Demand for ecosystem services drive large-scale sifts in land use in tropical watersheds prone to landslides

Carla Restrepo[1], Francisco Javier Álvarez-Vargas[2], and María Angélica Villa Castaño[3]

[1] Department of Biology, University of Puerto Rico at Rio Piedras, P.O.Box 23360, San Juan, Puerto Rico 00931
[2] Universidad del Valle, Cali, Colombia
[3] Fundación EcoVivero, Cali, Colombia

Supplementary Materials File S1: Provides a detailed account of the time line presented in Figure 3

Located between the Western and Central cordilleras of the Andes in the Cauca and Valle del Cauca, Colombia lies the inter-Andean Cauca valley, a stretch of ~3,000 km^2 tropical dry forest [sensu Holdridge; 1] drained by the middle Cauca river. In this region the Cauca river runs in a south-north direction and receives the waters of numerous tributaries draining the eastern and western flanks of the Western and Central cordilleras, respectively. In contrast to the Cauca valley, most of the cordilleras are classified as humid/very humid pre-montane to montane forests [sensu Holdridge; 1]. In the Central Cordillera, heavy rains frequently result in the formation of landslides, torrential flows, and flooding that affect the slopes, river channels, and low-lying areas, respectively [2,3]. The contrasting conditions between the valley and the mountains have shaped their relationship through the use of water with important consequences on land cover. Over time, these relationships have increased the *connectivity* between the lower and upper regions of these small mountainous watersheds and among watersheds. These relationships may have also contributed to the *homogenizatio*n of lowland and upland regions through different mechanisms. We group important economic, infrastructure, policy/legal, and climatic events that shaped the use of water-derived ecosystem services in our study area into three to four periods to better understand how the demand for water-derived ecosystems has become major drivers of land cover change.

Colonial manorial hacienda (<1875; green) - Until the mid 1800's a system of colonial manorial haciendas and small villages sustained diverse land covers and land uses in the lowlands, that included forests interspersed with pastures devoted to cattle ranching, tree gardens, orchards, sugarcane, rice, export products (cocoa, coffee, tobacco), and a vast system of wetlands along the Cauca river and the low lying areas of its tributaries draining both cordilleras [4-7]. Low mean annual, and highly seasonal precipitations characteristic of tropical dry forests, may explain the ongoing development of a vast system of irrigation canals or *acequias* that diverted water from the rivers to the *acequias* and finally to water-needed fields [5]. One important water diversion during this period occurred ~1770 when part of the waters of the Rio Nima were diverted to create the Rio Palmira to provide domestic sanitary and drinking water services to the recently established village of Palmira; today Palmira has a population of ~ 312,000 people [8,9]. The generation of hydraulic power became a new use of water with the introduction of water-powered mills to process sugarcane in the sugar mills or *trapiches* and coffee in the *beneficiaderos* [4,10]. The introduction of water-powered mills involved water transfers between rivers as well as deepening of river channels [10]. Further processing of sugarcane and coffee required heat produced from burning bagasse and wood; the latter would come from within the haciendas [e.g., 7,10]. An additional event during this period, was the arrival in 1864 of Mr. James Eder from Lithuania to Colombia via New York [5,8]. Known in Colombia as Santiago Eder, Mr. Eder catalyzed significant changes in our study region, and what became to be the Valle del Cauca department, for years to come. Established near Palmira, Mr. Eder acquired important tracks of land, including rights to water, and consolidated an agribusiness model that was quickly adopted by locals [5,7,8]. The transformation of the colonial manorial haciendas into capitalist production systems had begun.

Transition to agroindustry (1875 - 1950; pink) – This period is marked by the diversification and intensification of water use. Mr. Eder knew about global markets, had the capacity to establish commercial connections with regions seeking goods produced in the fertile Cauca valley, and had an interest in technologies that made possible the industrial revolution elsewhere. Mr. Eder experimented with export crops (e.g., cacao, coffee, tobacco, indigo, quina, cotton, sugar) and the

