MANAGING WATERSHEDS FOR ECOSYSTEM SERVICES IN THE STEEPLAND NEOTROPICS

Smithsonian Tropical Research Institute

Managing Watersheds for Ecosystem Services In the Steepland Neotropics

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Finally, we acknowledge and are grateful to United States Peace Corps and the U.S. National Science Foundation for their support to the conference and report.

Preface

Many Latin American economies are experiencing an exciting period of growth. However, without careful planning, increasing human population and demand for food, energy, water, and land will put natural resources at significant risk. Understanding the flow of goods and services provided by ecosystems and how this flow is affected by human activity has become essential to ensure long term sustainable development. Watersheds and forests, main subjects of this publication, provide an endless number of services to societies with enormous economic benefits—from freshwater supply and flood control to air purification and climate regulation – making their sustainable management fundamental to safeguard this continuous flow of natural wealth.

The Latin America and the Caribbean region has been deemed the superpower of biodiversity: with only 16% of the planet's land, it holds 40% of the world's biological diversity, including seven of the world's 25 biodiversity hot spots and six of the 17 megadiverse countries. The Inter-American Development Bank (IDB), aware of the region's natural capital, has a long history investing in this powerful competitive advantage. The Bank's strengths and experience create an excellent opportunity to expand biodiversity conservation and promote ecosystem services maintenance in this highly biodiverse region. In particular, the IDB's Biodiversity and Ecosystem Services (BIO) Program was created in 2012 looking to put Latin America and the Caribbean at the forefront of environmental economics and promote sustainable development by integrating natural capital into the IDB´s general development strategy.

The BIO Program strives at setting a solid regional dissemination network of information on the value of ecosystem services and their relationship to sustainable development. The productive collaboration between Smithsonian Tropical Research Institute (STRI), the IDB and other organizations resulted in a milestone regional conference and publication on "Managing Watersheds for Ecosystem Services in Steepland Neotropics". This effort represents the first of many initiatives from the BIO Program and STRI to mainstream and disseminate cutting edge knowledge and research on the benefits of managing watersheds. We hope this initiative will provide a forum for rich cross-sectoral discussions on real experiences and best practices in mainstreaming biodiversity, ecosystem services, and watershed management.

I am grateful to STRI, the Environmental Leadership and Training Initiative (ELTI), and PRORENA for their dedication, hard work and valuable insights. Special thanks go to Jefferson Hall and his Agua Salud Project colleagues and Jacob Slusser, whose ground-breaking research and effort to convene practitioners, scientists and policy makers led to this publication. I would like to acknowledge the support given by the BIO Program team to the STRI team in the preparation of the conference and e-book, especially Michele Lemay, Enrique Ibarra and Carmen del Río.

The IDB and the BIO Program are committed to building capacity and creating knowledge on the role of natural capital in sustainable development in the region.

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Preface

Global climate and land use change caused by the activities of 7.3 billion humans are directly or indirectly affecting all parts of our planet. The loss of biodiversity and extinction of species is well documented as landscapes are converted to meet human needs. Climate change resulting from increasing concentrations of CO_2 and other greenhouse gases in the atmosphere is warming our planet, with glaciers in retreat, islands and coast lines threatened by sea level rise, droughts becoming more intense and longer-lasting, wildfires more frequent and larger, and fresh water supply stressed because of reduced mountain snowpack, higher evaporation, and poor management practices around the world.

We face significant challenges in addressing these and other negative impacts of climate and land use change. Scientific understanding of these processes is key to our response, as we learn to adapt to, and mitigate these global changes. New science-based tools and good governance will allow us to undertake the necessary steps to manage lands for the benefit of all while not sacrificing biodiversity, forest, water, and other natural resources of our planet.

At the Smithsonian Tropical Research Institute (STRI) we strive to understand and sustain a biodiverse planet. Researchers at STRI study terrestrial and marine environments in the present and the past, work from the scale of molecules to ecosystems, and conduct research in both theoretical and practical realms. We educate children and the public in general, mentor students, collaborate with scholars, and make our science relevant and available to decision makers. The Agua Salud Project is a STRI led effort to understand ecosystem function in the provision of a diverse suite of ecosystem services produced by seasonally moist forests and how these services change with land use and climate change. We participate in the Environmental Leadership Training Initiative (ELTI), a program based at the School of Forestry & Environmental Studies at Yale University (Yale FES) that is designed to bring the best science to landscape management decision makers.

STRI hosted a two-day conference in Panama in 2014 under the auspices of ELTI and the PRORENA project (a collaboration between STRI and Yale FES with the goal of understanding the barriers to reforestation with native tree species) in collaboration with the Biodiversity and Ecosystem Services Program of the Inter-American Development Bank. The conference highlighted new science and policy developments for watershed management in the steepland Neotropics: an area of important cultural heritage and biodiversity that is under intense economic and climate and land use change pressure.
The conference:

- identified advances in science, governance, and landscape management that are focused on the needs of residents in the steepland Neotropics;
- presented research at selected sites that addresses fundamental questions related to the provision of fresh water and interactions with other ecosystem services;
- described novel approaches to employing economic incentives to improve management that are now moving beyond pilot stages to larger scale implementation;
- provided examples of where and how good governance is advancing.

This report synthesizes the results of the conference and includes recent research and practices related to watershed management in the region. It provides a biophysical understanding of ecosystem function for key land uses in the area, summarizes ecosystem services, addresses the implications of climate and land use change, and provides socio-economic foundations of ecosystem services and advances in the region. The report presents a road map for improving watershed management and provides selected case studies to illustrate examples of where advances are being made.

I thank Michele Lemay and her team at the Biodiversity and Ecosystem Services Program of Inter-American Development Bank for their efforts to advance management and policy and base it on the best available science. I am grateful to PRORENA and ELTI – particularly Jefferson Hall, Jacob Slusser, and Saskia Santamaria – for their efforts in organizing an informative and innovative conference. I congratulate all of the authors and contributors for their efforts in writing a first of its kind report describing the foundations of, and highlighting the best practices in watershed management in the region. Lastly, special recognition goes to Jefferson Hall, Vanesa Kirn, and Estrella Yanguas, for their efforts in producing this important new e-book.

Matthew C. Larsen
Director
Smithsonian Tropical Research Institute

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Executive Summary

Understanding Linkages Between Ecosystems and Human Well-being

Humans derive a great number of goods and services from terrestrial ecosystems (Millennium Ecosystem Assessment, 2003). Some, like timber, fruits, bush meat, and other forest based food stuffs, are evident but others are not so obvious. Increasingly policy makers have realized the importance of forests and other ecosystems in sequestering carbon. Scientists and conservationists have long called attention to the value of Neotropical landscapes for biodiversity conservation and there is much interest in the potential of Neotropical forests and other ecosystems to regulate water flows and serve as filters, ensuring clean water flows from the landscape. All of these goods and services are part of what is collectively referred to as ecosystem services, or goods and services that are provided to humanity through the unimpeded natural function of the ecosystem.

The Millennium Ecosystem Assessment (MA) highlighted the interdependence between human well-being and the natural processes that drive ecosystem function. An influential review by Hooper et al. (2005) further summarized the science linking biodiversity to the natural ability of ecosystems to survive, thrive, and thus continue to provide a vast array of goods and services to humanity – many of which have long been taken for granted. While thinking has advanced beyond the conceptual framework of the Millennium Ecosystem Assessment in terms of designating ecosystem services as (1) supporting, (2) provisioning, (3) regulating, and (4) cultural, it has allowed decision makers and scientist to advance their understanding and management of ecosystems with an emphasis on different objectives depending upon the goals of different stakeholders.

A basic understanding of the biophysical processes that drive ecosystems will help policy makers and managers better understand and appreciate the benefits provided by natural areas as well as understanding the trade-offs inherent to the tough decisions required to ensure human well-being in an era of global change. Land and ecosystem management, however, is a human endeavor driven by socio-economic forces and dependent upon the principles of good governance for positive outcomes. It is critical to understand the different social and economic drivers of change as well as the scales upon which they operate in a given management unit. It is of equal importance to disentangle the jurisdictional web governing land management.

Watersheds and the Steepland Neotropics

Watersheds are areas of land bounded by ridges of hills or mountains for which all the rainfall falling within the land either returns to the sky through evapotranspiration, flows overland to a common stream, or enters the soil matrix. They can be extremely large and cross different ecosystems (e.g., a *Paramo*-Montane Forest-Lowland Forest altitude gradient) or be limited to a few hectares. Because they form hydrological boundaries, they are an attractive study system for scientists and for managers within which to manage water. They are also an attractive socioeconomic unit in that they link upstream communities to downstream water users.

Steeplands include areas of rolling hills and mountains defined as "land with an average slope of more than 12%" (Shaxson, 1999). They define the drainage basins from which water flows to towns and cities and are home to rural farmers. Because of their slopes they are not conducive to mechanized agriculture. While traditional farming systems here have been subsistence systems using traditional and relatively low impact technologies, "*there is a growing awareness that sustainability of subsistence agriculture on steeplands is steadily deteriorating as a result of rapid growing population and overexploitation of the land resource base*" (Shaxson, 1999). Major population centers throughout the Neotropics get their water as well as a host of other ecosystem services from steeplands surrounding and above them in hinterland watersheds. Because the livelihoods and well-being of 100s of millions of people in the Neotropcis are linked to steepland ecosystems, it is critical that they be managed efficiently for the benefit of all.

A Set of Guiding Principles for Watershed Management

Watershed management is a human endeavor that not only must be grounded in state of the art science and management practices but also depends upon good governance. The diversity of cultural, political, and biogeographic histories across the steepland Neotropics dictates that governance systems will have to be adapted to the local conditions. Whether creating new entities or reforming existing laws and institutions, a set of principles – described below in no particular order of importance – ought to guide practice of watershed management:

Invest in Public Education and Capacity Building about How Watersheds Function and the Goods and Services They Provide

- Deepening watershed awareness is critical for decision makers from all levels of government to understand the consequences of policies and actions, particularly important given the expansion of large infrastructure development in watersheds. Equally important is that the general public, in particular upstream communities act as "water citizens" to play a land and water stewardship role. Building such awareness is essential to further sustainable development in the steepland Neotropics;

- Public education and capacity building explaining connections among political jurisdictions in a watershed and demonstrating the variety of the watershed's ecosystem services is essential to maximize cooperation and participation and move towards bioregional planning and governance;

- Technical staff within municipalities, water utilities, forestry, conservation, and agricultural agencies should be supported in deepening knowledge about basic watershed dynamics (both ecological and political), including gathering and analyzing scientific data, participating in effective governance processes and resolving conflicts among competing watershed users.

Rigorous Use of Diagnostic Tools Based on Ecological Science and Mapping of Formal and Informal Decision-making in the Watershed

- Good scientific data (e.g., forest cover baselines, stream flows, groundwater reserves, etc.) are essential to guide watershed planning and management decisions. They must be publicly available and updated frequently following an appropriately designed monitoring program;

- An inventory of existing laws, programs, agencies and organizations affecting resource use within a watershed is an essential diagnostic tool to plot watershed governance reform.

Rigorous Use of Integrated and Participatory Planning Tools and Innovative Governance Structures and Processes

- Watershed planning must combine land use planning and water use planning. It must bridge and integrate urban and rural jurisdictions both upstream and downstream to advance towards bioregional watershed governance. Governance and management must take into consideration different spatial and temporal scales of biophysical, social, and economic processes. Multi--stakeholder engagement, including significant involvement of community organizations and public agencies is critical for long term sustainability;

- Water and land use policies should be conceived, coordinated, and enforced by a federation of neighbouring jurisdictions, but implemented in a decentralized fashion. They must enjoy adequate local authority with resources transferred to the local level from national agencies to perform the job;

- Resource use priorities within a watershed should be publicly debated and made transparent and thereafter be used to guide governance decisions;

- Civil society efforts can deepen the impact of public protection and incentive programs, which may include playing a watchdog role to ensure public accountability.

Provide Financing and Incentives While Enforcing Laws for Effective Watershed Stewardship

- Financing of watershed protection to guarantee ecosystem services is a national priority - it cannot in all cases be financed strictly through local user fees or watershed funds capitalized voluntary and may require central government allocations;

- Payment for ecosystem services (PES) are a promising tool but cannot be a substitute for creating an enabling environment for a viable rural economy that safeguards the health of watersheds (e.g., extension services and credit programs to sustainable farmers, foresters, and other rural land stewards);

- Incentives are only one part of the solution; good governance requires mobilizing resources for law enforcement and watershed policing.

Chapter 1

Introduction to Watershed Ecosystem Services

1 Introduction to Watershed Ecosystem Services

Introduction

Humans derive a great number of goods and services from terrestrial ecosystems (Millennium Ecosystem Assessment, 2003, 2005). Some, like timber, fruits, bush meat, and other forest based food stuffs, are evident but others are not so obvious. Increasingly policy makers have realized the importance of forests and other ecosystems in sequestering carbon, as clearing of once vibrant vegetation or draining of swamps releases carbon dioxide (U.S. DOE, 2012) and where planting trees – particularly in the tropics - takes carbon dioxide out of the atmosphere (Bala et al., 2007). Scientists and conservationists have long called our attention to the value of Neotropical landscapes for biodiversity conservation as forests and other ecosystems harbor vast numbers of species. In recent decades conservationists and policy makers have also highlighted the potential of forests and other ecosystems to regulate stream flows (Ibáñez et al., 2002, Laurance, 2007 but also see Calder et al., 2007) and play a role in assuring clean water (Uriarte et al., 2011). All of these goods and services are part of what is collectively referred to as ecosystem services or goods and services that are provided to humanity through the unimpeded natural function of the ecosystem.

Ecosystems do not exist within a vacuum. They are defined and their dynamics are constrained by the biophysical context within which they are found. As all plants require sunlight, nutrients, and water for growth; the availability of these resources serves to define the rate at which plants can grow and can also determine both the ecosystem type as well as the species that exist within the system (ter Steege et al., 2006). For example, moist lowland tropical forests require abundant water throughout the year. In contrast, dry tropical forests are largely composed of species adapted to long periods without rain and have a different structure. Geological processes define the bedrock at a given site and help determine the soils upon which the vegetation grows (Brady, 1990). Soils, in turn, help determine the supply of nutrients to plants which helps to determine growth rates (e.g., van Breugel et al., 2011), species composition (Condit et al., 2013), and the extent to which nutrients are recycled within the ecosystem or allowed to wash away with the rains. Thus, the biophysical context not only determines the vegetation but also shapes the way in which nutrients and water are cycled within and exit the system through rivers and streams or return to the atmosphere as gases.

The rates at which plants grow, die, and regenerate determine the system's dynamics, which in turn are influenced by the type of natural and, increasingly anthropogenic disturbance (U.S. DOE, 2012). A single tree fall in a forest creates a small gap that will be recolonized and disappear to all but the best trained eyes in the matter of a few years whereas a large fire caused by human activities can scar the landscape for decades or more. The processes by which the forest closes the gap or replaces itself almost entirely in the case of a fire or other catastrophic disturbance are essential to the system's continued existence. There is a general consensus that biodiversity plays a key role in an ecosystem's ability to naturally replace vegetation (Hooper et al., 2005) as well as the processes needed to reconstitute nutrient stocks and return the system's ability to absorb and recycle water.

The foundation that underpins an ecosystem and assures its continued existence depends upon its biophysical context but also includes the natural processes and cycles that allow it to both continue its unimpeded existence and to bounce back from disturbance, be it relatively benign or catastrophic. The provision of all of the goods and services that people get from the ecosystem depends upon the ecosystem's ability to persist. Yet the driving forces that affect a watershed's ability to adequately and sustainably provide and regulate these goods and services are socio-economic and political in nature. Thus, the watershed's biophysical context is complemented by a human context, making an integrated system of interactions in which diverse actors– small landholders, local communities, local authorities, environmental organizations, businesses, and many others – make decisions that impact the physical dimensions of the watershed. It is therefore imperative that policy and other decision makers understand the basic principles and concepts related to ecosystem function as well as the different needs and values of watershed stakeholders in order to make informed decisions for improved management of ecosystem services in multi-use, human dominated landscapes.

What are Watersheds?

Watersheds are areas of land bounded by ridges of hills or mountains for which all the rainfall falling within the land either returns to the sky through evapotranspiration, flows overland to a common stream or enters the soil matrix. They can be extremely large and cross different ecosystems (e.g., Amazon Basin) or be limited to a few hectares. Because they form hydrological boundaries, they are an attractive unit to hydrologists as study systems and to managers within which to manage water. Because water is a driving force in cycling nutrients, they have also proven extremely useful units of study for ecologists (Bormann and Likens, 1979). They are an attractive socioeconomic unit in that they link upstream communities to downstream water users. At the same time, they can be messy to manage as they do not necessarily correspond to political boundaries or governance units. Although there are biophysical and social challenges to using watersheds as management units, they nevertheless provide an excellent context within which to conceptualize and manage ecosystem services (Bennett et al., 2013).

What are Steeplands?

This document focuses on tropical upland areas with steep topography and clearly defined watersheds. This includes not only mountainous regions, but also hilly landscapes with steep topography – steeplands. These differ from flatter landscapes not only by slope but by historical agricultural practices. Shaxson (1999) points out that topography has an important role in defining styles of agriculture. He defines ‘steepland’ *“as land with* an average slope of more than 12%*, which is approximately equal to 7°. Indeed, “small farmers living on steeplands in the tropics comprise a large sector of the world population. They operate in subsistence agricultural systems using traditional technologies designed to achieve sustained crop production at very low yield and income levels. Thus, most steeplands have relatively stable, sustained production systems with minimum land degradation. However, there is a growing awareness that sustainability of subsistence agriculture on steeplands is steadily deteriorating as a result of rapid growing population and overexploitation of the land resource base.”* Shaxson (1999). It is within this context that ecosystem services are considered in this document.

Scope of this report

In March of 2014, the Environmental Leadership Training Initiative (ELTI) and the Native Species Reforestation Project (known by its Spanish acronym, PRORENA), held a conference sponsored by the Biodiversity and Ecosystem Services Program of the Inter-American Development Bank (IDB) at the Smithsonian Tropical Research Institute (STRI) in Panama City, Panama to highlight recent advances in ecosystems service research in the steepland Neotropics. The conference titled “Watershed Management for Ecosystem Services in Human Dominated Landscapes of the Neotropics” aimed to distill the best available research into language and concepts accessible to policy makers, land managers, and other decision makers in order to advance watershed management in the region. The underpinning premise of the conference was that in this era of land use change due to a growing population and economic growth, as well as the challenge of climate change, it is increasingly essential to make the best possible decisions in policy and practice for the well-being of the diverse group of stakeholders in Neotropical watersheds. Indeed, maintaining economic development and human well-being demands this. This report represents a synthesis of the science, policy, and management practices discussed during the conference. While the

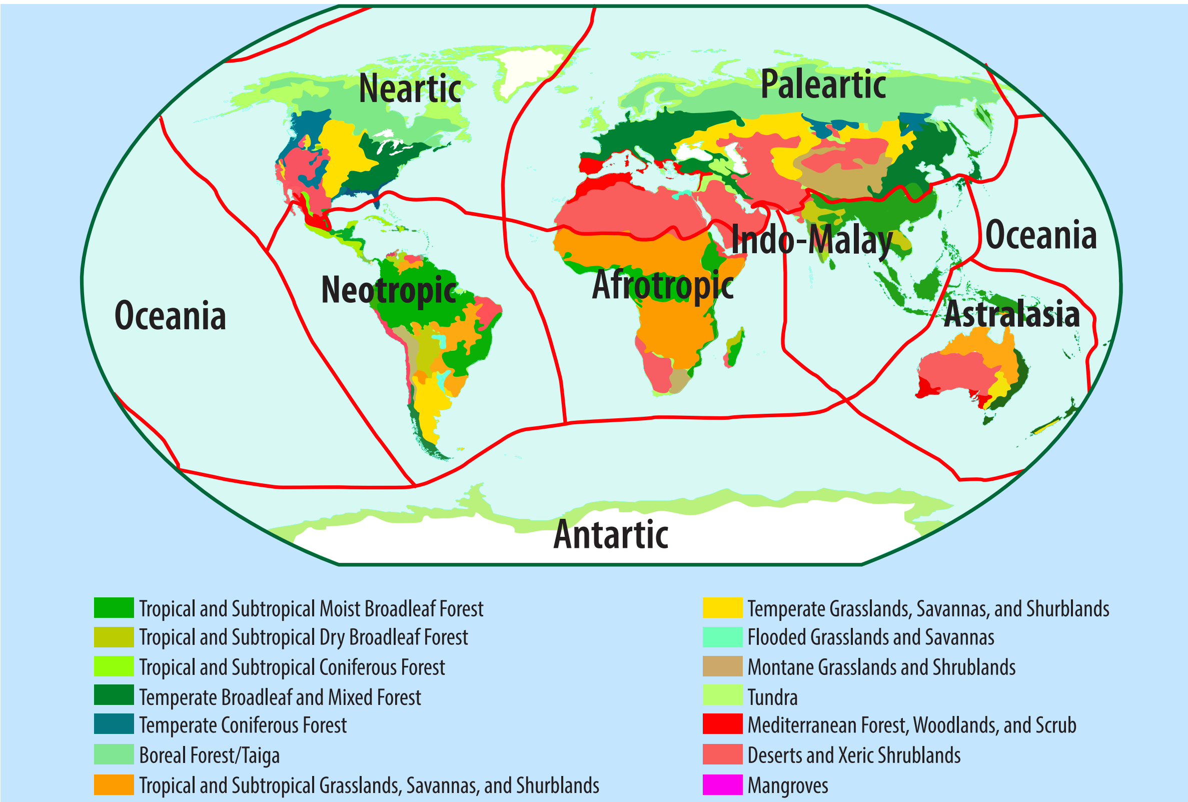


Figure 1.1 Biogeographical Realms and Terrestrial Biomes of the World (From Olson et al. 2001)

report is focused on four broad ecosystems, it can be used to frame management in other ecosystems within the region.

The Neoptropics represent one of eight biogeographic realms (Figure 1.1). This document follows the classification of Olsen et al. (2001) in defining 14 biomes within the Neotropic realm. Country level statistics are presented in maps and figures throughout this document but are limited to countries representing the majority area of the tropical steeplands in the Neotropics. Notably, Brazil is left out of these figures as the flatter landscape of the Amazon Basin differs in terms of watershed management. However, the discussion of natural capital and management of ecosystem services does apply to the steeplands of the Atlantic rainforests of Brazil.

The report begins with a discussion of the biophysical context and ecosystem processes that underpin the production of ecosystem services - the natural capital (Chapter 2). It then defines and describes different types of ecosystem services following the Millennium Ecosystem Assessment (MA) framework (Chapter 3). Chapter 4 discusses of the impacts of land use and climate change on the provision of ecosystem services in the region and is followed by a discussion of socio-economic considerations, including governance challenges in watershed management (Chapter 5). Chapter 6 describes the state of the knowledge in ecosystem service management in steepland Neotropical watersheds and culminates with a set of guiding principles for their management. The authors firmly believe that the social and biophysical complexities prohibit the use of a "cookie cutter" approach to management for ecosystem services. A series of case studies (Chapter 7), designed to present the state of practice in using science to inform management, concludes the report. This final chapter by no means represents the wealth of examples of advances in watershed management in the region. Rather, it is meant to call attention to the diversity of contexts and novel approaches that are being applied to the management of Neotropical watersheds.

Chapter 2

Understanding Natural Capital

2 Understanding Natural Capital

This chapter describes the biogeophysical context and ecosystem processes that underpin the production of ecosystem services. The ecosystem services, described in Chapter 3, are the natural capital of landscape management in the Neotropics.

Geophysical Context

Climate and Weather – What Defines the Tropics

Found roughly between 30° north and south of the Equator, the meteorological tropics are defined by atmospheric air circulation patterns. In broad terms they consist of a band of low pressure systems bound by parallel high pressure systems to the north and south. These low pressure zones near the equator produce convective storms, mostly thunderstorms, where rising humid air is warmed and buoyed by heat released during the formation of raindrops from atmospheric water vapor. This band of low-pressure zones and associated storms is called the Inter-Tropical Convergence Zone (ITCZ), the location of which varies during the year, moving seasonally toward the hemisphere that is in summer, and is strongly modified by monsoonal circulation on land (caused by heating of continents relative to the adjacent ocean), and equatorial and coastal upwelling at sea (Christensen et al., 2013).

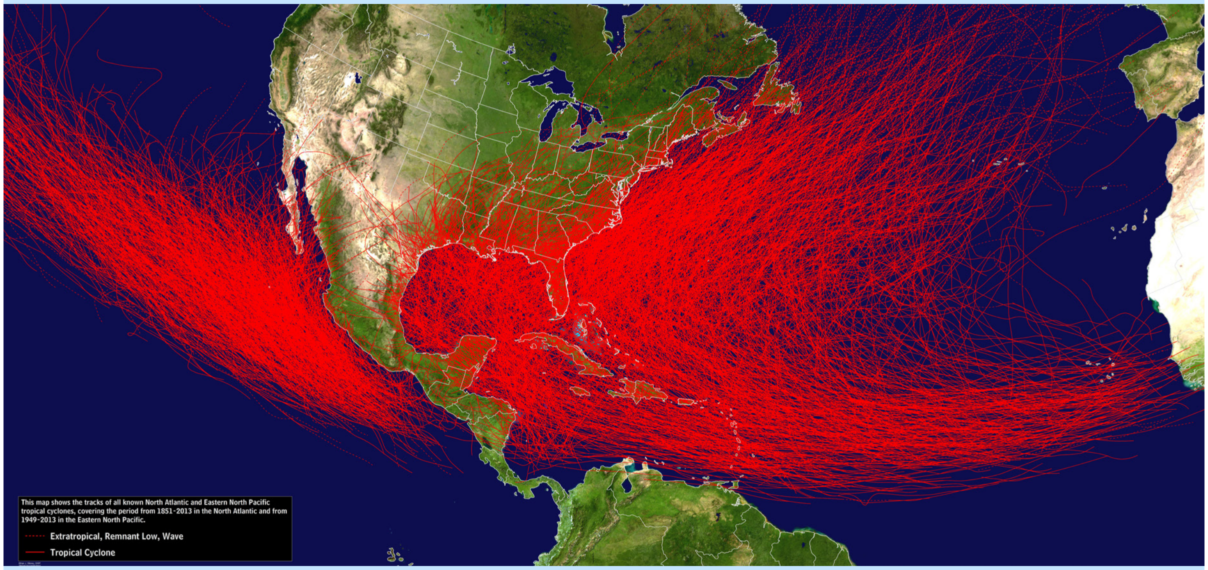
Beyond 10° from the Equator, the Earth's rotation imparts an effective lateral force to moving air; this force is to the right in the northern hemisphere and to the left in the southern (the Coriolis Effect or vorticity; Strahler, 1969). This phenomenon helps organize a strong easterly air flow in the lower atmosphere towards the ITCZ – the Trade Winds. Low pressure systems form in the Trade Wind flow as it moves over the ocean. These are referred to as tropical waves. If these lows develop and intensify over warm water outside of the 10° latitude band around the Equator, a cyclonic (counterclockwise, north; clockwise, south) circulation may develop. If there is sufficient warm water to serve as a latent-heat source, this circulation can intensify into powerful cyclonic storms (Emanuel, 1988) – in the western hemisphere, with increasing strength, these are referred to as 'tropical depressions,' 'tropical storms,' then 'hurricanes.' Cyclonic storms affect the east and west coast of Mexico and Central America north of Panama, the Caribbean and Atlantic coast of North America, and the Caribbean Islands (National Hurricane Center, 2014). Only one has ever been has been recorded off of the coast of Brazil, Cyclone Catarina, on March 26, 2004 (Marcelino et al., 2004).

The northern and southern bounds of the tropics are defined by the typical limits of wintertime cold fronts in the respective hemispheres, which are often associated with freezing weather. Fronts, however, can move well into the tropics, reaching almost to the Equator (Strahler, 1969; Marengo et al., 1997a,b). These fronts are typically associated with prolonged strong rains and marked temperature drops.

The above general styles of tropical air circulation establish the principal features of tropical precipitation and seasonality. In the equatorial zone, seasonality of precipitation is considerably reduced compared to elsewhere in the tropics, and the weak Coriolis Effect allows precipitation to fall on both east and west sides of north-south mountain ranges. To the north and south of the equatorial zone, the climate is generally dry during the Trade Wind season (in the hemisphere experiencing winter), and the windward east flanks of mountains are watered by orographic precipitation, while westward-facing leeward flanks are much drier (Strahler, 1969). With increasing distance from the Equator the annual rainfall decreases considerably, and west coasts away from the equatorial tropics can have profoundly dry deserts.

Huge storms typically drive weather-related land-

BOX 2.1 Hurricanes and Hurricane Mitch



All Known North Atlantic and Eastern North Pacific Tropical Cyclones Through 2013
(From http://www.nhc.noaa.gov/climo/images/1851_2013_tc.jpg)

Hurricanes are the most powerful storms that affect the humid tropics. The United States National Hurricane Center (NHC) of the National Oceanic and Atmospheric Administration (NOAA) monitors, describes, documents, and models hurricanes in the North Atlantic and Northeast Pacific Oceans. The NHC climatological summary <http://www.nhc.noaa.gov/climo/> and data archive <http://www.nhc.noaa.gov/data/> are updated regularly to reflect the prior years of storms. The NHC archive describes individual storms, and there is a list of the deadliest storms from 1492 through 1996 <http://www.nhc.noaa.gov/pastdeadlyapp1.shtml?>; scanning these archives suggests that during the worst storms, tens to tens of thousands of people have been killed. Of particular note is Hurricane Mitch, a storm that post-dates this list (Guiney and Lawrence, 1999; Molnia and Hallam, 1999). Between October 27 and November 1, 1998, Central America was devastated by this force-five hurricane – one of the most destructive storms in the recorded history of the western hemisphere (Molnia and Hallam, 1999). Honduras, Nicaragua, El Salvador, and Guatemala all suffered significant damage. Parts of Honduras may have received more than 1 meter of rain. Many areas were subjected to winds of more than 290 kilometers per hour (80 meters per second). More than 9,000 lives were lost as a result of the severe floods and landslides caused by the storm. Molnia and Hallam (1999) provide extensive aerial-photographic documentation of the aftermath of these floods and landslides.

scape disturbance regimes (treefalls, floods debris flows, landslides), and the nature of these storms also changes with distance from the Equator. The largest storms near the Equator are convective. Tropical cyclones become important farther away (Box 2.1), and near the high-latitude limits of the tropics, frontal storms can be important. In the equatorial zone, convective storms often drop considerable precipitation in very short times. The intense rain, alone, can cause a full suite of disturbances. Occasionally the largest convective storms are associated with major downdrafts that radiate from a center. If the winds are strong enough to topple trees, these zones of fallen trees, as seen in satellite imagery, radiate from a center in defined spokes that are often tens of kilometers long (Etter and Botero, 1990). Local convective storms can be important in the tropics outside of the equatorial zone, but no storms rival the destructive winds and extreme rains of cyclonic storms. Wintertime cold fronts can produce intense rains and strong winds across the region outside of some west-coast deserts (Marengo et al., 1997a,b; Murphy and Stallard, 2012b). The fronts are more frequent at higher latitudes. Some of the most serious storms in the equatorial tropics have been frontal, including the destructive December 1999 coastal storms in Vene-

BOX 2.2 Landslides and the Flood of Record in the Panama Canal Watershed

Gatun Spillway on the Panama Canal During the Flood of Record on 7-9 December 2010 Photo credit: Erik Nicholiasen

From 7-9 December 2010, the Panama Canal watershed was affected by an enormous rainstorm that resulted in deaths, property damage, infrastructure failures, interruption of drinking-water supply, and a 17-hour Canal closure (ACP, 2011b; Espinosa, 2011). The northeastern part of the Canal watershed had the greatest rain, up to almost a meter. Twenty Panama Canal Authority (ACP) rain gauges averaged over the watershed collected about 400 mm, and the storm has the greatest 3-day runoff on record. It is estimated to be a 150-year to 300-year event. The storm was named "La Purísima – 2010." "La Purísima" is a name that rural farmers typically give to whatever storm within five days of the December 8. This is often the last large storm before the beginning of the dry season and the end of the traditional cultivation season. One of the two bridges across the Panama Canal, the Centenario Bridge, was completely closed for two months and partially closed for another six due to landslides. Sediment (up to 10,000 to 15,000 mg/L) associated with tremendous erosion in the Canal headwater regions overwhelmed water-treatment facilities handling water from Lake Alhajuela, filling settling ponds and clogging filters (ACP, 2011c). The cities of Panamá and Colón were without reliable drinking water for about two months.

Much of this erosion was caused by landslides. To assess the impact of these landslides, in early April 2011, Stallard and Hruska (2012) flew a 42-by-5 km north-south photographic transect across the central Canal watershed over the western half of the Lake Alhajuela subbasin. This transect crossed the landscape affected by the rainfall gradient for the La Purísima – 2010 storm, from about 200 mm precipitation in the south to almost 1,000 mm in the north. The transect included the three major stream gages, several rain gages, roads, agricultural land, and mature forest. Once mapped, landslides were compared to a mosaic of landscape classifications. They counted more than 850 slides at 4 slides per km^2 and a coverage of 4,800 m^2 of slides per km^2 (0.48%). Landslide erosion in the transect (assuming complete suspension, a depth of 3 meters, and a density of 1.32 t/m^3) would provide about 37,000 mg/L. The average estimated denudation caused by landslides in the transect was 19,000 $tons/km^2$ compared to average annual rates of about 700 $tons/km^2/yr$ estimated by Stallard and Kinner (2005) – a factor of 27. Eighty five percent of the slides were in mature forest. If representative of landslide erosion in the headwaters of the Lake Alhajuela drainage these results are more than sufficient to account for the observed maximum concentrations of 15,000 mg/L suspended sediment.

zuela during which at least 15,000 people were killed (Larsen et al., 2002; Wieczorek et al., 2002) (See more detail here) and the December 2010 storm in Panama (Espinosa, 2011; ACP, 2014b; Box 2.2).

To structure observations about average climate in ways that can be easily mapped, climatologists and ecologists have developed a variety of climate-classification indices. Two are in common use, the Köppen-Geiger climate classification (Kottek et al., 2006; Peel et al., 2007) and the Holdridge climate classification (Lugo et al., 1999). Köppen-Geiger climate classification considers annual temperature and precipitation and the seasonality of temperature and precipitation. The role of altitude is not considered directly. The Holdridge climate index considers annual temperature, precipitation, evapotranspiration, and altitude. The role of seasonality is not considered. Failure to include seasonality is a major shortcoming in that this appears to be one of the most significant factors driving the biodiversity of woody vegetation in mainland tropical forests (Ashton et al., 2004). (Click here for potential changes related to climate change).

Climate Variations and Trends

In the Neotropics, it is difficult, at this time, to distinguish between inter-decadal climate variations and the long-term systematic trends associated with global change, because most meteorological-data time series of observations are shorter than the longest climate variations (Christensen et al., 2013). The Central America and the Caribbean (CAC) region are affected by several climate phenomena, including the ITCZ, the North America Monsoon System, the El Niño Southern Oscillation (ENSO), and tropical cyclones. ENSO is the main driver of climate variability, with El Niño years being associated with dry conditions and La Niña years with wet conditions. (See more detail here). South America (SA) is affected by similar climate phenomena. ENSO and Atlantic Ocean modes (Atlantic Multi-decadal Oscillation, the Atlantic Meridional Mode, and the Madden-Julian Oscillation) have a role in interannual variability of many regions. (See more detail here).

Topography, Geology, and Soils

The Köppen-Geiger climate classification indices generally correspond to the distribution of various tropical-vegetation types at a global scale, but there are strong disagreements about the details, such as the presence of grasslands where forest would be expected based on climate-zone classification (Walter, 1979). Typically these disagreements relate to edaphic factors – topography, geology, and soils – and to land-use history, such as a history of deforestation and burning or abandonment and regrowth.

Geology and Soils

There are four groupings of upland landscapes in the tropical Americas. The dominant upland encompasses the numerous, roughly parallel ranges that form almost the entire western margin of North, Central, and South America. Collectively, these are the Rocky Mountains in the north and the Andes in the south. These mountains have formed from numerous collisions of oceanic tectonic plates with continental plates over the last several hundred million years. With each episode of uplift, volcanic centers formed along the mountain chain and deep depositional basins formed to the east only to be incorporated in later uplifts. There are in fact only a few gaps of less than 500m elevation in this wall of mountains (Broecker and Denton, 1989) – from north to south, these are the Isthmus of Tehuantepec in Mexico, Lake Nicaragua, the Isthmus of Panama, and the Atrato – San Juan River valleys in Colombia. These gaps are the primary ways moisture moves from the Atlantic or Caribbean side to the Pacific side of the Americas. Lowland organisms can migrate through these gaps, whereas upland organisms are often blocked. Elsewhere, the mountains rise thousands of meters, and many countries from Mexico on south have elevations exceeding 5,000m. On their eastern flanks, the mountains are moist, rising from lowland tropical forests, through a variety of montane forests, cloud forest, *paramo*, tundra, and finally bare rock and sometimes glaciers. Except within a few degrees of the Equator, the west flanks tend to be dry, starting in coastal deserts or dry forests, rising through a variety of ecosystems dominated by plants adapted to drier conditions, drier *paramo*, and then bare rock (Walter, 1979). The Andes branch in the region near the Colombia-Venezuela border near the immense Santa Marta Massif. The eastern branch through Venezuela receives moisture on both flanks with wet and dry regions, depending on orographic precipitation.

The Greater and Lesser Antilles have extensive steepland and montane areas (Figure 2.1). All of these mountains are still being formed by active geologic processes, such as faulting, folding, and volcanism caused by colliding oceanic tectonic plates (island arcs). In southern Nicaragua and Colombia, island-arc basement abuts continental basement, and now an island arc forms the basement in Costa Rica, Panama, and northwest Colombia (Coates, 1997).

The extensive uplands of the Guyana Shield to the north of the Amazon Trough and the Brazilian Shield to the south of the trough are associated with slow uplift driven, in part, by slow erosion of very tough bedrocks and crustal buoyancy (Stallard, 1988). Except near the south coast of Brazil, where steeplands are common, the Brazilian Shield has extensive flat regions. Despite the passive and low nature of the uplift, the Guyana Shield has large areas of steep topography and a few summits are almost 3,000m.

