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Contemporary human uses of tropical forested watersheds and riparian corridors: Ecosystem services and hazard mitigation, with examples from Panama, Puerto Rico, and Venezuela

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ABSTRACT

Humans have long favored settlement along rivers for access to water for drinking and agriculture, transport corridors, and food sources. Settlement in or near montane tropical (and other) forests include additional benefits such as food and wood supply, and high quality water derived from watersheds where upstream human disturbance and environmental degradation are generally low. However, the advantages afforded by these floodplain and montane settings are offset by episodic risks to communities located there as floods, landslides, wildfires, volcanoes, (and tsunamis for coastal communities), cause loss of life and damage or destroy infrastructure and crops. A basic understanding of rainfall and flood patterns, as well as hillslope stability, by residents in these environments mitigates these risks. Modern global urbanization, particularly in regions of rapid economic growth, has resulted in much of this "organic" knowledge being lost, as megacities encroach on floodplains and mountain fronts. Moreover, the most likely occupants of these hazardous locations are often marginalized economically, which increases their vulnerability. Effective stewardship of river floodplains and upstream montane forests maintains a key ecosystem service, which in addition to the well-described services, (i.e. water, food, hydroelectric energy, wood products, carbon sequestration, maintenance of biodiversity, etc.) is the mitigation of natural hazards and vulnerability.

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1. Introduction

We cannot live far from water. Humans live near rivers, mountains, and coasts, for reasons of access to natural resources, *i.e.* water for drinking and agriculture, transportation corridors, food sources, hydroelectric energy, and recreational/esthetic values. These settings are ecotones, and for early hunter-gatherers, particularly in regions of humid tropical forests, served as productive locations to live. Scientific debate examines whether early humans could subsist in tropical forest environments, which some have described as food-poor, not food-rich, biomes (Headland and Bailey, 1991). Recent work suggests that early humans were able to effectively exploit humid tropical forests (the forest type in the three example locations discussed in this paper) for food resources (Roberts and Petraglia, 2015). Current patterns of human settlement in or near montane forests are related in part to access to the services noted above, but also to high quality water resources derived from these montane watersheds where upstream human disturbance and associated environmental degradation is generally reduced relative to downstream locations. The importance of proximity to water resources for survival, and the risks and benefits of flooding that this proximity entails, have not been closely examined in the archeological and anthropological literature. Understanding of modern human adaptation to montane forests and riparian corridors provides insights into how early humans may have responded to the environmental challenges and benefits they encountered in these environments (Fig. 1).

Environmental benefits from forested watersheds are numerous and include reduced peak river flow during storms, increased availability of groundwater and base flow in streams during droughts, reduced soil erosion and landslide probability, and enhanced resilience to wildfire, pathogens, and invasive species, and enhanced biodiversity, and genetic resources (Noble and Dirzo, 1997; Stallard et al., 2010; Ogden et al., 2013). Examples from the Panama Canal watershed, the Luquillo mountains of Puerto Rico, and the coastal mountains of Venezuela illustrate how and where environmental and hazard-mitigation ecosystem services have

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Fig. 1. Riparian corridor, Canóvanas River, Puerto Rico, showing cattle grazing on vegetation growing on nutrient-rich flood plain deposits.
Photo source: M.C. Larsen.

been used or in some cases, not well understood or managed, resulting in sometimes severe consequences.

2. Early human uses of tropical forests and riparian corridors

Human use of tropical forests and riparian corridors for ecosystem services, i.e. extraction of benefits from nature, is not a new behavior; we cannot long survive when far from dependable water supply, which is of course closely linked to food supply. For example, in the current debate regarding the degree of prehistoric human impact on the Amazon, Bush et al. (2015) state that prehistoric settlements are more likely to have been located in forests that are within 15 km of a river floodplain because of access to fish and other aquatic protein sources, rather than in inter-fluvial regions far removed from rivers.

Much of the study of traditional human resource exploitation has focused on the adequacy and availability of food sources in forests, particularly tropical forests (Hart and Hart, 1986; Dentan, 1991; Headland and Bailey, 1991; Roberts and Petraglia, 2015). While closely linked, the availability of water resources has received less explicit attention, both in terms of benefits (in association with food sources) and costs (water-related hazards such as floods, landslides). As noted above, these same hazards also provide a benefit (Colinvaux and Bush, 1991), as in cases of floods and landslides, whereby habitats and soils are episodically “reset” with additions of soil nutrients and disturbances that open gaps for new vegetation.

Ecotones and gallery forests tend to be productive settings for food resources (Dentan, 1991), and recent literature demonstrates that humid tropical forests in general could have served as sufficiently productive environments for hunter-gatherers (Roberts and Petraglia, 2015). As such, riparian corridors and mountain fronts are favored human habitats because they provide access to multiple environments from which to exploit water, food resources, and to trade with neighboring groups of hunter-gatherers or cultivators. Riparian corridors are not without hazards, such as floods, described below, but also because rivers can serve as routes for groups to prey on one another, and as stated by Dentan (1991), few known foraging populations confined themselves to a single ecological setting. Some of these settings, in areas with marked seasonal changes in precipitation, challenged these inhabitants, as wet and dry cycles limited various food and water sources, i.e. periodic declines in edible plant foods and faunal biomass during the annual dry season (Headland and Bailey, 1991). Furthermore, over longer time scales, humid tropical forests expanded and contracted with century-to millennial-scale fluctuations in precipitation and temperature (Kuper and Kröpelin, 2006; Barton et al., 2009; VanDerWal et al., 2009; Summerhayes et al., 2010).

The resource- and aesthetic-advantages of riparian, montane, and coastal environments come with risks and benefits associated with floods, landslides, wildfires, tsunamis, and volcanoes, which have always been episodic natural disturbances in these settings. Prehistoric humans in these settings, by living out-of-doors most of the time, were likely more aware and perhaps more mobile than modern humans, which may have enabled them to reduce the potential loss of life and other impacts. Well described evidence for the recognition of flood benefits comes from the human occupation of the Nile River valley and the expansion of agriculture in that region. Early Egyptians depended on a sophisticated understanding of flood hazards but also of the benefits of the nutrient and sediment-bearing annual flood cycle of the river (Brooks, 2006; Bernhardt et al., 2012). Approximately 5000 years ago the Egyptians used stone structures along the river's edge to measure the rise and fall of river level to assure the timing of planting and crop management (Manning, 1997). A contemporary example of this is along the Orinoco River, Venezuela, where villagers living near the river have marked the boundary of the annual high-water margin of the river with wooden stakes. During the rainy season when the river begins to rise, they move their belongings and domestic animals to areas above the line of stakes (Pedro Delfin, Universidad Central de Venezuela, written communication, 2015).

