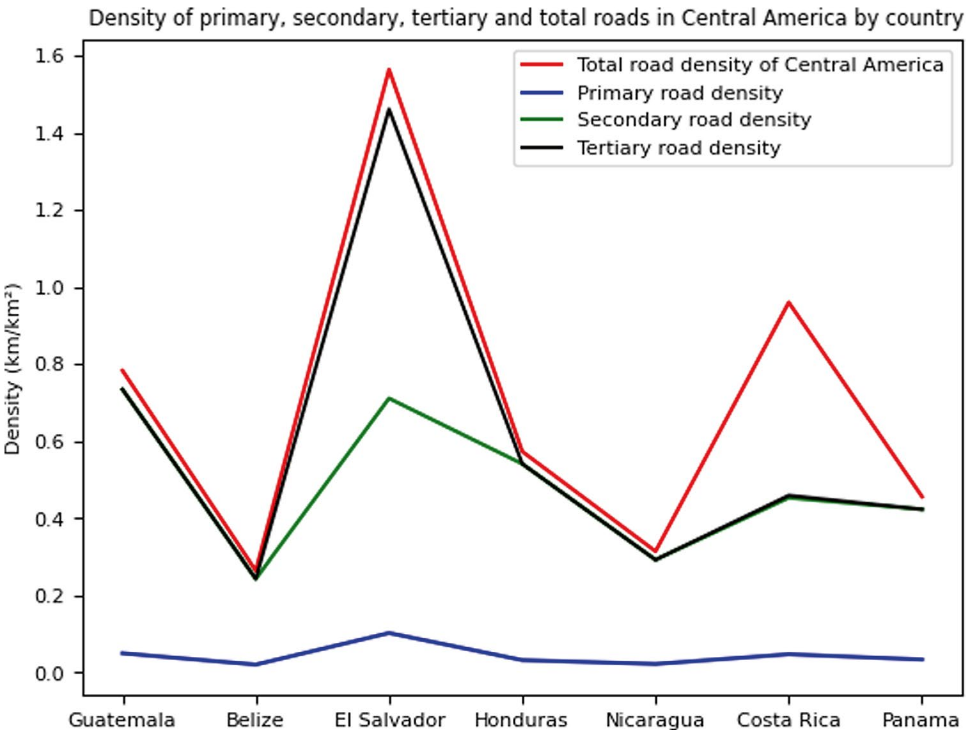


Fig. 12.6 Road network of Costa Rica clearly shows the high density of roads, particularly in the GAM (Greater Metropolitan Area). At the same time, national parks and reserves have very low density, even zero roads, such as Braulio Carrillo, La Amistad National Park (including Chirripó, Quetzales, and Tapantí), Corcovado, and Tortuguero

Fig. 12.7 Road density (primary, secondary, tertiary, and total roads) in Central America based on Open Street Maps. Despite being the fifth largest country in Central America, Costa Rica has the second highest density of roads in the region