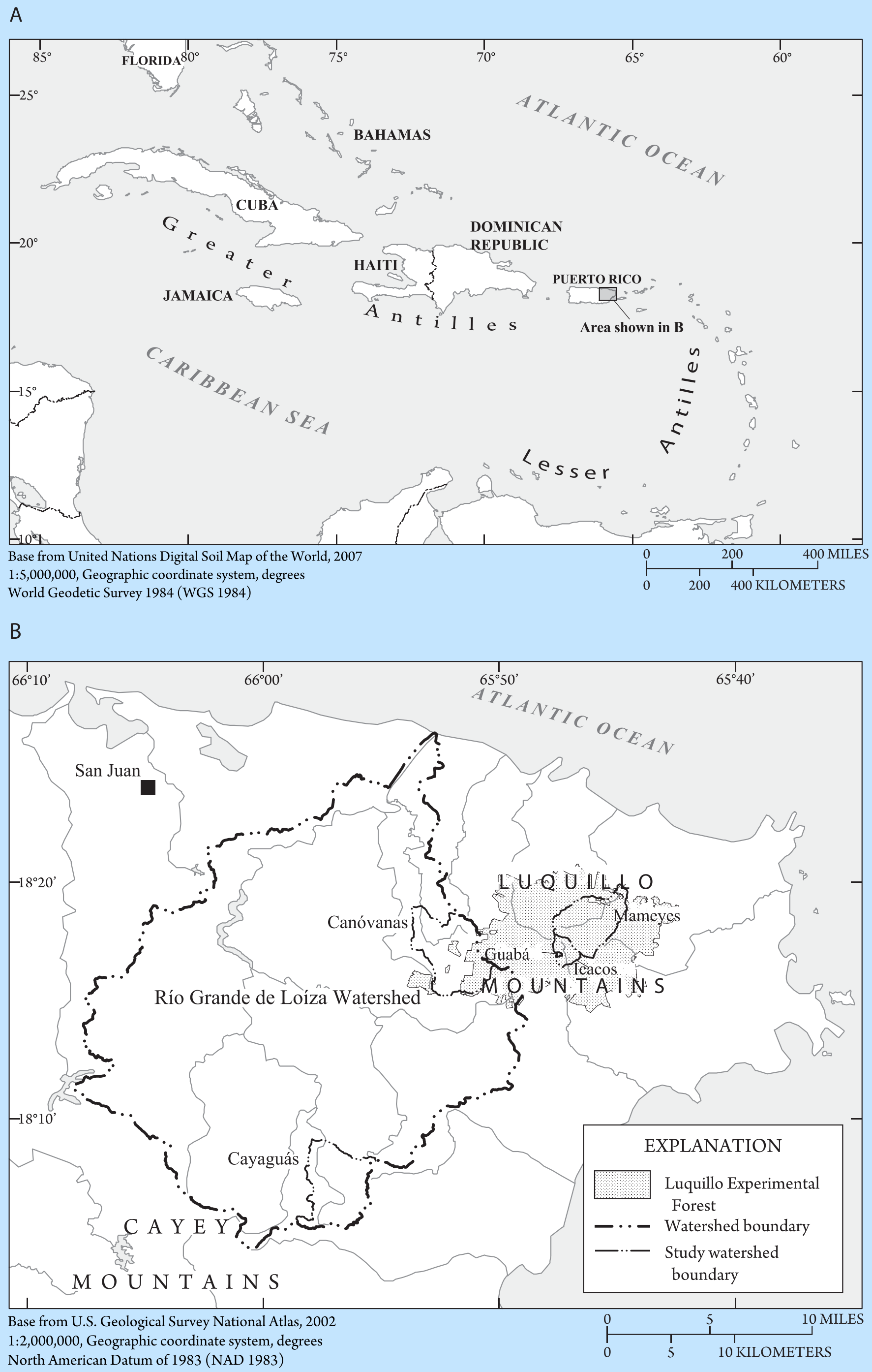


Figure 2.1 Islands of the Caribbean and Watersheds of Eastern Puerto Rico Discussed in this Chapter (From Murphy et al., 2012)

Continental mountains, such as the Andes and many ranges north of Costa Rica are developed from the collision between ocean and continental plates (Stallard, 1985, 1988, 1995a,b; Stallard et al., 1991).

While there is often a component of fresh and young volcanic material and plutonic rocks, much of the bedrock is derived from continental sediments, including mudstones, shale, sandstone, limestone (including dolomite), and even evaporites, or igneous and metamorphic rocks exhumed by tremendous uplift (this uplift is vastly greater in continental mountains than island arcs). Each of these rock types is associated with characteristic soils. The poorest soils are associated with pure-quartz sandstones and poly-cyclic sedimentary rock (formed from sedimentary particles that have gone through many cycles of deposition, uplift, and erosion) and lowland sediment derived from the erosion of these. Poor-soil regions include much of the lowlands to the east of the Andes and along the Amazon Valley. The richest soils are associated with fresh volcanic rocks, more mature volcanic rocks, immature sandstones, and limestones. The largest rivers that drain the derived from the erosion of these rich soils and the floodplains of these rivers also have rich soils. Quartz is the toughest of the common rock-forming minerals with respect to both chemical weathering and physical erosion. With multiple cycles of erosion, deposition, and uplift, quartz is abundant, thus rivers and soils are often sandy.

The uplifts of the Guyana and Brazilian Shields have exposed ancient igneous rocks, metamorphic rocks, and sediments. These weather slowly, and soils developed on these substrates tend to be quartzose and especially depleted in nutrients and cations (Herrera et al., 1978; Medina and Cuevas, 1984; Franco and Dezzeo, 1994; Stallard, 1985, 1988; Stallard et al., 1991; Johnsson et al., 1988, 1991).

The weathering of bedrock is the dominant source of most dissolved material in rivers and of several important plant nutrients, notably potassium and phosphorus, along with many trace nutrients. In some regions these nutrients have additional sources such as desert dust, volcanic ash, and seasalt blown inland near the ocean. In hilly to mountainous tropical landscapes, the susceptibility of the underlying bedrock to weathering and its chemical and mineralogical composition control the supply of nutrients and the composition and richness of soils (Stallard, 1985, 1988).

As a rule of thumb, younger volcanic landscapes form some of the richest soils, and oceanic island arcs and landscapes derived from these tend to also have richer soils (Stallard, 1995a,b, 2012a).
(See more detail here).

Island Arcs are formed at subduction zones where oceanic plates collide. The Greater and Lesser Antilles formed this way. Much of Central America and northwestern South America is island-arc material that has been brought into contact with continental crust through plate movement. While younger volcanic material is found in island arcs, in many cases, the volcanoes are long extinct and erosion has exhumed the inner workings of the arc. (See more detail here).
Montane rivers that drain volcanic rocks tend to have abundant black boulders and little sand. Only in the deepest cores of the exhumed arc does one encounter coarse crystalline plutonic rocks and quartz. Soils on plutons are sandy, and montane rivers that drain these rocks have especially large boulders and sandy beds. In lowland areas, the change in river slope allows deposition of sand and gravel in localized deposits which are often mined as aggregate for making concrete, much to the detriment of the associated rivers. Common island-arc sediments include shales (derived from deposits of clay-rich sediments) and limestone platforms that have been exposed by local sea-level changes and uplift.

Hillslopes and Erosion

Hillslopes are used to characterize landscapes. For example, as mentioned in the Introduction, hillslopes greater than 12 degrees define steeplands. This section explains the role of hillslope in controlling landscape-scale processes related to erosion. Hillslope form is central to weathering and erosion processes. Carson and Kirkby (1972) presented the concept of weathering regime, focusing on the relation of the supply of loose material and the role of transport processes in controlling its eventual transport downslope. In weathering-limited or supply-limited erosion, the rate of erosion is limited by the ability of weathering processes to generate loose or transport material. Such landscapes are typically hilly to mountainous, and slopes are frequently steep and straight, often near the angle of repose (30°).The contrasting condition is transport-limited erosion, where the rate of supply exceeds that capacity of transport processes to remove materials. Landslides are rare on hillslopes of less than 12 degrees (Larsen and Torres Sánchez, 1998). Such landscapes tend to be much flatter with less steep convexo-concave slopes. Accumulations of loose, typically deeply weathered material develop in place forming thick soils. In landscapes with weathering-limited erosion, peaks, ridge crests, and valley bottoms often behave as transport-limited landscapes.

Stallard (1985, 1988) examined the role of chemical weathering in weathering-limited and transport-limited landscapes. In weathering-limited landscapes, the resistance of the particular bedrock to chemical weathering controls erosion rates and many aspects of overall landform development, with susceptible bedrock forming topographic lows, and resistant bedrock forming topographic highs. Bedrock is typically near the soil surface and soils are often nutrient rich from an agricultural perspective, but difficult to cultivate. Much of the solid erosion products is partially weathered bedrock minerals along with cation-rich clays. During transport-limited erosion, thick soils develop, and the role of bedrock differences can become muted through the development of a thick and deeply leached mantle of soil. This leaching is typically associated with agriculturally poor soils. Natural vegetation interacts with soils and topography in different ways and on different time scales. During average years, forested areas often have lower rates of erosion as compared to deforested areas, because as the network of intertwined roots can hold soils in place during rains. However, by anchoring soil, vegetation promotes landslide erosion, because once the soil accumulation is thick enough, a large rainstorm or an earthquake can cause slope failure and a landslide. (See more detail here).

During rainstorms, landslides can occur given sufficient slopes (greater than 12 degrees) and loose substrates, but a minimum rainfall threshold is needed for a given storm duration (Larsen and Simon, 1993; Larsen and Torres Sánchez, 1998). Once this threshold is exceeded, landslides may happen, and the greater the excess rainfall, the more likely the landslides (Stallard, 2012a). Some huge storms associated with major landslide outbreaks include Hurricane Hugo in Puerto Rico (Larsen and Torres Sánchez, 1992), Hurricane Mitch in Honduras and Nicaragua (Molnia and Hallam, 1999) and the huge rainstorms on the north coast of Venezuela in December 1999 (Larsen et al., 2002; Wieczorek et al., 2002). Landsliding is exacerbated by human activities such as agriculture, grazing (Larsen and Torres Sánchez, 1998; Larsen, 2012), and in particular road building (Larsen and Parks, 1997). Climate shifts and forest degradation due to pollution, species invasion, and climate change may also accelerate landsliding over what would be expected as the natural or equilibrium rate (Stallard, 2012a). This erosion depletes the supply of loose material (soil) developed on the hillslope, and over sufficiently long times soil will redevelop once vegetation cover is restored.

Lakes and Reservoirs

Natural and artificial lakes (reservoirs) are an important component of landscape management because these provide water for domestic and industrial uses, irrigation, hydroelectricity, and habitat for fish and other organisms. Natural lakes are rare, whereas reservoirs are being constructed at a great rate. Because of headwater erosion, natural lakes, worldwide, generally are either large, young, or in landscapes with very low erosion rates (Herdendorf, 1982; Stallard, 1998). There are few large natural lakes within the montane Neotropics – Lakes Nicaragua and Titicaca are the largest. Most of the natural lakes are associated with active faulting, volcanism, and glacial erosion. (See more detail here).

One of the largest changes in river function is the ongoing construction of dams and reservoirs (Stallard, 1998; Meybeck, 2003; Meybeck and Vörösmarty, 2005; Vörösmarty et al., 2003; Lehner et al., 2011). Many of the lakes in steepland regions of the Americas are artificial reservoirs, built for hydroelectricity, water supply, irrigation, or other issues (Lehner et al., 2011). In Neotropical montane regions, Mexico

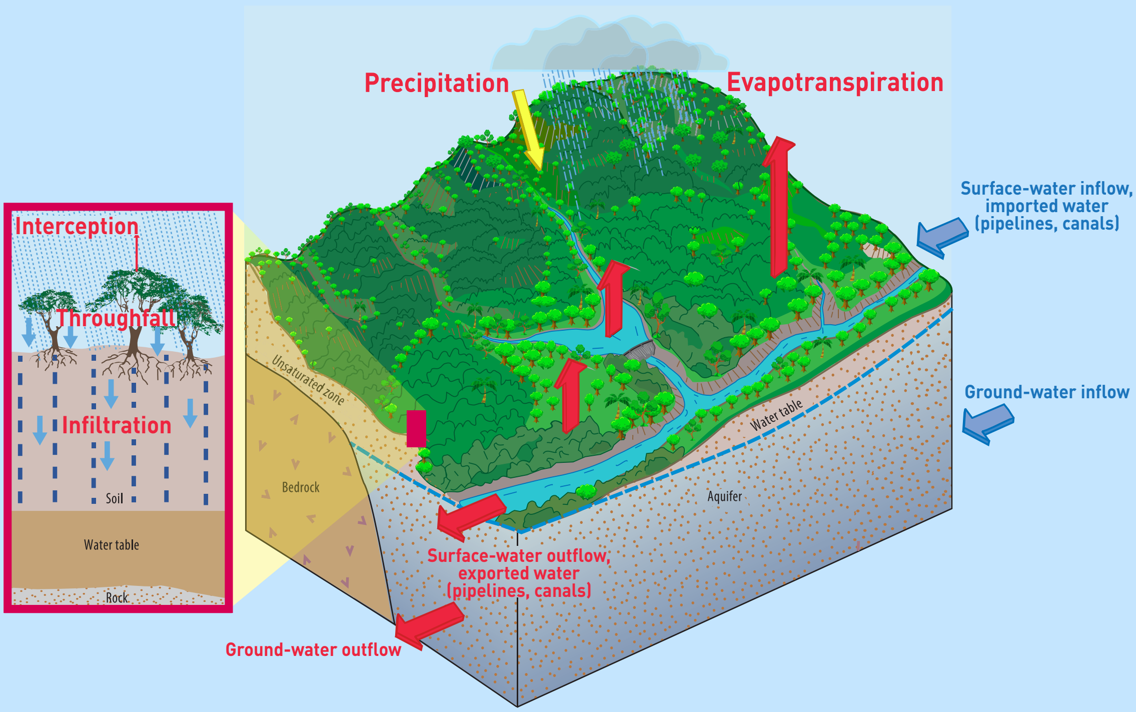
BOX 2.3 Challenges of Water Management: The Loíza Reservoir in Eastern Puerto Rico

Puerto Rico provides an example of some of the problems of reservoir management and maintenance. Stream valleys in the mountains of Puerto Rico are narrow and steep. Streams therefore respond rapidly to precipitation and Puerto Rico has the greatest threat of flash flooding of any state or territory under the jurisdiction of the U.S. National Weather Service (Carter and Elsner, 1997). In order to mitigate flood peaks and to store this water for year-round use, many reservoirs have been constructed. The Loíza Reservoir supplies more than half of the water delivered to San Juan (population 421,958 in 2000) (Gellis et at., 2006; Murphy and Stallard, 2012b), and the mountains of eastern Puerto Rico provide about 20 percent of the water used on the island. In 1999, this water was estimated to be worth about US$25 million per year in terms of the cost paid by consumers (Larsen and Stallard, 2000; Scatena, 2001). Water shortages are a chronic problem in Puerto Rico. Reservoir storage is lost because of high sedimentation associated with storms (Webb and Soler-López, 1997). In the 20th century, major droughts affected the island in 1966–1968, 1971–1974, 1976–1977, and 1993–1996 (Larsen, 2000). The drought of 1993–1996 led to severe water rationing for the city of San Juan. In response, residents collected water in open containers, which lead to outbreaks of dengue fever (Rigau-Pérez et al., 2001).

has the most reservoirs. Colombia and Venezuela are in the next tier, and numerous projects are planned throughout the Andes (Finer and Jenkins, 2012; Little, 2014).

The construction of dams and reservoirs can have social, ecological, and even economic consequences that are not necessarily contemplated during project development. The construction of a reservoir changes how organisms move through channels, creates and destroys habitats, alters flow regimes downstream, traps sediments, and buries organic carbon and other chemicals. Beyond these generalities each reservoir represents an individual case that must be examined within the landscape context in which it is built. Box 2.3 describes one such example from Puerto Rico. Once proposed and financed, the construction of a new dam and reservoir has the

BOX 2.4 Water Balance and the Concept of Paired Catchments in Hydrological Research



Movement of Water Entering, Moving Through, and Exiting a Watershed

A water balance is a more complete accounting of the disposition of the storm-derived rainfall (Healy et al., 2007). When water falls on vegetation, some part is retained in the canopy, and much of this water evaporates (a small fraction runs down the trunk as stemflow). Water that eventually hits the soil surface either becomes direct runoff which is integrated to calculate the peak runoff volume, while the remainder infiltrates where it becomes delayed runoff and base flow or it is intercepted by roots and is returned to the atmosphere through transpiration.

Researchers use the similarly sized small watersheds or "Paired Catchments" to understand how vegetation or land use affects watershed hydrology. Ideally these small watersheds are adjacent to one another and on the same bedrock, have the same precipitation and original vegetation type such that the only major difference is their land use history. Researchers track the different components of the water cycle as water moves through the ecosystem and calculate a water balance. As all the water is accounted for, they can understand how the land use change has impacted the different components of the water cycle. This is, for example, how researchers are studying the effects of land use change on flood regulation and dry season stream flow in the Agua Salud Project (see below).

BOX 2.5 Measuring River and Stream Flow

To determine the amount of water leaving of a watershed, the primary measurement is discharge, Q, which is the volume of water that passes through a channel cross section per unit time. Typically, Q is reported in units of cubic meters per second (m^3 sec^{-1}). Measurements are done at a gaged cross section (gaged is the USGS spelling, many writers use 'gauged'). For a typical cross section, the relation between water depth, S, and Q is developed through use of direct measurement or through weir calibrations, and S is then used to determine Q. The difficulty that is typically encountered is that for most of the time the river is not being influenced by big storms, but it is typically such storms that move much of the water, sediment, some chemicals out of a watershed. The inability to calibrate the Q—S relation at high discharge can be a major source of error.

Because discharge increases with watershed area, A, discharge cannot be used directly to compare landscape processes in watersheds. To compare among watersheds, it is necessary to normalize to area. The resulting measurement is instantaneous runoff, R, where $R = Q \cdot A^{-1}$. Preferred units for R in small watersheds (<1,000 km^2) are (mm hr^{-1}), because these typically are the units used for active precipitation, P. Engineers often use 'unit discharge' in m^3 sec^{-1} km^{-2} instead, but this is an awkward unit for comparisons with other phenomena such as precipitation and evaporation. To aid this discussion, four subscripts are used: A = annual total; a = average; b = base flow, referring to dry, rainless periods; p = peaks during storms. In most tropical steepland rivers, R_p, is often 10,000 to 100,000 times R_b, and measurement over this range is a major challenge. In most steepland watersheds, the greatest measured R_p are slightly greater than 100 mm hr^{-1} (Stallard, 2012b). Moreover, to reach solid conclusions about water movement and land cover, watersheds have to be well matched in terms of rainfall, geology, and topography, with the only substantial difference being land cover. The Panama case study is an example of such a matched pair.

character of inevitability. Groups are now working on techniques and approaches to mitigate the impacts to aquatic ecology. For example, Hartmann et al. (2013) develop a suite of approaches that are designed to mitigate the net impact of dam construction by preserving as broad a suite of aquatic habits as is possible.

Effects of Land Cover on Water Quantity and Quality

Land-use decisions can affect water supply and water quality. These decisions in the Neotropics are usually based on limited data, and there are surprisingly few studies about the effects of land cover on water supply and water quality in the steepland tropics that report quantitative conclusions with sufficiently small errors as to be decisive. Instead, decisions are often driven by anecdotal reports, metadata syntheses, and generalized empirical models (for example, Trabucco et al., 2008). The principal reason is that such quantitative conclusions generally require years of work, involving measurements of water movement that are both accurate and precise, and in the case of water quality, a large, possibly prohibitively expensive, number of samples and analyses are needed for quantitative results. Two boxes (Box 2.4 and 2.5) describe the components and steps necessary to undertake measurements sufficiently accurate and precise to derive empirical data to inform water quantity and quality management decisions.

From the perspective of ecosystem services, various characteristics of runoff have different significance. Accordingly, land-cover choices have economic impact through hydrologic and hydrochemical effects. For example, in watersheds of equal precipitation, greater annual streamflow in one watershed, compared with another indicates that some characteristic of the first is releasing more water downstream, which is typically considered a service because of its positive downstream effects. Here the role of forests is interesting. Because forest evapotranspiration is typically much greater than that of other land covers, forests reduce average annual streamflow, often between 150 and 600 mm $year^{-1}$ (Brown et al., 2005; Jackson et al., 2005). This reduction has to be considered in the context of tradeoffs (an ecosystem cost) in seasonal flow (Bruijnzeel, 1989, 2004; Stallard et al., 2010; Ogden et al., 2013). Greater dry-season streamflow due to base flow is beneficial and is considered a service. Indeed, preserving dry season flow may be more important than annual flow, particularly in drought prone areas where drinking water comes from rivers and streams. Likewise, a reduction in flood-peak volume is also considered a service, because larger flood peaks are associated with more downstream damage and enhanced channel erosion. Another characteristic that is considered a service is the reduced export of plant nutrients (nitrogen and phosphorus compounds) and sediment from forested landscapes (Stallard and Murphy, 2012b; Stallard, 2012).

Many have argued that forests mitigate flood peaks – both maximum peak discharge and peak volume, where peak volume is the total water that is rapidly discharged following the storm. The detractors of the argument that forests mitigate floods have argued, based on theory and anecdote, not observation, that while forests may reduce peak discharge and peak volume in most storms, the largest storms would overwhelm any ability of canopy intersection and soil infiltration in forests to reduce peaks – basically that large storms overwhelm the forest's plumbing (CIFOR, 2005; van Dijk, 2007). Alternatively, forest may affect runoff of small local storms, but not large synoptic storms (van Dijk, 2007). Alila et al. (2009) points out that the statistical approaches in metadata syntheses in these and similar studies are inadequate in that they do not appropriately compare flood peaks and require revision. CIFOR (2005), whose report is cited as definitive by many subsequent papers critical of the idea that forests mitigate floods, presents a table (their Table 1) of conclusions based on river-basin size that cannot be traced to any primary references that rely on data-based studies. For similar reasons, studies of dry-season base flow enhancement in forested landscapes compared to other landscapes are severely limited (Bruijnzeel, 2004).

Two examples follow – one from Panama, the other from Puerto Rico – of how land cover typical of the steepland Neotropics affects the hydrology and hydrochemistry of watersheds. These studies have sufficiently accurate and precise measurements over a wide range of conditions so as to provide quantitative results. Although these two studies encompass only two small regions in the humid steepland Neotropics, the conclusions reached are sufficiently decisive as to be a source of guidance for other regions.

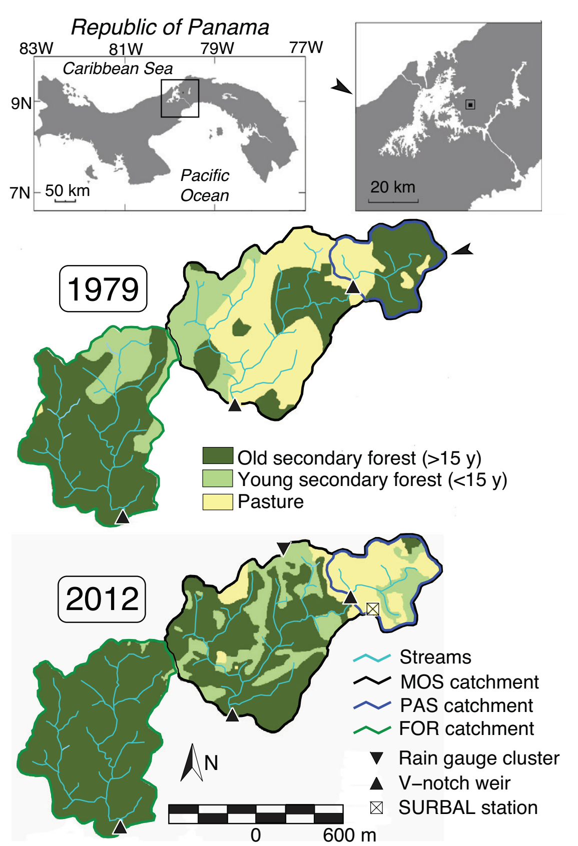


Figure 2.2 The Location of the Agua Salud Project focal research site and paired watersheds used in this Example (From Ogden et al., 2013)

Example: Comparison of Runoff and Land Cover – the Agua Salud Project

The Agua Salud Project is located in the central part of the Panama Canal watershed on the eastern side of the Canal (Figure 2.2). Its design uses protected forested lands in Soberania National Park and adjacent agricultural lands to compare runoff dynamics under different types of land-cover treatments. Each treatment includes at least one watershed where precise river gages and rain gages have been installed (Ogden et al., 2013). A central objective is to see whether various types of reforestation will restore landscape-scale ecosystem services typically demonstrated by forests, including those related to water (Stallard et al., 2010). Control treatments include a mature forest (FOR), a mosaic of pasture, agriculture, and secondary succession (MOS),

Table 2.1 Water Budget of the Agua Salud Control Watersheds for the Storms of 7-12 December 2010 (6 days) Including the Largest Storm on Record for the Panama Canal Watershed, 'La Purísima – 2010' from 7-9 December

Control watershed[1]	Forest	Mosaic	Pasture[2]
Watershed Area (hectares)[1,3]	144.2	182.9	42.2
Percent cover[1]	98%	51%	16%
Rain Total (mm)[1,4]	520	520	520
Forest canopy interception Total (mm)[5]	45	24	8
Non-forest evapotranspiration (mm)[5]	0	9	16
Runoff Total (mm)[6]	242	362	311
Infiltration (mm)[7]	233	125	185
Runoff relative to forest as percent	0%	50%	29%
Infiltration relative to forest as percent	0%	-46%	-21%

(See here for footnotes)

and an active cattle pasture (PAS). Reforestation treatments include natural secondary succession, native-species plantations, and teak plantations. The Agua Salud weirs are designed to precisely measure discharge, within 2%, and triplicate rain-gage clusters were spread across the landscape to establish water budgets that are sufficiently accurate and precise to allow rigorous comparisons of both low and high discharges.

Research using the three control treatment watersheds in Agua Salud successfully addresses both flood-peak reduction and enhanced dry-season base flow associated with forests. Ogden et al. (2013) completed a synthesis of more than three years (2009-2012) of water-related measurements in the control watersheds (Figure 2.2). This period includes one of the wettest years, (2010), on record (> 100 years) for the Panama Canal watershed and the largest storm of record, 7-9 December 2010 (called La Purísima–2010). The sampling of a particularly wet year is especially significant. Using rainfall and runoff data from 435 storms, Ogden et al. (2013) demonstrate that for the three years of record, peak heights were greatest in the pasture, the mosaic came next, and the forest had the smallest peaks. The same was true for peak volumes, with the differences among treatments becoming more pronounced with increasing storm size. The last observation completely contradicts the concept that forest plumbing is completely overwhelmed by large storms.

The results of a water balance for La Purísima – 2010 and three subsequent smaller storms that followed are especially instructive. Ogden et al. (2013) present a water balance procedure that was used for entire years, but which can also be applied to this particular cluster of storms (Table 2.1). Using the forest results as a reference, the table is quite easy to interpret – for the cluster of storms, the mosaic watershed produced about 50% more runoff than the forest, while the pasture produced about 29% more. Compared to the forest, the mosaic had 46% less infiltration, while the pasture had about 20% less.

The contrast between storm-cluster runoff volumes from the different types of land cover was so great as to have consequences related to the benefits of the presence of forests in the headwaters of the Panama Canal during 'La Purísima – 2010'. The runoff volume for la Purísima – 2010 was sufficiently large that the two main dams in the Panama Canal watershed (Gatún and Madden) were at capacity, and emergency measures, involving closing the Canal for 17 hours and using the plumbing of the locks as sluice pipes, were required to reduce the possibility of dam failure (Espinosa, 2011; ACP, 2014b). Currently, about 50% of the land cover in the Canal watershed is forest (Unidad de Sensores Remotos, 2006), and much of this is protected. It is reasonable to suggest that if this 50% had been converted to an agricultural mosaic, runoff volumes for what is now forested landscape would have been on the order of 50% greater, or about 20% greater for the entire Canal watershed. Given the precarious situation in which both dams were placed during the storm, a major infrastructure failure would have been more likely with a complete agricultural-mosaic land cover.

In contrast to flood peaks, the supply of base flow is especially important during dry seasons and droughts. Base flow provides water when other sources such as rainfall and reservoir water may be limited or absent. The dry-season base flow comes from groundwater that has penetrated soil and bedrock below the reach of most plant roots. These flows maintain in-stream and wetland habitat, and provide downstream water for domestic uses, irrigation, lakes, reservoirs, hydroelectricity, and shipping. The water for dry-season base flow infiltrates into the soil during the wet season. With greater infiltration rates and deeper penetration, more water enters deep storage. The idea that this phenomenon, sometimes referred to as the 'sponge effect', is enhanced in some, perhaps many, forests as compared to other land covers is also quite controversial (Bruijnzeel, 1989, 2004; CIFOR, 2005; van Dijk, 2007; Stallard et al., 2010; Ogden et al., 2013).

In the three years of study, Ogden et al. (2013) observed the sponge effect in two dry seasons, 2009 and 2011. In 2010, conditions never dried sufficiently to see the effects of deeper groundwater storage. In addition, during an earlier study (Stallard et al., 1999) the forested and mosaic catchments were compared during the driest year of record (1997) and the sponge effect in the forested catchment was especially pronounced.

To summarize, the Agua Salud project demonstrates large peak height and peak volume reductions associated with forests as compared to pasture and an agricultural mosaic. Significantly enhanced dry-season base flow in forest compared to other land covers, the sponge effect, is also demonstrated.

Water Quality

The concept of water quality incorporates both physical aspects of solids and dissolved chemical components (Box 2.6). Important suspended solids (particulate constituents) include sand, silt, and clay components of soil, whereas dissolved chemical components includes both bioactive (e.g., dissolved organic carbon, nitrate, sulfate, and potassium) and those that are not substantially bioactive (e.g., alkalinity, silica, calcium, magnesium, sodium, and chloride) solutes. Erosion results in increased sediment loads in rivers and streams, which affects water quality. As noted above, erosion has both physical and chemical aspects, and the amount of sediment making it to a stream at a given time can depend upon geology, topography, slope angle, rain storm intensity, and vegetation cover. Water chemistry depends in part on geology, soils, and precipitation inputs, but also on land management activities and industry upstream within the watershed.

Example: Comparison of Water Quality and Land Cover – The WEBB Project in Eastern Puerto Rico

In eastern Puerto Rico, the U.S Geological Survey (USGS) started a study of water, energy, and biogeochemical budgets (WEBB) in four watersheds that were chosen to provide a four-way comparison of geology and land cover (Figure 2.1; Table 2.2). Two watersheds were on volcanic rocks (lavas and volcaniclastics) and two were on plutonic rocks (granite-like rocks having abundant coarse-crystalline quartz). In turn, one watershed on each type of bedrock is forested while the other is a mosaic of pasture, cropland, and secondary forest, with some minor urbanization. A confounding factor in interpreting the results, however, was that the mosaic watersheds had less rainfall than the forested watersheds, precluding the type of hydrologic comparison as in Agua Salud.

A 15-year record of landscape processes, including stream runoff and chemistry was recently assembled by Murphy and Stallard (2012a). The hydrological component integrated several million discharge measurements from USGS stream gages at 5- to 15-minute time steps with many of thousands of measurements from automated rain gages operated by the USGS and National Ocean and Atmospheric inistration (NOAA). (See more detail here).

BOX 2.6 Measuring Water Quality

A water-quality comparison involving land cover adds an additional level of measurement, that of water composition. For each constituent, i (the various dissolved or solid substances in the river), a concentration, C_i, should measured over a full range of runoff rates – the many orders of magnitude of R. The output of a watershed involves the comparison of instantaneous constituent yields, Y_i, where $Y_i = C_i \cdot R$ (units mass km^{-2} hr^{-1}). The estimation of Yi requires either the collection of a sample or an automated measurement such as for specific conductivity or turbidity. For most constituents, however, a sample must be collected. In many river systems without big urban areas or industry (these add considerable complexity that cannot be discussed here), there are fairly simple relations between log(C_i) and log(R). For most constituents, log(C_i) decreases with increasing log(R) or holds steady (Stallard and Murphy, 2012, 2014). Because a river spends most of its time with R between Rb and Ra, routine sampling can be used to reasonably estimate YA_i for this class of constituents. For a few constituents, such as suspended solids and particulate organic carbon (POC), log(C_i) increases dramatically with increasing log(R). For these few constituents, storms must be sampled to get accurate annual yields, Y_{Ai}. The Puerto Rico case study, below, is the only landscape study in the Neotropics to have accomplished this goal.

Fortunately, in side-by-side comparisons of watersheds, one does often not have to measure YA_i through the full range of runoff to qualitatively establish the effects of land cover on water quality. Typically, the comparison is between forested lands and agricultural lands, where agricultural $R_A >$ forest R_A, or between two types of agricultural treatments where the R_A are similar. Commonly the relation between log(R)— log(C_i) decreases with increasing concentration and is offset such that C_i in one watershed is consistently greater than C_i in the other. Moreover the C_i in the forested watershed are typically less than in agricultural watersheds for constituents that are plant nutrients (in part because of the use of fertilizers and minor domestic wastes in agricultural landscapes) and for particulates such as suspended solids. When samples of both watersheds are collected at approximately the same time, R is reasonably matched. The watershed with the consistently greater C_i must have the greatest Y_{Ai}, even if Y_{Ai} cannot be precisely calculated. Moreover, water quality standards are typically based on exceedence levels of C_i (Murphy, 2006). Thus, if a C_i in a watershed consistently exceeds a standard, there is a problem that should be addressed.

Because of the broad range in instantaneous runoff rates that were sampled, this study provides an exceptional description, which likely applies to many tropical rivers, of how water quality relates to discharge. In the four watersheds, there is a consistent pattern of responses (Stallard and Murphy, 2014). For solutes that are not substantially bioactive (alkalinity, silica, calcium, magnesium, sodium, and chloride), the relation is almost log-linear and can be described as a weighted average of two sources, bedrock weathering and atmospheric deposition. Godsey et al. (2009) present a strong model framework that explains why this should apply to minimally polluted rivers generally. The bioactive constituents (dissolved organic carbon, nitrate, sulfate, and potassium), which are recycled by plants and concentrated in shallow soil, demonstrate arched or nearly flat or arched relations. When arched, the peak of the arch presumably represents a transition from dominantly soil-matrix flow, to near-surface macropore flow, and finally to overland flow. (See more detail here).

To examine the effects of land cover, one must correct for the substantial difference in average rainfall among the four watersheds. (See more detail here). The correction for the watersheds in eastern Puerto Rico demonstrates that both mean annual concentrations and annual net yields are greater in the mosaic watersheds than the forested watersheds for bioactive and particulate constituents (Table 2.2). The relative enhancements for constituents used in fertilizers or domestic waste (potassium, phosphorus, and nitrogen) and particulates are especially large. The greater chloride in the developed watersheds could be anthropogenic, but it is more likely that greater dry deposition relative to wet deposition of seasalt effectively increases the apparent rainwater-chloride deposition.

Case-comparison Conclusions

These two case studies represent examples of watershed research that demonstrate the difference between the hydrologic response of forested and non-forested landscapes. Many more such studies are needed. For example, Bruijnzeel (1989, 2004) has noted on several occasions that the sponge effect need not occur in all tropical watersheds, being dependent on geology, soil process, vegetation, erosion styles, and landscape history. It is reasonable to say that the study of the Agua Salud control watersheds clearly demonstrates that when compared to agricultural mosaics or pasture, the forested watershed has less overall runoff (trade-off), smaller runoff peaks (service), and generally greater base flow (service), especially in drier years. Much work and many years are required in the Agua Salud project to establish whether reforestation of pasture and cropland can restore these landscapes to a state that resembles forest. The work in Puerto Rico shows that pasture and cropland land covers in the agricultural mosaic generate greater yields of sediment and other par-

Table 2.2 Watershed Yields for Selected Properties as Observed and Adjusted to a Common Intermediate Runoff (1,860 mm/yr), Based on the Relation Between Runoff and Annual Yield. The Two Greatest Values for Each Constituent for Each Type of Calculation are in Bold.

DIC: dissolved inorganic carbon | **DOC**: dissolved organic carbon | **POC**: particulate organic carbon | **TIN**: total inorganic nitrogen | **Ssol**: suspendedsolids | **mm year^{-1}**: millimeters per year | **tons km^2 year^{-1}**: metric tons per square kilometer per year

				Nonbioactive			Bioactive				Particulate	
				Geologic		Atmospheric	Geologic		Atmospheric		Geologic	Atmospheric
Watershed	Bedrock	Land cover	Runoff mm year^{-1}	DIC	Si-Si(OH)$_4$	Cl$^-$	K$^+$	P-PO$_4^{3-}$	TIN	DOC	Ssol	POC
Annual net yields, tons km^{-2} year^{-1}												
Canóvanas	Volcanic	Mosaic	970	**11.1**	10.0	11.5	1.24	0.024	0.66	3.8	355	7.5
Cayaguás	Granitic	Mosaic	1,620	11.0	18.6	14.6	**3.45**	**0.057**	**1.20**	4.7	**1,981**	**19.2**
Mameyes	Volcanic	Forest	2,750	**14.1**	**20.8**	**19.2**	1.98	**0.025**	0.40	**6.9**	270	6.0
Icacos	Granitic	Forest	3,760	10.4	**24.0**	**20.7**	**2.27**	0.011	**0.68**	**10.1**	**1,985**	**21.5**
Annual net yields, adjusted to a common runoff, tons km^{-2} year^{-1}												
Canóvanas	Volcanic	Mosaic	1,860	**17.1**	17.1	**20.5**	**2.45**	**0.028**	**1.44**	**7.3**	**955**	**20.8**
Cayaguás	Granitic	Mosaic	1,860	11.6	**21.0**	**16.9**	**4.16**	**0.062**	**1.44**	**5.7**	**2,370**	**27.6**
Mameyes	Volcanic	Forest	1,860	**12.3**	15.5	13.9	1.36	0.021	0.22	4.6	73	2.2
Icacos	Granitic	Forest	1,860	8.0	**18.3**	12.1	1.25	0.005	0.30	3.9	158	3.7
15-year mean concentration, mg L^{-1}												
Canóvanas	Volcanic	Mosaic	970	**11.5**	**10.3**	**11.8**	**1.28**	**0.024**	**0.68**	**3.9**	366	7.8
Cayaguás	Granitic	Mosaic	1,620	**6.8**	**11.5**	**9.0**	**2.13**	**0.035**	**0.74**	**2.9**	**1,223**	**11.8**
Mameyes	Volcanic	Forest	2,750	5.1	7.6	7.0	0.72	0.009	0.14	2.5	98	2.2
Icacos	Granitic	Forest	3,760	2.8	6.4	5.5	0.60	0.003	0.18	2.7	**528**	**5.7**
Adjusted mean concentration, mg L^{-1}												
Canóvanas	Volcanic	Mosaic	1,860	**9.2**	9.2	**11.0**	**1.32**	**0.015**	**0.77**	**3.9**	**514**	**11.2**
Cayaguás	Granitic	Mosaic	1,860	6.2	**11.3**	**9.1**	**2.23**	**0.033**	**0.77**	**3.1**	**1,274**	**14.8**
Mameyes	Volcanic	Forest	1,860	**6.6**	8.3	7.5	0.73	0.011	0.12	2.5	39	1.2
Icacos	Granitic	Forest	1,860	4.3	**9.8**	6.5	0.67	0.003	0.16	2.1	85	2.0

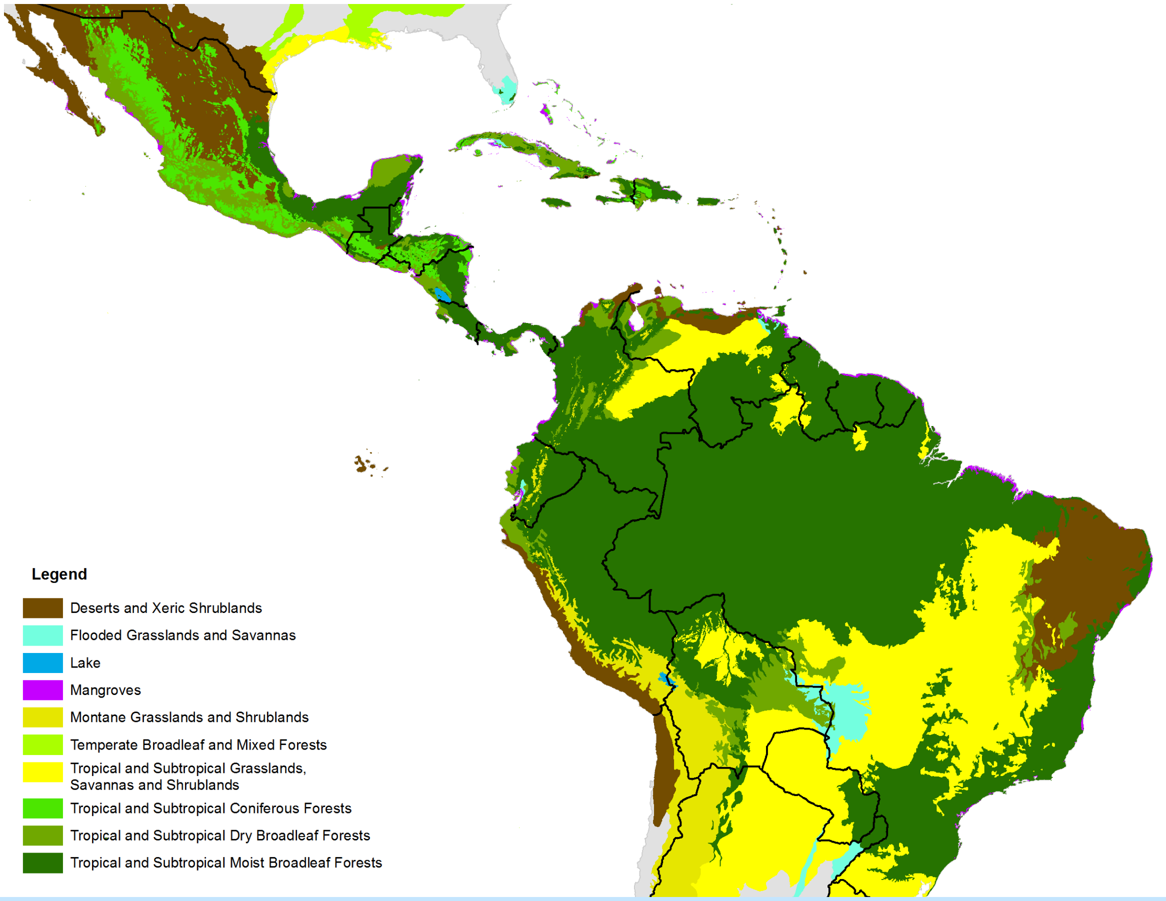


Figure 2.3 Terrestrial Biomes within the Steepland Neotropics and Adjacent Areas of the Neotropical Realm (From Olson et al., 2001)

ticulates as well as constituents related to fertilizers. Paired watersheds can be compared through simultaneous sampling, as explained here, to qualitatively demonstrate the presence of enhanced yields in comparisons between forests and other landscapes.