The benefits of landscape disturbance by floods are well known, i.e. delivery of nutrients to flood plains (Fig. 1). Similarly, landslides open forest gaps that create small-scale opportunities for successional vegetation growth, while hurricanes, wildfires, tsunamis, and volcanoes serve as large-scale mechanisms for opening up landscapes and creating new habitats. According to Tilling (1989), in the past 10,000 years of human development, we have directly experienced the eruptions of 1300 volcanoes, and have adapted to living in these hazardous but also beneficial locations around the world. Volcanic rock can develop into fertile soil and volcanoes episodically deliver mineral nutrients to soils (e.g. intensive agriculture around Vesuvius in Italy, Poas in Costa Rica, Barú in Panama, etc.).

One newly described example of human response to their hydrologic setting is landscape management by pre-Hispanic occupants of Central America, documented in eastern Panama (Martín et al., 2015). In a region of seasonal flooding (seven months/year), agricultural use required landscape transformation using raised fields to minimize the impact of flooding on settlements and agriculture, but also to improve water management during the dry season. These raised fields consist of at least 22 blocks of parallel banks and ditches approximately 50 m in length, 2.5 m in width and 0.6 m in height. Parallel ditches between the ridges likely retained enough water for the dry season. Additionally, the system is associated with a stream that seems to have been artificially channeled towards the area (Martín et al., 2015). The raised fields have been preliminarily dated to approximately 1300 BP, and demonstrate sophisticated landscape management to divert water flow to both reduce flood hazard and to mitigate drought.

In general, patterns of human use and occupation of tropical forests remains a challenging topic because as noted above, these forests expanded and contracted during Pleistocene and Holocene changes in precipitation and temperature (Roberts and Petraglia, 2015). Moreover, humid tropical forests, particularly in mountainous settings, are not favorable settings for the preservation of archeological evidence, particularly the organic remains used to reconstruct human diets and palaeoenvironments. In addition to the generally warm, moist conditions which contribute to rapid weathering of rock, soil, and non-lithic evidence of human occupation buried in that soil, montane humid tropical forests are dynamic settings with abundant, active soil macrofauna and frequent disturbances such as landslides and treefalls that limit preservation and render evidence of past human occupation extremely difficult to find. An example of this dynamism is in eastern Puerto Rico where it has been estimated that the upper meter of soil is turned over or moved from hillslopes to stream channels on average every 10,000 years (Larsen, 2012).

3. Modern urban population expansion, forest loss, and climate change

More than half of the world's population now lives in urban areas, which are expected to absorb all the population growth over the next four decades; mostly in the cities and towns of the less developed regions (Fig. 2). The United Nations (2011) has defined 23 megacities with at least 10 million inhabitants; all but six of these are in the developing world. About half of these megacities are in the humid tropics and are expanding into forested regions and/or extracting resources from nearby forests (Fig. 2). Most cities in Latin America and the Caribbean, including those discussed herein, are located in areas exposed to natural hazards, and in general, flooding is the most frequent and greatest hazard for the 633 largest cities (United Nations, 2011). Rapid population growth in these urban centers means that traditional environmental understanding has been eroded, and more people are now at risk as megacities encroach on riparian corridors, floodplains, mountain fronts, and coastlines (United Nations, 2011). Moreover, the most likely occupants of these hazardous locations are often marginalized economically, increasing their vulnerability (IPCC, 2014).

20th century forest cover loss has been well described (FAO, 1997; Noble and Dirzo, 1997). This loss continues in the 21st century and recent work by Hansen et al. (2013) and Kim et al. (2015) shows that forest cover in tropical America is in decline. For example, from 1990 to 2010 in Panama and Venezuela, forest cover decreased from 4.6 to 4.01 M ha and 51.2 to 47.1 ha, respectively (Kim et al., 2015). The reduction and fragmentation of forest cover compromises ecosystem services derived from forested areas, and elevates risk for floods, landslides, wildfire, (and tsunamis, in the case of coastal forests). Moreover, flood and landslide risks are likely to increase over most land areas in the 21st century with projected increases in the frequency, intensity, and/or amount of heavy precipitation that are predicted as a result of a warmer atmosphere (IPCC, 2014). At the same time, warmer air temperatures and increases in intensity and duration of drought are likely over many land areas (IPCC, 2014), contributing to greater likelihood of drought and wildfires. Fluctuations between these extremes of drought and heavy precipitation are likely to occur in spatial and temporal patterns that may not conform with past weather and climate patterns.

To take advantage of hazard-mitigation ecosystem services, there is an increasing need for local land-management actions and adaptation, which includes sustaining diverse forest cover, minimizing soil erosion and degradation, assuring that road networks and essential infrastructure are well-planned (Larsen and Parks, 1997), and avoiding the most hazardous areas (Larsen and Torres Sanchez, 1998; Annan, 1999; Larsen and Wieczorek, 2006; IPCC, 2014). A recent review of these concepts is found in Cochard (2013), who describes hazard-mitigation ecosystem services as those that regulate global, regional and local climates (via carbon storage, evapotranspiration, and albedo), provide structural stability to soil substrates (reducing risk of shallow landslides, and erosion during flooding), retain and transpire water (reducing flooding frequencies and intensities in catchments); and buffer against solid and fluid mass impacts (landslides, rockfalls, snow avalanches, wind-driven sea waves, storm surges, and tsunamis).

Human use of forested watersheds and ecosystem services in the Americas, as elsewhere in the world, has increased substantially as global population has grown to more than 7 billion. The intensity of this use puts all ecosystem services at risk and requires attention at multiple societal and governmental levels so that these services are not severely compromised. This paper discusses early human uses of forests and riparian areas, describes examples of contemporary human uses and ecosystem services derived from three