production of alcohol for local markets, improved the infrastructure needed to process coffee and sugarcane, and sponsored and invested in transportation systems (road linking the inter-Andean valley with the port of Buenaventura on the Pacific coast, navigation through the Cauca river, and construction of a railroad system) to move goods [8,11]. In 1901 Mr. Eder inaugurated a steam-powered mill to process sugarcane which expanded considerably the capacity of sugar mills to produce sugarcane-derived products. As a result, large expanses of tropical dry forests began to be cleared to grow sugarcane, a land use change that in turn required the development of infrastructure to bring and remove water as necessary; also, the processing of sugar juices required the burning of wood to produce heat [7,12]. In 1903, the Eder family constituted the Cauca Valley Agricultural Co. in New York (it would be transformed in 1919 into the Compañia Agrícola Caucana) to centralize all the components of their agribusiness model, facilitate commercial transactions, and diversify their portfolio [7,8]. Later on, in 1927 Ingenio Manuelita, S.A., from now on Manuelita, was created as an offshoot of the Compañia Agrícola Caucana to manage the sugar business [8].

In the meantime, Palmira faced with water shortages and sanitary problems, approved in 1913 incrementing the volume of water of the Palmira river through the diversion of additional water from Nima and the diversion of water from the Rio Aguaclara [13]. In 1913 the Compañia de Instalaciones Eléctricas de Palmira was established and in 1916 put into operation Nima-I, the first hydroelectric plant on the Nima river; this represented a new water use in the region [8,14]. Nima-I together with the Cali hydroelectric plant, began to work as an interconnected system to supply electricity to Palmira and Cali, the capital of the newly created Valle del Cauca department [8,14,15]. A drought in 1914 together with the first plan to regulate the use of the Rio Nima waters suggest increasing tensions on water use to move water-powered mills, and supply water for domestic, industrial, and irrigation (sugarcane and rice) needs [4,13]. In 1929 a new aqueduct and sewage system for Palmira was inaugurated, the former using water directly from the Nima river [13]. In 1926 the Compañia Colombiana de Electricidad purchased the Compañia de Instalaciones Eléctricas de Palmira, with the subsequent transfer of Nima-I [13,15]. The new company began planning the construction of a second hydroelectric plant in the Nima watershed that raised concerns among water users, including the Palmira aqueduct and farmers that relied on the waters of this river; Nima-II was finally inaugurated in 1942 [14-16]. According the Offner [17] a drought in 1936 "inspired headier ambitions to control the region's water supply." A plan for a third hydroelectric plant on the Rio Palo, immediately south of our study region, and diversion of its waters to irrigate part of our study region was also planned during this period [18]. Not only droughts like the one in 1936 affected the Nima watershed. Between 1935 and 1938 several seismic events in SW Colombia, and intense rains triggered landslides and dammed the river; this resulted in damage of the water infrastructure and mobilization of large quantities of sediment [19,20]. El Relator describes in 1936 [20] the extent of the damage to Nima-I and states that "the public street light system and other electricity needs were not affected due to the connections between the Cali and Palmira systems." El Relator writes in 1937 [19] that the city "is extremely mortified by the dirty water coming through the aqueduct and by the amount of water running through the river, *acequias*, and *zanjones* resulting from the heavy rains in the upper reaches of the Nima watershed." We have a similar account 34 years later [3]. Thus, the increasing *connectivity* of this region through the use of water in one case mitigated, but in another expanded the impact of these natural hazards to a larger region. Also, this increased *connectivity* contributed to the *homogenization* of land cover in the lowlands with the expansion of the sugarcane industry.

During this time period, an increasing number of accounts indicate that the mountainous regions were also experiencing important transformation due to increased deforestation. For example, Resolution Number 17 of 1938 established a forest reserve in the Amaime watershed which includes Nima in an effort to stop "the loss of forest due to indiscriminate deforestation" that is reducing water flows; the protection of the remaining forests would conserve and regulate the waters of these rivers [21]. We have not found references suggesting drivers of land cover and land use change in these mountainous regions but it would be something important to investigate in the context of water-use.

The approval in 1946 of Law 80 for the creation of the Instituto Nacional de Aprovechamiento de Aguas y Fomento Eléctrico-Electroaguas would provide the basis for major changes in land use mediated through the use of water [22]. Electroaguas would study the regions in Colombia that required irrigation and desiccation, regulation of surface waters, and construction of infrastructure for the production of electricity. In the Valle del Cauca, these efforts can be link to the creation of new institutions, expansion of sugarcane plantations, and the intensive use of water.