Ecosystem Patterns and Processes

Neotropical Ecosystems

The Neotropical zone is one of the eight biogeographic realms of the planet (Figure 1.1) and contains a wide range of forest ecosystems (Kricher, 1999). Eight major regions are recognized (Amazon, Caribbean, Central America, Central Andes, South America Eastern, Northern Andes, Southern South America, Orinoco), which share many species of animals and plants. These regions are the product of different biogeographical history, climate, geology, soil types and hydrology, and, within each of these regions many different ecosystems are found. For the purpose of this document, ecosystems are collapsed and restricted to the discussion of four broad upland vegetation types: Tropical and subtropical moist broadleaf forest, tropical and subtropical dry broadleaf forest, montane forest, and *paramo*, a subset of montane grasslands and shrublands (Figure 2.3).

These ecosystems vary in their ecological characteristics (structure and ecosystem function) and biodiversity, and, importantly, in their resilience (see below) to natural and anthropogenic perturbations. Although considered independently, the spatial juxtaposition of vegetation types and formations is important to different aspects of ecosystem services

(Noss and Harris, 1986). Connectivity – where different vegetation types and habitats abut one another across the landscape – is of particular concern, both to ensure the movement of species between systems for species dependent on large areas and/or a diversity of habitats and to permit species' migrations due to habitat shifts associated with climate change (Saura et al., 2014). Policy, management decisions, and evaluations need to be based on a robust understanding of the characteristics of the system (Heller and Zavaleta, 2009; Hodgson et al., 2009).

The major environmental gradients that define the distribution of Neotropical ecosystems considered herein are rainfall and additional environmental variables associated with elevation (Gentry, 1988). Other drivers of ecosystem properties are soils and hydrology and both natural and anthropogenic disturbance regimes. Individual species are adapted to different ranges of resource gradients which constitute their niche. As no two species are exactly alike, species have different niches and use resources in different ways. These differing adaptations can help species to coexist in a given ecosystem or habitat and may lead to more overall efficient use of resources (Kinzig et al., 2003).

Rainfall

Plants need water as a building block for the sugars produced by photosynthesis and for transport of plant nutrients. Water is released due to transpiration when stomata open for the uptake of carbon dioxide. The efficiency with which plants "manage" this tradeoff between carbon dioxide uptake, water loss, and their ability to avoid water stress during dry periods by losing their leaves helps determine which species can thrive and survive along a rainfall gradient and thus helps determine the distribution of vegetation types (Condit, 1998; Maharjan et al., 2011). On continental and regional scales, seasonal drought shapes the distribution of tree species and tree species diversity tend to decline with increasing length and severity of the dry season (Gentry, 1988; Brenes-Arguedas et al., 2009; Engelbrecht et al., 2007; Condit et al., 2013).

Elevation

Several climate variables change with elevation as one passes from lowlands to mountain peaks, including temperature, solar radiation, and rainfall. Temperature decreases and precipitation increases with elevation, while increases in cloud cover with elevation typically lead to a decrease in solar radiation and vapor pressure deficit. These changes in climate conditions with increasing elevation are typically associated with changes in forest structure and function. For example, net primary productivity (see below), tree height, and leaf area index generally decrease with increasing elevation (e.g., Unger et al., 2012). (See more detail here).

Soils and Hydrology

Soil type and hydrological characteristics also help determine productivity, the distribution of vegetation types within ecoregions, and changes in species composition within vegetation types. For example, thin soils and permeable bedrock may lead to the presence of dry forest types in regions that get abundant rainfall and thus might otherwise be expected to support moist or wet tropical forest. Soil properties, including fertility, have been shown to help determine species distributions (e.g., Condit et al., 2013; Clark et al., 1995) and forest type and productivity across landscapes (Unger et al., 2012; Figure 2.4). As the diversity of soil types within the tropics is every bit as diverse as those of temperate regions, they must be considered when evaluating ecosystem services in a given area. (See more detail here).

Disturbance

Another factor that strongly influences forests is the prevailing disturbance regime. The ability of a forest to recover from a disturbance is governed by two related ecosystem properties: resilience and redundancy (Box 2.7; Naeem, 1998; Gunderson, 2000).

The dynamics of many forests is characterized by a forest regeneration cycle in which canopy gaps are formed by the fall of single or multiple trees (Hartshorn, 1980). New trees regenerate in these gaps from seed banks and seed rain and from surviving seedlings, saplings and small trees that established and survived in the understory before the gap was formed – also known as advanced regeneration (Uhl et al., 1988; Martinez-Ramos and Soto-Castro, 1993; Dalling et al., 2002). Colonization of small gaps is usually dominated by advanced regeneration of species that can survive in shade but often need more light to grow into the canopy. In contrast, large gaps are usually colonized by light-demanding pioneer species from seeds. Since the latter cannot regenerate below canopy shade, they will be replaced by shade tolerant species after dying off. These forests can be described as a small scale shifting mosaic of patches that represent different successional phases within the forest (Lieberman et al., 1985; Whitmore, 1989).

In many tropical ecosystems larger-scale and more severe disturbance events occur periodically. For example, forests that are situated along tropical cyclone paths in the Atlantic and Pacific Oceans may be struck several times per century by a big hurricane (Box 2.1). Landslides may be common and cause periodic destruction of larger areas of forests in mountainous areas with steep slopes, unstable soils and heavy rainfall and/or earthquakes (Box 2.2). The importance of periodic droughts causing large scale mortality and helping to determine species composition has gained recent attention (e.g., Lewis et al., 2011). Fires of anthropogenic and natural origin (e.g., lightning strikes) are of increasing concern in both dry and moist forests, particularly if severe drought events become more common due to climate change (e.g., Cochrane, 2003).

Vegetation structure, composition and functioning will reflect these disturbance regimes, with forests that are characterized by a coarse-scale mosaic of successional phases. Large stands dominated by fast-growing, well dispersed pioneer trees and spe-

Figure 2.4 Soil Type or Edaphic Factors Help Determine Species and Forest Type Distributions

Panama has a high diversity of soil types owing to its geological history. Here two forest types are found adjacent to each other within the Panama Canal Watershed where the one dominated by the deciduous species, Cuipo - *Cavanillesia platanifolia*, is on marine sedimentary soils high in phosphorus and the diverse forest with leaves is on basalt. Photo credit: STRI archive

BOX 2.7 The Concepts of Resilience and Redundancy

Resilience encompasses the idea of an ecosystem's ability to bounce back and return towards a relatively steady state post disturbance. For example, forests that experience repeated hurricanes may include an increased number of species and individuals that are able to resprout and thus regain forest cover relatively quickly. They may also contain more species of palm trees that are able to bend and not break under severe winds.

Redundancy encompasses the notion of the number of different species that are present within the forest that are functionally equivalent and thus can replace one another should one species drop out of the system for one reason or another (e.g., disease or perhaps, selective logging or harvesting). Thus, for example, if a forest that is subjected to a severe hurricane only has one species that has the ability to resprout, should that species be lost to the system, then the forest may not be able to regain forest cover as quickly as a forest that has other species that can resprout. Other examples would be the presence of multiple species adapted to fire in forests subject to repeated fires or those able to capture atmospheric nitrogen through N_2 fixation and return it to the ecosystem, shown to be particularly important in the early stages of secondary forest recovery in at least some areas (Batterman et al., 2013).

cies with other adaptive life history traits, such as resprouting capacity, will be common and wide spread (e.g., Whitmore, 1998).

Ecosystem Properties

Productivity and the Carbon Cycle

Plant growth depends upon the supply of sunlight, nutrients, and water. In forests and grasslands, trees, shrubs, and grasses capture energy from sunlight with leaves and, in some instances, other tissues. Carbon dioxide enters plants through stomata or openings in leaves and when combined with water and energy through the process of photosynthesis, is converted into sugars. The ability of a plant to produce these sugars, convert them into other carbon based products, and cycle these products determines a plant's growth and productivity (Landsberg and Waring, 1997). Carbon sequestration refers to the amount of carbon a plant or ecosystem acquires over time through growth and is measured as a sink or pool.

Carbon is cycled through the ecosystem as plants produce leaves, roots, and other tissue that they shed during the year as part of their normal growth cycle. Leaves, fine roots, and other plant tissues decompose and release carbon dioxide into the soil and atmosphere (Figure 2.5). The rate at which a plant cycles carbon in this way is often measured as an index or component of productivity and can give an indication as to its response to different ecosystem stressors, including climate change. These transient carbon pools are often referred to as fluxes (Lambers et al., 1998).

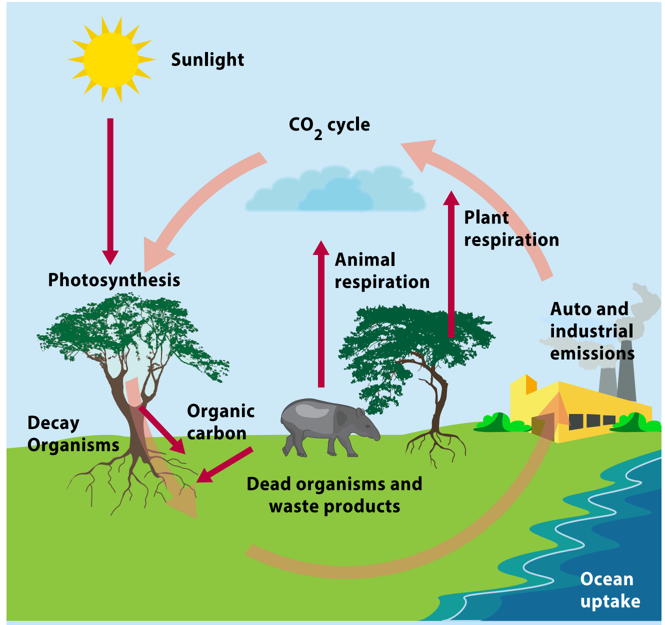


Figure 2.5 The Carbon Cycle

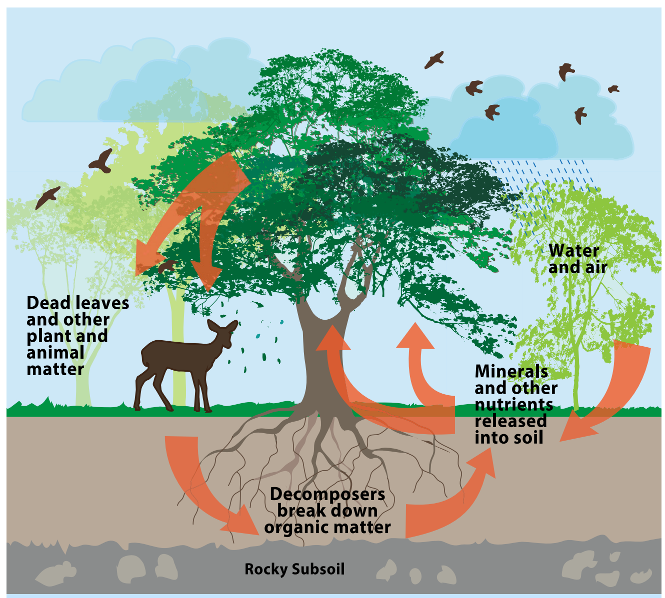


Figure 2.6 The Nutrient Cycle

Nutrient Cycling

All plants require a set of basic nutrients to grow. Some are required in relatively large quantities (macro nutrients) and others are still essential but required in smaller quantities, for example as essential components of catalysts in different chemical reactions (Lambers et al., 1998). Nutrients originate from the soil and also from external inputs such as atmospheric deposition and nitrogen (N_2) fixation. As plants shed tissues as part of their natural growth cycle or die, these nutrients cycle back to the soil through decomposition (Figure 2.6). They also leave the system through volatilization as gases and movement into streams with water. As plant growth requires relatively constant quantities of nutrients, the growth of trees and other plants as well as the productivity of many ecosystems may be nutrient limited. Tropical forests on infertile soils are generally thought to have a tight nutrient cycle where most nutrients are taken up by plants before they exit the system. Animals are key components of an ecosystem's nutrient cycle as they consume leaf, fruits, and other plant tissues (and consume other animals) and return nutrients to the system as byproducts of consumption (feces and urine) or decomposition upon death. Microbes can serve as decomposers leading to the rapid conversion of organic matter into component molecules.

Water

Plants depend upon water for growth, taking it up through their roots and either transforming water molecules into carbon based products during photosynthesis or losing it through their stomata. At the ecosystem level water is essential for transporting nutrients and other chemicals as well as solid particles (Aber and Melillo, 2001; also see discussion above).

Tropical and Subtropical Moist Broadleaf Forests

Broad Characteristics and Biodiversity

Tropical and subtropical moist broadleaf forests (Figure 2.7) typically receive approximately 2000 mm or more rainfall that may be relatively evenly distributed or may exhibit some degree of seasonality with one or two dry seasons throughout the year (Richards et al, 1996; Whitmore, 1998). All things being equal, seasonal forests closer to the Equator have two short dry seasons and those further away have a longer, more pronounced dry season. The largest block of tropical moist broadleaf forests in the Neotropics lie in the Amazon and Orinoco basins, a second stretches from the pacific coasts of Ecuador and Colombia up to Veracruz in Mexico. These forests have a very high diversity of tree species with up to two or more hundreds of tree species per hectare, with most species being rare (i.e. < 1 tree ha^{-1}), and generally no species or group of species dominate large areas of the forest (Gentry, 1982; Hubbell and Foster, 1986; Wright, 2002). As tree species are

Figure 2.7 Tropical Moist Broadleaf Forest Photo credit: STRI archive

not generally distributed uniformly throughout the forest, the actual number of species within a forest can far exceed the number of species on a single plot. Further, distinct forest types are related to special soil and hydrological conditions (e.g., peat swamp forests, heath forests on acid, dry, and poor sandy soils with a very distinct flora, and riverine and freshwater swamp forests). Lianas and epiphytes are common elements of tropical forests.

Vegetation Structure, Biomass, and Productivity

The wettest tropical lowland forests are characterized by a closed evergreen canopy up to 45 m high and a complex canopy structure with different canopy layers. Emergent trees spread their crowns above the canopy and are a regular feature of tropical and subtropical broadleaf forests. Due to the predominance of evergreen species and the presence of several distinct layers, relatively little light makes it to the ground or understory with seedlings and shrubs persisting there being adapted to low levels of light and taking advantage of sun flecks (Chazdon and Pearcy, 1991).

With the exception of those forests with pronounced dry seasons, forests benefit from a virtually year round growing season. Productivity is thus uniformly high as compared to northern, temperate forests but can be limited by the availability of water and nutrients. Mature forests are generally thought to be in a near steady state with increases in growth being offset by mortality. Nonetheless, there is some concern that climate change leading to an increased frequency of drought would lead to carbon loss in the Amazon Basin (Phillips et al., 2009), something that could also happen in other Neotropical forests. Tropical broadleaf forests are known for their very high biomass and typically maintain (sequester) over 200 tons of biomass per hectare (e.g., Saatchi et al., 2011; Asner et al., 2013).

Disturbance and Recovery

The prevailing disturbance regime in tropical and subtropical moist broadleaf forests is often thought of as being that of one or two trees falling, causing a gap, followed by the forest gap being occupied by either species already present in the understory or seed bank. However, large blow downs caused by localized storms also occur in lowland forests (Chambers et al., 2009). Hurricanes are common in Caribbean and Central American forests north of Panama (see Box 2.1). Landslides and fires (both natural and anthropogenic) are additional small to large scale disturbances. Land clearing for agriculture and pasture – often associated with fires – is a major form of disturbance and forest conversion (Chazdon, 2003; Chazdon et al., 2007). Hunting can also leave an apparently pristine forest "empty" of large mammals (Redford, 1992; Stoner et al., 2007).

Disturbed areas that are adjacent to or nested within a matrix of forest can recover from natural disturbances quite rapidly in terms of diversity and return to a forest structurally similar to undisturbed forest within 100 years or less (Chazdon, 2014). However, forest patches that are cleared for and subjected to agriculture or pastoralism may not return to forests due to some level of severe degradation (Aide and Cavalier, 1994) or form of arrested succession resulting from competition with grasses or ferns (see, e.g. Holl and Cairns, 2002). These areas may require active intervention to reestablish forests.

Tropical and Subtropical Dry Forest

Broad Characteristics and Biodiversity

Tropical dry forests (TDF; Figure 2.8) are defined by their strong rainfall seasonality. Globally, they encompass 42% of tropical ecosystems. In the Neotropics, they are found from northwestern Mexico and the Caribbean to northern Argentina and southwestern Brazil. Their characteristic dry season lasts from four to up to seven months and annual rainfall ranges from as low as 500 mm up to 2000 mm, with dry months receiving less than 100 mm or no rain at all. At the dry and wet end of the drought stress gradient, dry forests transition to tropical savannas and moist forests, respectively, with the distinction between vegetation types being far from clear-cut (for instance, some authors would include tree dominated savannas as dry forests while other would define dry forests at the end of the wet gradient as seasonal rain forests). TDF are highly variable but,

Figure 2.8 Tropical Dry Forest in Oaxaca, Mexico
Photo credit: Edwin Lebrija-Trejos

overall, they are shorter in stature, less vertically structured, less species rich and have lower biomass than tropical rain forests. In contrast, spatial turnover of species, life-form diversity and species endemism are high (Medina, 1995; Trejo and Dirzo, 2002). TDF are recognized for hosting a distinct set of plant species with very low overlap with rainforests (Murphy and Lugo, 1986). (See more detail here). Because of the strength and seasonality of water stress, TDF are generally more water than nutrient or light limited and thus the ecosystem and its constituent species have very synchronic phenological, physiological and functional responses that are tightly coupled to the temporal course of water availability.

Vegetation Structure, Biomass, and Productivity

Tropical dry forests canopies range from 10 to 40 meters in height and commonly have a vertical structure with one or two strata that are partially or practically leafless during the dry season. Consequently, light reaching the understory year-round is high compared to moister forests (Lebrija Trejos et al., 2011). This results in low to high ground vegetation cover which contrasts with very low levels in tropical rainforests (typically <10%). Total plant biomass ranges from 78 to 320 Mg ha^{-1}, with some forests on floodplains reaching up to 452 Mg ha^{-1} (Murphy and Lugo 1986; Jaramillo et al., 2011). As a consequence of drought-stress, up to 50% of total live biomass can be represented by roots (range = 8 – 50%). Tree growth in TDF during the growing season can compare to growth in rain forests but the shorter growing season in TDF reduces their net annual primary productivity (NPP), which ranges from 8 to 21 Mg ha^{-1} y^{-1} with 6 to 16 Mg ha^{-1} y^{-1} aboveground. Allocation of NPP to roots can be nonetheless high, 44% in average in a Mexican dry forest (Martínez-Yrizar et al., 1996). Few studies of carbon cycling are available for TDF yet they suggest that belowground processes may be as or more important than aboveground processes for cycling of carbon and other nutrients. (See more detail here).

Disturbance and Recovery

Like other tropical forests, TDF experience large scale disturbance from cyclones, landslides and natural fires (Velázquez and Gómes-Sal, 2007). Yet, none of them is predominant. Cyclones are rare or do not occur south of Costa Rica, Central America, where the majority of TDF occur. In contrast to Asian dry forests, fire is not part of the natural environment of most Neotropical dry forests (Sanchez-Azofeifa and Portillo-Quintero, 2011). Canopy gap disturbances, significant for rainforest dynamics, are also much less important for TDF, since most dead trees remain standing and gap formation rates and sizes are low (Dickinson et al., 2001; Duran et al., 2002). In contrast to natural disturbances, anthropogenic exploitation, deforestation and burning are widespread and impact Neotropical dry forests more than any other disturbance factor. Dry forests ecosystems are also more threatened by these disturbances than any other tropical forest type (Janzen, 1988; Miles, 2006). It is estimated that only 44% of Neotropical dry forests remain (Dirzo et al., 2011), with regional estimates as low as 27% in Mexico, 15% in Venezuela and only 2% for Central America (Trejo and Dirzo, 2000; Janzen, 1988; Rodriguez et al., 2008). This largely results from the comfortable climate, including a comparatively low incidence of disease, that dry forest zones represent for human inhabitance (Murphy and Lugo, 1986).

Because of high soil fertility, reduced species richness, simple vertical structure, and commonness of wind dispersal and sprouting ability, TDF are expected to be particularly resilient. TDF do regenerate naturally from a variety of land use types and disturbance intensities, but they are not intrinsically more resilient than rainforests (Lebrija-Trejos et al., 2008; Martin et al., 2013). As in rain forests, rates of recovery largely depend on the extent and intensity of the disturbance and on the conservation status of surrounding forests (e.g. Molina Colón and Lugo, 2006). When disturbed areas occur within a matrix of preserved old-growth forests, plant species richness and composition may indeed recover fast (Lebrija-Trejos et al., 2008; Chazdon et al., 2011), yet such conditions seldom occur and, as in rainforests, species composition may not return to pre-disturbed states (Murphy and Lugo, 1995; Molina Colon and Lugo, 2006). Rates of recovery from disturbance are also a function of the ecosystem attribute. For instance, rapid rates of recovery have been documented for vegetation cover, stem density, bird species richness, plant insect-interactions and soil carbon stocks but not for bird species abundances, bat species richness or abundance, tree basal area or aboveground carbon stocks (Vargas et al., 2008; Lebrija-Trejos et al., 2008; Chazdon et al., 2011; Villa-Galavitz et al., 2012).

Figure 2.9 Tropical Montane Forest in Panama
Photo credit: STRI archive

Hydrology

Tropical dry forests, which constitute about 42 percent of the world tropics, have been far less studied than humid tropical forests (Farrick and Branfireun, 2014a,b). Defining characteristics include a 3-to-7 month dry season and greater potential evapotranspiration than precipitation on an annual basis. In the northern Neotropics these forests are dominantly mixed deciduous and pine-oak. Farrick and Branfireun (2014a) demonstrate that unlike temperate arid soils, where storm-water infiltration is frequently limited by low hydraulic conductivities and water repellency, water repellency is lost once the wet season starts in tropical dry-forest soils and infiltration rates are sufficiently high that sub-surface flow is the dominant runoff mechanism. Farrick and Branfireun (2014a) demonstrate that over the course of the wet season in tropical dry forests, the dominant controls on runoff generation change from antecedent soil -water storage to the depth of rainfall. Basically tropical dry-forest soils behave hydrologically more like humid-tropical soils than temperate arid soils.

Tropical Montane Forests

Broad Characteristics and Biodiversity

Tropical montane forests (Figure 2.9) can be broadly characterized as forests that occur in mountainous regions of the tropics, and which typically are affected by some degree of cloud and/or fog due to the relatively cool air, high relative humidity, and often associated with higher elevations. A subset of TMFs, known as tropical montane cloud forests (TMCFs), are typically located in upslope, headwater regions of tropical mountains and are distinguished by the presence of frequent and persistent clouds or fog, which result in unique species assemblages and biogeochemical and hydrological processes (e.g., Bruijnzeel et al., 2010). (See more detail here). Because of their unique characteristics and ecological and hydrological importance, TMCFs have been the focus of extensive study, and thus receive particular attention in this section. Tropical montane forests are most common from 1000-3500 m elevation in the Neotropics and southeast Asia ranging from central Mexico to northern Argentina and from Nepal to northern Australia. With regard to TMCFs in particular, although they cover only approximately 0.26% of the Earth's land surface (Bubb et al., 2004), TMCFs are considered one of the world's most important biodiversity hotspots (Barthlott et al., 2005) and harbor a disproportionately high number of species of plants, birds, mammals, amphibians, and reptiles. Additionally, TMCFs are critical for conservation as they have extremely high levels of endemism with new species frequently being discovered. For example, in Peru alone, 32% of endemic invertebrates are confined to TMFs (Leo, 1995).

Vegetation Structure, Biomass, and Productivity

Compared to lowland moist forests and rainforests, montane forests tend to have shorter stature, richer soil organic layer, lower leaf size and area, and in turn, lower levels of productivity. At lower elevations within the TMF zone, tree size can reach over 30 m height (Richter, 2008) which decreases with elevation to ~5 m height at the upper TMF limit. Tree species are often combinations of holarctic and tropical lineages due to the unique microclimates that historically allowed temperate species to remain in these high elevation forests. At lower elevations, TMFs are dominated by broadleaf evergreen trees, transitioning to a greater number of deciduous, semi-deciduous, and coniferous trees at higher elevations. Tropical montane cloud forests have the additional distinction of harboring a remarkable number of species of epiphytes that can account for up to 35% of the vascular flora and exceed the biomass of herbs and shrubs (Nadkarni, 1984; Gentry and Dodson, 1987). These humid environments also support high abundances of mosses, lichens, and ferns, which combined produce a highly diverse and dense understory vegetation. In particular, tropical montane cloud forests contribute significantly to global carbon budgets, storing up to 195 Mg C ha^{-1}, equal to the quantities stored by some lowland rainforests and greater than tropical alpine grasslands and *paramo* ecosystems (Gibbon et al., 2010; Girardin et al., 2010). This high storage is due primarily to shifts in carbon allocation below ground with the majority of carbon stored in fine root biomass and soils (e.g., Girardin et al., 2010; Malhi et al., 2011). Although TMCFs are major carbon sinks their net primary productivity (NPP) is significantly lower than lowland forests sequestering 5.68 ± 0.44 Mg C ha^{-1} yr^{-1}, less than half of the estimated 12.6 ± 2.5 Mg C ha^{-1} yr^{-1} in lowland tropical forests (Aragão et al., 2009; Girardin et al., 2010). Scientists have not been able to identify any single cause for the low productivity and stunted structure typical of cloud forests, but it is likely a combination of several factors, including periodic water shortage, chronic soil saturation and oxygen deficiency, low radiation and temperatures due to foggy conditions, limited nutrient uptake (due to low soil water uptake rates, extreme soil acidity or low fertility, and/or soil toxicity), exposure to strong winds, and high intensities of UV-B radiation (Bruijnzeel et al., 2011). Despite their relatively low levels of productivity, TMCFs are still important in terms of their capacity to sequester and store carbon in the soil and vegetation for long periods of time.

Disturbance and Recovery

The predominant disturbance in TMFs comes from anthropogenic land-use conversion to agriculture and pasture and rapid changes in climate. While a global number of TMF loss does not exist, analyses in northern Colombia and eastern Mexico have shown respective losses of 90% and 86% to agriculture and pasture (Bruijnzeel and Hamilton, 2000; Muñoz-Villers and López-Blanco, 2008). As with other tropical regions, a combination of factors contribute to land conversion that include the need for land to sustain livelihoods and a lack of policing infrastructure to maintain conservation zones. Specific evidence from TMFs in Mexico found that logging within TMFs was common and caused substantial changes to long-term vegetation structure (Doumenge et al., 1995). Natural disturbances are also common with TMFs. In the same TMFs of Mexico mentioned above, tree mortality was high, with 130 dead trees/ha due to both snapping or uprooting from severe natural disturbances (e.g., hurricanes, high winds; Lawton and Putz, 1988; Williams-Linera, 2002). Despite the perception of TMFs as ever-wet ecosystems, severe drying and fires can cause significant disturbance and mortality, often associated with El Nino years (Asbjornsen et al., 2005; Román-Cuesta et al., 2011). Tropical montane cloud forests do not seem to be particularly resilient at recovering from landscape-scale disturbances. Species distribution and composition, stand density, and basal area all have been found to be negatively correlated with disturbance intensity (Ramirez-Marcial et al., 2001). Frequent disturbances lead to community shifts towards early successional species such as *Pinus* spp. and the loss of endemic TMF species (Cayuela et al., 2006). Studies of recovery following disturbance in TMCFs suggest that although recovery processes vary widely depending on species composition, severity of the disturbance, and climate, TMCFs generally recover slowly and thus do not seem particularly adapted to high disturbance frequency or climate change and will face increasing pressure in the near future. The evidence of high mortality rates in TMCFs following both natural and anthropogenic disturbances combined with their relatively slow recovery processes suggests that TMCFs may be particularly vulnerable to increasing frequency or severity of disturbance as well as future climate change (e.g. Williamson et al., 2000).

Hydrology

Tropical montane cloud forests have received the greatest attention with respect to their important hydrological functions, in large part due to their location at stream headwaters where they strongly influence both water quality and quantity within a watershed. In particular, TMCFs provide critical hydrological services to lower-lying regions by maintaining abundant and reliable water supplies due to a combination of high annual precipitation, additional water inputs from canopy interception of cloud water, and low evapotranspiration rates. In tropical montane cloud forests, rainfall interception often increases with elevation ranging from 1% to 37% of total rainfall with large proportions coming during the dry season (Holder, 2004; Holwerda et al., 2010). Base flow in streams flowing from watersheds supporting TMCF typically demonstrate seasonality with peaks during the late wet season and relatively lower levels (with greater reliance on fog) during the dry season. When TMCFs are converted to other land uses (agriculture or development), greater peak flows and lower seasonal base flows may occur due to decreases in soil infiltration, increased runoff, and reduced soil water storage capacity and recharge (Zadroga, 1981; Bruinjzeel, 2004). In one study of the impacts of land use change on TMCF hydrology in Mexico, conversion of TMF to pasture resulted in an estimated 12% increase in the total annual water yield compared to mature TMCF (Munoz-Villers and McDonnell, 2013). This conversion also has contrasting effects across seasons as the watershed dominated by pasture had 35% less base flow in the dry season and 17% higher storm discharge in the wet season compared to the watershed dominated by mature TMCF. TMCFs also intercept and store significant quantities of water within canopies, as much as 17% of dry season rainfall in one study (Holwerda et al., 2010), which reduces transpiration rates and provides a direct moisture subsidy for canopies and epiphytes. Within tropical regions, numerous rural communities rely directly on hydrologic services provided by TMCFs and thus their management and conservation is critical. For example, policies that promote "Payments for Hydrological Services" are increasingly targeting TMCFs as a means of protecting and enhancing water yield and quality to downstream users (Muñoz-Piña et al., 2008; Toledo-Aceves et al., 2011).

Paramo

Broad Characteristics and Biodiversity

Paramo are high altitude tropical ecosystems that form the zone between the tree and snow lines (Figure 2.10). The vegetation is low statured with a high diversity of grasses and shrubs adapted to intense ultraviolet radiation, temperatures, and the desiccating effects of winds. Temperatures are often below freezing during the night but can get up to 25 degrees Celsius during the day (Hofsted et al., 2003, Llambi et al. 2012). Paramo are concentrated in the Andes Mountains in Venezuela, Colombia, Ecuador, and northern Peru but also extend into Costa Rica and Panama (e.g., Llambi et al. 2012). Although their species diversity is lower than tropical forests, they harbor thousands of species of plants and maintain

Figure 2.10 ***Paramo*, Podocarpus National Park, Ecuador** Photo credit: Nikolay Aguirre

particularly high levels of endemism. For example, the total number of vascular plants found in South American *paramo* is approximately 4,000, 60% of which are endemic (Llambi et al., 2012; also see Hofsted et al., 2003). Although not necessarily residents, many mammals and birds use paramo as biological corridors to transit between areas of optimum habitat. *Paramo* are biodiversity "hotspots" (see Myers et al., 2000) for Central and South America.

Vegetation Structure, Biomass, and Productivity

As noted above, the short statured vegetation contained in *paramo* is adapted to the local environmental conditions. Although rainfall is abundant, frequent winds and intense sunshine can rapidly desiccate plants as they lose water through stomata during CO_2 uptake as part of photosynthesis. Plants living in *paramo* are therefore adapted to dry conditions. Lower temperatures than those of lowland forest and anaerobic conditions created by high water retention result in slower rates of decomposition of organic material produced as plants shed leaves, fine roots, and die as part of the natural life cycle. This organic material is incorporated into the soil such that *paramo* soils contain significantly more soil carbon than tropical forests. Indeed, combining both above and below-ground carbon storage, *paramo* store more carbon per hectare than tropical forests in spite of the low stature of the vegetation (Hofstede et al., 2003). Thus, they play an important role in combating climate change (Cuesta et al., 2014, Vargas et al., 2010).

Disturbance and Recovery

Paramo undergo a variety of natural and anthropogenic disturbances that return at very different frequencies. Glaciers occur on geologic time scales while volcanic eruptions can return more frequently. Fire is part of the natural disturbance regime but is also a tool used by humans to clear and or convert *paramo* to other uses. Agriculture, cattle grazing, mining and conversion to plantations are other anthropogenic disturbances (Vargas and Velasco, 2011). The nature (intensity and magnitude) and extent (in both time – frequency - and space) of the disturbance will govern the ecosystem's ability to recover from a given disturbance. (See more detail here). As *paramo* include vegetation adapted to disturbance, they are inherently resilient but still require at least 10 to 15 years of uninterrupted succession to recover from disturbances (Sarmiento et al., 2003; Aguirre et al., 2014). However, systems that cross biophysical thresholds in resiliency and/or redundancy into a permanently altered state require assistance and are the most difficult to restore (Vargas et al., 2010; Van Andel and Aronson, 2010).

In addition to threats of conversion and those due to climate change two divergent processes are underway with respect to *paramo*: degradation and "paramization" (Figure 2.11). The former refers to the changes in species composition of the vegetation as well as physical properties due to a natural or anthropogenic stress. The latter refers to the conversion of forest followed by colonization of *paramo* species. This can lead to an expansion of *paramo* below the timber line as the highly competitive nature of grasses associated with *paramo* makes it difficult for tree seedlings to establish (Gonzales et al., 2011; Llambi et al., 2012)

Hydrology

Paramo typically receive abundant rainfall, often on the order of 4,000 mm per year (Hofstede et al., 2003; Buytaert et al., 2006). Rainfall is frequent but at low intensity and water also enters the system through interception of horizontal rainfall and snow. Evapotranspiration is low as plants are adapted to desiccating conditions (De Biévre et al., 2006; Llambí et al., 2012). The elevated level of organic material stored in the soil affords the ability to store vast quantities of water. Indeed, watersheds with *paramo* yield 60 to 70% more water than watersheds without *paramo* (De Biévre et al., 2006) such that *paramo* serve an important function in both the provision and filtration of water (Celleri and Feyen, 2009). *Paramo* are considered of strategic importance for their hydrological benefits (Hofstede et al., 2003,) as they provide up to 80% of the water for human consumption for the cities of Quito (Ecuador) and Bogotá (Colombia; Mena, 2010; Cuesta et al., 2014).