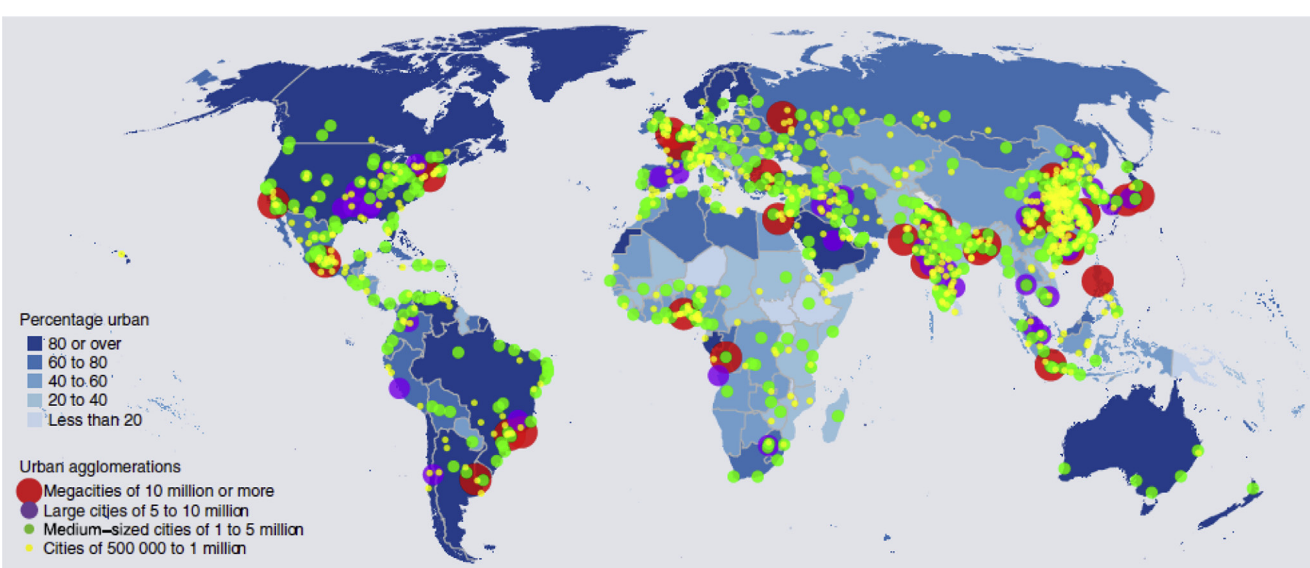

Fig. 2. Locations of urban agglomerations with at least 0.5 M inhabitants, 2014.
Source: United Nations, 2014.

Caribbean region humid-tropical forested watersheds and riparian corridors, and discusses hazard mitigation as an ecosystem service. A range of other important services are derived from these settings, i.e. carbon sequestration, maintenance of biodiversity, etc., but discussion of these services is beyond the scope of this paper. One of the natural hazards, tsunamis, is discussed only generally here, as tsunamis are an infrequent natural hazard in the Caribbean region but nonetheless have impacted the three countries discussed (Lander et al., 2002; Parsons and Geist, 2009).

4. Hazard-mitigation and ecosystem services in the Americas

The Millennium Ecosystem Assessment established a benchmark for ecosystem services based on a four-year United Nations assessment of the condition and trends of the world's ecosystems and the services that we humans draw from them (MEA, 2003). Although the term "ecosystem services" has become widely used and discussed, the concept is not new. For example, von Thünen (1842) discussed land use and landscape-derived services needed to sustain an agrarian-based self-sufficient state by describing a series of increasingly distant zones around a community. The most proximal zone was a source of vegetable, dairy and other perishable products, with the next zone being one used for forestry, providing wood for fuel and other products, with the outermost zone being one of less perishable crops and grazing animals.

Discussion of hazard mitigation as an ecosystem service is also not a new concept, but as governments and societies increasingly attempt to assign specific economic values to ecosystem services, reduction of hazard has received more attention (SCEP, 1970; MEA, 2003; Kosoya et al., 2007; Cochard, 2013; IPCC, 2014; Hall et al., 2015). Hazard mitigation however, is notoriously difficult to evaluate economically because of the dilemma of estimating a cost for an event that did not occur. As well stated by Kofi Annan, former UN Secretary General:

More effective prevention strategies would save not only tens of billions of dollars, but save tens of thousands of lives. Funds currently spent on intervention and relief could be devoted to enhancing equitable and sustainable development instead, which would further reduce the risk for war and disaster. Building a culture of prevention is not easy. ***While the costs of prevention have to be paid in the present, its benefits lie in a distant future. Moreover, the benefits are not tangible; they are the disasters that did NOT happen*** (UN Secretary General, 1999).

5. Tsunamis

Many hunter–gatherers/farmers that lived in tropical forests appear to have relied on riverine, estuarine, and coastal resources for food. Estuarine and coastal settings are a rich source of marine and terrestrial proteins but these benefits are offset by episodic hazards that are particular to coastal regions. Modern coastal benefits additionally include infrastructure for industry, ports, housing, tourism, and recreation.

The geologic and tectonic setting of the northern Caribbean is capable of generating tsunamis caused mainly by earthquakes in the region (Grindlay et al., 2005; ten Brink et al., 2006). Since the arrival of Europeans in 1492, there have been six documented tsunamis in the northern Caribbean that are associated with loss of human life (Grindlay et al., 2005). Tsunamis in the larger Caribbean region have affected 22 countries and administrative areas, including Central America and northern South America. According to Lander et al. (2002), there have been 27 tsunamis in the Caribbean region during the past 500 years of recorded history and the last destructive tsunami in the Caribbean occurred in 1946. Parsons and Geist (2009) report that for the 500-year history of the region, the northern Caribbean region seems to have higher tsunami hazard than the Caribbean coast of South America, including Venezuela.

Along the Pacific coast of Central America, for the period 1539 to 2013, 52 tsunamis have struck the region between Guatemala and Panama (Brizuela et al., 2014). Nicaragua, El Salvador, and Honduras are the most prone to tsunamis (Brizuela et al., 2014). These authors report that modeling and historical data indicate that the Pacific coast of Panama is likely to experience tsunami wave run-up of 0.5–3.5 m, with recurrence intervals of 50–500 years. The 500-year run-up, 3.5 m, is predicted for Panama's border regions with Costa Rica and Colombia, whereas the lesser run-up of 0.5 m is more likely for central Panama, including the capital city, across the recurrence interval range (Brizuela et al., 2014).

Tsunami hazard is partially reduced by the presence of natural coastal barriers such as barrier islands, coral reefs, mangroves and other coastal forests, and by the frictional resistance and shallowing of a tsunami wave by a broad shallow marine shelf such as that underlying the Gulf of Panama. These environments provide an ecosystem service in that they can reduce the impact of a tsunami or similarly, waves associated with large storms. A particular problem for Puerto Rico is that some sites of potential tsunami generation are close to the island, so warning time is short, minutes, rather than the hours. This is also be true for the heavily populated Venezuelan coastal state of Vargas, currently estimated at 353,000 people, and other coastal regions of Venezuela, although, as noted above, frequency of tsunamis along the Venezuelan coast has been low, at least for the 500 years of recorded history in the region (Parsons and Geist, 2009). As such, improved geologic understanding for the region is key for alert systems, public education, planning for construction, and siting of structures.

6. Panama

The 3313 km^2 Panama Canal watershed is located at 9° north latitude, with elevations that are mostly 300 m or less above sea level, although several peaks reach 1000 m elevation (Condit et al., 2001; Stallard et al., 2010). Annual rainfall is variable across the watershed, from a low on the Pacific side of the isthmus of 1600 mm, to more than 3000 mm on the Caribbean/Atlantic side. Approximately half of the watershed is in forest, mostly evergreen canopy, defined as tropical moist forest (Fig. 3). Forests near the Pacific coast are about 25% deciduous, while the wetter region near

Fig. 3. Chagres river valley, showing river flood plain and forest of multiple ages in the Panama Canal watershed.
Photo source: Smithsonian Institution, photo by Marcos Guerra.

the Atlantic has few deciduous trees and includes wet forest and submontane forest (Condit et al., 2001).