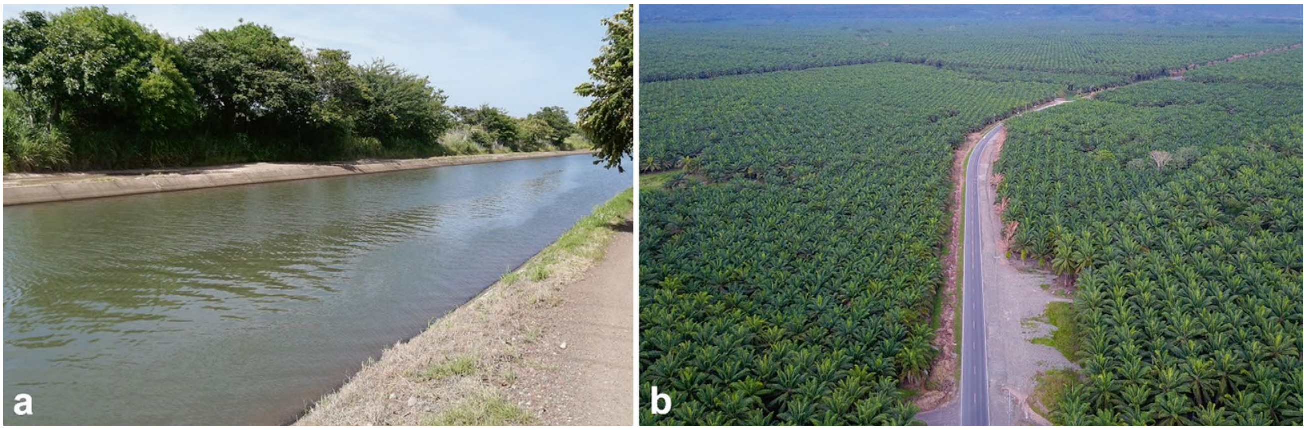


Fig. 12.8 Artificial channels. **a** Cañas irrigation channels, **b** Parrita oil palm fields and their artificial channels to irrigate these extensive croplands (Credit: Drone pilot 506)

Ocean (1897–1910) such as the Cambalache and Carballo tunnels, and to the Caribbean Sea (1870–1890), with several tunnels near Peralta. Another less known old small train tunnel, now used by cars, is located in Chase (national route 801), at the Panama boundary, and was constructed in 1914 (45 m long, 4.25 m wide, and 4.45 m high) by Chiriquí Land Company. The very known Zurquí street tunnel (562 m long, 12 m wide, and 10 m high) was inaugurated in 1984.

More impressive and extensive was the construction of tunnels, galleries, and vertical shafts for hydroelectrical projects by the Costa Rican Electrical Institute (ICE) since 1950. According to the summary compiled by David Núñez, in total 117 km of underground human-made structures was constructed, including 26 vertical shafts (1078 m total length), 44 galleries (13,436 m total length), and 68 tunnels (102,821 m total length); the oldest tunnel is La Garita, and the longest one is Tapantí (14.9 km long).

12.3.2 Terrain Leveling

12.3.2.1 Airfields

The previous international airport was La Sabana in San José, with international operation between 1940 and 1955, and for local airplanes still during the first years of the decade of 1960. Now, Costa Rica is well connected through air transportation (Fig. 12.10), with its four main international airports: (a) the Juan Santamaría (also known for the pilots as Coco airport) in Alajuela, in operation since 1958 and with a landing track of 3.1 km long, (b) the Daniel Oduber in Liberia, in operation since 1975 with a landing track of 2.7 km long, (c) the Tobías Bolaños in San José, in operation since 1975 with a landing track of 1.6 km, and (d) Limón, an international airport but with irregular operation since end of the decade of 1960 past century and with a landing track of 1.7 km These airports serve as major hubs for both international and domestic flights.

In addition to these main airports, there are many airfields located in the Caribbean coast, particularly near the extensive pineapple and banana croplands. These airfields provide crucial access to the agricultural sector and allow for efficient crop dusting of extensive croplands. Furthermore, there are numerous airfields located near the Pacific coast, typically associated with large private ranches, crop dusting, and tourist beach destinations. These airfields provide convenient access to these properties and destinations, allowing owners and visitors to arrive and depart quickly and easily. The presence of these airfields is also a key factor in the development of tourism industry, attracting more visitors and helping to drive local economic growth (Fig. 12.11). Geomorphologically, associated landforms modifications are localized as roads, landing tracks, and other structures associated to the airport size and dynamic (Pijet-Migoń and Migoń 2018).

12.3.2.2 Urban Areas

Urban development is also associated with significant anthropogenic landform modifications (Thornbush 2015). Urban areas of Costa Rica are characterized by their unique geomorphology and environmental issues that stem from the region's complex topography and climate (Quesada-Román et al. 2021a). Costa Rica is in a tropical zone with a diverse landscape that includes mountainous areas, volcanic ranges, and coastal plains. The urban areas of the country, including the capital city of San José, are situated in valleys and basins, surrounded by rugged terrain and high mountain ranges. This topography makes it difficult to manage the flow of water and to prevent runoff and flooding in the cities (Quesada-Román 2022). Geomorphology of the region

Fig. 12.9 Tunnels. **a** Gold tunnel at Tres Hermanos Mine in 1975, Juntas de Abangares; **b** the former Costa Rican president, Cleto González (third from right to left), possibly at the Cambalache tunnel along the Pacific railroad, around 1909; **c** Zurquí pilot tunnel in 1980 cutting volcanic breccias and two volcanic dykes (~5 m thick); **d** coal mine at Tablazo (Aserrí), 1922. **e** Railroad tunnel at Chase (Talamanca, beside Sixaola River, Costa Rica, and Panama border), built by the United Fruit Company in 1914, now used by cars; **f** Reventazón hydroelectric dam tunnel made by ICE, 2012

also affects local climate, leading to high levels of humidity and temperature, which can exacerbate environmental issues such as air and water pollution. Additionally, the densely populated urban areas of Costa Rica are surrounded by areas of high conservation value.