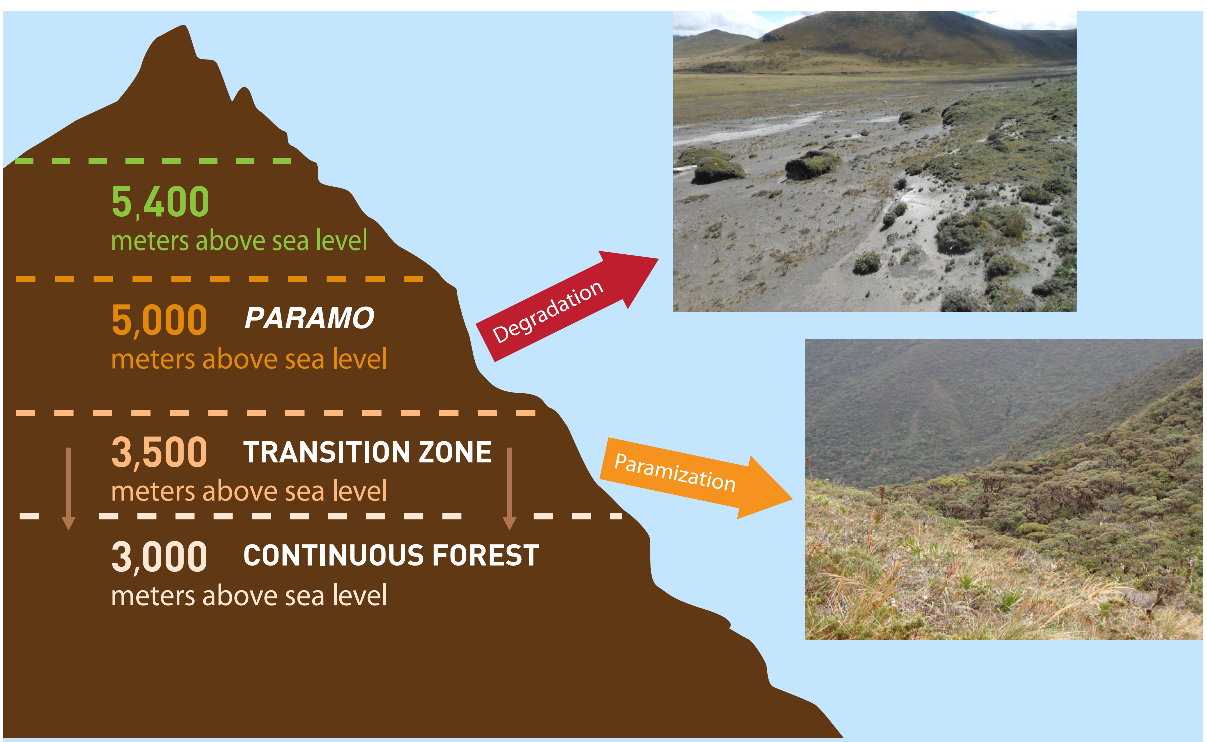


Figure 2.11 Pathways of Ecosystem Development Leading to *Paramo* with Disturbance at the Forest-*Paramo* Boundary

Chapter 3
The Importance of Ecosystem Services to Society

3 The Importance of Ecosystem Services to Society

Ecosystem Services and the Millennium Ecosystem Assessment

Ecosystems and their processes result in the provision of benefits to all species, but the concept of ecosystem services focuses attention particularly on the human species' dependence on natural processes. It includes multiple dimensions of this relationship ranging from very tangible use of resources, to the regulation of health, and to the intangible benefits of nature to people. The Millennium Ecosystem Assessment (MA, 2001) brought the concept into the mainstream and provided a foundation for ecosystem service science, which has since greatly expanded. Ecosystem services is therefore an anthropocentric concept with a particular purpose and an evolving body of research focused

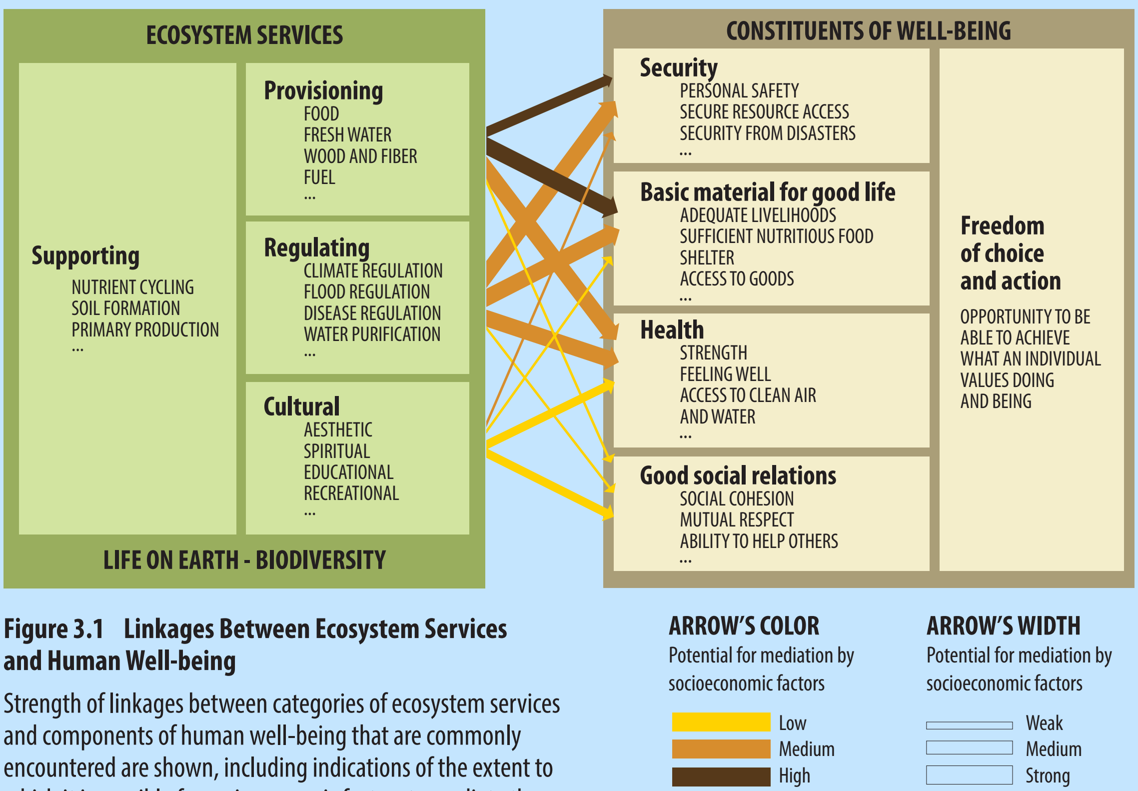


Figure 3.1 Linkages Between Ecosystem Services and Human Well-being

Strength of linkages between categories of ecosystem services and components of human well-being that are commonly encountered are shown, including indications of the extent to which it is possible for socioeconomic factors to mediate the linkage. (For example, if it is possible to purchase a substitute for a degraded ecosystem service, then there is a high potential for mediation.) The strength of the linkages and the potential for mediation differ between ecosystems and regions. In addition to the influence of ecosystem services on human well-being depicted here, other factors – including other environmental factors as well as economic, social, technological, and cultural factors – influence human well-being, and ecosystems are in turn affected by changes in human well-being. Taken and modified with permission from Millennium Ecosystem Assessment, 2005.

on measuring the benefits that people obtain from ecosystems. Most often this research is intended to inform planning, policy, and decisions that may cause changes to the natural availability of these benefits.

The Millennium Ecosystem Assessment (MA) developed a very useful conceptual framework to better understand how societies and ecosystems interact. Drivers of change emerging from societies (e.g., demographic, economic, cultural, governance) influence the decisions people make to manage ecosystems. Drivers of change associated with these management decisions (e.g., input use, technologies, species introductions) have intentional and unintentional consequences in the ecosystem, fostering some ecosystem services at the cost of reducing others. The resulting suite (or bundle) of ecosystem services then contributes to the different components of human well-being (e.g., materials necessary for a good life, health, security, good social relations).

The generation and flow of benefits from ecosystems to societies is strongly dependent on the adequate functioning of ecosystems. Biodiversity, that is all the variability found in living organisms, interacts with non-living component of terrestrial and aquatic ecosystems to contribute to ecosystem functioning. Ecosystem services are not only provided by relatively unaltered or "natural" ecosystems but also by some agroecosystems or agricultural landscapes that conserve habitat heterogeneity. Key ecosystem processes such as the transformation of solar energy into biomass through photosynthesis, the hydrological cycle, and the nutrient cycle depend on the number and type of species present in the ecosystem, as well as on the amount of water, energy and nutrients available (Quijas and Balvanera, 2013; Chapin et al., 2011).

The MA identified four kinds of ecosystem services: provisioning, regulating, cultural and supporting services (Figure 3.1). Supporting services encompass the above described key ecosystem processes and those that allow for the maintenance of biodiversity. Given that supporting services do not have direct links to human well-being, they are often considered ecosystem processes rather than services (IPBES, 2013). The key message, irrespective of the terminology, is extremely important: for services to flow to societies, biodiversity and processes within ecosystems need to be maintained.

Typology of Ecosystem Services

Watersheds are an important level of ecological organization for understanding and analyzing the fundamental life-support services upon which human societies depend. Nutrient recycling, habitat for plants and animals, neutralization of pollutants, protection from natural disasters, control of pest outbreaks and diseases, and water supply are among the many beneficial services provided by ecosystems that can be conceptualized at the watershed scale. In making decisions about human activities such as draining a *paramo* for cattle, or deforesting a parcel of land for agriculture or development, it is essential to consider both the value of the development and the value of the ecosystem services that could be lost (Summers et al., 2012). Many people believe that nature provides these services for free and therefore, that they are of little or no value. However, everyday decisions almost always have some effect on the magnitude and quality of ecosystem services provided. Societies "pay significantly for their loss" in terms of water treatment facilities, moratoriums on resource extraction, illnesses, reduced soil fertility, and the loss of aesthetic landscapes that contribute to our basic happiness (Summers et al., 2012). Considering the full range of relevant ecosystem services when making decisions can help to mitigate the loss of services that are important to people, thereby increasing net human well-being. A general overview of the different categories of ecosystem services followed by selected examples is provided below.

Supporting Services

Supporting services as described in the Millennium Ecosystem Assessment (MA) are also referred to as ecosystem processes. The conversion of light energy into chemical energy of sugars and carbohydrates through the process of photosynthesis is such a process and determines an ecosystem's productivity (see Chapter 2). This and other processes such as the nutrient and hydrological cycles are interlinked and critical to supporting an ecosystem's ability to provide other services. The ability of an ecosystem to maintain these processes is linked to the system's ability to recover from disturbance and thus linked to biodiversity through the concepts of redundancy and resilience (Box 2.7).

Seed Dispersal

In tropical forests, many species of animals are involved in dispersal of plant seeds. The most common taxa include birds, monkeys, rodents, and in some cases even insects (such as ants) are involved in seed dispersal. Seed dispersal involves moving the seeds away from the parent tree. This can be a critical service to plants, because when they are dispersed far from their parents, the seeds are less likely to encounter species-specific pathogens and herbivores that attack the parent trees (Janzen, 1970; Connell, 1971). In tropical areas that are deforested or degraded, animal seed dispersal has the potential to aid in the re-colonization of native vegetation. Land managers can increase the attractiveness of sites to dispersers by increasing the availability of perches, increasing structural complexity in the vegetation, and by retaining fruit trees to attract dispersers (Wunderle, 1997).

Biological Corridors

Many birds and mammals depend upon the continued juxtaposition of desirable habitats to allow sufficient areas to forage and/or support minimum viable populations of a given species. With an increasingly fragmented landscape it is more important than ever to maintain habitat connectivity. Examples of the importance of connectivity include its role in providing access to large-bodied, wide-ranging mammals like jaguar to sufficiently large areas for foraging and maintaining genetic diversity (Figure 3.2), and in providing Neotropical migrant birds like warblers with forest migration corridors to make their annual trek from North to South America.

Figure 3.2 Biological Corridors Exist Within and Connect Watersheds in the Steepland Neotropics

The Jaguar Corridor Initiative is a range-wide conservation plan for the jaguar. The corridor map was created through expert information on core jaguar populations, followed by a least-cost analysis for corridor mapping. Conservation actions are focused in priority corridors and core populations to maintain connectivity. Photo credit: Panthera Colombia

Provisioning Services

Provisioning services are the tangible resources that people obtain from ecosystems. They are finite, can be renewable, and are directly consumed, appropriated, and traded. All natural resources are provisioning services.

Food

Whether produced locally at small scales close to markets or on large industrial farms hundreds or thousands of kilometers from market, food production (be it fruits, grains, meat, and poultry to name a few) depends upon the supply of light, nutrients, and water. Some farming practices result in whole scale ecosystem conversion while other practices preserve or even depend upon remnants or some large portion of the original ecosystem. Food production is a critical ecosystem service.

Water

Access to abundant fresh water is perhaps one of the biggest development challenges of the 21st century not only in terms of drinking water for humans but also for agricultural production (see Schiermeier, 2008). The ecosystem's ability to provide water links both provisioning and regulating services in ways that obscure the boundaries of these concepts and are also linked to supporting services. *Paramo*s accumulate and store vast amounts of water in their soils and organic matter. The water that is released over time helps ensure a sustainable supply of water for millions of people in Ecuador, Colombia, Venezuela and northern Peru (Buytaert et al., 2006). Trees in cloud forests can help strip moisture from the atmosphere and thus deliver significant water to the watershed. The ability of tropical montane and lowland forests to provide increased dry season stream flow through enhanced rainwater infiltration (see Panama Canal Watershed and Veracruz case studies, Chapter 7) is particularly important with the ever increasing need for water due to population growth and increased human activity. Finally, as noted above, rainfall cycled locally through convection thunderstorms due to high evapotranspiration in rain forests can help serve agriculture in adjacent areas (as long as the proportion of these land uses does not tip too far towards large scale agriculture).

Hydropower

In addition to providing abundant clean drinking water, tropical watersheds have increasingly been dammed to provide energy through hydropower, for flood protection, and to ensure water for agriculture and human consumption. Dams can lead to unintended social and ecological consequences. Nevertheless, many countries are pressing ahead with large dam construction projects. Panama, for example, meets 50% of its energy needs through hydropower. Costa Rica gets 80% of its energy from hydropower and some 40 hydropower plants are under design in Nicaragua (Locatelli et al., 2010).

Wood – Natural Forest

The forests of Latin America and the Caribbean (Neotropical forest) have been a source of high value timber for well over a century. Dozens of tropical hard woods have long been recognized for timber value (see e.g., Ashton and Hall, 2011) with the extraction so intense and sustained over time that several tree species face commercial extinction throughout their range. Indeed, many of the highest value species such as *Swietenia* spp. (mahoganies), *Dalbergia* spp. (Brazilian Rosewood, Cocobolo, etc.), *Cedrela* spp. (Spanish cedar, etc.) and *Dipteryx oleifera* (Almendro de montaña) benefit from some measure of protection under the Convention on International Trade of Endangered Species (CITES; USDA, 2010). European and US markets have been supplanted by exports to Asia and timber export, as well as extraction for local consumption and to benefit to local communities and cultures, remains an important component of the economy in many countries (UNECE/FAO, 2014).

Wood - Plantations

Plantation forestry for the production of wood products for both local consumption and export has grown steadily in the Neotropics in recent decades. Globally, four genera or species dominate plantation forestry as much is known about how to grow and manage these species: Acacias, Pines, Eucalyptus, and Teak. However, there has been recent attention focused by conservationists, policy makers, and researchers on the potential of native species to produce multiple benefits in addition to timber values (Hall et al., 2011). Thus, a number of groups have

Figure 3.3 Plantation of *Dipteryx oleifera*, a High Value Native Timber Tree (known in Central America as Almendro de montaña) in the Forest Finance Plantations, Las Lajas, Panama Photo credit: Andres Hernandez, STRI

been working to advance the science to overcome the barriers of planting with native species (see e.g., Montagnini and Finney, 2011; Breguel et al., 2011).

Wood - Firewood

Firewood is extracted from tropical forests to meet the energy needs of rural populations. Collection of firewood for individual household consumption depends largely on dead material and minor twigs, and thus rarely poses a threat to tropical forests. However, charcoal, that is produced from harvesting slow growing species and turned into slow-burning coal through a highly inefficient process can often lead to overexploitation (Mwampamba, 2007).

Non-timber Forest Products (NTFPs)

A wide range of food items, construction materials, medicine, pets, and ornamental plants are extracted from tropical forests. They are normally encompassed under the name of non-timber forest products to separate them from wood and biofuels. A single species can have many uses; different parts of the individuals are often used. Insects, amphibians, reptiles, birds and mammals have been an important source of protein in the Neotropics since early humans came to settle, but consumption has greatly increased and animal population densities have greatly decreased over the past few decades (Redford, 1992; Milner-Gulland and Bennett, 2003). Rural populations across the tropics also use herbs, lianas, trees, shrubs and ferns to meet their everyday needs. While sustainable management can be achieved (Peters, 1994), non-sustainable harvests have led to local extinctions, largely driven by regional and global markets (Arnold and Ruiz Perez, 2001).

Regulating Services

Regulating services refer to benefits obtained from the regulation of ecosystem processes. These services specifically regulate the conditions where humans live and make a living. Such regulation determines both the average and the variance in such conditions. Regulating services result from the contribution of multiple ecosystem processes operating at spatial scales ranging from a few meters to the whole planet, and at temporal scales ranging from a few seconds to millions of years (Kremen, 2005). Regulating services have been highlighted by scientists as life supporting, but have often been taken for granted by most of the human population and are generally overlooked in decision-making because information and knowledge of regulating services is usually lacking. However, recognition of regulating services has been increasing somewhat since the publication of the MA.

Water Regulation Services

Society has tended to take for granted the ability of tropical forests and other ecosystems to regulate groundwater recharge and provide dry season flow. They may also reduce peak flows. Given the need to more efficiently manage land, it is increasingly essential to better understand the regulatory potential of forests. Recent studies based on careful monitoring of experimental watersheds in both lowland seasonal forest in Panama and montane forests in Mexico have shown that forests can indeed function as a "sponge" with higher dry season stream flow in forests over areas that have been converted to cattle pasture (Ogden et al., 2013; Munoz-Villers and McDonnell, 2013). These same studies have also shown the ability of forests to reduce peak flows, a service that helped avoid a potential catastrophe in the Panama Canal Watershed in December of 2013. (See more details here).

Erosion and Landslide Regulation

Forests contribute to soil retention and reduced impact of rainfall on soils. They do not halt erosion (e.g., Zimmermann et al., 2012) but can greatly reduce it in normal years. For example, a 15 year record from Puerto Rico comparing forested and agricultural mosaic on two different geologies found an exceedingly higher volume of suspended sediment in rivers draining the agricultural mosaic than the forested watersheds with difference on the level of an order of magnitude (Table 2.2). In addition, in a multiyear record of forested and deforested watersheds in the Panama Canal watershed Stallard and Kinner (2005) found markedly higher volumes of suspended sediments in deforested as compared to forested watersheds. This undoubtedly reduced filtration costs for the water plant on Lake Alhajuela as much of the upper watershed is protected by Chagres National Park. However, landslide probability during extreme events has more to do with slope angle, soil depth, and rainfall intensity than with forest cover. Thus, in 2010 approximately 0.5% of the Chagres National Park succumbed to landslides due to a single, sustained storm (Stallard and Hurska, 2012; also see examples in Chapter 2).

Carbon Regulation

The past decade has seen a significant focus on the importance of tropical forests in helping to regulate the global carbon cycle. Indeed Latin American forests are estimated to harbor on the order of 1,000 gigatons (Gt) of carbon that if released through forest clearing would greatly exacerbate climate change (Saatchi et al., 2011). While significant attention is paid to aboveground biomass held in forests (see e.g., Asner et al., 2013), carbon loss from soil can also be important (e.g., Lugo and Brown, 1993; Lal, 2004). For example, Neumann Cosel et al. (2011) found that decades of forest conversion to cattle pasture in the Agua Salud study area of central Panama resulted in 10 tons of carbon lost per hectare from the upper 10 cm of the mineral soil. However, Powers et al. (2011) point out that the limited geographic distribution of existing studies on the effect of land use change on soil carbon in tropical regions impedes our ability to draw broad conclusions. While insufficient data may be available to quantify carbon in soils across broad regions, loss associated with land use change is nonetheless a concern. Although their geographic distribution is limited and vegetation short in stature, *paramo* and montane forests also harbor important stocks of carbon owing to the vast amount of organic material in the soil and humus (see Chapter 2).

Shade and Improved Animal Well-being

Hot temperatures throughout the year in the Tropics and during summer months in the Subtropics can lead to heat stress in cattle and other livestock, negatively impacting the animals' well-being and productivity (Chara et al., 2014; Nardone et al., 2010). Strategies to mitigate the impact of heat stress are therefore important to improve animal well-being, and generally include the combination of shade trees, access to fresh water, and the selection of heat tolerant animals. Intensive Silvopastoral Systems improve conditions for livestock by providing shade during summer months and shelter during rainy months, as well as access to green forage and fresh water throughout the year (Murgueitio et al., 2011). For example, in the dry Caribbean equatorial conditions of Colombia, the presence of trees and bushes lowers the average air temperature in pastures to between 2 and 3°C as compared to traditional systems without trees (Calle et al., 2013). This difference in microclimate is accentuated during the hottest times of the day when a treeless pasture can reach temperatures of 42°C while a neighboring Silvopastoral System

registers 34°C (Chará et al., 2014). This is important because shade helps cattle maintain body temperature more efficiently, resulting in reduced energy losses and increased grazing activity for the animals.
(See more detail here).

Pollination

Pollination of crops by wild animals is a key ecosystem service. Animals that pollinate include insects, birds, rodents and bats. In most cases, these organisms require some forest habitat to persist, such that pollination in agricultural settings will likely be increased near forests. A list of 1330 cultivated plant species was developed for tropical areas, and 70% of the crop species showed improved production when pollinated by animals (Roubik, 1995). In Central American watersheds, insect pollination of coffee and cocoa is an important ecosystem service. For example, one experiment in Costa Rica showed that having forests close to coffee farms increased pollinator visits and coffee yield by 20% and increased coffee quality (by reducing small, misshapen beans by 27%). The authors calculated an overall value of $60,000 USD/year for the pollination services of two forest fragments (46 and 111 hectares; Ricketts et al., 2004). Similar findings for the value of forest for crop pollination have been found in other tropical regions (Klein et al., 2003).

In some tropical agroforestry settings, bats play an important role as pollinators, thereby directly impacting crop yields. For example, in Southeast Asia, nectarivorous bats and fruit bats are pollinators to petai (*Parkia* spp.), durian and *Oroxylum indicum*, common plants in agroforestry farming. Bat pollination accounts for 80-100% of fruit set in these crops (Bumrungsri et al., 2008, 2009; Srithongchuay et al., 2008). In southern Thailand alone, such pollination services to durian and petai were estimated to be worth $13 million USD annually (Bumrungsri et al., 2009). In the Neotropics, bats pollinate *Agave* spp. from which Tequila and other products are derived as well as cedro espina or spiny cedar (*Pachira quinata*), an important timber tree (Tschapka, 2009; Figure 3.4).

Figure 3.4 Bats, Insects and Other Animals Preform an Ecosystem Service by Pollinating Trees, Shrubs and Crops

Here *Glossophaga sp*. is visiting a flower of *Pseudobombax sp*. Bats are pollinators of many species of economic importance, including *Pachira quinata*, a close relative of *Pseudobombax sp*. Photo credit and copyright: Christian Ziegler

Pest Control

Vertebrates such as birds, bats, and lizards play an important role as predators of insects (Figure 3.5). In tropical forests and plantations, this role is indirectly important for the health of trees and other vegetation, because insect herbivory can result in the mortality of seedlings, reduced reproduction in adult plants or reduced productivity (Plath et al., 2011; Riedel et al., 2013). In agricultural settings,

Figure 3.5 Birds and Other Animals Preform an Ecosystem Service by Controlling Pests on Trees and Crop Plants

Here a Trogon consumes a caterpillar on *Ochroma pyramidale*, the balsa wood tree. *Ochroma pyramidale* is also used by the Maya to help speed up forest fallow recovery (Diemont et al., 2006). Photo credit and copyright: Christian Ziegler

predation by vertebrates constitutes an ecosystem service when it reduces insects that are herbivores on crops; otherwise referred to as biological control. Moreover, herbivorous insects may vector crop diseases (Campbell, 1983; Evans, 2007; Wiegloss et al., 2012; Wiegloss et al., 2014), so the limitation of herbivore populations by vertebrates may have direct and indirect positive effects on crop plants.

To address whether vertebrates perform an ecosystem service, a key question is whether their predation on arthropods results in reduced plant damage and higher crop yields. Across seven coffee and cacao studies, bird and bat predation reduced leaf damage significantly (Van Bael et al., 2008). One study has measured cocoa yield changes directly and found a 31% reduction in crop yield when birds and bats combined were removed from foraging on cocoa trees, constituting an estimated loss of $730 USD/ha (Maas et al., 2013). Whether or not vertebrates can limit pests may depend on proximity of forest to agricultural fields. For example, the coffee berry borer has recently invaded Costa Rica and is a pest on coffee. A recent study found that having forests nearby can contribute to vertebrate control of this pest provided an estimated $75-300 USD/ha/year in damage protection (Karp et al., 2013). Taking care to conserve forested areas within the agricultural matrix is likely to bolster pest control and provide win-win situations for biodiversity conservation and for farmers.

Cultural Services

Cultural services are ecosystems' contributions to the non-material benefits that arise from the interaction between people and ecosystems. The benefits include a range of capabilities and experiences (Chan et al., 2011). This category of services has been harder to define at broad scales as benefits are highly context-dependent and encompass many dimensions of the non-tangible interactions between people and nature as well as recreation and education. At the local scale, however, cultural services are highly valued and are generally straightforward to define. Given that the value of cultural services does not scale up easily they have seldom been explicitly incorporated into decision-making (Chan et al., 2012), likely because decisions makers at higher scales do not hold the same values, which are context-dependent.

A Sense of Place

Cultural ecosystem services include opportunities for people to develop a sense of belonging, commitment, identity and community. Together these contribute to a somewhat intangible benefit that can

Figure 3.6 Cattle Ranchers Overlooking Landscape in Colombia Photo credit: CIPAV

be called 'sense of place'. Intangible or immaterial benefits such as this are commonly underrepresented in ecosystem assessments and decisions, but are more important than commonly thought (Daniel et al., 2012). Feeling at home in our own 'place' provides us with opportunities for self-expression and empowerment, as well as a feeling of stewardship towards that place that comes from a sense of commitment and responsibility. A range of other ecosystem components, functions and services can contribute to an individual's sense of place (e.g., landscape configuration, water, vegetation, particular species, etc.), as can different socio-economic characteristics (e.g., time living in an area, personal relationships, socio-economic position, etc.). Sense of place has been found to be a primary driver of subjective happiness, which is one of the principle elements of human well-being (Summers et al., 2012).

Spiritual Values

Cultural services include the existence and bequest value of a site or a species for future generations. Moreover, the sense of awe and spiritual or aesthetic inspiration from a site or species is also considered a cultural service. Cultural services can be related to different types of values (e.g., moral, spiritual, or aesthetic values), that vary across social and institutional contexts and stakeholder groups (Chan et al., 2011). The development of important cultures such as the Maya in southeastern Mexico, the Kayapo in eastern Amazon, or the Quechua in the Andes, depended on these spiritual connections to their surrounding tropical forests.

Societies have attached cultural values to particular parts of species, types of species, or types of landscapes that are particularly valued due to their appearance. Positive effects of nature on mental and physical health have been rigorously demonstrated; knowing (thinking about an ecosystem in the absence of immediate sensory inputs), and experiencing (physical, active, direct multi-sensory interactions with ecosystem components) nature makes people generally happier and healthier (Russell et al., 2013).

Outdoor Recreation and Ecotourism

Biodiversity also has a cultural aspect to it in that many people feel their life is enriched by knowing it persists and also through recreational aspects of ecotourism. Each year visitors spend billions of dollars (Chardonnet et al., 2002) to visit remote forest areas to view rare birds and mammals as well as for sport fishing. In addition to promoting opportunities for local conservation, ecotourism can also increase opportunities, such as capacity building and income-generation, for local communities.

Chapter 4

Implications of Climate and Land Use Change

4 Implications of Climate and Land-Use Change

Climate Change in the Steepland Neotropics

It is clear that the Earth's climate is changing such that even near- or mid-term decisions that can impact management for ecosystem services – the natural capital of the Neotropics – need to take climate change into consideration. According to Christensen et al. (2013), by the end of the 21st Century, climate change models project greatest warming in the Central American and Caribbean region during the months of June, July, and August. Warming is projected to be larger over Central America than the Caribbean in summer and winter. Different models suggest that warm-season precipitation will likely decrease in the Caribbean region over the coming century. However, there is only medium confidence that Central America will experience a decrease in precipitation. In South America, it is very likely that temperatures will increase over the whole continent, with greatest warming projected in southern Amazonia. The warming is likely to be accompanied by an increase in frequency of warm nights in most regions.

It is very likely precipitation will increase in northwestern South America and decrease in the extreme north of the continent. It is also very likely that less rainfall will occur in eastern Amazonia – northeast and eastern Brazil – during the dry season, but in the same regions, projections of changes in wet-season precipitation are of medium confidence. There is high confidence in an increase of precipitation extremes.

It is difficult to take model assessments of changes in precipitation and temperature and distil this into a description of impacts on natural vegetation or agriculture. The properties that are incorporated into the Köppen-Geiger climate classification (see Chapter 2) can be extracted from climate models (Rubel and Kottek, 2010), and it is possible to speculate about the future of tropical climate zones. However, where this has been attempted, changes in the Köppen-Geiger climate zones appear to be small, much less than in boreal and polar regions.

Landscape management is typically adapted to normal conditions rather than inter-annual or inter-decadal climate variability. Nevertheless, extremes are of great concern to land managers. In the tropics these include very wet times, especially large storms and associated effects, and droughts. Two factors affect thinking about climate variability and global-climate change. First, inter-annual or inter-decadal variations dominate over secular climate trends, so much so, that unambiguous global-change effects are not currently obvious in the tropics. Second, these climate variations, notably ENSO, may also mediate the effects of climate change related to the intensification of climate extremes, of wetter years, bigger storms, and deeper droughts. At a minimum, landscape managers must think about the range of variability that is now encountered because of climate variations, and to build in margins of error and resilience based on the assumption that the extremes may grow with time (Figure 4.1).

Figure 4.1 Flooding in Panama due to Heavy Precipitation

Climate change models for the steepland Neotropcis predict increases in precipitation extremes with high confidence. Photo credit: Jacob Slusser

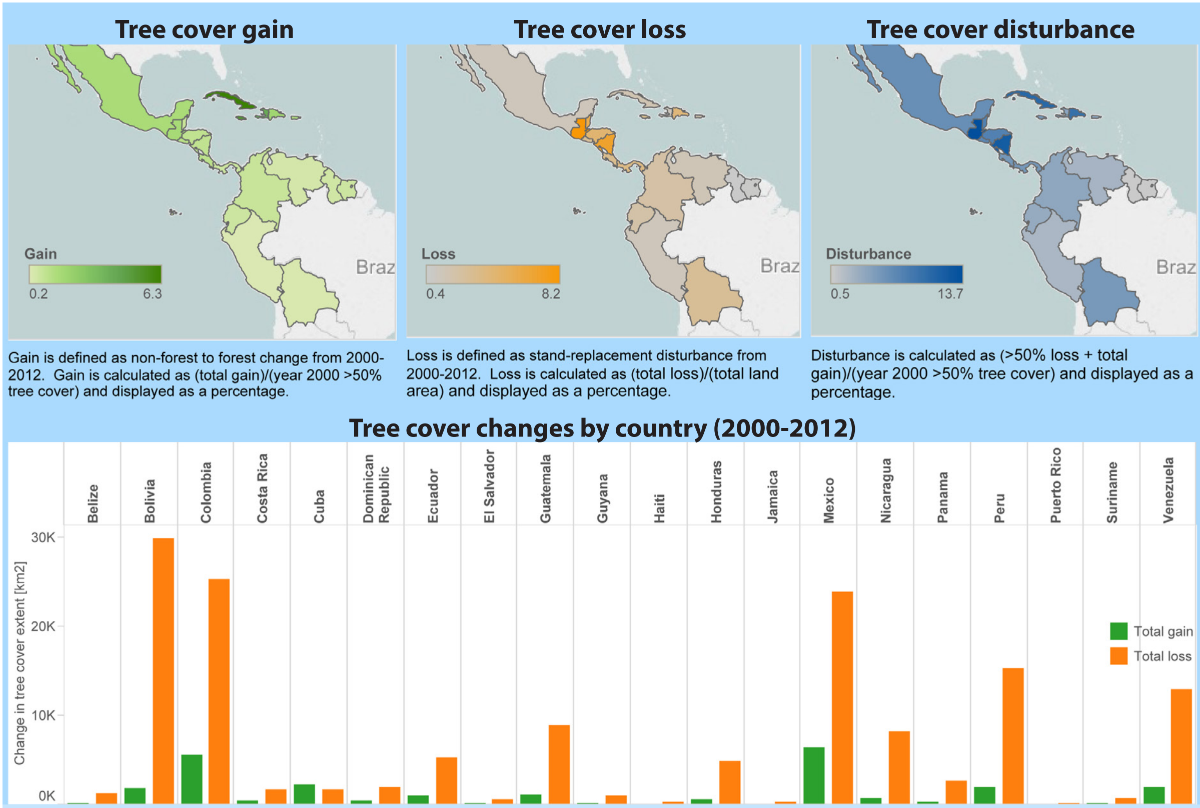


Figure 4.2 Tree Cover Change in the Neotropics (From Hansen et al., 2013)

Click here for the interactive display.

Land-Use Change and the Supply of Ecosystem Services

Societies have extensively transformed ecosystems to obtain the goods that meet needs for food, water, fuel, and many other resources to sustain income and livelihoods. Land-use and land cover can change for a variety of endogenous socio-ecological forces and exogenous socio-economic factors (Lambin and Meyfroidt, 2010). The forest transition – where land once cleared for agriculture has been allowed to return to forests – recognized in developd countries (Mather, 1992) has also been documented in several Central American (Costa Rica, Mather and Needle, 1998; El Salvador, Hecht and Saatchi, 2007; Panama, Wright and Samaniego, 2008) and South American countries (Ecuador, Rudel et al., 2002). It is important for policy makers, planners, and managers to understand the forces driving land-use change within their watersheds, but a detailed analysis of the drivers of land-use change is beyond the scope of this report. There is, however, some evidence that the gains in forest recovery previously observed in countries of the Neotropics may have stalled or been reversed. With the exception of Cuba, every single country and Puerto Rico included in the steepland Neotropics of this report had a net tree cover loss between 2000 and 2012 (Hansen et al., 2013; Figure 4.2). All countries except Cuba had more than two times more forest lost than gained. Although these country-level statistics mask net forest gains (or loss) in particular watersheds, they nevertheless represent a potentially disturbing trend in the provision of ecosystem services from watersheds encompassed within the scope of this report. Indeed, even areas one would assume to be at the lowest risk follow this trend. A recently completed study by Leischer et al. (2013) found land and forest degradation in Latin American protected areas to have more than doubled between 2004 and 2009.

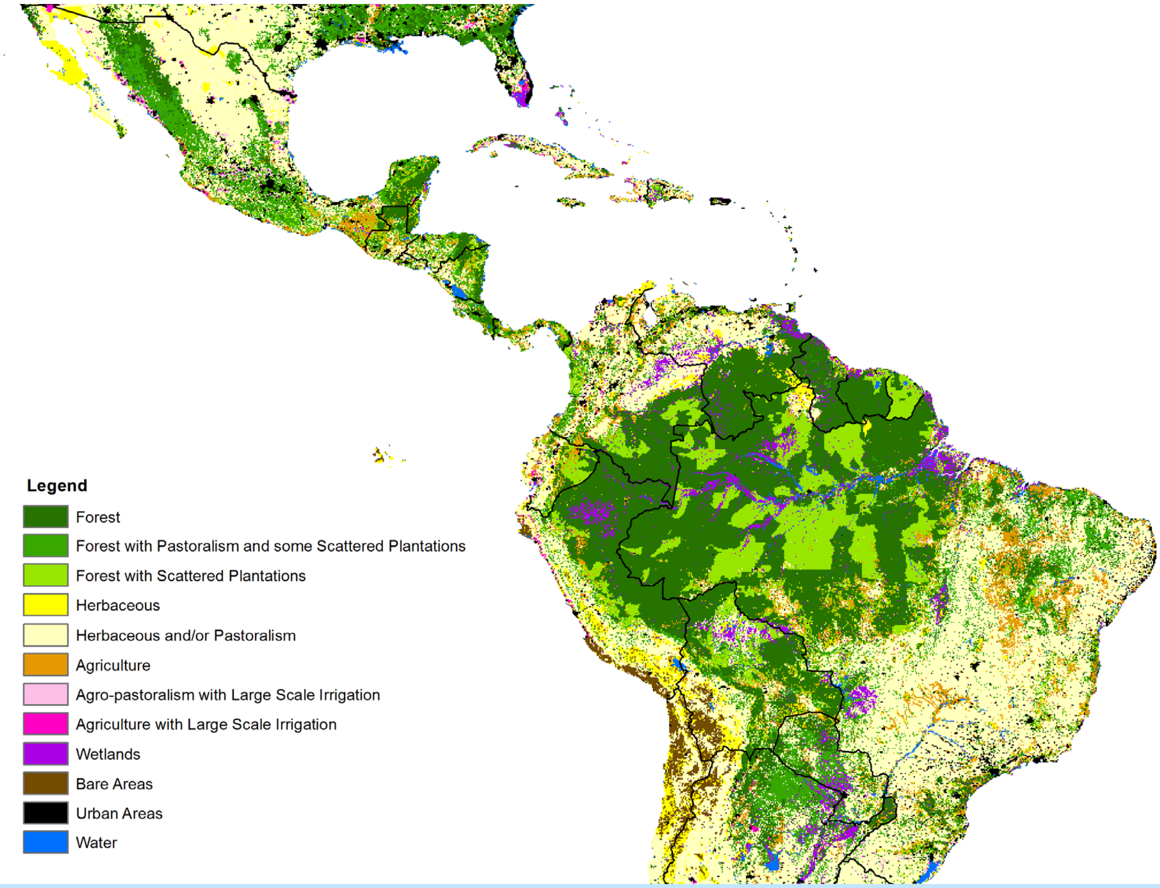


Figure 4.3 Land-Use in the Steepland Neotropics and Adjacent Areas (Modified from Nachtergaele et al., 2011)

Today more than 40% of the Earth's surface is covered by croplands and pastures (Foley et al., 2005) with few areas in the steepland Neotropics being spared (Figure 4.3). Extractive activities like logging and mining, road construction, and large infrastructure development projects are additional examples of human interventions in watersheds that drive land-cover and land-use changes, often causing ecological degradation (Aide et al., 2012; Foley et al., 2005).

The transformation of ecosystems has led to dramatic changes in the conditions of ecosystems and their ability to provide services to societies. Emissions of greenhouse gases have increased, water available for ecosystems has decreased, amounts of nutrients such as nitrogen or phosphorus have increased through fertilizer addition, and biodiversity has decreased; many of these changes are way beyond thresholds that allow for the functioning of ecosystems in the way they have been operating for the past 10,000 years (Rockstrom, 2009). Overall, services such as crops, livestock, and aquaculture have increased while services like the provision of wild products, fresh water, and pollination; the regulation of air quality, erosion, water quality, and pests; and the mitigation of natural hazards have decreased (MA, 2005).

This broad global perspective holds true in general terms but gets more complex when scaled down to watersheds and landscapes. The proportion of land transformed into croplands and pastures varies among and within watersheds. Croplands and pastures can be managed more or less intensively. Forests and freshwater systems can be more or less degraded with respect to their biotic (e.g., amount and type of biodiversity) and abiotic (e.g., amount of water or nutrient) conditions. As a result, very different combinations of ecosystem services emerge from each section of the watershed. For example, an intensive monoculture enhances the production of a certain crop at the expense of reducing erosion, pest regulation, carbon stocks, and the maintenance of biodiversity. By contrast, a diverse agroforestry system shows relatively lower yields of any single crop, higher yields of other crops and cattle, and higher erosion and pest regulation, carbon stocks, shade, pollination, and biodiversity maintenance (Jose, 2009; Box 4.1).

BOX 4.1 Land with Cattle

In Latin America and the Caribbean over one quarter of the territory is used for grazing cattle, horses, sheep, goats, and buffalo (FAO, 2011). Thus, this activity has a close connection with the supply and demand of ecosystem services. The production of the forage resources that are the basis of animal husbandry such as grasses, legumes, and fruits and foliage obtained from shrubs, trees, and palms, requires preserving the natural fertility of the soil. Biodiversity and the services it provides are also essential for feeding, reproduction, and growth of these livestock. Although the water demand of the livestock sector has not been adequately quantified in the region, it is clear that without the water resources provided by watersheds livestock activities would be unviable and the assets they generate for society would no longer be available.