Ecosystem services derived from the Panama Canal watershed provide a robust example of multiple high-value services with national, regional, and global significance (Hall et al., 2015). Water is the most important control on virtually all canal watershed ecosystem services. Annual precipitation in the canal watershed was reported as a volume of 8.9 km^3 for the period 1993–2004 (IADB, 2008). Of this, roughly half, a volume of 4.4 km^3 streamflow, with 2.6 km^3 (59%) used for lockages of vessels transiting the canal, 1.2 km^3 (27%) for hydroelectric power generation, and 0.27 km^3 (6%) for drinking water supply, according to an average canal watershed water budget published by Stallard et al. (2010). The balance of the streamflow, 7%, is mainly evaporation and groundwater infiltration (IADB, 2008).

With respect to financial income as an ecosystem service of the canal watershed, the Panama Canal Authority (ACP) has 9000 employees, but activities directly or indirectly related to canal operations generate some 200,000 jobs (Panama Canal, 2015). A total of $1.91 billion in tolls were collected in 2014 for ships using the canal. About half of this is used for operations, and the balance goes into the general fund for the republic of Panama. Shipping companies pay these tolls because of major fuel and time savings, which prevents substantial burning of fossil fuel and consequent emission of greenhouse gases. For example a ship traveling between New York and San Francisco saves about 13,000 km by using the Panama Canal instead of going around Cape Horn. About 14,000 ships use the canal every year (ACP, 2014a,b). Most of these are from the U.S., followed by those from China, Chile, Japan, Colombia and South Korea. The fuel savings and greenhouse gas emissions achieved by the shipping companies from these countries (and others) is an example of a valuable ecosystem service provided by the canal watershed. For example, studies of the emissions of oceangoing container ships indicate that marine transportation is 32%–55% more efficient than rail transportation at typical operating conditions. According to Bittner et al. (2012), the addition of a new, expanded system of Panama Canal locks in 2016 is expected to reduce annual carbon dioxide emissions for US East Coast – Asia trade by 1.4 billion kg in 2025.

Approximately 197,000 m^3 of water was used for each vessel to transit the canal on average in recent years (Panama Canal, 2015). That totals 2.76 km^3 of water per year for shipping purposes, which, using the US $1.91 B in tolls, equals a value of 1.4 m^3 of water per dollar, or conversely, a value of $0.69 per m^3 of water. This is an overly simplistic valuation of the water, but provides a gauge of the value of this particular water use to Panama. The cost approximation does not include the important hydroelectric, esthetic, recreational, carbon sequestration, biodiversity maintenance, or overall ecosystem habitat values that are also provided by this water.

Drinking water and energy production are other major ecosystem services of this watershed. Drinking water for more than half of the nation's population is obtained from the watershed. Similarly, energy production for about half of Panama's electrical energy supply is hydroelectric, from dams in the canal watershed. In 2014, the canal generated $246 M in revenue from the sale of electric power and $29.4 M from the sale of potable water (Panama Canal, 2015). The Panama water authority charges approximately $0.26 per m^3 to the consumer for potable water (IDAAN, 2015).

As noted above, recreation, tourism, carbon sequestration and maintenance of biodiversity are other important ecosystem services derived from the Panama Canal watershed. Estimating dollar values for these services is a complex exercise, beyond the scope of this paper (see Hall et al., 2015 for discussion of some of these services).

Panama is fortunate in that it has fewer natural hazards than much of neighboring Central American or Andean region, where seismicity and volcanism are greater and the percentage of population located on or near mountain hillslopes is higher (Simkin et al., 2006). Nonetheless, some regions of Panama are vulnerable to earthquakes and volcanoes, particularly near the borders with Costa Rica and Colombia (Garwood et al., 1979; Sherrod et al., 2008). Volcán Barú, located near the Costa Rican border, is a potentially active volcano that has had four eruptive episodes in the past 1600 years, most recently in the past 400–500 years (Sherrod et al., 2008). In 1976, two large magnitude earthquakes (6.7 M and 7.0 M) affected an area of 450 square kilometers and associated landslides denuded 54 square kilometers of forest in Panama in the Darien province, near Colombia (Garwood et al., 1979). Earthquakes of this magnitude are considered to be rare in Panama and seismic activity in Panama, as noted, generally affects regions near the borders, where population density is low.

At 9° north latitude, Panama has the good fortune to be located just south of the hurricane zone. In the past 150 years of tracking of Atlantic-Caribbean hurricanes, none have directly impacted the country (Fig. 4). Nonetheless, floods caused by other weather systems, often convective disturbance associated with the location of the intertropical convergence zone (a dynamic band of convective moisture associated with the convergence of near-equatorial easterly tradewinds from the northern and southern hemispheres), are not uncommon, and flood risk is the principal natural hazard faced by Panama where many people live along or near riparian corridors. Storms with significant flooding in the canal watershed tend to occur at the end of the rainy season, for example: October 1923, November 1931, November 1932, November 1966, December 1985, December 2000, November 2004, and, December 2010 were all periods of major flooding in Panama (Cuevas, 2011). A notable example of a major storm on this list, with associated significant flooding, is the event of December 2010. This storm, known as La Purisima, serves as a good illustration of flood and landslide hazard mitigation as an ecosystem service in the Panama Canal watershed (Espinosa, 2011; ACP, 2014a,b). The storm also illustrates what happens when hazard-related ecosystem services are at or beyond their limits as a rare, large-magnitude storm has major impacts on hillslopes and riparian corridors.