Modern transformation of deforested land and urban spatial development in Costa Rica started in the sixteenth century, but increased significantly after 1821 (Hall 1984; Vargas 2014). At least 7165 km^2 (14% of the country) is now urbanized, in most cases leading to widespread

Fig. 12.10 Historical photographs of main airports of Costa Rica. **a** Predominance of vegetation around the old Sabana airport. **b** Construction of water infrastructure of the Juan Santamaría airport in Alajuela. **c** La Sabana airport years after expanding its size. **d** La Sabana airport with surrounding vegetation at the old airport. **e** Juan Santamaría airport starting operations in 1958. **f** Construction of ICE building (about 1971) nearby La Sabana airport in San José. Credit: Costa Rican Aeronautic Museum

removal of natural vegetation, creation of entirely artificial surfaces, and heavily modified drainage systems (Fig. 12.12; Gobierno de Costa Rica 2018). Impermeability of urban constructions (houses, edifices, and pavement roads) increases the volume of water runoff and discharge to the urban rivers. This in turn increases garbage transportation to the reservoirs and littoral beaches. These processes affect marine littoral hydrodynamics and sediment transport, resulting in coastal engineering and management interventions (e.g., groins, navigation structures, storm surge barriers, and dredging).

12.3.2.3 Croplands

Since the period of independence in 1821–1823, croplands in Costa Rica have undergone significant evolution and change. During the early years of independence, agriculture was the primary economic activity in the country, and much of the land was devoted to crops such as coffee, sugarcane, pastures, and tobacco (León 1948). Strong transformation of rural and urban areas promoted deforestation and agricultural development, first around the Central Valley and later in other areas (Hall 1984; Vargas 2014). The literature demonstrates that agricultural land use typically accelerates erosion tenfold to 100-fold and that physical erosion in old belts is not as rapid compared to young mountain belts having equivalent relief. Possibly, the most vulnerable lithologies have been removed by earlier erosion (Stallard 1995). This could be the case of older terrains along the Pacific coast of Costa Rica, with rocks spanning the Jurassic to the Eocene interval, compared to the Neogene–Quaternary magmatic front in the central column of the country.

In the twentieth century, the country underwent a period of modernization and industrialization, which led to a shift away from traditional agricultural practices and an increase in urbanization (Astorga et al. 2005). This resulted in the reduction of cropland, as forests and wetlands were cleared to make way for urban development and industrial activities (Fig. 12.13; Rosero-Bixby and Palloni 1998). However, in recent decades, there has been a resurgence of interest in sustainable agriculture and crop production in Costa Rica. The country has become a leader in eco-friendly and sustainable agriculture, with many farmers embracing organic farming methods and promoting agroforestry, which integrates trees and crops in a sustainable system (Nanni et al. 2019). Additionally, there has been an increase in the production of specialty crops such as organic coffee, cocoa, and fruits, which have become important export products (Ferreira et al. 2017).