Traditional methods of cattle ranching, which homogenize landscapes to establish pasture monocultures, have obvious negative impacts on forests (deforestation for land-use change), soils (compaction and erosion), water (depletion and pollution), and biodiversity (Murgueitio et al., 2011). However, recent research has shown the environmental and productive benefits of wildlife-friendly cattle production as compared to traditional models. Wildlife-friendly cattle production is based on agroecology principles that combine sound management of grasslands with soil protection, incorporating trees in various types of silvopastoral systems and efficient water planning (Calle et al., 2013; Murgueitio et al., 2011; Nair et al., 2009; Pagiola et al., 2007; Harvey et al., 2011). Farming systems that apply these principles act in synergy with forest conservation and restoration of connectivity corridors. Thus, sustainably managed livestock can become a powerful ally of ecological restoration and the provision of ecosystem services (Calle et al., 2013).

Traditional Cattle Ranching in Los Santos, Panama
Photo credit: Jacob Slusser

Silvopastoral System Located in San Juan de Pequení, Province of Colon, Panama Photo credit: Jacob Slusser

The impacts of land-use change on ecosystem services have implications on human health. While it is often difficult to disentangle the effect of biodiversity on the emergence and transmission of infectious diseases due to confounding factors (e.g. potential of increased host density with decreased diversity), there is an increasing body of evidence to suggest that it often has a buffering effect, reducing infectious disease transmission (Kessing et al., 2010). As increased forest clearance has put people and wildlife in closer contact with potential pathogens (Kessing et al., 2010), Jones et al. (2008) recommend identifying emerging disease hotspots. This recommendation is supported by Kessing et al. (2010) as well as preserving and protecting habitats in these potential disease hotspots as a way of reducing the likelihood of the emergence of new pathogens. While controlling infectious diseases would not necessarily be the goal driving watershed management in Neotropical steeplands, given the economic costs associated with fighting infectious disease, it is a potential additional benefit of forest conservation to be considered.

Temporal and Spatial Dimensions of Ecosystem Services

An important and challenging issue when assessing ecosystem services is determining at what scale the ecosystem services should be observed, measured, and managed. The answers to questions about the production (yield) and quality of ecosystem services flowing from a given system are often scale-sensitive – the answer you get depends on the scale (in both space and time) at which you pose the question and observe the phenomena of interest. Several factors impact our ability to evaluate these services, including sampling issues, non-linear scaling, and emergent phenomena (Scholes et al., 2013). Sampling issues relate to trade-offs between cost, effort, and methodologies employed. (See more detail here). Some services aggregate through simple area proportionality or time-proportionality ('linear scaling'). To do so, they must either be evenly distributed through space and time, or randomly distributed at a fine scale. More frequently, ecosystem services (like many other natural phenomena) are not homogeneously or randomly distributed in space and time; they are 'lumpy' and therefore patterns will look different depending on the scale at which you are observing them. Finally, emergent phenomena are patterns that 'emerge' and can be described at a certain scale, but not predicted from observations at lower scales. A temporal example of this is when changes in some regulating services (e.g., nutrient cycling) occur very slowly in time, leading to unexpected and abrupt collapse in associated services once a threshold is crossed (e.g., agriculture that does not adequately manage soil nutrient stocks and degrades soil to the point where nothing further will grow without intensive intervention).

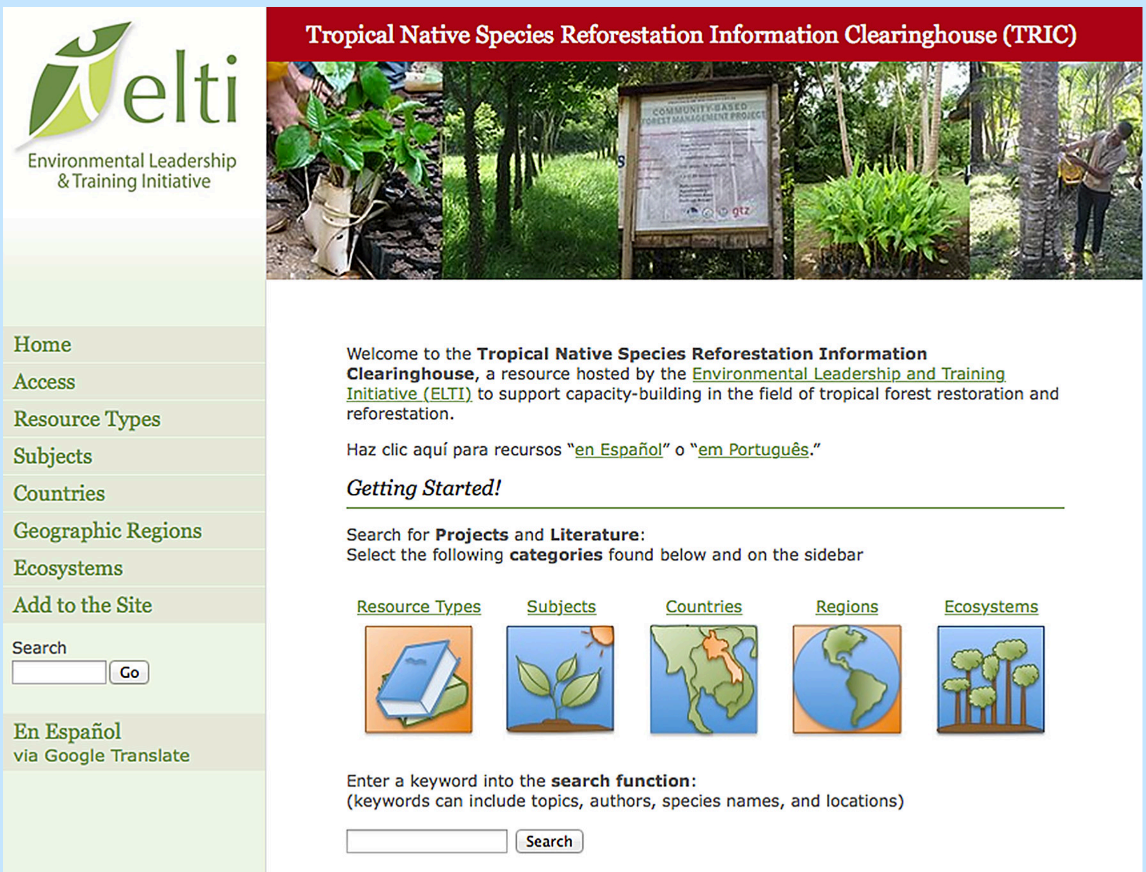
In addition to understanding how the scale of observation may affect the patterns being observed, it is important to understand the scales at which ecosystem services are produced, consumed, and managed. Individual and collections of ecosystem services are generated by a variety of social-ecological processes and structures, all with distinct spatial scales. Managers need to know at what scales ecosystem services are produced and at what scale(s) associated benefits are distributed and accessible in order to determine how to manage the underlying factors in ecosystem service production, and to identify societal values and management incentives associated with ecosystem services (Brauman et al., 2007). Scale mismatches can occur when ecosystem service managers operate at inappropriate scales, or production and consumption of services occur at different scales (again, both in time and space).

Restoring Ecosystem Services

The methods and approaches taken to ecosystem restoration depend upon balancing the level of degradation with the ultimate management objective. Restoring some level of a specific ecosystem service may entail a management intervention that does not result in returning the ecosystem to its natural state. Indeed, in recent years there has been some discussion whether this is feasible or even desirable given the forces of global change (e.g., climate change, invasive species, and human population growth; Hobbs et al., 2014; Lugo, 2009; Stanturf et al., 2014).

A first step to restoration will be to assess the level of degradation of the ecosystem. Whether or not an ecosystem still has basic ecosystem processes like nutrient and water cycling intact will help define the starting point for restoration. For example, a once forested area that has been cleared and subjected to decades of cattle ranching where erosion has removed topsoil, compaction has reduced the soil's ability to rapidly absorb water (Hassler et al., 2011), and it is 10s or 100s of kilometers from the nearest natural forest such that forest seeds do not reach the site either by aid of wind or animals (Griscom and Ashton, 2011), will require significant effort and resources to reboot ecosystem function and much more to restore it to its original complement of biodiversity. In contrast, a forest badly damaged by a hurricane but is adjacent to areas escaping damage may simply require time to bounce back from its altered to its forested state (e.g., Zimmermann et al., 1994). Indeed, the hurricane would be part of the forest's natural disturbance regime such that as long as the natural complement of species has been maintained to preserve redundancy and resiliency (Box 2.7), the system returns to the pre-disturbance state with time.

BOX 4.2 Tropical Native Species Reforestation Information Clearinghouse (TRIC)



The Tropical Native Species Reforestation Information Clearinghouse is an educational tool managed by the Environmental Leadership and Training Initiative (ELTI) which serves researchers, students, and project managers, allowing them to learn about restoration and reforestation efforts in the tropics and share their own work with a global audience. The site contains descriptions of projects and literature on reforestation and restoration in tropical Latin America, Asia, and Africa, and hosts information about documents written in English, Portuguese, and Spanish. The clearinghouse is searchable by a word search as well as by the following categories (resource types, subjects, countries, regions, and ecosystems). To date the website contains over 880 literature and project profiles.

It is important to understand whether or not a system has suffered an acute disturbance that while destructive, may not occur again on a time scale to impact management decisions, or a series of chronic disturbances that erode some aspect of ecosystem function and the provision of services over time. An example of the former may be a forest fire due to a combination of a uniquely severe dry period and land management practices, such as those seen during the 1997-98 E Niño in Central America (e.g., Cochrane, 2003). An example of the latter would be a forest subjected to repeated selective logging such that forest structure and species composition have been eroded over time (Ashton and Peters, 1999; Ashton and Hall, 2011). Evaluating the type of disturbance and deciding whether active or passive management is warranted are essential first steps to restoring the provision of ecosystem services (Ashton et al., 2001; Ashton and Griscom, 2011; Holl and Aide, 2011).

Defining the management objective and cost are also critical to determining the management intervention. Restoration that targets returning the system as close as possible to its natural state would focus on biodiversity-related services that require returning the natural complement of native species. This would likely go hand-in-hand with preserving certain target species, ecosystem function, or cultural services. For example, the International Union for Conservation of Nature (IUCN) long ago proposed a hierarchy of protected areas (IUCN, 1994; Dudley, 2008) ranging from strict nature preserves to those allowing significant multiple uses and human intervention. If the goal of a reserve is the preservation of the complement of species and their genetic diversity in the natural system, then restoring degraded sections within the reserve to meet this objective will require knowledge of the species and genetic diversity found within the area and how to best facilitate the return

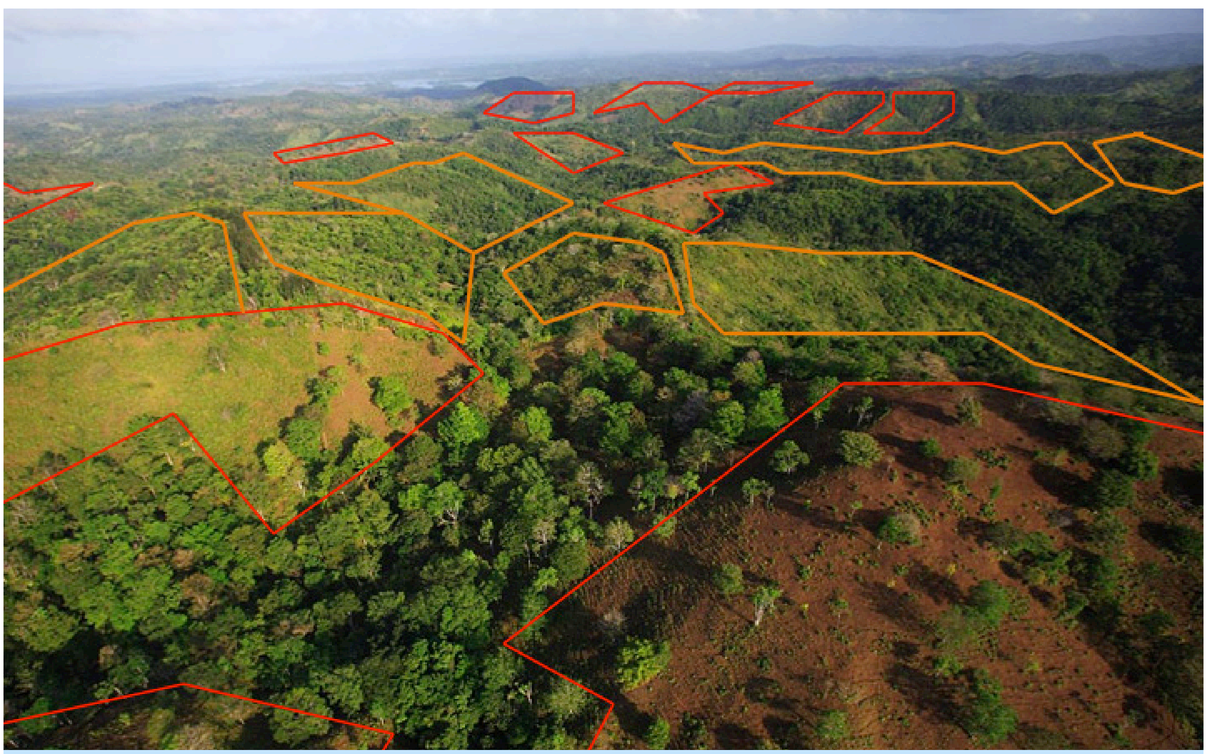


Figure 4.4 The Landscape Matrix Can Be Critically Important in Maintaining Biodiversity-Related Ecosystem Services

This landscape in the Agua Salud study site within the Panama Canal Watershed includes cattle pasture (delineated in red), different ages of secondary forest (delineated in burnt orange), living fences, streamside and other forest patches. The living fences and gallery forest can serve as corridors and habitat for birds and other animals, allowing them to pass between forest blocks of higher quality habitat.

to its natural state. If the goal is to create a biological corridor that permits the safe passage of a wide ranging habitat generalist between optimum habitats, then restoring targeted habitat patches and working with landowners to minimize negative impacts and secure safe passage may be all that is required. An example of this would be maintaining living fences with sufficient crown density to permit the passage of primates or birds between forest patches (Figure 4.4; e.g., Harvey et al., 2008).

The restoration of ecosystem function in the provision of ecosystem services may not require returning the ecosystem to its natural state. For example, one key process in a forest's ability to absorb and store water is that of infiltration. It may be that a forest plantation restores infiltration at a rate comparable to that of secondary forest, while at the same time providing the provisioning service of timber production. In this case, an ecosystem function may be restored but timber production is valued over biodiversity as a management goal.

Advances in Restoration of Ecosystem Services

A recent review by Balvanera et al. (2012) has shown an increased interest in ecosystem service research in the Neotropics with the restoration of these services being a major area of interest. A motivating factor for considering watershed management is to maintain high water quality or improve water management for the benefit of all. Thus, managing for abundant, clean, fresh water throughout the year is desirable. While forests may use more water than grasslands overall (Zhang et al., 2001), managing for sufficient water in the dry season and too much water in the wet season may be specific challenges to be considered with restoration (Chapter 2). There is an emerging body of evidence that watersheds in the steepland Neotropics can indeed regulate stream flows and also deliver improved water quality in terms of pollutants and particulate matter over deforested watersheds (Chapter 2 and references therein). It may not be trivial to maintain forests in areas of increasing human population but protecting existing forests and their services is an important component of sustainable watershed management.

Strides are being made in the restoration of hydrological services. Evidence suggests that soil saturated hydraulic conductivity can recover in reasonably short time intervals (years or decades, not centuries), through the natural processes of secondary forest recovery (e.g., montane rainforests, Zimmermann and Elsenbeer, 2008; lowland seasonal rainforests, Hassler et al., 2011). This is important in that it can reduce overland flow and the risk of perched water tables (Zimmermann et al., 2009). Few studies have been completed in the steepland Neotropics on the extent to which stream flow can recover post disturbance with active or passive restoration (Locatelli and Vignola, 2009). However, in central-eastern Mexico, Muñoz-Villers et al. (2012) found that 20 years of natural regeneration post disturbance of cloud forest can be sufficient time to produce near original hydrological behavior.

In Panama, the Agua Salud project is monitoring streamflow in watersheds with different management regimes (e.g., native tree species plantation, exotic tree plantation, secondary forest, silvopastoral systems, etc.) where forest and pasture watersheds are land-use extremes for comparison. Detailed studies to disentangle tree interactions in carefully designed mixtures in the production of hydrological and other ecosystem services are being undertaken as part of Smart Reforestation® in the Agua Salud native tree species plantations (also see Kunert et al., 2010).

A larger body of knowledge exists regarding reforestation to restore biodiversity (e.g., Holl et al., 2010; Rodrigues et al., 2011) and there is an increased interest in tropical restoration to mitigate climate change through carbon sequestration (e.g., Marin-Spiotta et al., 2007; Potvin et al., 2011). It is beyond the scope of this report to describe different restoration approaches and methodologies. The PARTNERS network brings together scientists, policy makers, and others engaged in the region and beyond to advance understanding and practice of reforestation and restoration research. It is a useful place to start for those interested in learning more.

Chapter 5

Society and Water Related Ecosystem Services

5 Society and Water Related Ecosystem Services

Ecosystem Services and Human Activities

Across the Neotropics, people's well-being and livelihoods are heavily dependent upon goods and services provided by local and regional watersheds. Forests form a critical component of these watersheds, ensuring food, fiber, and water for rural and urban communities alike. By one estimate, around a fifth of Latin America's rural population relies directly on Neotropical forests (Pacheco et al., 2011). Likewise, ecosystem dynamics are directly and indirectly affected by human activities. Thus, it is critical when thinking about watershed management to consider the watershed as an integrated system in which myriad decisions are made about land and water use that affect the watershed's integrity. In addition to the physical dimensions of watershed, understanding demographic, economic, socio-political, and cultural dimensions can help reframe watershed management as a complex system of interactions. When viewed as a holistic system, it is clear that diverse factors from population growth, to economic development goals and political agendas play a large role in changing ecosystems and the services they provide.

Population, Urbanization, and Migration

Population growth, urban expansion, and migration are demographic processes that can have impacts

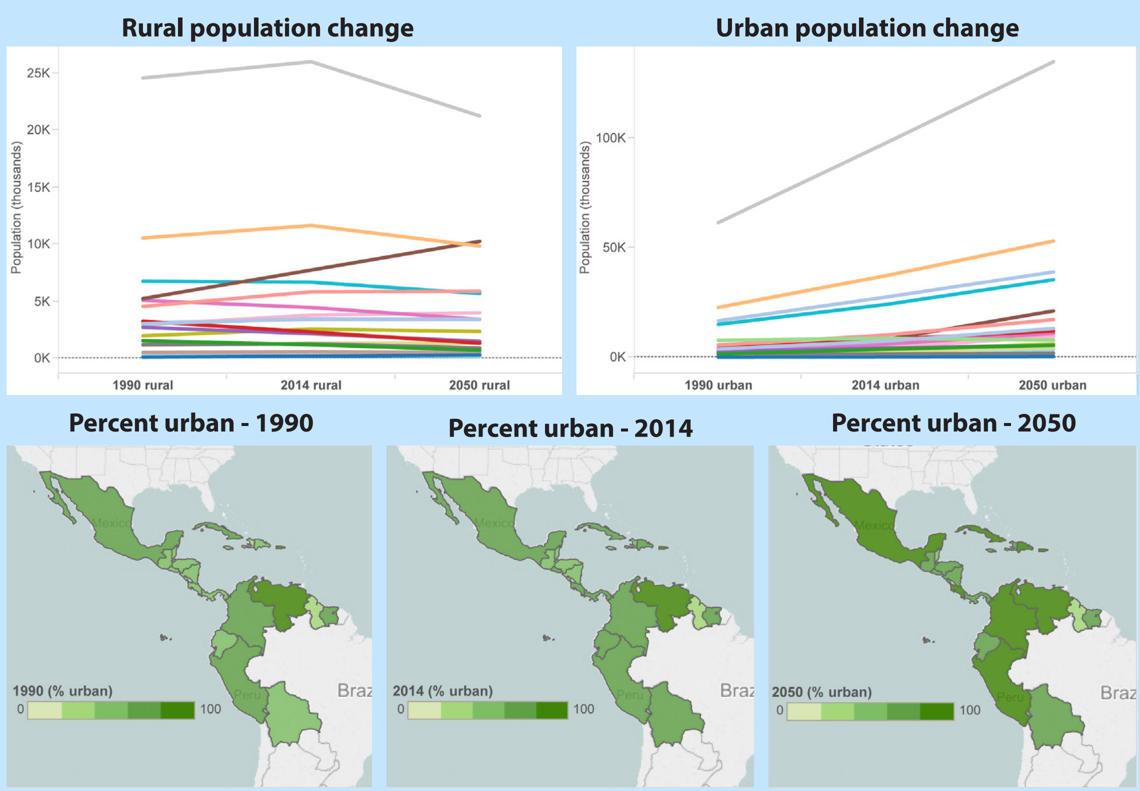


Figure 5.1 Rural and Urban Population Change
(UN, Department of Economic and Social Affairs, Population Division, 2014)

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Population and population density

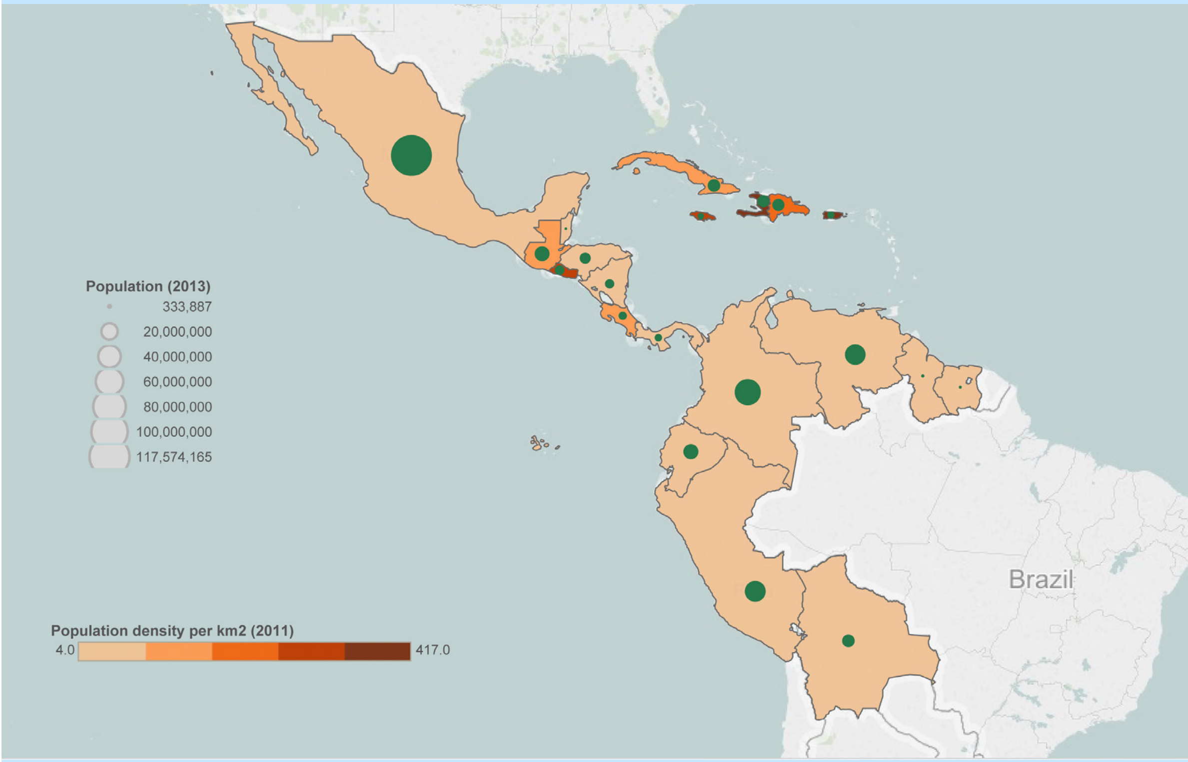


Figure 5.2 Demographic Portrait of Countries in the Steepland Neotropics (United States Census Bureau, International Programs, 2013)

Click here for interactive map

on watersheds. In the Neotropics, the population of Central and South America has grown significantly during recent decades, especially in urban areas where populations have tripled and reached approximately 80 percent of the total population (CEPAL, 2010). Aide and Grau (2004) describe a regional trend of rural inhabitants migrating to cities. However, demographic trends also vary geographically. For example, rural areas in Central America and the Caribbean tend to be more densely populated than rural areas in South America (De Fries et al., 2010), while South American countries tend to have faster growing urban populations than similar areas in Central America and the Caribbean (Carr et al., 2009; Figure 5.1, 5.2).

Though South American countries tend to have larger populations, overall population density is higher in Central America and the Caribbean, where, for example, Haiti and El Salvador have over 300 people per km^2 and Puerto Rico over 400 people per km^2, as compared to Bolivia's 10 people per km^2 or Peru's 23 people per km^2 (UN DESA, 2012). Population growth increases the demand for food, water, and energy, which in turn affect land use patterns, air and water pollution, water use for irrigation, fertilizer use, and many other drivers of ecosystem health (MA, 2003). Since the majority of population growth in the Neotropics is projected to occur in urban areas where consumption levels are higher, pressures on forests are likely to remain strong. Indeed, urban consumers' demand for agricultural products, as well as other products like biofuels, may increase forest conversion in rural landscapes (DeFries et al., 2010).

Watershed Economics

The degradation of ecosystems and their services may be partly due to the fact that most decision makers have largely ignored the non-market benefits provided by nature (Farley, 2008). One of the underlying causes of degradation of ecosystem services and biodiversity loss is the undervaluation of ecosystems and the services they provide (TEEB, 2012). The lack of understanding of the value of biodiversity and ecosystem services has hindered efforts to protect, maintain and enhance ecosystems (Jones-Walters and Mulder, 2009). The valuation of ecosystems and their services could help make conservation financially sustainable by demonstrating to stakeholders the benefits that ecosystems produce, as well as the increased benefits or averted losses that conserving these ecosystems has (Pagiola et al., 2004).

Water as an Economic Good

The economic characteristics of water and hydrological services' can have different forms. This has an impact on how their provision can be organized. Bottled water can be sold through the market, while rain water is a public good. Water can also be a club or toll good, which means that it can be consumed by many individuals without affecting the consumption of others, but whose consumption by non-members can be prevented (Engel et al., 2008). Water utility infrastructure is an example of technology that can prevent users from benefiting from water provision (Porras et al., 2008). Water scarcity has a big impact on the economic characteristics of a good, as scarcity can increase rivalry (as in a common pool resource) when not well-managed and priority resource uses have not been established – for example, public authorities grant a concession to a mine which affects potable water quality. A watershed may provide water to downstream irrigators. (See more detail here). As nobody can be excluded from using the water resource, it could potentially become depleted. However, collective action by, for example, the creation of an irrigation association to manage water use, may help in the establishment of collective rules to govern this resource (see e.g., Ostrom, 1990).

Water Pricing and Valuation

Unlike many other goods and services, the prices charged for water and/or hydrological services related to the provision of water often provide only a poor indicator of their economic value. Some key reasons for this arise from the unique characteristics of water (Pascual et al. 2010; UNSD 2012):

- As a commodity, water is subject to heavy regulations. The price charged often shows little relation to its economic value or even to the cost of supplying it;
- The supply of water frequently has characteristics of a natural monopoly, because water storage and distribution are subject to economies of scale;
- Property rights are often absent and not always easy to define when water and hydrological services exhibit characteristics of a common, club, or public good;
- As such there can be missing markets, imperfect markets, and market failures; and
- There exists uncertainty concerning knowledge over demand and supply.

However, the need to treat water as an economic good, by pricing it, has been recognized as an essential component of Integrated Water Resources Management (IWRM). IWRM identifies maximizing economic value from the use of water and from investments in the water sector as one of the key objectives along with equity and environmental sustainability (GWP, 2000).

The Global Water Partnership's (GWP, 2000) definition of IWRM states that "IWRM is a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". Beyond the requirements of satisfying basic needs and safeguarding ecosystems, water users should be charged appropriately (UNSD, 2012) to sustain the protection of the water source and the distribution of water. This does not mean that all water users, for example poor families, need to pay for sufficient water for basic survival or that a public water utility needs to employ full cost recovery. Creative financing, including low-interest loans, can significantly reduce costs to consumers. This is important because

Table 5.1 Classification of Monetary Values (Pascual et al., 2010; UNSD, 2012)

Use values	Non-use values
Direct use values: Results from direct human use of water resources such as input to agriculture or domestic use, and non-consumptive uses such as the production of hydroelectric power. *Indirect use values:* Derived from the regulation services provided by water such as waste assimilation. *Option value:* Relates to the direct or indirect importance that people give to the future use of water.	*Bequest value:* Value attached by individuals to species and ecosystems left for future generations. *Altruist value:* Value attached by individuals to the fact that other people of the present generation have access to the benefits provided by species and ecosystems. *Existence value:* The intrinsic value of water and water ecosystems, including biodiversity. Value related to the satisfaction that people place simply on knowing that a for example, a pristine lake, exists and will continue to exist.

Table 5.2 Main Methods for Monetary Valuation (UNSD, 2012)

Valuation methods	Type of value
1. Water as an intermediate input to production: agriculture, manufacturing • Residual value • Change in net income • Production function approach • Mathematical programming models • Sales and rentals of water rights • Hedonic pricing • Demand functions from water utility sales	Average or marginal value of water based on observed market behavior
2. Water as a final consumer good • Water rights' sales and rentals • Demand functions from water utility sales • Mathematical programming models • Alternative cost • Contingent valuation	Average or marginal value of water based on observed market behavior, except contingent valuation measures, which provides total economic value based on hypothetical acquisitions
3. Water for waste assimilation • Damage prevention costs • Averted damage benefits	Average or marginal values

the right to water was passed at the level of the UN General Assembly in 2009. However, it is true that in order to manage water efficiently, it is important to budget costs for its protection and provision. In order to obtain an economic value necessary for water accounting in IWRM through prices, monetary valuation is necessary. According to the prevailing literature, monetary values can be classified as Use values and Non-use values (Table 5.1).

The above valuation discussion notwithstanding, even when water can be priced and/or valued correctly, this does not automatically imply that this is what water users should be charged. As mentioned earlier, equity considerations are an integral part of IWRM. Access to water is considered a human right (see UN Resolution 64/292). Pricing of water is only one of the key steps in the establishment of a system for water accounting (Table 5.2).

Water-accounting

Water accounting is part of IRWM. Vardon et al. (2007) define water accounting as "a method of organising and presenting information relating to the physical volumes of water in the environment and economy as well as the economic aspects of water supply and use". Water accounting integrates data about the environmental and economic aspects of water and links water statistics directly to national income accounts. These accounts provide aggregate indicators that can provide warnings of a trend that may be unsustainable or socially undesirable. In addition they can present more detailed sectoral indicators that can help understanding sources of pressure on water resources, opportunities for reducing pressure, and contribution of economic incentives to problems and possible solutions (Lange et al., 2007). Water accounting can be used as a tool for policy makers in granting water concessions, ensuring that permits for more water than can be sustainably extracted are not issued.

The System of Environmental-Economic Accounting for Water (SEEAW; UNSD, 2012) provides detailed and comprehensive guidelines for organizing the hydrological and economic information in a coherent and consistent manner to construct water accounts (Lange et al., 2007).

The SEEAW includes the following information (UNSD, 2012):

- Stocks and flows of water resources within the environment;
- Pressures of the economy on the environment in terms of water abstraction, and emissions added to wastewater and released to the environment or removed from wastewater;
- Supply of water and use of water as input in production processes and by households;
- Reuse of water within the economy;
- Costs of collection, purification, distribution and treatment of water, and the service charges paid by water users;
- Who is paying for water supply and sanitation services;
- Payments of permits for access to abstract water or to use it as sink for wastewater discharge;
- The hydraulic stock in place, as well as investments in hydraulic infrastructure during the accounting period.

Understanding Water Use: The Water Footprint

Monetary valuation of water and hydrological services is considered a key input to water accounting. Other useful indicators that have been developed are of a biophysical nature. They include the concept of 'virtual water' and the 'water footprint'.

The water footprint concept was introduced by Hoekstra and Hung (2002) and refers to all forms of freshwater use that contribute to the production of goods and services consumed by the inhabitants of a certain geographical region (Hoekstra and Chapagain, 2008). The water footprint provides a consumption-based indicator of water use by mapping water consumption along with different consumption items across the entire supply chain (Feng et al., 2011). A distinction can be made between the water footprint of a product, which is the amount of water consumed directly or indirectly to produce a product, and the water footprint of an individual, which refers to the total amount of freshwater used to produce those goods and services that are consumed by this individual (UNEP, 2011). The water footprint (WF) is given by the following formula:

$$\text{WF} = \text{Blue WF} + \text{Green WF} + \text{Gray WF}$$

Where
'**Blue WF**' is the volume of stream and ground water consumed,
'**Green WF**' is rainfall and soil moisture that is used directly by plants and,
'**Grey WF**' is the volume of polluted water consumed.
(Falkenmark, 2003; Feng et al., 2011)

The *water footprint of a country* (or another geographically delineated area) is defined as "the volume of water needed for the production of the goods and

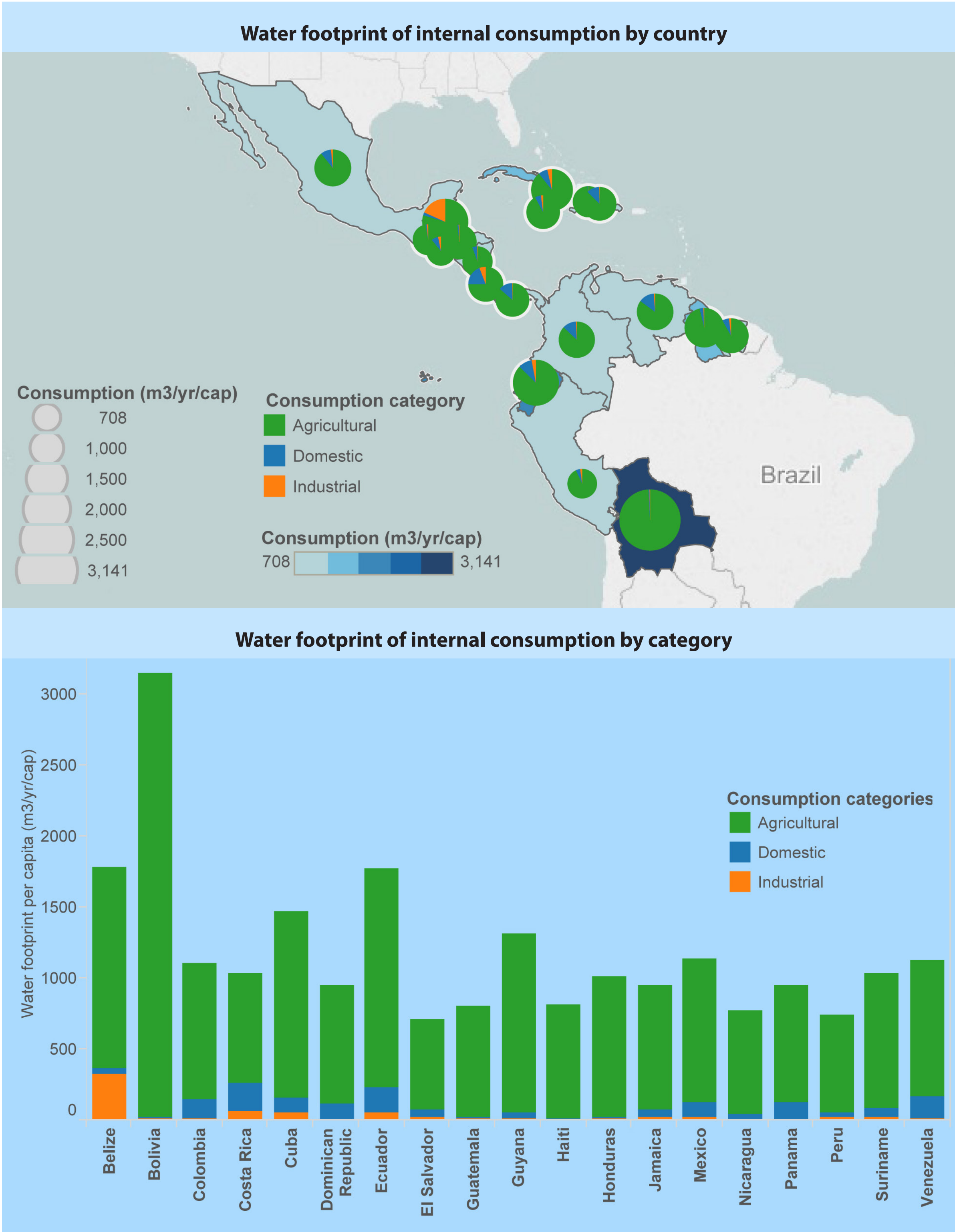


Figure 5.3 Water Footprint of Internal Consumption by Category in the Steepland Neotropics (Mekonnen and Hoekstra, 2011)

Click here for interactive map

services consumed by the inhabitants of the country" (Hoekstra and Chapagain, 2006). It consists of the internal and external water footprint. The *internal water footprint* is the share of water used from domestic water resources to produce goods and services consumed by inhabitants of the country (Hoekstra and Chapagain, 2006; Figure 5.3). The *external or foreign water footprint* refers to the volume of water used in other countries (or regions) to produce goods and services imported and consumed by the inhabitants of the country (Chapagain and Hoekstra, 2004; Hoekstra and Chapagain, 2006). A water footprint can be a useful water management tool for assigning concessions as well as a clear way to see the impact of competing water uses.

Hydrological Services and PES

From an economic point of view, although the conversion of ecosystems can be desirable, degradation is often much greater than would be socially optimal. Ecosystem degradation and the diminishing provision of ecosystem services, such as hydrological services, as a result of this has a wide variety of causes. One of the main causes of this is the appearance of externalities due to the public good nature of some ecosystem services (Engel et al., 2008; Jenkins et al., 2010; Kinzig et al., 2011). An externality can be defined as the effect of one party's actions that impose a cost or benefit on another party, without that cost or benefit being accounted for in the market. As such there is often no incentive for parties to take into account the externalities they generate (Darghouth et al., 2008). In a watershed this could be, for example, the negative impact of raising livestock on water quality for downstream water users.