La Purisima, described as the largest three-day storm in Canal watershed's 100-year recorded history, was associated with the interaction of a frontal system and the intertropical convergence

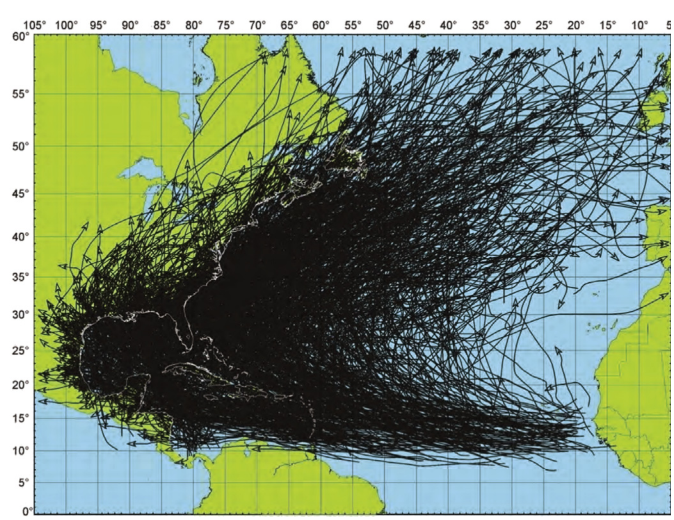

Fig. 4. North Atlantic tropical storms and hurricanes, 1851–2006.
Source: NOAA, 2009.

zone, and produced 760 mm of rainfall in 24 h. The three-day mean streamflow for the principal Canal watershed fluvial system, the Chagres River (Fig. 3), was 908 m^3 per second, and total streamflow volume of 235 M m^3 was calculated. This volume has a recurrence interval of approximately 300 years and was the largest flow recorded in the 78 years since record keeping began (Espinosa, 2011). In a rare mitigation step, the ACP was forced to open the canal locks to discharge water, halting ship transit through the Canal for 17 h (Espinosa, 2011). Additionally, the rainfall caused more than 500 landslides and temporarily closed the two roads that connect the two major cities of the country, Panama City and Colón. Landslides also introduced a massive pulse of sediment into river channels, raising turbidity at a key public supply intake to 600 Nephelometric Turbidity Units, closing water supply facilities and leaving parts of Panama City without normal water supply for 50 days. These aspects of the environmental response to this rare high-magnitude storm illustrate what happens when ecosystem services are fully or partially overwhelmed.

About half of the Canal watershed has been deforested, and the official policy in the Canal watershed (Law 21) is to reforest in anticipation of regaining ecosystem services (Stallard et al., 2010). Canal watershed locks and dams were at their design limits during this flood, meaning that if much more water was moving through the system, which would have been the case if more of the watershed had been deforested (Ogden et al., 2013; Stallard, 2015) the dam and the locks could have failed—a major disaster for Panama and global shipping. This averted disaster shows the high ecosystem service value of the forested areas of the Panama Canal watershed. Important services were temporarily compromised, but an essential measure of the value of an ecosystem service with regard to hazard mitigation is loss of life. Despite the large magnitude of this storm, no casualties were reported. The great importance of maintaining forest in this watershed, with extensive high-value infrastructure downstream, as well as critically important public water supplies, cannot be overemphasized.

With respect to ongoing management of flood hazard as an ecosystem service, the ACP has a flood control program that identifies, mitigates, and responds to conditions that pose a danger to communities and property located along riparian corridors, and on key ACP reservoirs and Canal infrastructure that could potentially interrupt Canal operations (Cuevas, 2011). The ACP, like many agencies that manage multi-use reservoirs (i.e. reservoirs used for a combination of flood control, hydroelectric energy production, drinking water supply, irrigation, and recreation) uses a complex set of metrics to control watershed reservoir levels to ensure water availability for human consumption, ship transit, and hydro-power generation. One of the annual challenges faced by the ACP is associated with the timing and amount of rainfall delivered to the canal watershed by storms at the end of the wet season in December. The largest storms are often at the very end of the season, when reservoirs may be at, or close to their maximum volume.

7. Puerto Rico

Puerto Rico, the smallest island (9000 km^2) of the Greater Antilles, is located in the northeastern Caribbean at 18° north latitude, about 1700 km southeast of Miami, USA. It is an island of high relief with a maximum elevation in the central east-west trending mountain range of 1338 m. The rectilinear island measures 65 km north-south, and 180 km east-west. Forest removal began in the 1600s as land was cleared for agriculture by European settlers. After three centuries of extensive subsistence and plantation agricultural land use, most (94%) of Puerto Rico was deforested by the late 1940s (Gould et al., 2012). A shift away from agriculture towards industry began in the 1950s and resulted in much abandoned pasture and farmland that is now in secondary forest (Gould et al., 2012).

The Luquillo mountains, the focus of this discussion, are located in eastern Puerto Rico, and after the Smithsonian research sites in Panama, are the area with the longest, most detailed scientific record of natural processes in the neotropics (Leigh et al., 1983; Heckadon Moreno and Ibáñez, 1999; Condit et al., 2001; Ibáñez et al., 2002; Walker and Bellingham, 2011; Harris et al., 2012; Murphy and Stallard, 2012). Both regions have more than 100 years of extensive scientific data collection with resulting peer-reviewed scientific publications surpassing several thousand at each site.

Topography in the Luquillo Mountains is rugged, stream channels are deeply incised, and annual rainfall averages more than 4000 mm (Murphy and Stallard, 2012). The mountains are largely within the boundaries of the El Yunque National Forest (EYNF), also known as the Luquillo Experimental Forest (LEF), an intensely studied 11,300-ha preserve that is completely forested and under the administration of the U.S. Forest Service (USFS). Because of the 1000 m elevational gradient, multiple forest types are present in the LEF, including subtropical moist forest, subtropical wet forest, with subtropical rain forest, lower montane wet forest, and lower montane rain forest at high elevations (Gould et al., 2012).

Prior to the 1898 U.S. invasion, the Luquillo Mountains had been afforded some degree of forest protection during the 19th century by the Spanish crown, because of the value of the hardwood there for ship building. This, along with localized cutting of wood to make charcoal, was one of the first described ecosystem services derived from the forest. During the 20th century, the mountains gained new uses as they were managed by the USFS as a recreational area, and as the Puerto Rico Water Authority (PRASA) began to use high-quality streamflow for drinking water supply in the region (Crook et al., 2007). A first approximation of the value of public-supply water from the LEF was estimated by Crook et al. (2007) using streamflow from the nine rivers that drain the mountains. These rivers have modest water extraction sites, operated by PRASA, which is required to limit extraction in order to maintain minimum streamflow so as to sustain ecological function of the streams (PRASA, 2012). Water is extracted from 34 locations along these rivers and on a typical day, 70% of streamflow from within the forest is diverted before reaching the ocean. Two intakes draw particularly large amounts of water: the intake at Río Mameyes (outside of the forest) which is permitted to extract 18,940 m^3/day, and the intake at Río Fajardo, permitted to extract 45,460 m^3/day (Crook et al., 2007).

In 2004, an approximate total of 0.252 M m^3/day of water was withdrawn from streams draining the LEF. PRASA charges \$10.60 per m^3 for residential customers (this cost includes a wastewater charge as well). Using this price to the consumer for potable water in Puerto Rico, the annual volume of potable water withdrawn from the LEF has a total maximum possible value of approximately \$2.67 M.