Consolidation of agroindustry-I (>1950-1995; grey) - This period is characterized by the implementation of an increasing number of national- and regional-level policies centered on the use, regulation, and management of forests and water, including creation of new institutions. An increasing population, the expansion of the agribusiness sector, and natural hazards reveals that water services derived from the Nima watershed could be reaching a carrying capacity. A report from 1951 describes the impacts of exceptional rains on the hydroelectric plants and the Palmira aqueduct, and suggests adaptation measures to this recurrent problem. The problem is the intense rains during the "*invierno*" or rainy season in the upper reaches of the Nima and neighboring watersheds that trigger landslides, landslide dams, floods, and the mobilization of sediments. The adaptation measures for the aqueduct include taking water from a tributary of the Rio Nima, using the aquifers around Palmira, injecting part of the Nima waters into the aquifers, and modifying the water infrastructure to handle large amounts of sediments [23]. The same report indicates that Manuelita was already investigating the viability of using groundwater.

In the early 1950's Manuelita built a new sugar mill to expand the production of sugar-derived products, including sugar; similar efforts by other sugar mills followed [4]. In 1953 a new decree listed all the general rules regarding forest surveillance, conservation, improvement, establishment of reserves, reforestation and exploitation, and defined forest types based on their function (watershed protection, control of landslides and erosion, protection of roads, regulation of water courses, and health improvement) [24]. In addition, this decree identified beneficiaries of some of the services provided by the watersheds, and forms of payment. We have identified a first effort to purchase land within the broader Amaime watershed for protection purposes by the Providencia sugar mill in 1955 [25].

In 1954 the Corporación Autónoma Regional del Cauca (CVC; in the main text we refer to it as CVC_{or}) was established as the first autonomous government institution of Colombia [26,27]. The first article of the decree established that CVC_{or} would promote the conservation and development of a large territory that included the upper Río Cauca watershed, watersheds in the neighboring Pacific region, and other territories that would be affected by the activities of this Corporation. These activities included the generation, transmission, and distribution of electricity, the regulation

of surface waters to control flooding, the use of water for irrigation purposes, the recuperation and improvement of land through the construction of drainage systems, the establishment of norms to regulate the domestic and industrial use of water, the improvement of stream beds for various uses, the protection of waters against contamination, the promotion of appropriate land use for agricultural purposes, the promotion of soil conservation and reforestation, the promotion of the exploitation of mineral resources, and the protection of fauna and flora. CVC_{or} would operate in a fashion similar to the Tennessee Valley Authority of the United States.

The low-lying areas of this region experienced drastic changes that had been planned since the late 1940's and accounted for in national- and regional-policies, including the creation of CVC_{or}. This region had one of the largest wetland system in a tropical dry forest life zone in Colombia [28]. The conversion of these wetlands to cultivable land through the development of infrastructure to remove water, prevent floods, regulate surface waters, and irrigate fields was key to the agribusiness expansion [4]. The inauguration of the Salvajina hydroelectric plant in 1985 to regulate the waters of the Cauca river in many ways represented the culmination of a long-term effort to control the waters in a mountainous region.

In 1959, the national government created several large, national, forest reserves that included the central zone forest reserve ("*zona de reserva forestal central*") [29]. In these forest reserve zones, all public forests or *terrenos baldíos* located in watersheds that could provide water for internal consumption, production of electricity, and irrigation and located on slopes >40% would be protected. This law also included the possibility of purchasing land and compensating peasants inhabiting these regions in an effort to reduce soil and water degradation. The national government transferred in 1960 all of the *terrenos baldíos* within the Nima watershed to Palmira and the CVC_{or} and in 1964 a plan to purchase land was established [3,30]. In one of the first management plans for a watershed in the Valle del Cauca and Colombia, Schrimpff [3] indicates that the plan for purchasing land failed because the *terrenos baldíos* in possession by *colonos* and the number of *colonos* and sharecroppers was already too large, there were not enough funds to purchase all the land, and the displacement of *colonos* would have large social implications. In addition to the transfer of *terrenos baldíos*, CVC_{or} in 1962 purchased the Nima-I and Nima-II hydroelectric plants [30,31]. Since the 1940's a road running between the Valle del Cauca and Tolima department was in the planning, yet two documents from 1960 and 1970 suggest that the construction of this road started sometime between 1955 and 1960 [3,30]. This road running between Palmira the upper reaches of the Nima watershed (~3,500 m a.s.l.) became a major source of sediment, increased the *connectivity* between the low and upper reaches of the watershed, and attracted *colonos* that based their livelihoods on agricultural systems characteristic of high elevations, thus contributing to the *heterogeneity* of these cultural landscapes.