Payments for ecosystem services (PES) schemes aim to internalize positive externalities generated with the objective of maintaining and expanding the flow of these externalities (Ibrahim et al., 2006). Two definitions of PES are widely used. Wunder (2015) defines PES as "voluntary transactions between service users and service providers that are conditional on agreed rules of natural resource management for generating offsite services". After years of debate, this is a new definition and incorporates some observations made after years of analyses. In contrast Muradian et al. (2010) defines PES as "a transfer of resources between social actors, which aims to create incentives to align individual and/or collective land use decisions with the social interest in the management of natural resources" (Figure 5.4). PES are increasingly being used as mechanisms to convert external, non-market values of the environment into actual incentives for local actors to provide such services (Engel et al., 2008). PES are contractual arrangements that offer payments (monetary or in-kind) to land owners and managers, conditional on the provision of environmental services or land-use practices that secure those services (Greiner and Stanley, 2013; Persson and Alpízar, 2013; also see Veracruz, Mexico and Panama Canal Watershed case studies in Chapter 7). Properly supported by regulation, these incentives can be used to motivate the production of ecosystem services beyond critical levels by private individuals and communities (Farley, 2008). PES schemes can focus on 'use-restricting' or 'asset building' (Wunder, 2005). In the first type of scheme, providers receive money to freeze some rights over the natural resource, while in the second the payment is conditional on investing in alternative activities that are compatible with the permanence of the ecosystem service (Pirard and Billé, 2010).

PES works best when nested in a favorable policy environment for the ecosystem service providers, or when an ecosystem good or service is well defined and has paying customers. A payment to farmers to preserve x% of land as forest may be unsustainable for two reasons: a) the land may be needed for agriculture or b) the program providing the payments may run out of funds.

One often cited example of the model development of a temperate watershed that has balanced the investment in "grey" infrastructure with that of upstream improved land management or "green" infrastructure is that of New York City (Appleton, 2002). PES schemes like that of New York City (NYC) do involve some direct payments, but just as important, they involve non-monetary payments to service providers. Farmers in NYC's watershed receive technical assistance to improve their dairy farm excrement management and have improved access to NYC markets through publicly funded programs. These policies create an overall environment of

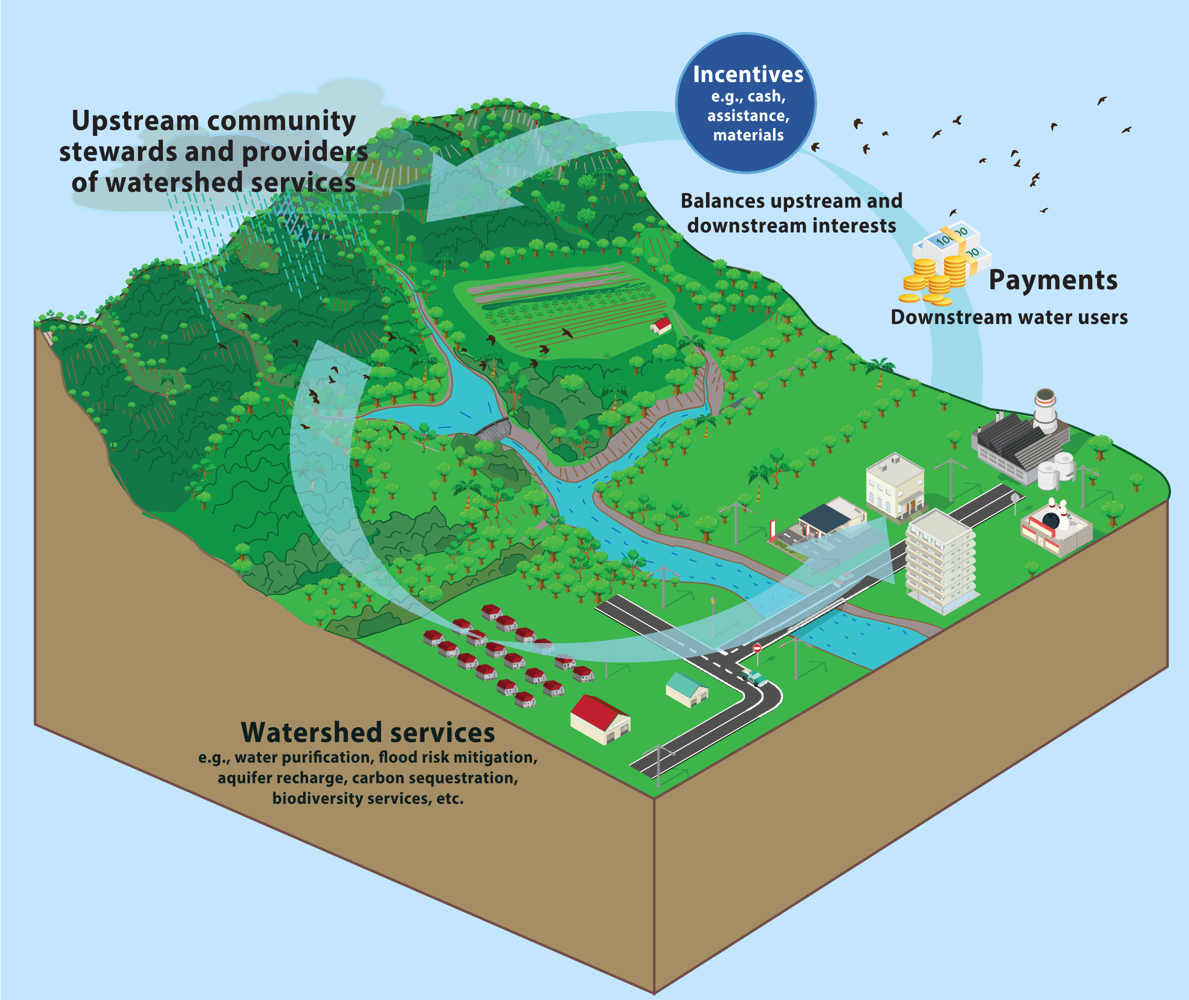


Figure 5.4 Diagram of Payments for Ecosystem Services (PES) (Adapted from Bennett et al., 2013)

economic health for the farm that in turn gives them more leeway to adapt farm practices to ecological requirements. Without accompanying programs, traditional payment for ecosystem services may not always succeed.

PES schemes for the provision of hydrological services have been widely implemented. In Latin America examples include the scheme of the Gil-Gonzalez watershed in Nicaragua, or the one implemented in the municipality of Pimampiro, Ecuador (Hack, 2010; Wunder and Alban, 2008, 2010; also Chapter 7, Panama Canal Watershed). Not all schemes will consider themselves PES and use alternative dominations, such as reciprocal water agreements and renumerations for hydrological ecosystem services. Finally, there is a significant emphasis on developing water funds (Box 5.1) in the Neotropics.

Ecological Conflicts, Water Use and Diverse Languages of Valuation

As recognized before, attempts to resolve water issues may find themselves with barriers that go beyond the possibilities of pricing issues. In many cases, the interests at stake for access rights may go beyond any possible monetary compensation. Further, it may be that different cultural groups do not accept such compensation either because they do not prioritize exchange values over use or cultural values or be-

BOX 5.1 Water Funds

Linking beneficiaries with providers to financially support local PES schemes for the provisioning of hydrological services is not always straightforward (Dillaha et al., 2007). A possible solution to this problem could be the development of water funds. These are watershed-oriented PES-type projects based on a trust fund model (Goldman-Benner et al., 2012).

The defining characteristic of a water fund is a trust fund financial model that is independently governed for a long term (Goldman-Benner et al., 2012). Water funds allow downstream water users (e.g. utilities, municipalities and industries) to finance upstream provision of a clean, regular supply of water. Collected resources go to a trust fund. The trust fund acts as a means to finance conservation projects and, in some cases, as a reserve fund. Interest from the trust, additional investments from water users or from external donors, and a portion of the trust itself may be used to pay for conservation projects. Which funding sources are used varies by water fund. The funds are governed by a multi-institutional body, i.e. a public–private partnership that includes a wide variety of stakeholders (e.g. local communities, public agencies, private corporations). They can cooperatively decide how to spend waterfund revenue. Funds should go at least in part towards conservation management of the watershed and biodiversity (Calvache et al., 2012; Goldman-Benner et al., 2012. For an example of a water fund see the case study on the Regional Water Fund of Ecuador.

There are important variations on water funds discussed in the FORAGUA case study section, for example, how water funds can complement other public programs such as the Quito water utility's in-house watershed conservation program.

cause they do not recognize, within their languages of valuation, the validity of the monetary measuring rod at all (Martinez-Alier, 2009; Muradian et al., 2013).

These divergent languages of valuation may then result in environmental conflicts over access to water resources. The EJOLT (Environmental Justice Organisations, Liabilities and Trade) project has documented 159 conflicts (among 1177 worldwide as of September 1, 2014) of water management of which 70 focus on water access rights. These are included in the world atlas of conflicts that they are creating under the "Mapping ecological conflicts and spaces of resistance" component of their project funded by the Seventh Framework Program of the European Union (Martinez-Alier et al., 2014).

Watershed Stakeholders

Virtually all residents of the Neotropics depend upon watersheds for their economic and social well-being and influence local land use practices based on their own needs and interests. In watershed management terms, they are known as stakeholders. Stakeholders' decisions and behaviors collectively impact land use and ecosystem function within the broader watershed, yet they often act as individuals or small groups, representing a variety of ethnic and socio-economic backgrounds, each with his or her own particular motivation. How and why stakeholders make decisions regarding land and water use practices are important considerations in watershed management policies given the impact of land use decisions on a watershed. In addition, understanding how stakeholders identify and meet their resource needs can help inform watershed policy and management decisions. Perhaps most importantly, effective participation by all groups of stakeholders is important to realistic design and successful implementation of integrated watershed management programs.

The Millennium Ecosystem Assessment organizes stakeholders into three levels or groups in order to assess their interactions with ecosystem services (Figure 5.5). The first group of stakeholders is comprised of individuals and small groups whose decisions "directly alter some part of the ecosystem" (MA, 2003). The second group is comprised of public and private groups whose directions, while not directly altering the ecosystem, influence policies that drive ecosystem change. The last group is comprised of international actors whose decision-making processes and policies also indirectly drive ecosystem change (MA, 2003).

Working with Watershed Stakeholders

The scientific, political and economic information essential for watershed management is often not available for the diversity of actors who influence land-use decisions that affect watersheds. It is common in the Neotropics that information is either not available (e.g., groundwater reserves) or not transparently shared (e.g., record of logging and water extraction concessions granted). Public agencies in charge of regulating land and water use are often not well equipped or politically prepared to disseminate essential information to stakeholders.

Additionally, engaging rural people who are often the default land stewards of upper watersheds has proven difficult for governments. In order to facilitate informed decision making for watershed management, it is necessary to involve diverse actors from land-holders, extension agents, and local authorities to policy-makers and business leaders in a participatory, collaborative watershed management process where each group's socio-economic context, needs, and values are understood and addressed (Farrington, 2000). Developing effective strategies to transmit relevant information, engage stakeholders, and build resource management skills across diverse stakeholder groups can help improve watershed management outcomes in multi-use, human-dominated landscapes.

Capacity Building Methods for Integrated Watershed Management

The United Nations Environmental Program (UNEP) defines capacity building as "building abilities, relationships and values that will enable organizations, groups and individuals to improve their performance and achieve their development objectives" (UNEP, 2002). Engaging and building capacity via education and training represents an investment in people who will become empowered to make well informed decisions (Eade, 1997). The United Nations Development Program (UNDP) utilizes a five step framework for building capacities in institutions by analyzing the individual contexts, making assessments on a potential intervention and developing an adequate strategy which is evaluated on its effectiveness (UNDP, 2008):

- Identify and engage stakeholders;
- Assess stakeholder capacity needs and strengths;
- Develop appropriate capacity building trainings;
- Implement capacity building trainings;
- Monitor and evaluate the intervention (See more detail here).

Figure 5.5 Key Groups and Organizational Levels of Stakeholders (Adapted from Millennium Ecosystem Assessment, 2003)

The challenge to implement capacity building is to develop effective strategies to reach and transmit the relevant information and skills to diverse watershed stakeholders. These actors are varied in their objectives and values as they range from resource providers to users, as well as policy makers and regulators. Information exchange gaps between the science and practice of watershed and natural resource management are common due to the lack of institutions and support, public awareness, and programs aimed at linking resources to those who need it. Increasing stakeholders' awareness and knowledge through improved networks is a successful method of capacity building to disseminate useful information. At the institutional level, linkages between public and private organizations and government ministries increase the collaborative efforts and pool resources to manage complex landscapes that share watersheds. In terms of working with local stakeholders, public agencies and non-governmental organizations (NGOs) often have access to financial and professional resources that are able to assist and incentivize rural people to adopt new technologies and practices (see Chapter 7). Engaging marginalized groups and small-holder farmers, who are often the residents of watersheds' uplands, is challenging and requires a flexible capacity building model that takes into account community traditions, local culture, and socio-economic values. Information needs to be provided in an accessible, culturally sensitive method in order to be effectively disseminated to rural populations (Garen et al., 2009). Capacity building for rural landowners should demonstrate how sustainable farming practices not only improve the delivery of desired ecosystem services but also improve on-farm production value-added crop processing, and marketing. In this way, what might otherwise be viewed as labor intensive measures present themselves as opportunities for integrated rural development and poverty alleviation, not a cost. Developing local leaders to be community promoters of environmentally friendly practices is a sustainable method to advance the replication of watershed management best practices as it utilizes the culturally appropriate "farmer-to-farmer" training and does not continually rely on outside experts (Box 5.2).

Watershed Governance

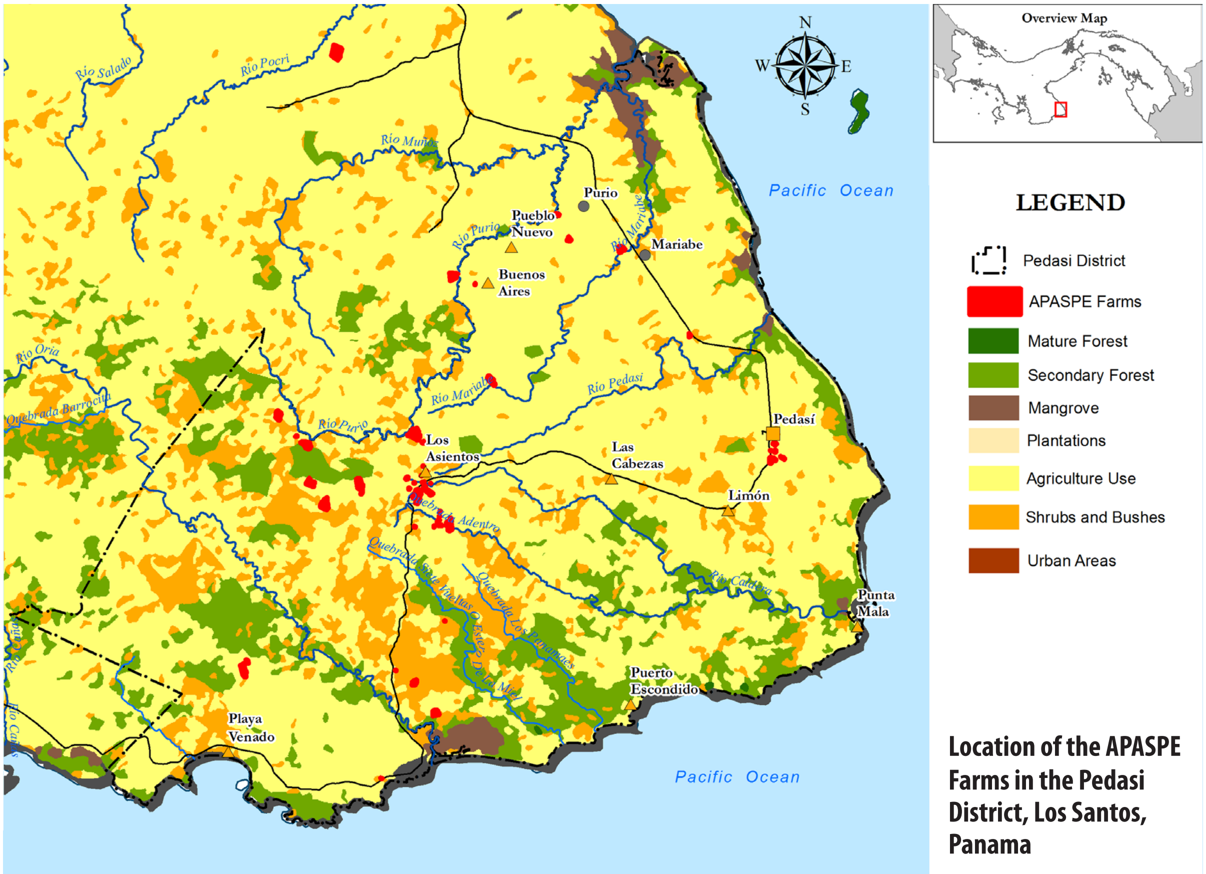
A Tense Marriage: Politics and Ecology in Watershed Governance

One of the more encouraging signs in recent years that public thinking about ecosystem services and water use is becoming increasingly informed and sophisticated is the growing use of the term "watershed". Whether used in reference to the California drought, mining contamination in the Andes, or by a local official explaining to constituents how s/he seeks to safeguard the municipal water supply, watersheds are making headlines. With climate change not bounded by political maps, there is increasing recognition that watershed governance is most effective when it pushes beyond municipal and national jurisdictions and institutions into bioregional contours. Just how to craft and operationalize watershed governance concepts and tools is one of humanity's most pressing challenges.

A Thought Experiment: Imagining an Idealized Watershed Governance

Imagine the ideal watershed governing body – one with a bioregional scope uniting political jurisdictions, issuing land and water use permits based on transparent priorities and scientific data, correcting "unjustified water right allocations" (America's Water Agenda, 2012), and guaranteeing ecosystems their fair share of water resources. It would have the following elements – a cross-section of stakeholders hammering out agreements, financial and programmatic accountability to a broad public, and a well-resourced enforcement capacity that controls extraction and pollution. A watershed governing body would be composed of upstream and downstream actors who establish indicators of watershed sustainability and govern accordingly. Nature would have a seat at the table – or at least an advocate to represent it. Watershed management – the day-to-day work of managing multiple uses of the watershed - would be guided by a coherent set of principles and laws.

While there is little question that this sort of basin-based governance makes a great deal of ecologic sense, it is a significant political hurdle to move away from present practices and embrace new ones. Watershed battles also make headlines, exposing rifts



Location of the APASPE Farms in the Pedasi District, Los Santos, Panama

BOX 5.2 Capacity Building and Local Environmental Stewardship

The Dry Arc region of the Azuero Peninsula in Panama is an area of relatively low rainfall and prolonged and marked dry seasons, during which the water level in aquifers drops significantly and puts at risk the region's quarter million inhabitants and their livestock (Castillo, 2011). To address the land and water degradation issues affecting farmers in the region, in 2009 the Environmental Leadership Training Initiative (ELTI) with the assistance of Colombia's Center for Research in Sustainable Agricultural Production Systems (CIPAV), implemented a number of field courses for land-holders and environmental authorities to improve their knowledge of native species reforestation, agroforestry and silvo-pastoral systems (SPS) by visiting SPS model farms in Colombia. As a result, several farmers decided to incorporate tree planting and conservation practices such as SPS into their farms. One group of farmers requested ELTI assistance and created their own legally recognized association to implement these practices. The majority of group members reside in a critical watershed consisting of the four largest rivers of the District of Pedasi that provide potable water and water for agricultural uses. In 2010, the newly formed group, APASPE (Association of Livestock and AgroSilvopastoral Producers of Pedasi) received the first in a series of grants to implement the first SPS demonstration farms and watershed restoration in the region. In just three years APASPE has demonstrated their environmental stewardship, reforesting 10km of riparian areas with over 10,000 trees of 25 different native species and establishing 20 hectares of SPS. In addition, their role as community leaders of sustainable practices has helped to inspire other regional landholders to explore SPS and other watershed conservation and restoration activities. To further transmit their experiences as an organization as well as the facilitation of a watershed restoration project, APASPE members have hosted more than 700 visitors on their model farms, advised two farmer cooperatives in the preparation of sustainable ranching funding proposals, shared their experiences in 25 public forums and served as co-facilitators in ELTI forest restoration courses (training 50 regional farmers). Providing adequate support to community watershed leaders could lead to a growing number of landholders working together at the macro level to conserve and restore watersheds in agricultural landscapes (Slusser et al., 2014; see Chapter 7 for more detail).

in values and inequalities of economic and political power. Current governance forms frequently to protect the wealthy and powerful and are likely to remain the norm for the time being. For example, scientists present data on diminishing groundwater reserves and surface water flows; the data is subsequently contested by private users seeking to maximize resource use – often with an army of lawyers behind them. Agribusiness pressure leads to underpriced irrigation water and unregulated fertilizer use, leading to low flow and eutrophication downstream. Competing government agencies are unsuccessful in aligning pro-development and conservation strategies. The road to sound water and land management is often littered with political landmines, back-room deals, and warring public agencies.

First Steps: Change the Frame and Initiate Cooperation at the Local Level

Borrowing a page from Nobel Prize winner Elinor Ostrom, an important first step is to establish a shared understanding of what the common pool resource is and the customs and organizations that might help to govern it (See more detail here). This is a hedge against Garret Hardin's pessimistic "Tragedy of the Commons", which predicts resource grabbing and anarchy. The term "watershed" suggests a shared territory. Its increased usage may help to change public perceptions about resource use cooperation, for example how urban water consumers downstream are impacted by farmers' agricultural practices upstream.

Even the best public education on how a watershed functions does not mean that cooperation in land and water use is forthcoming or that political decision-making is subordinate to ecological science. It does, however, increase understanding among a citizenry and politicians that cooperation among neighbors is essential. For example, municipalities from El Salvador, Honduras and Guatemala have joined together to form the Mancomunidad Trinacional. This international, inter-municipal body has drafted resource use ordinances that have been adapted by 14 cooperating municipalities – a considerable challenge across three different national legal frameworks. Each municipality contributes funds to a pooled forest management fund, contributions which can be challenging for a mayor of a poor rural municipality to justify to constituents. FORAGUA, in southern Ecuador, has created a similar inter-municipal watershed stewardship program. That effort is partially capitalized by a percentage of revenues drawn from water tariffs.

In broad terms, the biggest challenges to watershed governance are in the area of inter-jurisdiction cooperation (municipalities and nations) and inter-institutional cooperation (agriculture, housing and environmental ministries for example). With water and land use essential for nearly all human activity – from agriculture to computer manufacturing – there may never be one watershed mega-agency or "czar". The approximation will happen through collaboration among levels of government and the creation of new institutions such as the afore-mentioned inter-municipal consortiums. Within the Panama Canal Watershed, for example, there exists an inter-institutional commission for the management of the watershed (known by its Spanish acronym CICH, see Chapter 7). Indeed, cooperation may be easier to broker at the municipal rather than national level. Neighbors can more easily perceive shared risks and opportunities and overcome political differences for the common good. National level agencies may be stymied by inter-party squabbles and be more reluctant to cooperate.

Who's in Charge? Discovering De Facto Watershed Governance and Diagnosing Function and Dysfunction

One slightly uncomfortable truth about watershed governance is that it is generally a mish mash of, at times, contradictory laws and programs across many jurisdictions and institutions. Local conservation laws and programs may be undermined by multilateral trade agreements or large infrastructure projects that leave a deep mark on the landscape (Box 5.3).

A critical diagnostic step in mapping how a watershed is governed is to take inventory of the wide array of laws and programs operating in a watershed. It will likely be a large number, with some programs competing with others. Which public agencies - local, state and federal - fund and oversee which programs? An organizational chart of ministries and their dependent agencies will likely be needed to complete this exercise.

These public agencies are some of the many stakeholders – public and private - that need to be at the table. It is this collection of actors that constitutes the de facto governance structure of a watershed. Some local watershed governance efforts are caught surprised and disappointed when they bump up against the limits of their authority. A power analysis is essential to map out opportunities and constraints in watershed governance reform efforts (See Appendix 3 for suggested simple diagnostic tools to take stock of how decisions affecting watersheds are made.).

Establishing Priorities for Watershed Uses and Services

From an ethnocentric perspective, the goal of watershed governance and management is to maximize and distribute available ecosystem services to human communities dependent on the watershed. In a forward-looking version of this same mission, the goal is also to ensure sustainability of the watershed so that those ecosystem services are available in perpetuity to future generations of humans, animals and plants. Either version begs the question: what are the priority ecosystem services being sought and who are the priority users? Because a watershed can only offer limited resources, implicitly or explicitly, watershed governance must prioritize among competing uses and parties. Such prioritization is a political hornet's nest.

In practice, the prioritization generally happens on a case-by-case basis – a community wants to use water for household consumption while a power plant wants it for electricity generation. A conflict ensues and in most cases, the more powerful party prevails. Examples of conflicts over land use for mining and the potential harm to the ecosystem and the pollution of drinking water abound in the Neotropics.

Watershed use priorities may result from international agreements to which countries are signatories. For example, advocates from around the world led pressure campaigns for a UN Convention on Biodiversity and a UN recognized human right to water and sanitation. There is a movement afoot to debate nature's right to water in the UN. These international protocols lack enforcement teeth but can be used as leverage at the local level to safeguard watersheds and back up claims for prioritized ecosystem services.

Improving Watershed Governance – Create New Governance Bodies or Improve on Existing?

Because societies have tended to set up rule making, law enforcement, budgetary allocations, and other elements of governance along political rather than landscape lines, when it comes to watershed gover-

BOX 5.3 Local Watershed Management in Veracruz, Mexico

Veracruz, Mexico is home to instructive cases of innovative local watershed management; two are FIDECOAGUA in Coatepec and the Comité Pixquiac in Xalapa (see Chapter 7 Veracruz case study for more detail). In Coatepec, the municipality formed a trust fund to protect and restore diminishing forest cover in the Gavilanes watershed. The initiative is funded by a percentage taken from water tariff revenues and receives matching funds from the matching funds program of the national forest agency, CONAFOR. In Xalapa, the NGO Sendas, leads a multi-stake holder effort to protect the Pixquiac basin. Sendas supports sustainable rural livelihoods of upstream communities, precisely the kind of payment for ecosystem service strategy that a new state-wide fund, the Fondo Ambiental Veracruzano (FAV) supports with funds collected from an assessment on smog emission test fees. Both efforts would appear to have strong allies within state and national governments and have made important strides in demonstrating innovative watershed governance and management effectiveness. And yet, both are vulnerable to forces outside their control. Coatepec and Xalapa are growing cities - private and public developers see economic opportunity in the watersheds. A gold mine has been proposed for a nearby watershed. At the local level, at least one incoming mayor did not support FIDECOAGUA.

nance, our present rules and institutions may appear to be more of a nuisance than an aid. They may fail not only in ecological terms but in equity terms as well, allocating water and land to the more powerful and leaving some populations vulnerable to poverty and disease (See more detail here).

It is indeed a dilemma to know how to approach change. Countries like Uruguay and Ecuador have capitalized on the momentum of reform-minded administrations to write constitutional clauses that recognize the human right to water and the rights of nature. Peru has established a National Court for Water Dispute Resolution. New laws may recognize indigenous peoples' customary use of water and may move daily watershed management responsibilities to local levels. But it is also common for territorial planning ordinances and water laws to become bogged down in sectarian debates. For over a decade, Salvadoran legislators and civil society groups have been mired in a debate over a new water law, which if passed, would create new watershed-level institutions for watershed governance.

Watershed governance reform is this kind of creative process – heated struggles to forge new legal frameworks, create watershed councils and design innovative instruments such as water trust funds. These efforts may correct institutional and legal shortcomings, create coordination bodies and invite the participation of a broad swath of stakeholders (See more detail here). In Brazil, the Inter-municipal consortium in the Piracicaba, Capivari and Jundiaí basins (PCJ) works closely with the national water agency, ANA, and the Sao Paolo state government to manage the three river basin. The committee collects fees from hydroelectrical generation plants, among other users, that benefit from sustainable watershed stewardship and grants these funds to municipalities and other entities that make watershed improvements such as sewage treatment facilities. The PCJ is an example of a mixed civil society-public institution that collaborates closely with the public sector but is shielded from political electoral cycles and governed independently.

While these new institutions can offer new ways to govern watersheds, the inter-institutional report, "America's Water Agenda: Targets, Solutions and the Paths to Improving Water Resources Management" warns that efforts like these "have been most successful in decentralizing the "voice" rather than the "vote" on issues associated with managing water resources."(America's Water Agenda, 2012). New laws have not always made appreciable difference on the ground; existing political institutions won't easily cede power and control to new watershed governance entities. The report – perhaps overly skeptical– suggests that these new forums and funds may be "over-ambitious" or distract from the difficult task of simply making watershed governance part and parcel of any and all public officials' job description.

At least part of a politician's mandate is to ensure that his or her constituents can benefit from the ecosystem services provided by the watersheds in their district. It is true that they may be more accustomed to talking about creating manufacturing jobs than managing natural resources, but the alarming impacts of climate change on hydrological cycles has made water management an election issue. Citizens are in some cases demanding that the decision-makers they vote into office be fluent in how watersheds work and be held accountable for ensuring that they are not despoiled. While creating a new governance structure may be ideal, using informed and sophisticated grassroots power a great deal can be accomplished with existing laws, institutions and politicians.

Other public accountability mechanisms are worthy of exploration. At least on the books, most countries and development banks have public review processes for large infrastructure projects. These are opportunities to comment on, for example, the impact of a proposed dam and suggest mitigation measures. Some quasi-public authorities like water utilities have built-in public review mechanisms. Before being granted a water rate increase by a regulatory authority, a water operator may have to justify the new charges. These public reviews are "governance moments", an opportunity to push for improved watershed stewardship.

Encouraging Municipal and Water Utility Leadership

There are additional approaches to watershed governance that don't require forming new bodies. One is to look at how water operators, like the New York

City water authority, and other large public water users, like the Panama Canal Authority, mobilize resources and incentivize and oblige watershed co-operation (see Chapter 7 Case Study on the Panama Canal Watershed). These organizations hold a tremendous amount of political and economic capital in their respective watersheds and are dependent on watershed sustainability to conduct their business. How they orchestrate cooperation among multiple upstream and downstream actors and finance watershed protection efforts is instructive. In the case of New York City, the water authority and dairy farmers have signed a contract for watershed stewardship. The farmer-led Watershed Agricultural Council has mobilized technical assistance from the United States Forest Service while the water utility convinced the Environmental Protection Agency (its regulator) that green infrastructure (watershed protection) is less expensive and as effective for achieving water quality standards as grey infrastructure treatment plants. As public agencies, the Panama Canal Authority and New York City Water are tightly regulated, at least in principal. Motivated by their self-interest, these powerhouses can rally a multi-stakeholder watershed governance process-processes that often become bogged down with too many participants attempting to cooperate in a horizontal structure that is slow to act.

The Promise and Limits of Citizen Participation

Good watershed governance relies on the same principles as good governance generally. Citizen participation is considered a key feature. It is not uncommon today for there to exist multiple citizen groups engaged in a variety of conservation activities – environmental monitoring, water distribution, reforestation, or biodiversity protection – in the same watershed or contiguous sub-watersheds. Ideally, civil society efforts are well coordinated and complement and encourage public leadership and accountability in watershed governance.

A watershed committee, for example, may have more impact when building on a public program or leveraging additional resources. In Quito, Ecuador a strong relationship exists between the municipal water utility, EPMAAPS, and an independent water fund, FONAG. EPMAAPS seeks to protect its water sources but lacks the resources to work in all the micro watersheds that require attention. FONAG formed not only to safeguard Quito's drinking water supply, but to protect biodiversity and a host of additional ecosystem services. FONAG and EPMAAPS closely coordinate their watershed protection actions and monitoring data – in fact EPMAAPS sits on FONAG's board and holds most of the votes due to the fact that it provides the bulk of FONAG's funding, contributing two percent of its revenues. This level of collaboration is not the case with every watershed fund (See more detail here). In some cases, municipalities and water operators perceive the funds as competitors rather than collaborators.

Citizen action groups are likely to be more motivated to join coalitions and participate in watershed governance and management efforts if they understand their value added and power in a watershed. A citizens' watershed council or fund should be able to locate itself among other actors in a power map of the watershed. Where do they sit relative to other public and private agencies? Do they have any formal advisory or decision-making powers? Or are they strictly speaking outside advocates seeking to hold public agencies accountable to a set of standards? To the extent possible, clarification of roles and responsibilities may be helpful in attracting people to play a time-intensive, water citizen role.

It is a rich and productive time for experimentation with watershed governance, from forging new institutions and laws to retraining and retooling existing agencies. The havoc caused by climate change is forcing societies to grapple with disaster management, food security, and water scarcity and flooding in equal severity all at once. While local watershed management can only do so much when the focus is global climate change, these challenges – and numerous others – put our governance capacity to the test, sending politicians back to school to study Hydrology 101 and Ministries of Agriculture and Environment to the negotiation table to craft a shared watershed restoration program. We seem to be learning – too slowly perhaps for the urgency at hand – but there is slow and steady progress.

Chapter 6

Towards Integrated Watershed Management in the Steepland Neotropics

6 Towards Integrated Watershed Management in the Steepland Neotropics

Sustainability at Different Spatial and Temporal Scales

Sustainability implies taking the long view and balancing near term and future needs. Due to complexities and deficiencies in governance systems, ecosystem management regimes rarely use ecological data to guide policies and practices in the steepland Neotropics. Governance challenges notwithstanding, it is also important to understand how ecosystems provide goods and services in order for human communities to manage them. The provision of these goods and services can vary temporally due to natural changes in ecosystems and to changes induced by human activities (Nicholson et al., 2009). Good monitoring of systems can provide feedback on trends in ecosystem services over time. However, three problems remain:

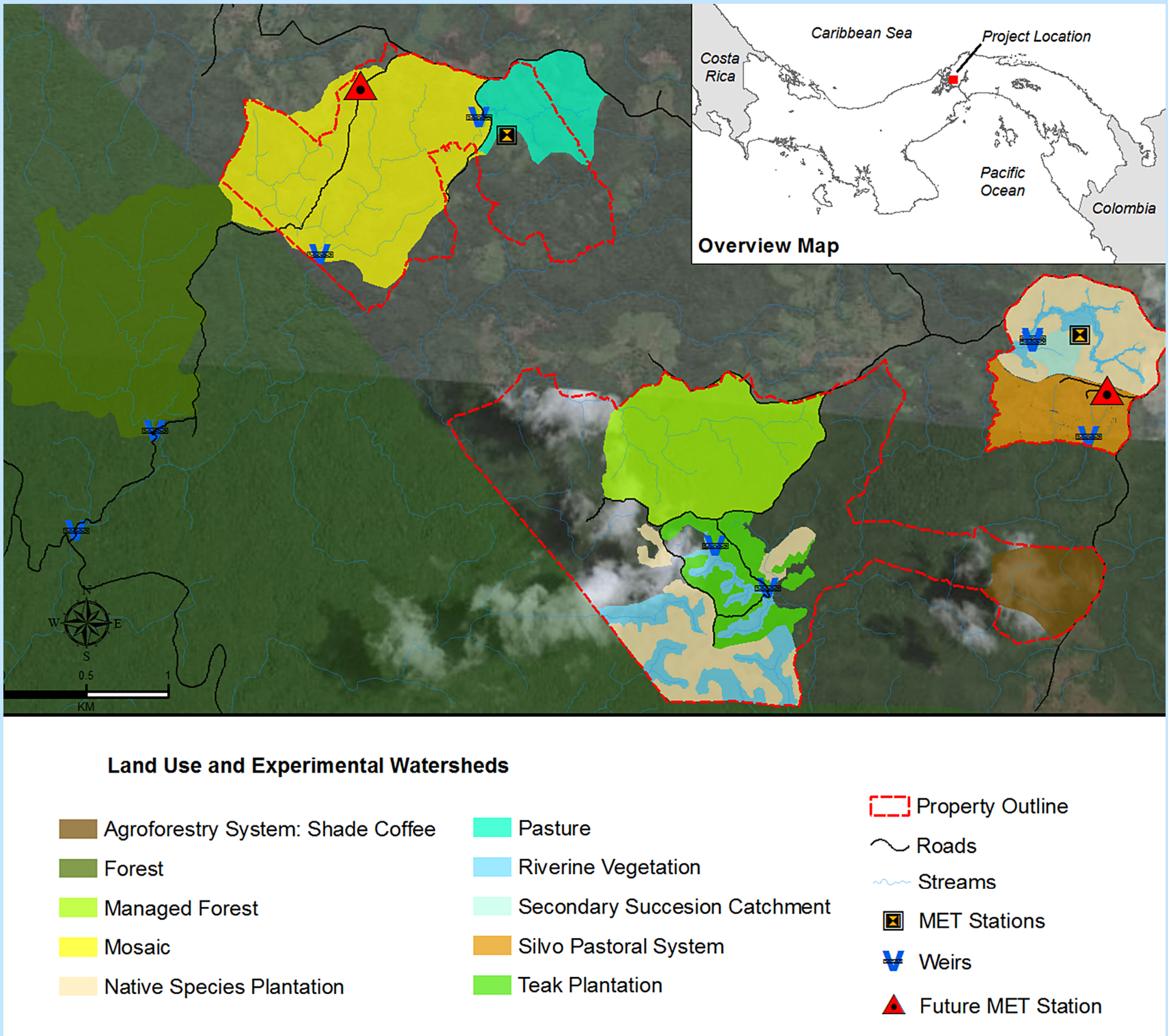
- the general absence of monitoring data – it takes significant institutional capacity to gather and analyze information;
- nonlinearities and thresholds in ecological dynamics make it difficult to predict sudden change in ecosystems; and
- political and economic priorities may outweigh scientific evidence.

When major disruptions to ecosystem service provisions occur, it can often take a very long time for them to recover (and they may never even recover completely).

The absence of an appropriate baseline hinders understanding of ecosystem processes and services. Decisions related to hydrology are often based more on conventional wisdom and politics than long term monitoring. The sustained rise of carbon dioxide in the atmosphere has led to impacts on ecosystems that we are only beginning to understand. The lack of monitoring information on changes in ecological variables is often an important contributor to environmental degradation and loss of resilience (Biggs et al., 2012). Policy makers are often not held accountable for poor management decisions and the effects of management plans and projects are often not observed for long time periods, thus leading to the potential for losses in important ecosystem services. For example, in the tropical dry forests of the Yucatan Peninsula, shifting cultivation is contributing to a gradual and irreversible reduction in phosphorus availability, which will eventually have a major impact on the resilience of that system (Diekmann and Lawrence, 2006). In addition to simply having monitoring systems in place, there is also a need to be able to identify thresholds that can result in rapid collapse or change of state of an ecosystem service, such as the potential for wildlife populations to collapse due to over-hunting (e.g., Redford, 1992). Such a collapse would not only deprive hunters and local communities from an important source of protein but also impede seed dispersal and other services. Process-based models of ecosystem services are needed to explore temporal variability in multiple ecosystem services and allow for wise management over time.

Another temporal dimension of ecosystem services is on the demand side of the equation. Preferences for different ecosystem services can change over time (e.g., carbon sequestration over biodiversity), leading to changes in management and therefore in the provision of ecosystem services. Long-term management for ecosystem services (including restoration and recovery programs) requires incentives to be set in place that will not disappear suddenly, for example, if funding dries up or if a supportive politician or champion leaves office. However, incentive programs may need to change over time to reflect the needs and preferences of ecosystem service beneficiaries and managers, as well as availability of public and private monies to finance both incentive and command and control programs.