Hydropower represents only one percent of total electric energy for Puerto Rico, most of which (69%) is generated by oil burning power plants (Liu et al., 2013). Hydropower generation is severely limited because the 224 rivers in Puerto Rico are relatively short in length (a few 10's of km), with only modest catchment size. A small hydroelectric facility on the south side of the Luquillo Mountains, on the Río Blanco, has a capacity to generate 5 MW according to Liu et al. (2013). This is 12% of the 41.8 MW capacity from a total of 21 hydroelectric units on six rivers around the island. Puerto Rico's electricity costs are about 27 cents per kW-hour, approximately twice what they are in the U.S. (Gross, 2014). One Megawatt equals 1000 kW, so at \$0.27 per kW, if the Río Blanco facility was operating at full 24 h/day capacity (it is reportedly not doing so), it would be producing electricity valued at $32,400 per day ($11.8 M/y).

The USFS describes a "Site Visit" as the entry of one person to a National Forest site or area to participate in recreational activities for an unspecified period of time. A "National Forest Visit" can be composed of multiple "Site Visits". In 2006 there were 1.336 million Site Visits to the EYNF, and in 2011, there were 1.123 million (written communication, Jose Ortega, Recreational Program Leader, El Yunque National Forest, Puerto Rico, USFS, September 8, 2015). The American Sportfishing Association (2007) quantifies the economic value of visits to USFS managed lands that are made for hunting, fishing and wildlife-viewing activities. Hunting and fishing are not permitted within the EYNF boundaries, so information for Puerto Rico was restricted to wildlife-viewing activities. Birdwatching is one the principal wildlife-viewing activities as Puerto Rico, in combination with the U.S. Virgin Islands, has approximately 270 species of birds (Raffaele, 1989). Additionally, there is great interest in the dwindling populations of the once widely-distributed Puerto Rican parrot (significant resources have been invested by U.S. and Puerto Rico governmental agencies to reconstitute this species). Between 2000 and 2003, an estimated annual average of $3.2 M was spent in Puerto Rico for wildlife viewing associated with the EYNF (ASA, 2007). As the number of visitors to the Forest has increased since 2003, it is likely that the economic contribution of wildlife viewing associated with the EYNF has also increased. USFS data show an EYNF recreational visitor rate in excess of 1,000,000 per year.

Puerto Rico is susceptible to earthquake, tsunami, landslide, and flood hazards, listed here in order of increasing loss of life during the 500 years of recorded history. There are no active volcanoes on the island. The island lies in a zone of active seismicity (von Hillebrandt-Andrade and Huerfano, 1999; Clinton et al., 2006) and small, non-damaging earthquakes, generally registering less than 4.0 on the Richter scale are, on average, a daily occurrence. At least seven local and regional large magnitude earthquakes (greater than 7.0 magnitude) have affected the island during recorded history, including in 1615, 1670, 1751, 1776, 1787, 1867, and 1918 (Clinton et al., 2006). The 1918 earthquake, whose epicenter was in the Mona Passage, off the west coast of the island, was recorded on October 11, 1918 and was estimated to have measured 7.3 on the Richter scale. The earthquake and associated tsunami killed 116 people (40 deaths attributed to the tsunami) (Reid and Taber, 1919; Clinton et al., 2006). Extensive damage to buildings (mainly in Mayagüez, on the west coast of Puerto Rico), and a number of landslides and rockfalls were documented.

The island of Puerto Rico is characterized as being moderately to highly susceptible to landsliding (Monroe, 1979). The majority of landslides documented during the 20th century were triggered by intense or prolonged rainfall (Monroe, 1979; Jibson, 1989; Larsen and Simon, 1993). During the period 1959 to 1991, 41 storms caused 10's to 100's of landslides on the island, resulting in infrastructure damage and loss of life (Larsen and Simon, 1993). The worst of these was in 1985 when 129 people were killed; most of these deaths were in a single unplanned community on a hillslope near the city of Ponce (Jibson, 1989).

Mitigation of landslide hazard is achieved largely through the practices of strong governance. An important part of the governance is minimization of forest removal in steeply sloping regions and zoning to prevent housing or other construction on, or near the base of steep hillslopes (Keefer and Larsen, 2007). Forested hillslopes provide a landslide hazard-mitigation ecosystem service that also applies to flood hazard mitigation for people and structures located along riparian corridors. The presence of forest reduces storm runoff volume and reduces storm runoff peak streamflow in rivers, spreading this lesser peak runoff volume over a longer time period than would occur if no forest was present (Ogden et al., 2013).

Larsen and Torres Sanchez (1998) documented a higher average frequency of landslides on hillslopes in agricultural land use as well as in land used for roads and structures compared to forested areas in three regions of Puerto Rico. They showed that although mean annual rainfall is high, intense storms are frequent, and hillslopes are steep, forested hillslopes are relatively stable as long as they are not modified by humans. The greater the modification of a hillslope from its original, forested state, the greater the frequency of landslides. Additionally, in three regions of Puerto Rico studied by Larsen and Torres Sanchez (1998), a slope angle in excess of 12° is a threshold above which the frequency of landslides increased, demonstrating that maintenance of forest cover on steeper hillslopes is particularly important.

In its recorded history, floods are the natural hazard that have caused the largest cumulative loss of life in Puerto Rico, which is the case for most countries around the world. Major floods during the 19th and 20th centuries were associated with rainfall delivered by tropical disturbances (depression, storms, hurricanes), and killed thousands (Ramos-Ginés, 1999). Most of these flood deaths were prior to 1940 when zoning for housing location and construction standards was non-existent. Improved governance, including planning and zoning, has greatly reduced loss of life from flooding across the island. Strong governance is also evident in Puerto Rico where an effective coordinated response system of governmental agencies each time that a tropical disturbance or other heavy rain threatens the island, general education of the public for hazard preparation, and a well-informed, decentralized civil defense network have combined to reduce loss of life to near zero during these large storms.

8. Venezuela

Vargas State, on the Caribbean coast, just north of Caracas, is the geographic focus of this example. Located at 10° 36′ north latitude, Vargas is a narrow rectilinear state that extends some 50 km to the east from the Caracas airport (Aeropuerto Internacional Simón Bolívar), which is on the coast at Maiquetia. Vargas is notable with respect to hazard vulnerability because its population resides on densely populated coastal alluvial fans. These communities are bounded closely on their south by a 2000 m high east-west trending mountain range, the Sierra del Litoral, commonly called the Sierra de Ávila. The crest of the Sierra de Ávila rises 2765 m above sea level within 6–10 km of the coast. Much of the Sierra de Ávila is a forested preserve established in 1958, called Parque Nacional Waraira-repano, with steeply sloping, forested hillslopes. The rivers and streams of this mountainous region drain to the north and emerge from steep canyons onto alluvial fans before emptying into the Caribbean Sea. The rainy season in coastal Venezuela normally lasts from May through October. Mean annual precipitation at the airport at Maiquetia, which is 43 m above mean sea level, is 750 mm (MARN, 2000). However, there is a strong orographic gradient and annual rainfall can exceed 1000 mm in the upper part of the Sierra de Ávila. This moisture gradient and a marked dry season explain the multiple forest types that are present in the Sierra de Ávila, which although are largely evergreen forest, range from xeric and dry tropical forest in the low elevations to montane wet forest and sub-páramo forest at upper elevations, to cloud forest near the mountain crests.