The 1970 Nima watershed plan [3] is a fascinating document that describes in detail the role of natural hazards in combination with human activities on the landscape, including water resources, and provides the first land cover and land use maps of the region. As with previous accounts, it indicates that the mobilization of sediments greatly affects the supply of water for the hydroelectric plants, the aqueduct, and irrigation canals. The watershed plan is fascinating because to some extent it is at odds with the legislation and practices that existed at that moment. The presence of people was viewed as favorable because among other things, people could help manage the region, particularly in the aftermath of natural hazards. This unique plan called for a re-structuring of land

use and of land ownership, structural mitigation activities to control the production of sediments and regulate water flows, and the establishment of a strategy that would allow the inhabitants of this region reach a good standard of living. This was not the trajectory followed by the Nima watershed on the long-term. In fact, this watershed experimented the consolidation of system of protected areas that started in 1973 with the creation of a Protection Forest Reserve [Páramo en Santa Teresa and Sector Los Cuervos; 32], followed in 1977 of a national park [Parque Nacional Natural Las Hermosas; 33], and in 1979 a forest protection zone of [Zona Forestal Protectora La Albania y La Esmeralda; 34]. The 1973 and 1979 protected areas were established in regions highly susceptible to landslides triggered by intense rainfall and seismic events as evidenced in 1968 [3]. The first watershed plan for Bolo, Fraile, and Desbaratdo is based on the premise of "the development of people within the watersheds" [35]. This document indicates that 6% of the total population in these three watersheds is rural, and that 80% of the rural population are indigenous. In addition, the plan indicates that at high elevations forest cover represents 14% of the area (7,750 ha) and that based on the slopes, additional 7,250 ha of forest need to be protected. It is recommended that reforestation should proceed with native and not exotic species due accelerate the recovery of the forest.

A drought in the late 1980's and early 1990's tested the ability of these small mountainous watersheds to cover the demand of water-derived services by the low-laying areas [36] at a time of population increase and agribusiness expansion. Water users of Nima that included the public aqueduct of Palmira-Empalmira, CVC_{or}, and the Department of the Valle del Cauca, created in 1980 the Comité Pro-Nima,[37]. The overall mission of Pro-Nima was to recover, improve, and regulate the quality and quantity of water used by the Palmira aqueduct; among other things they purchased land in the upper reaches of the Nima watershed for Empalmira. ASURNIMA (1991), ASODES (1992), ASOBOLO (1993), ASOFRAYLE (1994), ASOAMAIME (1996) would follow but in contrast to Pro-Nima, they were established as private, non-profit organizations [38-41]. These associations originally worked together with regional and local authorities to promote a diverse array of strategies that included land purchasing, enclosure of small headwater streams, establishment of vegetation buffer zones along streams, environmental education programs among others [42].

A new Constitution in 1991 strongly articulated in sustainability principles [43], a new environmental law approved in 1993 [Law 99 of 1993; 4,44], and the deregulation and privatization of public services in 1994 [45] brought important changes to our study region, as well as new actors. In 1994 CVC_{or} was re-structured and renamed as the Corporación Autónoma Regional del Valle del Cauca-CVC to reflect jurisdictional and functional changes aligned with the new environmental law. Among other things, CVC's public infrastructure assets were sold, technical work conducted previously by this organization began to be contracted with other companies and institutions, and the area under its administration changed. Specifically, CVC began to administer a smaller geographical area centered on the Departmento del Valle del Cauca.