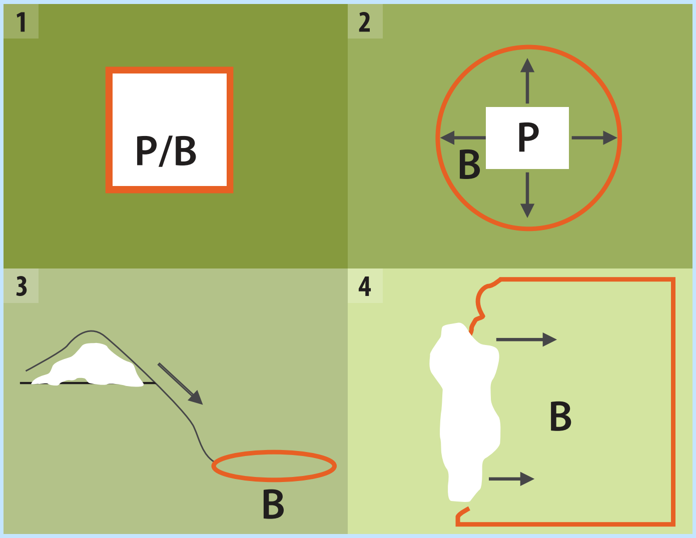
BOX 6.1 Understanding Ecosystem Bundles in the Panama Canal Watershed



In the Agua Salud site in the Panama Canal Watershed, the relationship between carbon storage, biodiversity, water related services and land uses of varying economic value are areas of focal research. The secondary forests in Agua Salud grow and sequester carbon rapidly (provisioning service), acquiring aboveground carbon stocks of close to half that of nearby mature forest in as little as 20 years. This is due in part to the nutrient cycling (supporting) service provided by nitrogen fixing species (Batterman et al., 2013). These rapidly growing forests are rich in tree species diversity (van Breugel et al., 2013) (providing regulation and cultural services), with forests under 30 years containing some 350 species of trees in 10 hectares. They also recover their water infiltration properties (property of provisioning service) in the course of a decade or two (Hassler et al., 2011; but see Ogden et al., 2014). Thus these supporting, provisioning, regulating, and cultural services are linked - bundled - in secondary forest regrowth. In contrast, soil carbon does not recover in similar time periods and thus this provisioning service is decoupled on this time scale from the other services just described (Neumann-Cosel et al., 2011). The link between carbon storage of mature forests (e.g., Asner et al., 2012), flood regulation (e.g., Ogden et al., 2013), and floristic diversity (van Breugel et al., 2013) is another ecosystem service bundle that has been demonstrated at this site. In contrast traditional cattle ranching and flood regulation services represent a tradeoff (Ogden et al., 2013).

BOX 6.2 Understanding the Spatial Relationship Inherent to Watershed Services

Ecosystem services are often not produced and consumed in the same place. Figure shows the possible spatial relationships between areas where ecosystem services are produced and areas where people benefit from them. Ecosystem services are produced throughout watersheds, but the benefits of many services often flow from the upper watershed down towards the lower watershed, where more people tend to live.



Reproduced and adapted from Fisher et al., 2009.

Possible spatial relationships service production areas (P) and service benefit areas (B).

- In panel 1, both the service provision and benefit occur at the same location (e.g. soil formation, provision of raw materials).
- In panel 2 the service is provided omni-directionally and benefits the surrounding landscape (e.p. pollination, carbon sequestration).
- Panels 3 and 4 demonstrate services that have specific directional benefits. In panel 3, down slope units benefit from services provided in uphill areas, for example water regulation services provided by forested slopes. In panel 4, the service provision unit could be coastal wetlands providing storm and flood protection to a coastline.

Bundles and Trade-offs in Ecosystem Services

Landscapes produce multiple ecosystem services, and most are connected to each other in some way. An ecosystem service 'bundle' is a set of ecosystem services that can vary in space or time (Raudsepp-Hearne et al., 2010). In some cases the same ecosystem components can contribute to multiple services, for example, when a row of trees along a river bank stops nutrients and sediment from polluting the water and serves as a wildlife corridor for birds and mammals. In these cases, drivers of change can simultaneously impact multiple services. In other cases, the services counteract each other in some way. For example, when fertilizer is added to facilitate the establishment of improved cattle pasture, some of the nutrients run off into nearby waterways and cause a decrease in water quality. This is what is termed a trade-off. In these cases, when one ecosystem service is impacted by a management decision, the decision indirectly impacts other ecosystem services as well (Bennett et al., 2009). The situation is complicated by the fact that incentives are often politically designed and may contradict one another. For example incentives to plant trees for carbon sequestration may lead to the establishment of monoculture plantations that have a negative effect on biodiversity or agricultural packages of fertilizers may boost food production but undermine soil health. It is important to try to understand how multiple services and policies interact in order to manage them simultaneously, encouraging positive synergies and minimizing negative trade-offs. While showing preference for some ecosystem services in management decisions often leads to trade-offs with other ecosystem services, developing understanding of how ecosystem services bundle together can make those relationships more transparent and minimize losses (Box 6.1). Certainly, it is critical for policy makers across sectors to understand and debate how programs may enhance or undermine one another.

Land-Use Planning

During the last fifty years the population of the steepland Neotropics has become increasingly concentrated in urban centers, many of which have had rapid and unplanned growth. Changes in national economies and the rising expectations of citizens have dramatically increased the demand for products and services derived from natural and agro-ecosystems. The sustainability of these growing cities remains intimately tied to healthy rural ecosystems. Pressures will certainly be greater in the coming decades (CEDES, 2002). The spatial vision that is implicit in the watershed approach enables public and private decision-makers to understand the close relationship that exists between socioeconomic development and ecosystem services (Box 6.2). Thus, spatial planning is an opportunity to ensure the present and future supply of all kinds of goods and services but especially for the multiple uses of water such as direct consumption, power generation, and industrial, commercial and agricultural activities.

City and countryside are linked in steepland Neotropical watersheds. Population growth in cities and urbanization in watersheds puts increased pressure on land and water resources. Biophysical and climatic parameters should inform land use planning boundaries and suggest the activities that should be allowed as well as how they should be carried out (Padin et al., 2002). For example, areas of special hydrological importance such as cloud forests, Andean highlands, wetlands, and groundwater recharge areas should be under a strict conservation regime that excludes urbanization, mining, logging and agricultural systems with high environmental impact. The creation of Podocarpus and Chagres National Parks in Ecuador and Panama, respectively, are two examples where national governments have had the vision to protect such areas. The creation of "La Cortadura" reserve in Coatepec, Mexico is an example where local municipal government established protection of the community's upper watershed cloud forest vegetation (see Chapter 7 for more information). Areas with high agricultural production and functional resource management regimes can serve as agro-ecosystems providing water services and at the same time maintain tree cover, conserve and connect native forest remnants, and prevent land-use change to industrial, mining or urban areas. For example, in Colombia, NGOs like CIPAV (Colombia's Center for Research in Sustainable Agricultural Production) and government agencies are advancing policies and practices for an agroforestry based grazing practice known as a silvopastoral system (see Box 4.1).

Recent research has provided strong evidence for the role of Neotropical forests as water flow regulators, as they may buffer the devastating effects of extreme weather events such as drought or floods (e.g., Muñoz-Villers and McDonnell, 2012; Ogden et al., 2013). These regulation ecosystem services are essential for climate change adaptation. The beneficial role of the application of agroecological principles and practices (e.g., conservation tillage, soil cover, agroforestry and silvopastoral systems) on hydrologic ecosystem services has also been acknowledged (Nair, 2011). Strengthening conservation and agricultural production practices in watersheds is critical to ensure the sustainability of ecosystem services that urban areas rely on. Careful multi-stakeholder planning with respect to the spatial juxtaposition of activities within the watershed is a critical element to maximizing benefits while reducing the negative effects of land management activities.

Incentives for Best Management Practices

Payments for ecosystem services (PES) have generated a lot of interest among conservationists and land managers because they are considered a promising new approach to protect biodiversity and ecosystem goods and services, such as climate regulation, water filtration, and nutrient retention, which contribute to human well-being (Pagiola et al., 2002; see Chapter 5). PES are defined as voluntary transactions between service users and service providers that are conditional on agreed rules of natural resource management for generating offsite services (Wunder, 2015). Specific PES tools include direct public payments, direct private payments, tax incentives, in-kind contributions, cap and trade markets, voluntary markets, and certification programs.

A number of recent studies have suggested ways to maximize the efficiency and cost-effectiveness of PES projects, including employing the concept of ecosystem service bundling (Wendland, 2010). There have been several recent studies focusing on the degree of overlap between multiple ecosystem services and biodiversity, and therefore the opportunities and constraints to bundling these services (Wendland, 2010). Even while the science of bundling is in its early stages, the simple awareness that ecosystem services interact and are not produced in isolation can improve the outcomes of ecosystem service management.

Although incentive programs hold promise for improving land management for the benefit of multiple stakeholders, they can also have unintended consequences. Bunch (1982) found that direct incentives can create dependency in rural communities and undermine local decision-making and experimentation with home-grown solutions to environmental challenges. In addition there is the risk that farmers will abandon incentivized practices when direct payment programs end (Hinchcliffe et al., 1995; Steiner, 1996; Schrader, 2002; Hellin and Schrader, 2003). Thus, careful planning and implementation of incentive programs is essential.

Tools for Valuation of Ecological, Economic, and Social Values of Ecosystem Services

In the past several years, a number of ecosystem service-specific tools and models have been developed to allow decision-makers and managers to develop relevant ecosystem service information. Many of the tools allow for the analysis of ecological, economic and social values. The tools include entire frameworks for analysis, such as those provided by The Economics of Ecosystems and Biodiversity (TEEB, 2014) program, rapid assessment methodology focused on ecosystem services such as the Toolkit for Ecosystem Service Site-based Assessment (TESSA; Peh et al., 2013), and a number of dynamic models that analyze multiple ecosystem services and the trade-offs among them. (See more detail here). The benefits of many of the models include that they enable the comparison of alternative scenarios of landscape management in terms of how they will affect multiple ecosystem services and beneficiaries. The limitations of many of these tools include that they do not work well in some systems, are not very accurate, need to be validated, and require a lot of time and resources to run. However, the act of engaging different stakeholders in participatory data collection methods and decisions through the use of models can be a powerful tool in gaining stakeholder ownership of the challenges of managing land for multiple objectives. Further, running these models off the shelf is still much less resource intensive than developing new models for a specific system, and they may be very useful for meeting some objectives. In general, it is important to examine what the outputs of any of these tools will be and determine whether they are sufficient for meeting the needs of decision-makers.

A Set of Guiding Principles for Watershed Management

Watershed management is a human endeavor that not only must be grounded in state of the art science and management practices but also depends upon good governance. The diversity of cultural, political, and biogeographic histories across the steepland Neotropics dictates that governance systems will have to be adapted to the local conditions. Whether creating new entities or reforming existing laws and institutions, a set of principles – described below in no particular order of importance – ought to guide practice of watershed management:

Invest in Public Education and Capacity Building About How Watersheds Function and the Goods and Services They Provide

- Deepening watershed awareness is critical for decision makers from all levels of government to understand the consequences of policies and actions, particularly important given the expansion of large infrastructure development in watersheds. Equally important is that the general public, in particular upstream communities, act as “water citizens” to play a land and water stewardship role. Building such awareness is essential to further sustainable development in the steepland Neotropics;

- Public education and capacity building explaining connections among political jurisdictions in a watershed and demonstrating the variety of the watershed's ecosystem services is essential to maximize cooperation and participation and move towards bioregional planning and governance;

- Technical staff within municipalities, water utilities, forestry, conservation, and agricultural agencies should be supported in deepening knowledge about basic watershed dynamics (both ecological and political), including gathering and analyzing scientific data, participating in effective governance processes and resolving conflicts among competing watershed users.

Rigorous Use of Diagnostic Tools Based on Ecological Science and Mapping of Formal and Informal Decision-Making in the Watershed

- Good scientific data (e.g., forest cover baselines, stream flows, groundwater reserves, etc.) are essential to guide watershed planning and management decisions. They must be publicly available and updated frequently following an appropriately designed monitoring program;

- An inventory of existing laws, programs, agencies and organizations affecting resource use within a watershed is an essential diagnostic tool to plot watershed governance reform.

Rigorous Use of Integrated and Participatory Planning Tools and Innovative Governance Structures and Processes

- Watershed planning must combine land use planning and water use planning. It must bridge and integrate urban and rural jurisdictions both upstream and downstream to advance towards bioregional watershed governance. Governance and management must take into consideration different spatial and temporal scales of biophysical, social, and economic processes. Multi-stakeholder engagement, including significant involvement of community organizations and public agencies is critical for long term sustainability;

- Water and land use policies should be conceived, coordinated and enforced by a federation of neighboring jurisdictions, but implemented in a decentralized fashion. They must enjoy adequate local authority with resources transferred to the local level from national agencies to perform the job;

- Resource use priorities within a watershed should be publicly debated and made transparent and thereafter be used to guide governance decisions;

- Civil society efforts can deepen the impact of public protection and incentive programs, which may include playing a watchdog role to ensure public accountability.

Provide Financing and Incentives While Enforcing Laws for Effective Watershed Stewardship

- Financing of watershed protection to guarantee ecosystem services is a national priority – it cannot in all cases be financed strictly through local user fees or watershed funds capitalized voluntary and may require central government allocations;

- Payments for ecosystem services (PES) are a promising tool but cannot be a substitute for creating an enabling environment for a viable rural economy that safeguards the health of watersheds (e.g., extension services and credit programs to sustainable farmers, foresters, and other rural land stewards);

- Incentives are only one part of the solution; good governance requires mobilizing resources for law enforcement and watershed policing.

Chapter 7

Case Studies

Managing the Panama Canal Watershed

Introduction

With some 14,000 ships, accounting for nearly 5% of global commerce, passing through each year, the Panama Canal is arguably the world's most important inland commercial waterway. The importance of the Canal extends beyond the narrow boundaries of the waterway. The Canal is an economic driver for the country of Panama and in 2014 directly provided over $1 billion to the National Treasury of Panama (ACP, 2014a).

Lakes and rivers in the Panama Canal Watershed (PCW) provide fresh water to the residents of Panama, including the metropolitan areas of Panama City, Colon, La Chorrera and Arraijan (CICH, 2008b). These same lakes power two hydroelectric dams with a total peak generating capacity of 60 MW (SNE, 2012). A large number of economically productive activities occur in the watershed including manufacturing, tourism, aggregate extraction, agriculture, livestock, forestry, and fishing among others (Heckadon-Moreno, 1999). Finally, the PCW's geographic location spanning the Isthmus of Panama makes it a critically important biological corridor.

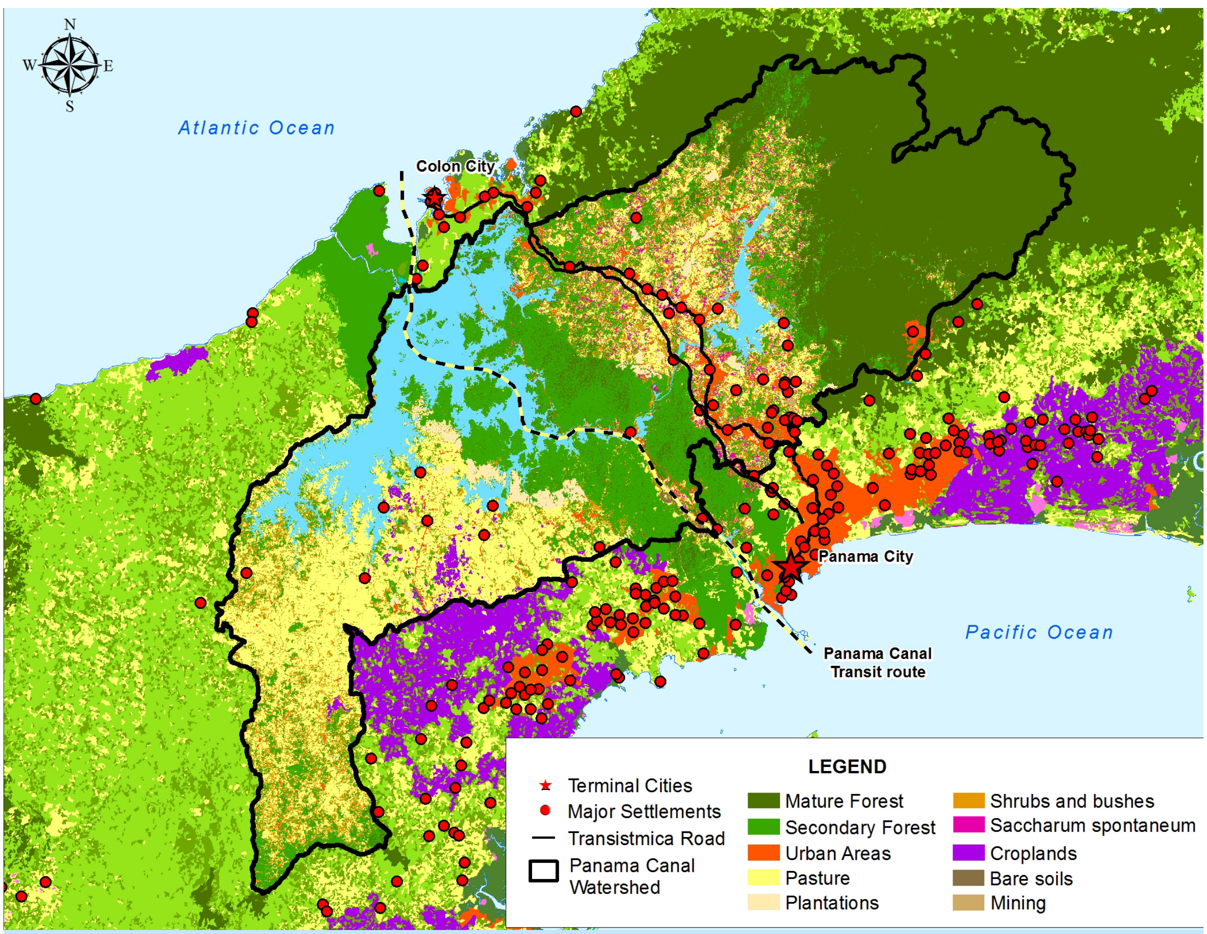


Figure 7.1 Population Centers in and Adjacent to the Panama Canal Watershed

Geographical Setting

The PCW is legally defined as the "geographic area in which the surface and ground water flows toward the Canal or is emptied into it, as well as in its reservoirs and lakes" (Law 19, 1997; Asamblea Nacional, 1997a) and encompasses 343,238 hectares (Figure 7.1). This area includes the provinces of Panamá and Colón, 7 districts, 41 counties, approximately 429 communities (CICH, 2015) and a total population of approximately 298,000 residents (INEC, 2010).

The PCW contains two large freshwater lakes – Gatun Lake and Alhajuela Lake – both created by damming the Chagres River for canal operations. Gatun Lake is located on the lower Chagres and forms part of the Canal. Alhajuela Lake is located further east, higher on the Chagres River and is used to store water for canal use as well as moderate flows from the Chagres River into Gatun Lake. In addition to these two large lakes, Miraflores is a small lake that forms part of the Canal. It is located at the entrance of the Panama Canal, in the Pacific Ocean, and links Miraflores and Pedro Miguel Locks.

The Canal creates a division between the eastern and western halves of the PCW. The unique biophysical and socio-economic characteristics of the two halves have led to their frequent separation as distinct management units: the eastern PCW (EPCW) and the western PCW (WPCW). The entire PCW is further subdivided into 50 smaller watersheds that also serve as independent management units (CICH, 2008a; CICH, 2008b).

The climate in the watershed is seasonal with a distinct dry season typically beginning in early December and ending in April or May of the following year. Annual rainfall ranges from under 2000 mm in the south to up to 3500 mm or more in the north (Condit et al., 2001). The long term annual rainfall average on Barro Colorado Island in the middle of the Panama Canal is 2600 mm with an annual daytime temperature of 25.5° C (S. Paton, pers. comm.).

The geology of the watershed is complex and dates to the rise of the Isthmus of Panama. The eastern watershed is covered by rolling hills that culminate in the Santa Rita ridge to the north and the mountains of Chagres National Park to the east. The western watershed, in comparison, includes relatively flat plains adjacent to Gatun Lake that steeply rises to form the mountains of Altos de Campana National Park to the southwest. The PCW is largely underlain by basalt and other bedrock of volcanic origin but with significant areas of marine origin, particularly around Gatun Lake (Stewart and Woodring, 1980). The complex geology of the watershed has given rise to a diversity of soil types that range from fertile loamy soils with relatively high pH above limestone to infertile clay soils with low pH above basalt (IDIAP, 2006).

Land Use and Infrastructure

Approximately 50% of the land in the watershed is currently forested: half covered by mature tropical forests (25%) and half covered by secondary forest (25%). The remaining 50% of the landscape is made up of cattle pasture (25%), with greater coverage in the WPCW; very young secondary forest (10%); other agricultural uses, including pork and chicken production, coffee, pineapple, watermelon, and subsistence agriculture that are of localized economic importance; urban areas (3%); an aggressive invasive grass, *Saccharum spontaneum*, related to sugar cane (2%); and timber and other plantations (2%; Martinez, 2011). Land cover maps produced by the former Panama Canal Commission indicate that with the exceptions of the formerly US controlled Canal Zone and the area east of Alhajuela Lake, most of the land in the watershed was deforested as of 1977 (Stallard, pers. comm.). There has, therefore, been an increase in forest cover in the PCW since this time (1977).

National Parks and Other Protected Areas

Several protected areas exist within and adjacent to the PCW (Figure 7.2). Created in 1984, Chagres National Park protects the upper reach of the Chagres and adjacent rivers, which collectively provide 49% of the water volume supplied by the major sub-watersheds of the PCW (Heckadon-Moreno, 1999; CICH, 2008b). A series of protected areas protect the forests along the eastern boarder of the Panama Canal. To the south in Panama City, Parque Metropolitano protects relatively dry forest and serves recreational, research, and conservation purposes. Just north of Parque Metropolitano, Camino de Cruces National Park protects the section of the path closest

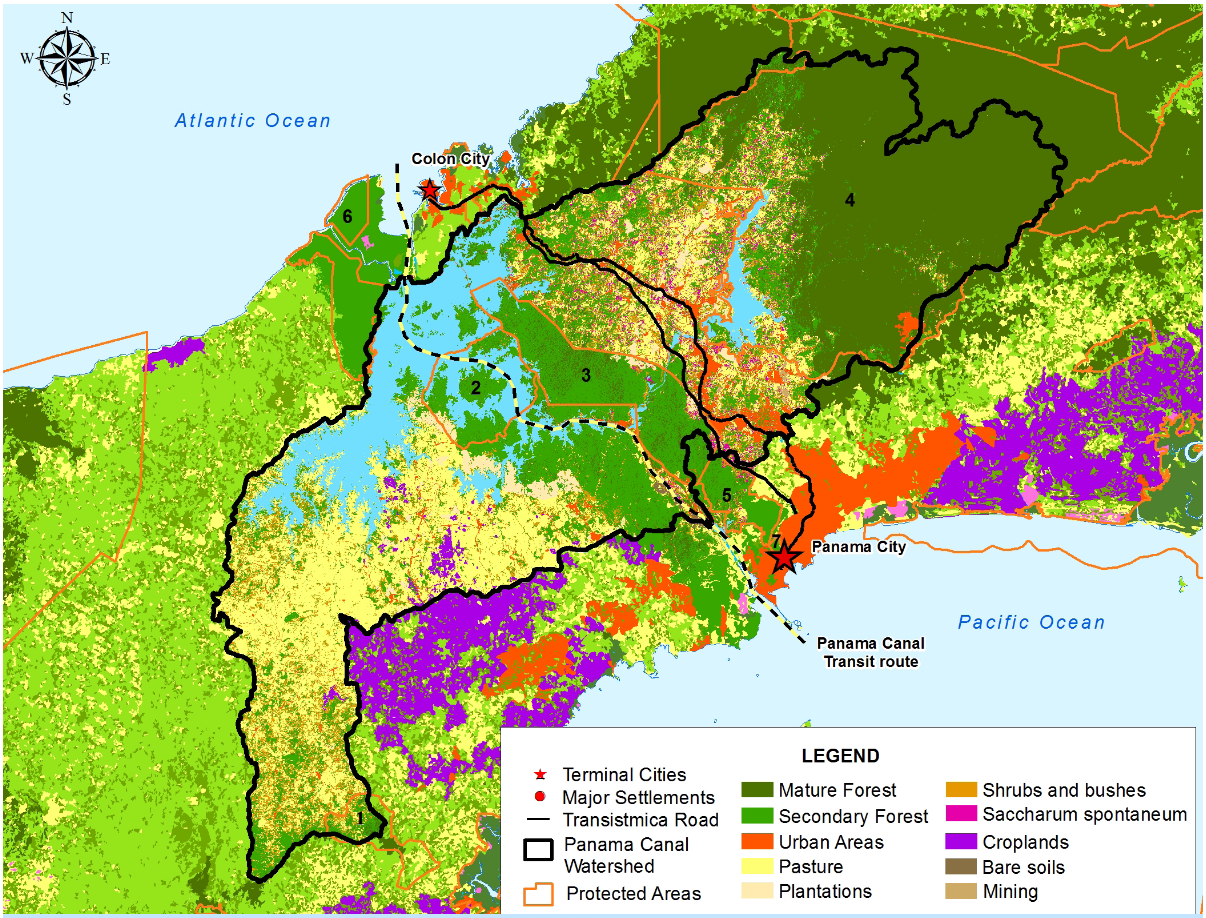


Figure 7.2 Land-Use and Protected Areas of the Panama Canal Watershed
1) Altos de Campana National Park, **2)** Barro Colorado National Monument, **3)** Soberanía National Park, **4)** Chagres National Park, **5)** Camino de Cruces National Park, **6)** San Lorenzo Protected Area, **7)** Metropolitan Park

to Panama City that was used by the first European inhabitants to cross the Isthmus of Panama and to evacuate silver and gold plundered from South America. Soberania National Park abuts Camino de Cruces NP and extends to the north along the Canal towards Colon. Soberania NP is world renown as and destination for international birders and other ecotourists. North of Soberania NP and on the western bank of the Canal is the San Lorenzo Protected Area.

Barro Colorado National Monument abuts Soberania NP on the west and spans the Panama Canal, including Barro Colorado Island (BCI), and mainland on both the eastern and western shores of the Canal. BCI has been home to a permanent biological research station managed by the Smithsonian Tropical Research Institute for over 80 years. Altos de Campana National Park protects the mountains in the southwestern extreme of the PCW and protects the headwaters of the Trinidad River.

The creation of the protected area network in the PCW is evidence of the remarkable vision of Panamanian conservation planners of the 1960s and beyond as they serve to protect biodiversity in situ as well as interlink biological corridors that afford the movement of wide ranging forest dwelling species to ensure habitat and viable populations and the potential for preserving genetic links between species over vast areas. The network of protected areas crosses the Isthmus from South to North also encompasses a rainfall gradient that spans relatively dry to wet forests. The protected areas of the PCW also serve as anchors within the Mesoamerican Biological Corridor, the goal of which is to preserve continuous forest throughout Central America to allow the movement and interbreeding of forest dwelling populations from Mexico to South America (Heckadon-Moreno, 1999).

Human Infrastructure

Deforestation and reforestation of the PCW has been relatively dynamic over the last half century. While historically agriculture drove deforestation, recent trends in infrastructure development and urbanization illustrate a shift in the dominant drivers of land conversion (loss of forest) in the Panama Canal region (Rompre et al., 2008). Largely unaffected by the global financial crisis of the late 2000s, Panama has experienced a development boom over the past decade; Panama City's metropolitan area is rapidly expanding upward and outward. Panama's urbanization front is evident in land cover maps produced by the Panama Canal Authority (ACP as it is known by its Spanish acronym).

The construction of roadways has stimulated the urbanization of the PCW. The Transistmica highway connects Panama (the Pacific) and Colon (the Caribbean) while also dividing the eastern and western watershed. Land maps by the ACP show not only metropolitan growth, but also urbanization along roadways and the dwindling of forest links capable of maintaining connectivity in the watershed. A second, parallel, toll road that also bisects the isthmus was finished in 2012. While the lack of on- and off-ramps have limited the urbanization front along this toll road, signs of land use conversion from agriculture, forests, and plantations to urban or industrial areas are beginning to appear along this highway. Ambitious improvements to rural roadways on both sides of the watershed over the past several years have also led to land ownership changes, if not changes in land use. Indeed, few places outside of protected areas remain more than an hour or two drive from Panama City or Colon.

Canal Infrastructure

The physical infrastructure within the PCW is dominated by the series of dams and locks. Built with the original construction of the Canal, Gatun Spillway closes off the mouth of the Chagres River from the Caribbean and forms Gatun Lake, through which ships travel as part of the canal system. Madden Dam was built on the Upper Chagres River in the mid-1930s and created Alhajuela Lake. The Alhajuela reservoir is filled in the wet season to ensure water for the Canal during the dry season and provide drinking water for Panama City. The Canal currently maintains three sets of locks (two on the Pacific and one on the Caribbean), each with two lanes; the Canal expansion, slated to be complete in 2016, will add a third lane to the locks on both sides.

The Gatun and Madden hydroelectric stations generate power to run the Canal during the rainy season. The Miraflores thermoelectric station, with fire internal combustion engines guarantees the power needed throughout the year. The newest two engines came into operation in 2014 in time to help meet the national demand during the power crisis of that year.

Water Treatment Plants

One of the great achievements that led to the successful construction of the Panama Canal was the creation of water infrastructure that provided relatively clean water to Canal workers and citizens of Colon and Panama City. Thus, these areas have benefited from the highest quality drinking water available at any given time for 100 years. Today, the PCW provides drinking water to half of the citizens of the country with 8 water treatment plants, 4 in the province of Colon and 4 in the province of Panama. The plants are located at Colon, Alhajuela Lake (Chilibre), Miraflores lake (on Canal between Pedro Miguel and Miraflores locks), and Gatun Lake (La Chorrera) – serving residents in and outside the western watershed.

Ecosystem Services in the Panama Canal Watershed

A recent review of ecosystem service research in Latin America found that Panama ranked second in the number of studies on the subject (Balvanera et al., 2012). An overwhelming number of these studies have been undertaken in the PCW. The Panama

Canal Watershed Monitoring Project (1996 – 1999) produced an eight volume set of studies on 21 compact discs that review the state of the environment and knowledge as it relates to ecosystem services at the start of the new millennium (summarized in Heckadon-Moreno, 1999; Condit et al., 2001; Ibanez et al., 2002). Significant research has continued to build on these and other studies.

The Millennium Ecosystem Assessment (MA) identifies four sets of ecosystem services, all of which are provided by the PCW.

Supporting Services

The forests and landscapes of the PCW contribute to the provision of supporting ecosystem services and life sustaining processes, including the conversion of carbon dioxide into organic molecules through primary productivity and nutrient cycling. Research on these topics include the ForestGEO® carbon program, which is dedicated to measuring carbon pools and understanding how carbon cycles through tropical forests, is based in Panama with countless studies being undertaken in the PCW (http://www.forestgeo.si.edu/group/Carbon/). Long term nutrient addition (Wright et al., 2011) and leaf litter manipulation (Vincent and Tanner, 2013) studies are underway on the Gigante peninsula on the banks of the Panama Canal. Studies of the role of biodiversity contributing to or constraining growth and productivity in forests (Chisholm et al., 2013; Batterman et al., 2013) and plantations (Healy et al., 2008; Potvin and Gotelli, 2008) have been undertaken. Biological corridors cross the PCW from north to south and east to west (see above) representing another aspect of supporting services.

Provisioning Services

It is clear that the PCW provides relatively clean water to over half of the people who live within the country of Panama (CICH, 2008b). Other provisioning services include agricultural production (livestock and crops), timber, and energy through the generation of hydroelectric power (ACP, 2014a). In 2008, approximatley 25% of the PCW was used as pasture (Martinez, 2011) and intensive agro-industry (pork, pineapple and chicken production) also exists (Sanjur et al., 1999). Timber plantations represent a small fraction of the land area within the PCW (2%), in part because much of the land area is not suitable for producing the large profits investors would expect from teak (e.g., Stefanski et al.,2015). However, significant research has been undertaken to understand the growth of native tree species in plantations (Wishnie et al., 2007; van Breugel et al., 2011) and agricultural settings (Plath et al. 2011; Riedel et al., 2013) as well as in different planting schemes (Hooper et al., 2002; Jones et al., 2007; Craven et al., 2008; Cerezo, 2011), important to meet the national forest policy and PCW land-use plan goals of converting agricultural lands into forests, or at least a tree dominated landscape (see below). Aguilar and Condit (2001) have shown that over 100 tree species are used by people living within the watershed for uses including non-timber forest products.

Regulating Services

Forests within the PCW regulate stream flow. Kinner and Stallard (1999) found a forested sub-watershed of the Agua Salud River had markedly higher streamflow during the drought of record (1997-1998) than a deforested catchment of similar area and recent work by Ogden et al. (2013) found forests regulated stream flow by both moderating peak flows and extending the period of higher flows in a forest as compared to a deforested watershed during dry periods. Forests also produce less erosion during times of all but extreme rainfall than non-forested areas (Stallard et al., 1999). Forests have been shown to store significant pools of carbon (e.g., Mascaro et al., 2011) and a complete map of carbon across the landscape is available (Asner et al., 2013). One need only visit a traditional cattle pasture and one containing significant tree cover to realize the role of pasture trees in contributing to animal well-being. Several research teams are currently investigating the role of forests in regulating human and wildlife disease.

Cultural Services

Relatively little research has been undertaken to understand the provision of cultural services within the PCW as compared to other services. However, Soberania NP is world renown as and destination for international birders and other ecotourists. Its forests serve as an important reservoir for biodiversity and also serve a large an important role in ecological research for researchers employed by or associated with the Smithsonian Tropical Research Institute (STRI).

Panama Canal Watershed Governance

The property rights, laws and governing authorities for resource management in Panama, as in many nations, are resource dependent. While land is privately owned, water resources are administers by ACP, for which private use rights are granted (ACP, 2005) and forests are legally designated as state patrimony. In practice however, rights to the forests on private land are linked to the property rights of the land and trees can be harvested upon permit approval by the government. Panama's Ministry of Commerce and Industry is responsible for mineral development and Panama's Authority of Aquatic Resources is responsible for programs related to fishing, aquaculture and marine-coastal management. Although the Ministry of Environment is the overarching governing institution for the management of terrestrial (i.e., non-marine) resources within Panama, there is considerable overlap in jurisdiction between ministries and authorities.

Panama's Ministry of Environment and Watershed Management

The environmental governing body in Panama was created in 1998 (Law 41, 1998; General Environmental Law) and named the National Environmental Authority or ANAM (Autoridad Nacional del Ambiente; ANAM, 2014a,b) as it is commonly known for its Spanish acronym and as it will be referred to throughout this document. The authority has recently (2015) been given ministerial standing, resulting in a formal name change to the Ministry of Environment (known locally as MiAmbiente).

Since 1998, ANAM has been responsible for the management of Panama's environment including wildlife, water, forests, protected areas, and monitoring programs. Laws promulgated over time have given ANAM the responsibility of land-use planning as a tool for environmental management (Law 41, 1998; ITTO, 2005) and prompted ANAM to lead the formation of multi-sector (public and private), regionally based watershed committees (Law 44, 2002; ANAM, 2010). The primary goals of these committees include the promotion of coordinated and cooperative efforts between public organizations, private organizations and civil society within the watersheds, the creation and implementation of management, development, protection and conservation plans; the adoption of tools to avoid, reduce or resolve conflicts between water users; and the inclusion of community-level participation and work with higher level government to recommend regulations or techniques directly rated to watershed management when necessary (ANAM, 2010).

Water Resource Management Laws, Policies, and Regulations

The Water Use Law (Law 35, 1966) is the legal foundation of water management in Panama and gives ANAM the governing authority over water use rights. Recently (2007) Panama's National Policy of Water Resources (PNRH) gives ANAM the organizational responsibility of coordinating governmental organizations and ministries in the achievement of integrated ecosystem conservation and management capable of ensuring the economic, social and environmental sustainability of the nation's water resources. In 2009, a national action plan was initiated to achieve the goals of the PNRH including achieving water provision needs (basic human needs, food production, electricity generation, industrial production), promoting water governance and watershed management, and encouraging a water culture (education, communication and extension; ANAM and GNRP, 2011).

Forest Management Laws and Regulations

The Forest Law (Law 1, 1994) is the legislative underpinning of forest management within the country. It declares all forest resources to be of national interest (state patrimony) and subject to the regulations under the law. Forest tenure is divided into public, private and indigenous areas (Comarcas), with ANAM being responsible for awarding forestry concessions on public land (ITTO, 2005).

The removal of primary or secondary forests on private or indigenous land requires approval and may require previous inspection (Law 1, 1994). Among other things, the law places harvesting restrictions on areas thought to impact water quality or quantity provisioning (stream banks, etc.).Through this law, fire protection of forests also falls on ANAM and burning, for all land uses, requires ANAM approval. Several laws and directives have updated the original forest law over the years. Of particular interest to land management and the consideration of ecosystem services are laws encouraging and providing incentives for reforestation (Law 24, 1992; Law 58, 1999) and Executive Directive 37 (2009) which provides the current national forest policy. Executive Directive 37, among other things, notes the need to work with civil society at all levels in the management of the country's forest resource as well as promoting agroforestry (including silvopastoral systems) and sustainable development. Nevertheless, it appears that no strategic plan has yet been finalized that implements this directive.

The Special Case of the Panama Canal Watershed

Legal Context

Upon signing the treaty outlining the transfer of the Panama Canal to the Republic of Panama, the Republic created the legal framework for the Canal transfer and management. In 1994, Panama amended its Constitution to include the Panama Canal and on May 14, 1997, the Legislature approved the Organic Law of the Panama Canal Authority (Law 19, 1997). Law 19 created the ACP as an autonomous legal entity charged with the private administration, operation, conservation, maintenance and modernization of the Panama Canal and its related activities (National Assembly, 1997a). This same law defines the regulations governing the daily activities and operations of the waterway and establishes the requirement to manage the Canal not only as an efficient and profitable enterprise but also one that promotes Panamanian socioeconomic development.

The ACP is responsible for the management, maintenance, use and conservation of water resources in the PCW. Construction plans, water use, development of ports and of any other work or construction on the banks of the Panama Canal, require the prior approval of the ACP (Assemblea Nacional, 1994). The ACP is also charged with overseeing new strategies, policies, programs and projects (public or private) that can affect the watershed, coordinating the administration of the watershed's natural resources with other organizations, and establishing and directing the Inter-institutional Commission of the Panama Canal Watershed (CICH, for its Spanish acronym; IRG Ltd., 2000).

Inter-institutional watershed management in Panama is generally overseen by ANAM; however, the PCW is a special case in that the ACP, or more specifically, the CICH, is the lead for all inter-institutional efforts. Inter-institutional resource management in the PCW is based in Law 19 (see above) and Law 41 (1998) which together provide the foundation of the CICH and give legislative power over water resources in the PCW jointly to the ACP and ANAM. Collaboration between ACP and ANAM allows for complementarity: the ACP focuses their efforts in the provision of drinking water and water for the functioning of the canal and ANAM is responsible for overseeing the implementation of their Environmental Impact Assessment (EIA) process, establishment of environmental laws and standards, and management of environmental sampling and monitoring (IRG Ltd., 2000).