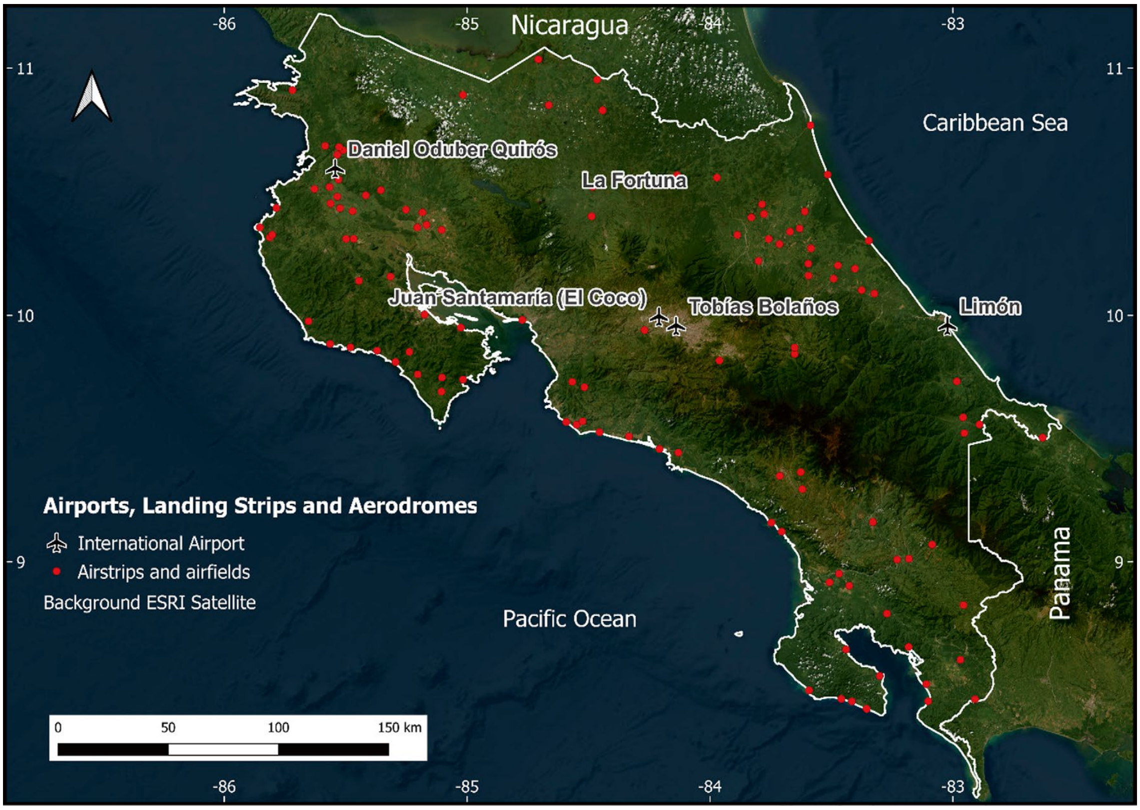


Fig. 12.11 Airports, landing strips, and aerodromes of Costa Rica

Overall, the evolution of croplands in Costa Rica has been marked by periods of expansion and contraction, as well as a shift toward more sustainable and eco-friendly agricultural practices (Fig. 12.14). Today, agriculture continues to play an important role in the national economy, providing livelihoods for many rural communities and supporting the development of sustainable tourism and conservation initiatives.

12.3.3 Artificial Landforms

12.3.3.1 Lake Reservoirs

Human activity can influence fluvial processes indirectly through land-use changes that modify flow discharge and sediment loads and river system connectivity. These approaches show that human impacts may either increase or decrease fluvial activity. River catchment developments (e.g., reservoir construction) may reduce coastal sediment supply (Syvitski et al. 2005). There are thousands of lakes in Costa Rica, with a total area of lacustrine wetlands of 166.3 km^2, and 113.3 km^2 of them are artificial (68% of the total; Veas-Ayala et al. 2022). The latter area includes at least 13 lake reservoirs of different sizes and depths (~5% of the territory). A summary of some of the principal lake reservoirs created for hydroelectrical energy is supplied by Segura (1998).

One of the most famous recreational lakes in the country is Lake Arenal, surrounded by verdant forests and crystal clear waters ideal for fishing and boating. Visitors can rent kayaks or take guided tours to admire its scenic beauty. In addition to being great for outdoor activities, Costa Rica's recreational lakes are also a heaven for nature lovers and adventure seekers (Quesada-Román and Pérez-Umaña 2020). Lake Arenal, for example, is situated in the northern highlands of Costa Rica, in the provinces of Guanacaste and Alajuela, near to the Arenal-Tilarán Conservation Area and is close to the Arenal volcano and Monteverde cloud forest (Fig. 12.15a, b). The lake is approximately 30 km long and almost 5 km at its widest point, making it the largest lake in Costa Rica at 87.8 km^2. Its depth varies between 30 and 60 m depending on the season and location (Castillo-Barahona 2015). Another important hydroelectric project was Reventazón with a lake reservoir of 8 km long and 7 km^2. Reventazón is the largest hydropower plant in Central America since 2017, and this project has been classified as an example of international good practice in hydropower sustainability, according to the International

Fig. 12.12 Greater Metropolitan Area (GAM in Spanish) where roughly 75% of the population of Costa Rica live in only 14% of the territory (Photograph credits: Ramón Masís-Campos). In the background is the Barva volcano

Hydropower Association. ICE (Costa Rican Electricity Institute), a government entity who oversees all the larger hydropower plants, has implemented watershed management programs to improve water quality, increase forest area, and control erosion (Fig. 12.15c). Through reforestation and Payments for Ecosystem Services (PES), the forest has increased significantly, which means less sediment volume lost than expected from the basins and more energy generation at the different plants.