Consolidation of agroindustry-II (>1995; grey) - This period is characterized by the strengthening of municipal and departmental administrative units, development of municipal and departmental land use plans, decentralization, and citizen participation, among others [46,47]. The 2011 Organic Law of Territorial Planning is important because it recognizes that the protected areas are of national interest, and promotes different forms of territorial and institutional integration aimed at

regional development, attracting investments, and improving competitiveness, based on regional strengths [47].

As part of the aforementioned processes, the electric assets of CVC_{or}, including Nima-I and Nima-II [48] were sold to a public company created in 1993, namely the Empresa de Energía del Pacífico-EPSA S.A. E.S.P.. In the nearby Amaime watershed, EPSA would build the hydroelectric plant Amaime that was put into operation in 2010. Part of EPSA's gains would be transferred to finance the CVC, one of their stakeholders [27]. Within two years of creation, EPSA was sold to a private company and after two additional transactions was purchased by Celsia, a private utility company that produces energy from renewable sources [48,49]. Nima-I, Nima-II, and Amaime are now part of Celsia's assets. Similarly, the Palmira Aqueduct began to be administered by private multinational companies. In 2011 policies that supported the production of biofuels provided a new impetus for the diversification and expansion of the sugarcane agribusiness in lowland regions [50]; the latter became key players in the production of renewable energy [51-53]. In addition to the production of ethanol from sugarcane and the combustion of bagasse, the sugar mills of our study region produce biodiesel from oil palms grown miles away in the Llanos Orientales de Colombia contributing in significant ways to land cover change [51-54]. The same agribusinesses are promoting the construction of a main national road linking the Llanos Orientales with the port of Buenaventura in the Valle del Cauca; this road passes through the Fraile watershed and the small urban center of Florida [55].

In Colombia the creation of the National System of Protected Areas (SINAP), integrated by regional (SIRAP), departmental (SIDAP), and municipal (SIMAP) systems has been a hallmark of this period. In the Nima watershed a regional natural park was created in 2006 [Parque Natural Regional del Nima; 56]. The creation of this area is interesting because it is partly justified based on Colombia's National Plan for Biodiversity, and the Biodiversity Plan of Action for the Valle del Cauca. Within the larger Amaime watershed, a number of private reserves have been established [https://geo.cvc.gov.co/visor_avanzado/; BD-Biodiversity] following their recognition as critical elements of the national strategy for the protection of biodiversity and ecosystem services [57]. Likewise, the water associations started to play an increasingly larger role in the region and with the support of international and local non-profit organizations and the sugarcane industry [36], transformed into water funds, developed payment for ecosystem services-PES mechanisms, and organized under the Fundación Fondo Agua por la Vida y la Sostenibilidad-FAVS [58-61]. Over the years, the mission, activities, and projects of these water funds have changed to meet new challenges and realities, including the achievement of biodiversity, climate change, and sustainability targets feeding into national ones [60,62]. In 2018, ASURNIMA and ASOAMAIME were merged into ASOAMAIMENIMA and together with ASODES, ASOBOLO, ASOFRAYLE partner with many institutions and participate in a wide variety of activities [38-41].

At least two remaining issues require some thought. First, in the Bolo, Fraile, and Desbaratado watersheds the Nasa indigenous communities [35] were granted lands in 1995 and 2007 to establish the El Triunfo Cristal Paez Reservation [63]. The local authorities and water funds have been involved in conversations and projects aimed at protecting the WES produced by these three watersheds that are critical for the lowlands. With the plans to pass the Orinoquía-Buenaventura road through the Fraile watershed, it is unclear how the multiple conflicts converging in this region

will be resolved. Second, landslides, torrential flows, and flooding continue to affect these watersheds as revealed by a quick search in local newspapers [e.g., 64,65]

Our timeline, including narrative, has shown how the supply of WES by upland regions has become critical for the development of the lowlands, including the consolidation of a "thirsty" agribusiness sector and urban centers. As part of this process, land cover and land use in the uplands have undergone numerous changes with consequences on the livelihoods of an unaccounted number of people. The upland and lowland areas have become increasingly connected, and this has enabled the homogenization of both sub-regions. The use of ground water [66], the elevated number of interventions in the upland regions, the de-population of some watersheds, the extension of the sugar agribusiness in areas far away seem to signal an overuse of WES with unknown consequences in a scenario of climate change.

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