Vargas state began a period of rapid development beginning in the 1970's, taking advantage of a multi-lane highway connecting the city of Caracas with the Caracas airport located on the coast at Maiquetia. Relatively little low-gradient area is available in Vargas for development, with the exception of the alluvial fans, where by the late 1990's, the population had grown to approximately 300,000. Because most Vargas residents had lived there for fewer than 30 years, local knowledge of debris-flow and flood hazard was limited (Larsen and Wieczorek, 2006).

Economically quantifiable ecosystem services derived from the Sierra de Ávila are modest. Streams are short and steep, eliminating hydropower as an option and making potable freshwater withdrawals challenging. Because of the steep gradients and narrow canyons through which streams flow, few areas exist for water storage, so water extraction is limited to local, low-volume run-of-the river intakes and small impoundments. In addition, because of strong seasonal rainfall variation, the smaller catchments host only ephemeral streams, making water supply unreliable.

Recreational use is perhaps the greatest economic value of the Sierra de Avila, with the national park (Parque Nacional Warairarepano) serving visitors and residents of the adjacent city of Caracas, with a population of 5.2 M. Visitation to the park consists mainly of day-hikers who use an extensive hiking trail network. Two cableways carry visitors from Caracas and from Macuto (in Vargas) to the top of the mountain (Pico El Ávila) where a few small facilities exist for recreation and food purchase. Extensive recreational use is limited in part because of limited economic investment in facilities and trail maintenance.

Vargas is vulnerable principally to seismic, tsunami, landslide, and flood hazards, listed roughly in order of increasing frequency, but not necessarily potential impact. Large earthquakes have affected the Vargas state and city of Caracas over the past 400 years. Notable earthquakes occurred in 1641, with an estimated 300 to 500 killed; 1812, 7.7 M, and 26,000 people killed; 1875, magnitude unknown, death toll in the 1000's; 1894, 7.0 M, 319 deaths; 1967, 6.5 M, killed 240, hundreds injured, more than $100 million in property damage; 1997, 7.0 M, killed 81 people; 2009, 6.3 M, injuring at least 14 people and damaging many structures; 2009 M6.3; 2010, 5.6 M (USGS, 2015).

Landslides and flooding are relatively common in Vargas. Historical records indicate that severe flooding and/or landslides occurred in this region in 1740, 1780, 1797, 1798, 1909, 1912, 1914; 1938, 1944, 1948, 1951, and 1954 (Rohl, 1950; Singer et al., 1983; Audemard et al., 1988; Salcedo, 2000). Because of the extremely steep stream channels and short channel lengths, the floods are invariably flash floods, which are particularly hazardous as little to no warning can be given to downstream communities. Furthermore, because stream channels actively laterally erode and migrate across alluvial fans, riparian corridors in these geomorphic settings are among the most hazardous environments in the world.

A rare, high-magnitude storm in northern Venezuela in December 1999 triggered debris flows and flash floods, and caused one of the worst natural disasters in the recorded history of the Americas. An estimated 10,000 to 15,000 people were killed and 15,000 people were rendered homeless when approximately 41,000 houses were damaged, with almost half of these structures being declared uninhabitable (Larsen and Wieczorek, 2006; Fernandez, 2009). The debris flows and floods inundated coastal communities on the alluvial fans at the mouths of the coastal mountain drainage network and destroyed property estimated at more than $2 billion. Landslides were abundant and widespread on steep slopes from near the coast to slightly over the crest of the mountain range. Some hillsides were entirely denuded by single or coalescing slope failures, which formed massive debris flows in river channels flowing out onto the densely populated alluvial fans at the coast and extending the shoreline in many areas (Fig. 5). The massive amount of sediment derived from 24 watersheds along the 50 km of coastline during the storm and deposited on alluvial fans and beaches has been estimated at 15–20 M m^3 (Larsen and Wieczorek, 2006). Sediment yield for the 1999 storm from the

Fig. 5. View to south, Vargas, Venezuela, showing numerous landslide scars on steep hillslopes and narrow river channel emanating from mountain front onto highly developed coastal alluvial fan. Note shoreline progradation resulting from massive quantity of sediment delivered onto and across alluvial fan.
Photo source: M.C. Larsen, January 2000.

approximately 200 km^2 drainage area of watersheds upstream of the alluvial fans was as much as 100,000 m^3/km^2. The combination of rapid economic development, much of it unplanned and unregulated, the dynamic geomorphic environment (i.e. extremely steep hillslopes with high-gradient streams), the recent large population taking advantage of proximity to the capital city of Caracas, and the severe rain storm, all contributed in the death of approximately 5% of the population (300,000 total prior to the storm) in Vargas state.

By 2006, Vargas state population had partially returned to the population estimated in 1999, and rebuilding of damaged infrastructure was in progress. However, the value of real estate had declined by as much as 70%. In the 15 years following the disaster, governmental work has focused on the construction of 5000 houses, plus 63 small dams and 22 km of stream channelization as part of an effort to reduce some of the flood potential (Fernandez, 2009; Noriega Ávila, 2014). In addition, approximately 500 km of roads are being reconstructed. Many of the damaged homes remain so, with a number of these being occupied without legal title by those who lost their homes in the 1999 disaster.

9. Discussion

Maintaining forest cover in watersheds provides numerous important ecosystem services including a service that reduces, but does not eliminate hazards such as landslides and floods, and (for forest in coastal areas) tsunamis. A recent example of this hazard-mitigation service in Panama was the 2010 storm of record for the Canal watershed (Espinosa, 2011). Landslide and flood impacts would likely have been far worse if the less of the watershed had been forested. The hazard-reduction ecosystem service is recognized because a deforested canal watershed could have had 50% more runoff, perhaps more than twice the sediment generation, and possibly a dam failure, according to work by Stallard (2015). Additionally, landslide hazard is reduced by maintaining steeply sloping montane watersheds in forest, thereby limiting exposure through prevention of human occupation and development of infrastructure in these settings.

Like Panama, Puerto Rico gains similar natural hazard reduction benefits from maintaining forest on hillslopes (e.g. the 11,300 ha El Yunque National Forest). Maintenance of forest cover is particularly important because much of the island is mountainous, with numerous small communities distributed throughout the countryside. Unfortunately, many of these communities are located on, or at the base of steep hillslopes along riparian corridors, which, typical of a largely mountainous region, offer one of the relatively few low-gradient locations for housing and other infrastructure such as schools and hospitals. In addition, limited economic opportunity means that a number of unplanned, unregulated communities exist, in locations where individuals or groups have occupied otherwise unused land, in hazardous areas along coasts, steep hillslopes, and riparian corridors. These areas are typically zoned as no-build areas, but without strong local and national governance, sometimes become unregulated, informal settlements.