These lakes also attract tourists, boosting local economic growth and creating job opportunities in the tourism industry. They help prevent soil erosion, reduce the impact of droughts, and provide habitats for wildlife. Moreover, recreational lakes offer a wide range of water-based activities and promote a healthy and active lifestyle, while also adding to the scenic beauty of the surrounding areas and providing opportunities for hiking, picnicking, and bird watching. Additionally, they can be used to store excess water during heavy rainfall, reducing the risk of flooding in nearby communities.

A geographic investigation indicates that dam impact in the tropics may be very different from that documented in temperate environments. Consequently, theories developed for temperate areas regarding expected dam impacts may not apply to tropical regions. This has important implications for hydrology, geomorphology, and ecology (Laurencio 2005). Therefore, the experience obtained at ICE in those fields is very important for other tropical and developing countries. In general, there is a clear link between urban development, denudation and sediment, and garbage transportation in Costa Rican rivers. Thus, if sedimentation rates increase in different regions, their magnitudes could affect the reservoirs and the beaches in different ways.

Fig. 12.13 Different croplands of Costa Rica. **a** banana fields in Parrita, **b** a mix of rice and oil palm surrounding Térraba-Sierpe wetland, **c** sugar cane plantation in Cañas, and **d** pineapple plantations in Buenos Aires (Credits to Manuel Camacho, Néstor Veas, and Daniel Quesada)

12.3.3.2 Garbage Disposal Hills

Three major garbage disposal hills are located in San José. The first one, operating in the early 1960 and perhaps before, was located in Pavas and is now a sport center of the Municipalidad de San José. The second one was Río Azul (La Unión, Cartago) that operated between 13 August 1973 and July 2007 (Fig. 12.16; Mora and Mora 2003). The area of the Pavas anthropogenic hill is now difficult to estimate but at least more than one hectare, and the Río Azul is considerably larger, 40 ha. Nowadays, the operating garbage dump is located in La Carpio, eastwards San José. There are other minor garbage disposal hills in the GAM or main cities of the country. In the Torres River catchment in San José, Quesada-Román et al. (2021b) reported that active quarries, old quarries, escarpments, and terraces have become clandestine garbage deposition sites for nearby informal settlements and municipalities that in the past deposited their solid waste in these areas.

12.3.3.3 Earth and Rockfill Dams

Sangregado dam, part of the Arenal-Corobicí-Miguel Dengo hydropower plants, is an earth core rockfill dam with a height of 66 m, crest length of 1012 m, crest width of 8 m, base width of 553 m, and rockfill volume of 4.66×10^6 m^3. Reventazón has a concrete face rockfill dam with a fill volume of 9×10^6 m^3 (loose materials), 130 m high and 535 m base width. Sandillal (part of Miguel Dengo hydropower plant) is a core rockfill dam with 470 m long. Other earth dams are smaller and mostly related to gold mines or local constructions.

12.3.3.4 Levees

Fluvial protection measures are implemented to prevent damage from floods along rivers, including the construction of levees. Levees are embankments built along the sides of rivers to contain water and prevent it from overflowing onto nearby land (Gupta and Ahmad 1999). These

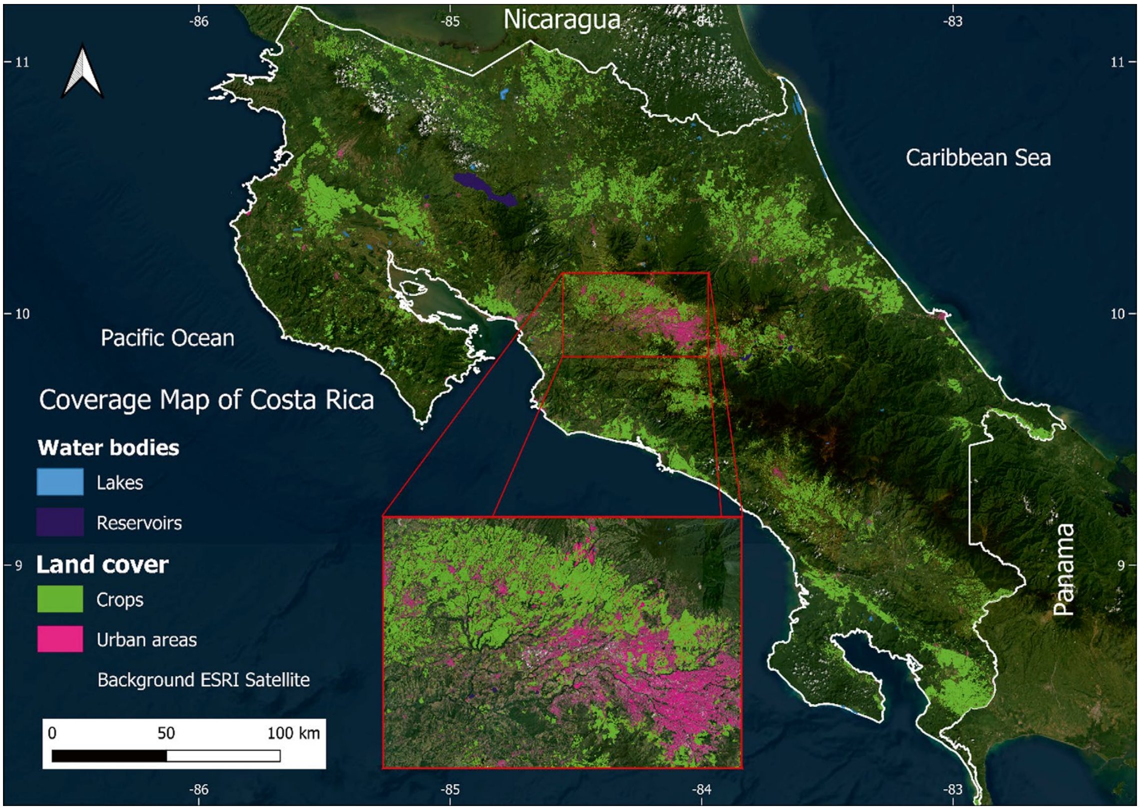


Fig. 12.14 Water bodies and land cover of Costa Rica. The box indicates the GAM

structures are designed to withstand high water levels and protect nearby communities, infrastructure, and crops from damage (Hudson 2017). Several examples exist to protect towns as Parrita, Sixaola, Nosara, Ciudad Neily, San Isidro del General, Turrialba, Siquirres, Aguas Zarcas, and several others (Fig. 12.1). In addition to levees, other measures such as the creation of retention basins, river channelization, and the improvement of drainage systems are used in Costa Rica to manage the flow of water and reduce the risk of flooding. These measures help to protect against the negative impacts of floods and promote sustainable development in the country. However, it is important to note that fluvial protection measures should be integrated into a comprehensive approach to river management that considers the needs of the environment, the local community, and other stakeholders (Bark et al. 2021).

12.3.3.5 Coastal Management

Coastal management to address sea level rise and coastal erosion is an important issue in Costa Rica, where many communities and infrastructure are located near the coast. Sea level rise, which is a result of climate change, can lead to the loss of coastal land and erosion of beaches and cliffs, while also increasing the risk of flooding and other coastal hazards.

To address these challenges, the national and local governments, the private sector, and NGOs have implemented several coastal management measures, including the construction of seawalls and groins, and the creation of artificial reefs (Barrantes-Castillo et al. 2020; Arias-Godínez et al. 2021). These measures help to protect coastal communities and infrastructure, while also promoting sustainable use of coastal resources. In addition, the government is working with local communities, NGOs, and other stakeholders to implement integrated coastal management (ICM) programs that address increasingly complex coastal issues (Calleja-Apéstegui and López-Arias 2022). These programs often involve the development of land-use planning policies and the implementation of ecosystem-based approaches to coastal management, such as the restoration of natural habitats and creation of green infrastructure (Yaney-Keller et al. 2019).

It is important to note that while coastal management measures can help to reduce the risk of coastal hazards, they should be integrated into a comprehensive approach to coastal management that considers the needs of the environment, local communities, and other stakeholders (Acuña-Piedra and Quesada-Román 2021). This will help to ensure that coastal management practices are sustainable and effective in addressing challenges posed by sea level rise and coastal erosion.