In the Venezuela example, some degree of hazard mitigation was afforded by the stewardship of forested watersheds with the establishment of the Waraira-repano national park in the Sierra de Ávila. This park, upstream of the coastal communities that developed rapidly after 1970, provides this ecosystem service because it is forested. However, because it has extremely steep slope gradients, the protective effect of the forest cover is limited (Fig. 5). Furthermore, the mitigation effect of the national park for the 1999 storm was reduced because of two additional factors: 1) the extremely rare storm magnitude, estimated to have an approximate recurrence interval variably estimated at between 150 and 1000 years (Larsen and Wieczorek, 2006); and, 2) the lack of planning and regulation in the siting of houses and other structures on extremely vulnerable alluvial fans along the Vargas coast (Fig. 5).

Alluvial fans are one of the most hazardous geomorphic settings on earth. Re-occupation of these locations would expose infrastructure and people to significant risk. The alluvial fans exist because flash floods and debris flows emanating from stream channels draining steep mountain fronts episodically deliver massive quantities of water and sediment out into lower gradient surfaces fronting mountain ranges. Over time scales of centuries to millennia, which is of course beyond human lifetime experience–limiting the accumulation of direct observational knowledge, episodic events build the fan surface in a largely unpredictable, violent fashion. As such, infrastructure built on the alluvial fan is likely to be impacted or destroyed unless significant, costly preventative planning and engineering works are undertaken. With respect to planning, the location of structures as far away from the mountain front and stream channels as possible reduces their vulnerability. Engineering works include barriers and large debris-flow/flashflood catchment basins upstream of communities. The usual challenges associated with these structures are the high cost to build them and the sustained high cost of maintaining them, including the requirement for regular removal of any debris trapped in the basins. Additionally, without strong governance and planning, these types of engineering works, like levees along rivers, sometimes serve to increase vulnerability by giving a false sense of security to those who might choose (or have no economic alternative) to reside on or near a mountain front or river flood plain (White, 1945).

Unfortunately, "*Although landslide hazard evaluation and mitigation strategies are advancing in many fundamental areas, the loss of life and destruction of property by landslides around the world will probably continue to rise as the world population increases, urban areas of many large cities impinge more on steep slopes, and deforestation and other human landscape alterations affect ever-larger areas*" (Keefer and Larsen, 2007).

These three American examples, while focused on contemporary uses of forested watersheds and hazard mitigation as an ecosystem service, also illustrate broader themes of prehistoric human use and adaptation to humid tropical forest environments and consider a range of forest uses by humans. While archaeologists and anthropologists have focused on food sources and the nutritional benefits of tropical forests, it is important to note that water availability, and the risks and benefits associated with living near rivers and coasts, also play an important role in the success of human adaptation to forested environments. While floodplains and nearby forests provide regular, reliable access to plentiful freshwater and associated resources, they are also subject to episodic natural hazards which are partially offset by forest cover (as shown from these three examples). The examples demonstrate that local knowledge of water availability and understanding of risk, are crucial for successful, long-term human occupation and use of forested and other areas. One of the better known early examples of this is from the Nile River valley in Egypt, where human occupation during the African Humid Period, ca. 8000 to ca. 5500 cal yr BP, was adapted to annual sediment-laden floods that helped to sustain nutrient concentrations in soils used agriculture (Brooks, 2006; Bernhardt et al., 2012).

10. Conclusions

Modern human adaptation to, and management of riparian corridors and montane areas provides insights into how early humans interacted and exploited these environments. Living on or near floodplains or mountain fronts exposes communities to hazards but brings benefits as well. Areas in or near steep mountains and high-gradient rivers are riskier than those that are more distant from mountains because of more frequent landslides and floods that rise quickly. Foragers and hunters would be better able to exploit these riskier environments because of their more ephemeral, mobile occupation. Agriculturalists gain advantage at the more distant locations, which generally have higher predictability of flood timing, plus lower risk and slower increases in river flow during storms, thereby minimizing potential for loss of life. By careful monitoring and timing the annual planting of crops, agricultural communities gained advantage from the periodic deposition of mineral and organic nutrients in flood deposits (Fig. 3).

Panama, Puerto Rico, and Venezuela provide a variety of contemporary examples of ecosystem services derived from forested watersheds, and offer insights into how we consider and take advantage (or sometimes ignore) the value of hazard mitigation as an ecosystem service. Each location shows the benefits and limitations of the ecosystem services provided by forested watersheds with respect to hazard mitigation. The examples also show the importance of strong governance, which includes thoughtful, science- and engineering-based infrastructure zoning, planning, and design, and the maintenance and expansion of forest cover in montane watersheds. Additionally, mountains and rivers are often transboundary, crossing political and cultural divisions. As such, effective management of ecosystem services is highly dependent not just on local strong governance, but also on the cooperation of local stakeholders, regional and national institutions, and in many cases international institutions (ISDR, 2005).

The examples presented here additionally illustrate a key limitation of hazard mitigation as an ecosystem service: natural hazards are highly stochastic in nature. Nonetheless, while the timing, frequency, and magnitude of catastrophic events is difficult (floods, landslides), or impossible (earthquakes) to precisely predict, (seismically-triggered tsunamis cannot be predicted, but because there is often lead time of minutes to hours following an earthquake, warnings can be issued) with detailed, long-term study, a probability of occurrence for a given region can be estimated at a scale of 10's to 100's of km^2 with reasonable confidence.

Even early humans had some understanding of flood frequency, and flood hazard is the most predictable of the hazards discussed here: we know where, and, in larger watersheds, when floods are likely to affect population and infrastructure. In spite of this, as stated by Gilbert White: *Floods are an act of God, but flood losses are largely an act of man* (White, 1945). A similar unattributed Spanish-language statement: "*Dios siempre perdona, el hombre a veces, la naturaleza nunca*". An emerging challenge is that flood (and landslide) hazard mitigation challenges are now increasing because the long-standing approach for estimating flood probability is based on the principal of stationarity, which means that the present likelihood of floods in a watershed can be well determined by examining the past 30 or more years of streamflow record. This approach has been weakened by changing rainfall and streamflow patterns observed in recent decades (Milly et al., 2008). The IPCC (2014) Fourth Assessment Report concluded that climate change has begun to affect the frequency, intensity, and length of many extreme events, thus increasing the need for additional timely and effective adaptation.

With respect to assigning economic values to hazard mitigation, these will always be difficult to precisely calculate because, as stated by former U.N. Secretary General Annan, "*the benefits are not tangible; they are the disasters that did NOT happen*".

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