Fig. 12.15 **a** Artificial lakes. **b** Lake Arenal reservoir at the bottom of the Arenal volcano. **c** Reventazón reservoir in 2016

Marinas in Costa Rica, such as Marina Papagayo, Marina Los Sueños in Herradura, Marina Quepos, and Marina Golfito, have had a significant impact on the country's economy and tourism industry (Fig. 12.17). However, it is important to carefully consider and mitigate any negative environmental impacts (e.g., damaging coral reefs, disturbing wildlife habitats, and water pollution) that may result from their development and operation (Radulovic 2022).

12.4 Conclusions and Future Research

At least since Holocene, there is indirect, direct, and extensively evidence available of early Pre-Columbian anthropic modification of landscape and vegetation in Costa Rica, particularly at 4.5 ka associated with the introduction of sedentarism and agriculture and its extensive development about 3 ka b.P. This includes building of the first villages, monuments, roads, stone fishing traps, and trails. Later, particularly in the nineteenth and early twentieth centuries, mining of volcanic rocks contributed to local landscape modification, among several other small and large infrastructure constructions.

Following the work of Castro et al. (2021), in the case of Las Juntas de Abangares, landscapes that were altered through gold mining over time have a cultural and heritage value and, therefore, compose the mining-related geoheritage. Major modification of the landscape has occurred since the second half of the twentieth century and the first decades of the twenty-first century, particularly in relation to the development of agriculture and pastures, quarries, building of dams, reservoirs, new roads, and urban expansion.

Multidisciplinary research approach, involving geologists, civil engineers, archeologists, geomorphologists, and geographers, is fundamental to evaluate the extent and long-term consequences of anthropogenic alterations at the landscape scale. Human-made landforms will continue growing in future, and these actions are inducing cascading

Fig. 12.16 Example of artificial accumulation landform is the Río Azul garbage disposal hills, now under WPP enterprise control (Credit: Ramón Masís-Campos)

Fig. 12.17 Yacht marinas and associated engineering coastline modifications. **a** Papagayo, **b** Quepos

environmental changes. These results should also serve to promote the implementation of socioeconomic tasks, including a better territorial planning, environmental protection, and nature conservation.

LiDAR technology and similar applications have become a fundamental tool to aid in mapping anthropogenic structures, including Pre-Columbian trails and other cultural interventions to create a three-dimensional geospatial database to document the true extent of humans as geomorphic agents in Costa Rica. The next goal is quantification of the degree of anthropogenic surface transformation within the concept of hemeromorphy (Rózsa et al. 2020). This methodology and its interpretation make the comparison of landscape units possible according to their anthropogeomorphological transformation, independently of the intensity and quality of their geomorphological processes. One of the best ways to evaluate the effect of human activities is through studies of paired watersheds. Such studies simultaneously address effects of human activities as well as the importance of denudation in smaller basis as described by Milliman and Syvitski (1992).

Future challenges in anthropogenic geomorphology in developing tropical countries like Costa Rica are numerous. One of the most evident trends is deforestation and conversion of forests to agricultural land, urban areas, and other uses. This can lead to soil erosion, changes in local water balances, and impacts on biodiversity. These countries are often more vulnerable to the impacts of rising temperatures, changes in precipitation patterns, and sea level rise.

Developing tropical countries are also more vulnerable to disasters such as hurricanes, earthquakes, and volcanic eruptions, which can have significant impacts on geomorphological processes and the built environment. An increasing demand for infrastructure in the Global South can lead to changes in the natural landscape, including the construction of roads, bridges, and other structures, which can have significant impacts on local geomorphology and hydrology. Undeveloped countries usually lack the resources to properly manage and mitigate the impacts of human activities on the Earth's surface (Campos et al. 2022; Quesada-Román and Peralta-Reyes 2023). This includes a lack of funds, trained personnel, and technology to monitor and manage changes in the landscape. In contrast to the anthropic disturbances that have shaped Costa Rica's landforms and landscapes since prehistoric times, contemporary alterations exhibit a commendable shift due to cultural and educational level of citizenship, and large extensions of natural continental and marine protected areas, which is characterized by a profound respect for nature and meticulous environmental planning, mitigating the impact of strong transformations.

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