Development of the canal area is established under the parameters of Law 21 (1997), the Regional Plan for the Development of the Interoceanic Region and the General Plan for the Use, Conservation and Development of the Canal Area, whereby the Government of Panama approved land-use zoning in the Interoceanic Region (Assemblea Nacional, 1997b). The Regional Plan provide the guidelines for the economic development of the Canal Zone, the PCW more generally, and the areas surrounding the cities of Panama and Colon which are located outside the PCW. In the long term, the plan must ensure the protection of the resources necessary for the operation of the Canal, the supply of water and energy required by the region's inhabitants, as well as the conservation of biodiversity. Land-use zoning in the plan is intended to decrease pasture land in the watershed by 94% by 2025 and expand the watershed's protected areas to cover 40% of the EPCW (Dale et al., 2005). In 2008, the ACP created a 20-year plan, the Sustainable Development Plan for Integrated Water Resource Management (known by its Spanish acronym DSGIRH), for the PCW to achieve the land-use goals of Law 21 (CICH, 2008b).

Inter-institutional Commission of the Panama Canal Watershed (CICH)

The CICH, created in 2000, has the task of working in close coordination with State agencies to integrate efforts, initiatives and resources for the conservation, management, and sustainable development of the PCW. Through this Commission, strategic alliances (the ACP, communities, institutions, local authorities, and civil society) have been made and a community participatory structure was established for water governance based on six Advisory Councils (ACP, 2012). In support of the implementation and promotion of programs and strategies for the PCW, the CICH is responsible for managing resources through the establishment of a funding mechanism for both domestic and international sources. In December 2014, state ministers, institution directors, representatives of the ACP, and members of governmental and non-governmental organizations re-iterated their promise to join efforts to achieve the objectives established in the PCW's Sustainable Development Plan (ACP, 2014b).

Stakeholders Within the Panama Canal Watershed

Given the global reach of the Canal, there is a very large group of stakeholders in the management of the PCW. Ships transiting the canal travel the world's oceans and management decisions of the canal have ramifications on almost all continents. The Canal expansion, for example, has led more than 60 ports in the United States to invest $46 Billion (FY 2012 – FY 2016) to accommodate the much larger, post Panamax vessels (US DOT and MARAD, 2013). Nationally, over 50% of the people of Panama get their drinking water from the PCW (Heckadon-Moreno, 1999) and, as noted above, the PCW contributes approximately $1 billion a year to the national treasury (ACP, 2014a). In addition to national and international stakeholders, there is also a broad coalition of local stakeholders including non-governmental organisations (NGOs), indigenous groups, industry (ranging from cement to forest plantation companies), tourism operations, universities and research institutions, agricultural producers, and local residents. At least three different trust funds have been established to provide financial assistance in management of different areas of the PCW: The Chagres National Park Trust Fund (set up with assistance from the United States Agency for International Development -USAID, the Panamanian government, and Nature Conservancy; managed by Fundacion Natura), the Ecological Trust Fund of Panama (EFIDECO, with same partners as Chagres Fund), and a water fund (set up by Fundacion FEMSA and the Nature Conservancy). In addition, foreign government development agencies (e.g., USAID, United Nations Development Programe-UNDP, United Nations Environmental Programme-UNEP, German Government Technical Cooperation-GIZ, Japanese International Cooperation Agency-JICA), and international lending institutions (e.g., Inter-american Development Bank-IDB, Development Bank of Latin America-CFA), and private companies (e.g., Argos, Banismo, Coca-Cola) have also contributed to activities in different ways. Finally, although no lands in the PCW are formally included within Panama's indigenous Comarcas, several indigenous communities are located within the EPCW and their members are active participants in eco-tourism and watershed management activities.

Incentivizing Beneficial Management Practices: The Panama Canal Authority's Environmental Economic Incentives Program (PIEA)

In its effort to meet the legislative and constitutional mandates to manage, maintain, use and conserve the water resources in the PCW, the ACP promotes an over-arching strategy known as the "Panama Canal Green Route." This strategy incorporates environmental management into Canal operations, promoting the energy efficiency of ACP facilities and acknowledging positive environmental actions made by the shipping companies and vessels that use the Canal (ACP, 2014a). For example, a partnership with the Develop-

ment Bank of Latin America (CAF) has supported the design of a tool for calculating the carbon footprint of Canal functions and currently assists in developing a consultancy that aims to identify positive actions taken by customers to reduce their CO_2 emissions.
The Green Route strategy builds on the 2008 Sustainable Development Plan for Integrated Water Resource Management which acts as a medium and long term strategy for achieving the goals outlined in the General Plan for Land Use (Law 21, 1997). This plan is developed and implemented by the ACP to coordinate resource use and conservation as well promote sustainable human development that is replicable in other regions of the country where water is a key consideration in land-use management (ACP, 2007). A key and multi-faceted program that has resulted from the PCW's Sustainable Development Plan is the ACP's Environmental Economic Incentives Program (PIEA, by its Spanish acronym).

Land Titling Project

The ACP recognized early on that one obstacle constraining an individual farmer's ability to take a long-term, sustainable approach to management decisions is the lack of land security or tenure (i.e., property rights). For this reason, ensuring clear land title in the PCW was one of the key goals of the 2008 Sustainable Development Plan. The long term goal in the PCW is to have 95% of lands titled (CICH, 2008b). Working with the National Land Authority (ANATI by its Spanish acronym) and the United Nations Development Programme (UNDP), the ACP has expended considerable effort in helping residents obtain clear land title. As of 2010, 72% of tenants and 54% of lands in the PCW had title (INEC, 2010; INEC, 2011b). At the end of Fiscal Year 2014, the land title program, had delineated and registered approximately 33,294 hectares of land (4,644 producers) in the district of Capira (ACP, 2014a).

Environmental Economic Incentives in the Watershed (PIEA)

The ACP carries out a series of activities in the PCW within the framework of the Green Route, chief of which is the PIEA, conducted on the basis of an agreement with ANAM and the Ministry of Agricultural Development (MIDA, for its acronym in Spanish; ACP, 2009). The PIEA was created under the PCW's Sustainable Development Plan with a planning horizon of 20 years – from 2008 until 2027 (ACP, 2014c). The overall objective of PIEA is to protect the water resources of the PCW both in quantity and quality, for the provision of drinking water for the population of the country's major cities and for operation of the Panama Canal, and to improve the quality of life of communities located in the Watershed.

Development of the Program

In 1987, the Panama Canal Commission (PCC) initiated a reforestation project in the Canal Operation Areas. These early efforts used exotic species due to limitations in seed availability and characteristics of rapid growth. Since 1998, the ACP has continued the Reforestation Project with a focus on ecological restoration, using only native species (Jones et al., 2004; Montagnini et al, 2008; Cerezo, 2011). In 2001, the ACP began implementing reforestation projects with community groups in the PCW, to protect water resources and aligned with the development of human activities. Hands-on training was included, incorporating a gender approach and a close relationship between technical and social components (ACP, 2003).

With the experience gained in these reforestation projects, in 2009 the ACP began field implementation of a Sustainability Program for the Watershed and its inhabitants (Figure 7.3). The centerpiece of this program is the PIEA, with actions to protect and conserve the water resources of the PCW within the context of the activities of its inhabitants. The ACP and agricultural producers integrate environmental, social and economic activities, generating profits for the company, for the country and for the inhabitants of the PCW. It is a commitment to corporate responsibility on the part of the ACP, and to protecting natural resources on the part of the area's residents, while improving their living conditions (ACP, 2014c).

Current Program Overview

The program has focused on three main lines of action to meet their conservation and management objectives:

- The protection of existing forest cover and the

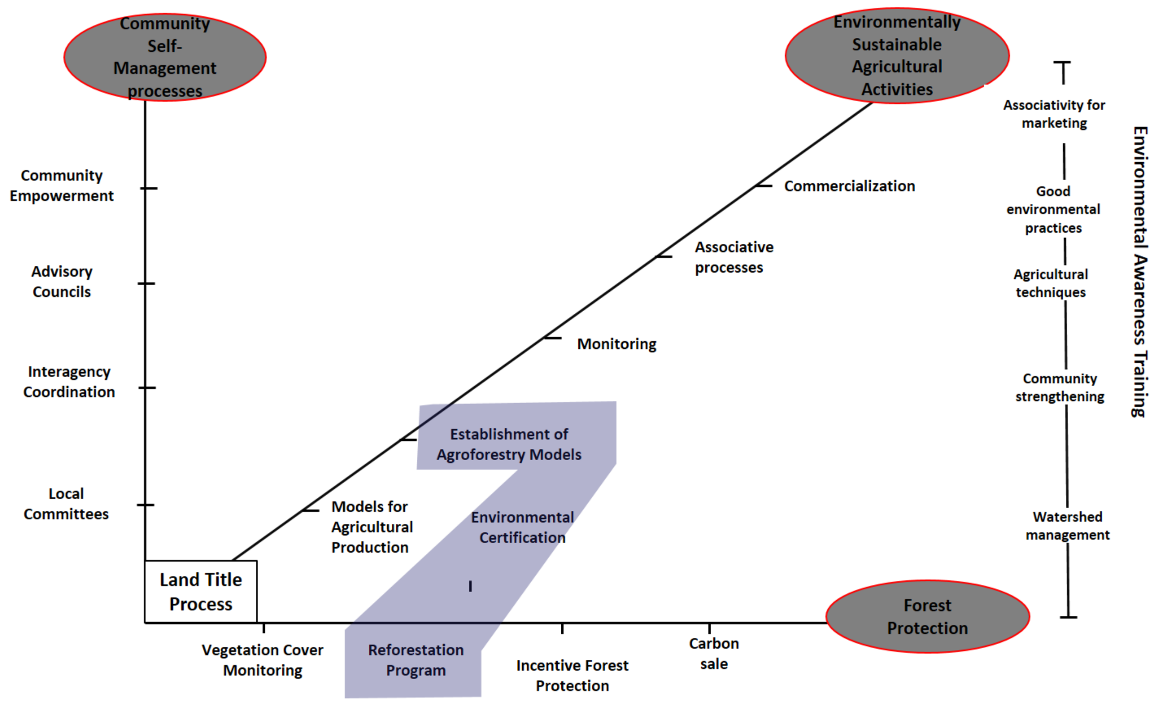


Figure 7.3 Sustainability Model for the Protection of Water Resources in the Sub-Watershed of Ciri-Trinidad
(ACP, Panama Canal Authority)

appropriate use of land according to its suitability, to preserve the quality and quantity of water resources in areas of strategic importance in the Canal Watershed;

- The conversion of degraded areas through the implementation of reforestation activities adjacent to protected and other areas of conservation importance, and development at the community level of agroforestry and silvopastoral systems;
- The inclusion of commercial reforestation activities that incorporate national lands located within the boundaries of the former Canal Zone.

Currently, the PIEA has four different methods of reforestation: conservation, commercial, agroforestry and silvopastoral. Each one represents a reforestation model with different levels of community participation and institutional involvement. As a result of the work done in these four categories from 2009 to 2013, 5,641 hectares have been established (Table 7.1).

Table 7.1 Method, Year and Hectares Established in the Environmental Economic Incentives Program, PIEA 2009 – 2013 (ACP, Panama Canal Authority)

	2009	2010	2011	2012	2013	Total
Conservation	185	405	50	0	0	640
Agroforestry	300	320	400	400	400	1,820
Silvopastoral	162	499	600	600	600	2,461
Commercial	0	609	111	0	0	720
Subtotal (ha)	647	1,833	1,161	1,000	1,000	5,641

Through the collaboration of government institutions, community involvement, technical support and advice from ACP specialists, the PIEA has reached more than 100 communities in the western sector of the province of Panama and in the province of Colon. Today, more than 6,635 hectares are included where landowners trained in conservation techniques use sustainable cattle farming and agricultural practices for the implementation of a profitable business model.

Program Model 1: Reforestation for Conservation

Reforestation for conservation is undertaken in national parks, protected areas and their buffer zones. The objective is the conservation of water and soil resources through reforestation of deforested areas, thereby connecting areas with plant cover and increasing protection of water resources. In this model, native species are used in a mix that seeks to replicate the diversity that occurs in nature, facilitating the development of biodiversity, the gradual recovery of plant cover in affected areas, the reduction of erosion processes, decreased runoff, and control of *Saccharum spontaneum*, among others (Cerezo, 2011; ACP, 2014c).

Plantations have been established in the Soberania National Park and Camino de Cruces, in close coordination with ANAM; in the Agua Salud Project, with the Smithsonian Tropical Research Institute (STRI); and in a buffer zone of Chagres National Park, with the University of Panama in a project known as the City of Trees. By fiscal year 2013, 640 hectares were planted (Table 7.1). The work sites exhibit elements of initial secondary forest succession which reveal ecosystem recovery. The elements exhibited include naturally regenerated pioneer tree species additional to those planted by the project and the presence of forest residues in the soil composition.

Program Model 2: Commercial Reforestation

This model refers to commercial plantations with valuable tree species, mostly teak, that are dedicated to commercial timber harvesting activities for periods of 25 years and provide tree cover that protects the soil and water resources. The program is expected to provide funds to cover the initial investment as well as reinvestment in the reforestation of harvested areas and expansion of the Environmental Economic Incentives Program to other areas (ACP, 2014c). The aforementioned Law 21 allocates land uses for the development of forestry activities along the stretch of land occupied by the former Canal Zone, in order to increase forest cover in these areas by encouraging commercial reforestation activities. Upon completion of the period of existence of the ARI, the management of lands zoned for forest use was transferred to ANAM for their better utilization.

These commercial plantations are located on public lands in the districts of Chilibre and Arraijan, in areas invaded by *Saccharum spontaneum*. When property and land occupied by the military forces of the United States reverted to the Panamanian government, an extraordinary amount of land with development potential was incorporated. These areas were initially administered by the Interoceanic Region Authority (ARI, for its acronym in Spanish), which used the General Plan for Land Use (Law 21, 1997) as a tool for land-use management. As of fiscal year 2013, 720 hectares have been planted (Table 7.1).

Program Model 3: Agroforestry Activities

Farmers in the PCW depend on slash-and-burn agriculture for food production, subjecting the forests to anthropogenic pressure aggravated by the creation of pastures. The terrain is generally hilly; soils are acidic, low in phosphorus and with an average amount of organic matter. The areas are difficult to access, with dirt roads that complicate transportation and marketing, especially during the rainy season (Fundacion Natura, 2010; IDIAP, 2006).

Under the agroforestry component of the PIEA, natural resource management and agricultural production are promoted (Figure 7.4). To date, the main activity that has been promoted is coffee production, since it is a permanent agricultural crop and a productive alternative that provides protective plant cover in these areas. (The production of cacao in the EPCW has also been explored in recent years.) In this model, community producers play a fundamental part in the development of projects. At the operational and farm levels, projects must take the characteristics of the terrain into consideration, for the protection

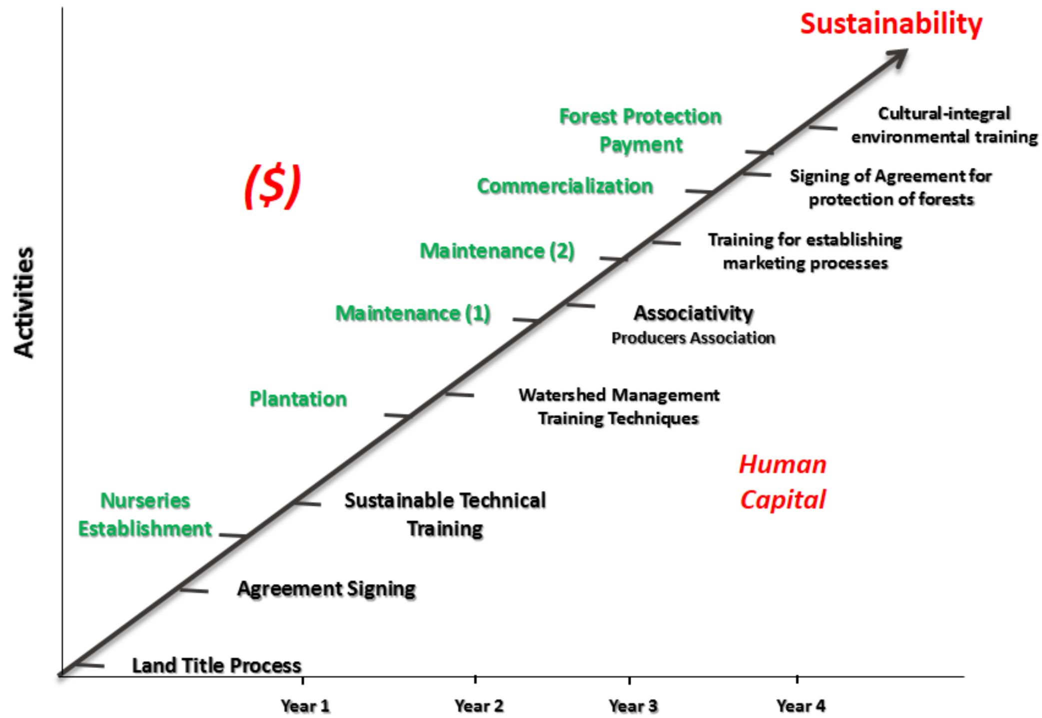


Figure 7.4 Sustainability Management in Agroforestry Systems of the Panama Canal Authority's PIEA Program
(ACP, Panama Canal Authority)

and conservation of natural resources and to meet the production needs of the participants (ACP, 2014c).

The agroforestry model consists of a combination of forest, timber, fruit and service species, together with agricultural crops. The forest species introduced provide services such as shade for crops and windbreaks, and contribute to the recovery of gallery forests and soil improvement. ACP engagement includes providing for plantation establishment and management for three years. Additional support includes delivery of materials, tools and fertilizer for the establishment and maintenance of the plantation, advice and support for pest control, and technical transfer processes through the training given to landowners. As an incentive, participants are paid a wage for the development of all project components. This method has benefited 1,010 small and medium agricultural producers that have property title, plots of 1-20 hectares, and are located in one of the more than 40 villages in the districts of Capira, La Chorrera and Colon. These areas are part of the sub-watersheds of the Cirí-Trinidad rivers, Caño Quebrado, Hules Tinajones, Gatuncillo and Alhajuela Lake. As of fiscal year 2013, 1,820 hectares have been planted 1,820 (Table 7.1).

Coffee occupies an important place in the economic and environmental development of the area of Ciri and the Trinidad Rivers, as the inhabitants depend on this crop for much of their income. It is also an important source of jobs, employing underprivileged people, and provides plant cover that helps reduce water erosion on land with a topography characterized by steep slopes (ACP, 2014d). As part of this program, the ACP is developing and implementing agroforestry models of shade-grown coffee production, mainly of the improved Robusta (*Coffea canephora*) variety. Together with MIDA, the ACP has trained farmers in production techniques, marketing techniques and the utilization of cooperatives. With the help of the ACP, in August 2012, the Association of Coffee Growers of the sub-watersheds of the Ciri Grande and Trinidad Rivers of the Panama Canal (ACACPA) was established in the community of Las Gaitas, Township of Ciri Grande. The organization was formed to explore the management, production and marketing of coffee and other environmentally friendly production activities. The overall objective of ACACPA is to improve and strengthen the activity of coffee growing by providing value added (Figure 7.5) and incorporating good technical and production practices that strengthen area production with the ultimate goal of entering the market in a sustainable, competitive, replicable and environmentally friendly way (ACP, 2014d). In the medium and long term, coffee production in these watersheds is expected to become a highly profitable agricultural activity, carried out with methods that favor soil and water conservation, and connecting farmers directly to national and international markets (ACP, 2013a).

Program Model 4: Silvopastoral Activities

Management of natural resources together with livestock grazing is promoted in this program model. The goals are to preserve and protect water resources while also improving cattle production (ACP, 2014c). The silvopastoral activities of the ACP consist of introducing forest species in pastures and farm areas that need to be protected. The forest species provide services such as living fences, windbreaks, protecting water bodies, shade and food for livestock and protection of soils. As part of the development of the ACP model, the establishment of improved pastures is promoted which improves animal nutrition and provides soil protection; wooded pasture plots are established and the banks of water sources and flows are reforested. Assistance with maintenance is provided for one year with this program model.

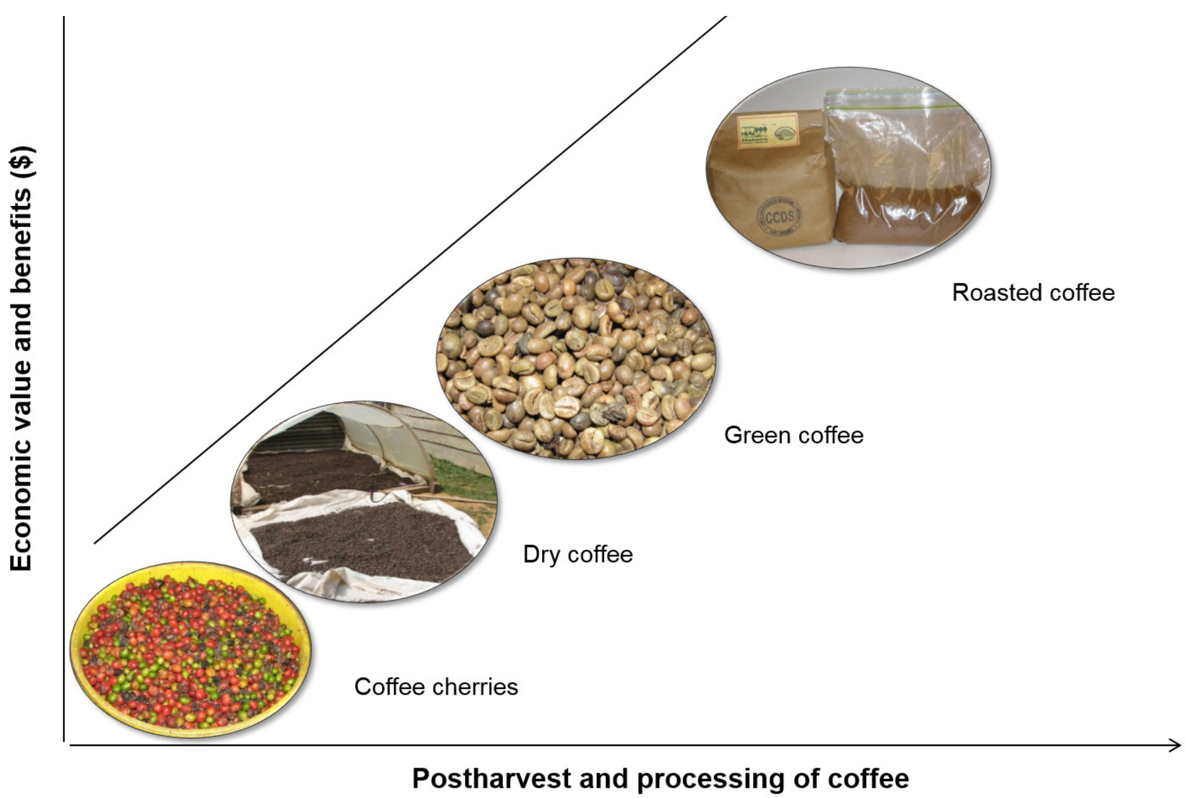


Figure 7.5 Post-Harvest Management and Added Value of Coffee (PIEA) (ACP, Panama Canal Authority)

More than 291 cattle farmers have benefitted from this program. Plots of areas between 5 and 50 hectares are located in the same communities as the agroforestry program. At the beginning of fiscal year 2013, 2,461 hectares incorporated into the program (Table 7.1).

New Program Model: Surveillance and Protection of Forests

Carbon monitoring and certification

German Agency for International Cooperation (GIZ) supports the monitoring of plant cover and the calculation of carbon stocks in the PCW's forests (ACP, 2014a).The quantification of the carbon sequestered by forests is based on estimates of plantation growth and absorption. The plantations of the PIEA are estimated to have an average absorption of 8.8 tons of CO_2 per year. The project, period is 30 years.

As part of the PIEA, the ACP has included the marketing of Verified Emission Reductions (VER) stored in vegetation through reforestation activities. These VERs have been quantified through the Voluntary Gold Standard, and the social and environmental co-benefits of these projects have been backed by international certification such as Climate, Community and Biodiversity (CCB). The VERs have been recorded in the financial portal MARKIT (Markit Environmental Registry).

Payments for protecting forest

In 2014, the ACP initiated a program to provide financial compensation to the owners of lands with endangered forests. These payments are intended to preserve the wealth of ecosystem services provided by these forests including soil protection, water regulation, and the maintenance of biological sanctuaries. The program centers on a concept known as "Incentive for protection and surveillance of Watershed forests". The project will begin with payment for the protection of 600 hectares of forest located in the basins of the Ciri and Trinidad rivers (ACP, 2014a).

Monitoring and Evaluation

The PCW Monitoring Program of the late 1990s was the first comprehensive study on the state of the PCW (discussed above). Since then, the ACP has published a report on the environmental state of the PCW in 2007 (CICH, 2007), a report on the Water and Forests of the PCW (ACP, 2011), and has another state of the watershed 2013 update forthcoming. Since 2003, the ACP has had a water quality monitoring program in the PCW (ACP, 2013b). The program includes chemical, biological and micro-biological monitoring and makes use of a permanent network of 38 sampling sites (ACP, 2013b). This monitoring program builds on the 100 year tradition, dating back to the construction of the Canal, of water quality sampling in the PCW. Indeed, the water division of the ACP has been monitoring stream flow in major rivers and meteorological conditions for many decades.

Continued monitoring and evaluation of the environment is consistent with the objectives of the 2008 Sustainable Development Plan for the PCW (CICH, 2008b), and the Watershed Environmental Information Centre of the CICH is designed as a clearinghouse of PCW information, including publications, summary reports, programs, projects and spatial data. Land cover maps have been produced regularly by the ACP with the most recent maps created in 2008 and 2013. Furthermore, the ACP is committed to integrating forest carbon mapping with their traditional land use maps by 2018.

Significant hydrological and ecological research in the PCW compliments the regular monitoring. Direct links throught collaboration exist between different divisions within the ACP and long term research initiatives at the Smithsonian Tropical Research Institute like those of the Agua Slaud Project (http://www.ctfs.si.edu/aguasalud/), the STRI Physical Monitoring Program (http://biogeodb.stri.si.edu/physical_monitoring/), and STRI's Smart Reforestation® Program (http://www.stri.si.edu/smartreforestation/). These collaborations can provide the best available science to questions of watershed management.

Lessons Learned

The lessons learned in the PCW likely parallel those of many watersheds, but the economic significance – globally, nationally and regionally – of the Panama Canal, and its dependence on the waters of the PCW, undoubtedly provides for unique resource management learning opportunities. Despite the link between hydrological services and the profitability of the Canal, convincing people of the importance of natural resources management, remains a difficult task to accomplish, even within the PCW. For the past 15 years the Panama Canal Environmental Division has been tailoring environmental programs, creating a niche for these types of efforts, together with the necessary budget for each program, in the Canal operational structure.

The PCW is an economically dynamic watershed with a unique legal context. As such, the CICH strives to promote sustainable development in the PCW by harmonizing the actions, initiatives and resources utilized for the integrated management and conservation of the watershed's natural resources. Experience has shown that only through dialogue, consensus and solidarity is it possible to address difficulties together and share in the successes (ACP, 2014a).

Commitment to the successful realization of environmental regulations and policies requires the continuation, growth and strengthening of inter-institutional collaboration and transparency in the watershed. An additional key goal is the inclusion of the best science available into funded environmental programs and projects. Only then will the programs and projects be able to successfully and efficiently achieve not only the goals of regionally-specific regulations, policies and plans but also the objectives of country-wide laws, regulations and policies.

FORAGUA, the Regional Water Fund of Southern Ecuador

Introduction

Water funds are user-funded mechanisms for the financing of watershed conservation, restoration, and management, designed to ensure water quality and enhance water retention through an ecosystems' natural capacity to store water. One of several water funds that operate in Ecuador is the '*Fondo Regional del Agua*' (the Regional Water Fund, known by its Spanish acronym FORAGUA).

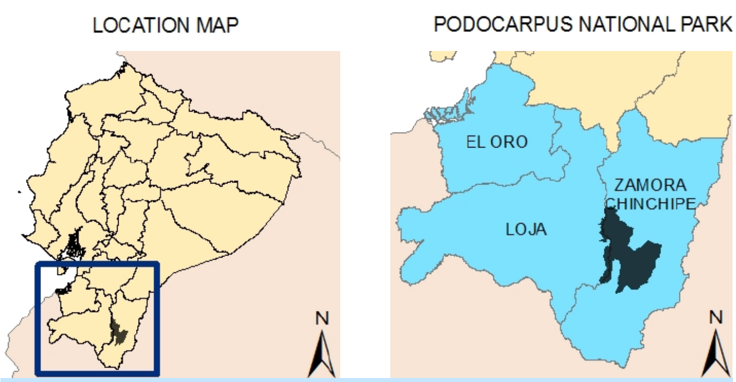


Figure 7.6 Ecuador's Southern Region

FORAGUA is established in the Southern Region of Ecuador which comprises El Oro, Loja and Zamora Chinchipe provinces (Figure 7.6). The region contains areas belonging to the Coast (*Costa*), the Andes (*Sierra*) and the Amazon (*Oriente*). The approximate total area is 27,400 km^2, which is 11% of the country. The altitude ranges from 0 meters in the coastal areas to around 4,000 meters in the Andean Region. Watersheds in the region can be at altitudes of 400 meters in the municipalities of Pindal and Macará to up to 3,900 meters in the municipality of Loja.

Southern Ecuador is known to be one of the most biologically diverse places in the Andes and Amazonian regions and is among the richest and most diverse in the world. It is represented by approximately 7,048 species (José, 2001; Lozano, 2002; Mutke and Barthlott 2005).

Around 19% of the area of the Southern Region is under protection (Ministry of Environment, Ecuador, 2013). Two national parks are located in Loja and Zamora Chinchipe provinces. The largest one, Podocarpus National Park, spans over 146,280 hectares of mainly mountain forests and several thousands of hectares of *paramo* (Keating, 2000). This national park is part of UNESCO's Podocarpus-El Condor Biosphere Reserve, which protects and promotes sustainable development of around 1.1 million hectares of Andean tropical forests in southern Ecuador (Barkman et al., 2013). The second national park, Yacuri, has an area of 43,091 hectares. Both protected areas are a source of water supply for surrounding areas. Other protected areas include the '*Reserva Biológica Cerro Plateado*' (26,114 hectares) and the smaller '*Refugio de Vida Silvestre El Zarza*' (3,643 hectares) located in Zamora Chinchipe. The '*Reserva Ecológica Arenillas*' (17,083 hectares) is located in El Oro (Ministry of the Environment, Ecuador, 2014).

Despite the existence of these conservation areas, around 70% of the Southern Region area is affected by human factors such as deforestation for agriculture and the collection of fuel wood among others (Lozano, 2002). Moreover, the ability of natural ecosystems to provide water services to people in up-and downstream areas has been degraded by the conversion of natural areas to agricultural land. Water quality is considered problematic as there is a high incidence of diseases due to contaminated water

(Gordillo, 2013). Livestock production and pesticide use are seen as the main causes. Cow manure can be a source of bacteria, while pesticides used for production of crops, such as corn, are often toxic (Webber, 2009). The clearing of forests to create pastures could contribute to erosion and consequently deliver excess sediment to the water. Furthermore, in Southern Ecuador many cities are experiencing a hydrological deficit (Dorado et al., 2011). Most municipalities suffer from a shortage in water supply which is exacerbated during the dry season.

FORAGUA was implemented mainly to improve the provision of hydrological services. According to Farley et al. (2011), the water funds in Ecuador only have limited information available linking land use with production of ecosystem services. However, although the key hydrological services targeted - water regulation and nutrient and sediment retention - are based on the assumed relationship between forests and hydrological service provision (rather than actual measurements), existing research suggests that mountain forests and Andean grasslands (*paramos*) provide hydrological services, the most important of which are water quality through sediment retention (Brauman et al., 2007; Célleri and Feyen, 2009) and regulation of water flow (Bruijnzeel, 2004; Roa-Garcia et al., 2011). Biodiversity conservation is also important as the Southern Andean region of Ecuador is a hot spot for biodiversity (Keese et al., 2007).

The Water Fund

To halt the degradation of watersheds, in 2009 the municipal governments of Loja, Celica, Macará, Puyango, and Pindal with the support of the NGO Nature and Culture International founded FORAGUA for the conservation, protection and restoration of ecosystem services and biodiversity of fragile and threatened ecosystems in the provinces of Southern Ecuador (Loja, El Oro and Zamora Chinchipe). FORAGUA is a joint public and private trust, valid for 80 years. It is administered by the '*Corporación Finaciera Nacional*' (National Financial Corporation, known by its Spanish acronym CFN) and implemented by the constituent municipalities.

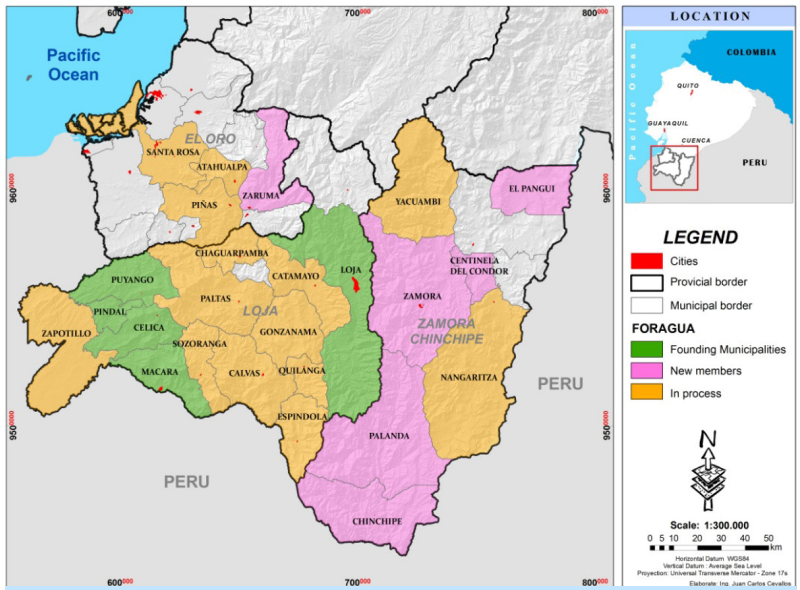


Figure 7.7 FORAGUA's Constituent Municipalities

Currently 11 municipalities are part of the trust, but the goal is to integrate all 39 municipalities of the Southern Region (Figure 7.7). The 11 municipalities have declared approximately 47,798 hectares as reserves, of which around 18,000 hectares is designated specifically for the conservation of water sources for human consumption (see Table 7.2). Over 300,000 people are beneficiaries, about a third of the total population of the Southern Region.

Watershed Governance

Water governance is enshrined in the Ecuadorian constitution. Article 411 states that "the State shall ensure the conservation, restoration and integrated management of water resources ... Any activity that may affect water quality and quantity, and an

Table 7.2 Conservation Status of Watersheds in FORAGUA Municipalities					
Constituent municipalities as of June 2013	**Year**	**Number of Watersheds**	**Name of the watersheds**	**Area of the watersheds (has)**	**% Conserved**
Loja	2009	6	El Carmen, San Simón, Jipiro, Pizarros, Puritroje y Shucos	4,220	95%
Celica	2009	3	Quira, Matalanga y Quillusara	690	25%
Puyango	2009	1	Luz de America	128	21%
Pindal	2009	1	Papalango	884	6%
Macará	2009	2	Mataderos y Jurupe	3,037	11%
Zamora	2011	1	El Limón	1,019	21%
Chinchipe	2011	2	Los Rubies y Chaupe	8,000	80%
Palanda	2012	2	SUHI, Los Molinos	1,698	-
El Pangui	2012	1	Cayamatza	2,669	-
Centinela Del Condor	2012	1	Zumbi	666	-
Zaruma	2012	2	Guando-Mirmir	1,285	-
Total		**22**		**17,978**	

ecosystem's balance, especially in springs and water recharge areas shall be regulated." For the purpose of planning and managing water resources for human consumption the national government created the '*Secretaría Nacional del Agua*' (National Water Secretariat, known by its Spanish acronym SENAGUA). Additionally, Article 264 of the constitution and Article 55 of the Code of Zoning, Autonomy and Decentralization state that it is the authority of the Municipal Decentralized Autonomous Governments to exercise control over land use within its territory. Municipal authorities thus have the power to zone their own territories and manage their watersheds. Article 137 mentions that "the responsibility for the provision of public drinking water in all its phases shall be implemented by the Municipal Decentralized Autonomous Governments."

The Regional Water Fund itself is based on the creation of municipal ordinances for the declaration of watershed reserves, the protection and restoration of degraded ecosystems and the creation of a charge for hydrological services in each municipality. The implementation of municipal ordinances establishes the authority to declare municipal reserves, in accordance with the Ministry of Environment (Figure 7.8).

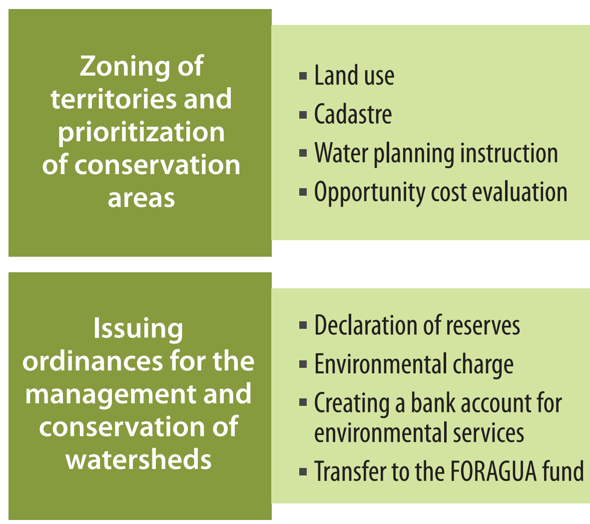


Figure 7.8 Synthesis of Legal and Zoning Procedures of Municipalities

The declaration of land as a municipal reserve limits the use of natural resources in the affected properties. Although the main focus is currently on purchasing land in the watersheds from individual landowners (see section on Watershed Management Activities), private individuals can maintain their land within the areas of hydrological importance, but with restrictions. In the case of private land, the owner or owners may retain ownership if they respect the limitations established by the municipal ordinance and its regulations (Constitutional Court of Ecuador, 2008).

The fund itself was created by deed, wherein the constituents established the mandates governing FORAGUA.

FORAGUA has the following regulatory and management bodies: a) the Trust Board, which is the highest authority of the trust and formed by the legal representative of each constituent; b) the Directory, composed of five members; and c) the Technical Secretariat, which provides support and assistance to municipalities and ensures the proper implementation of programs and funded projects. The Central Bank of Ecuador collects all payments and the CFN manages the fund (see also Figure 7.9) (Dorado et al., 2011).

On the local level, several members also have Environmental Services Committees. They consist of representatives of local government, water users, landowners with properties in the watersheds, and other interested parties. The idea is that these committees create the possibility for setting joint priorities, support the planning process, and provide supervision (Kauffman and Echavarría, 2013).

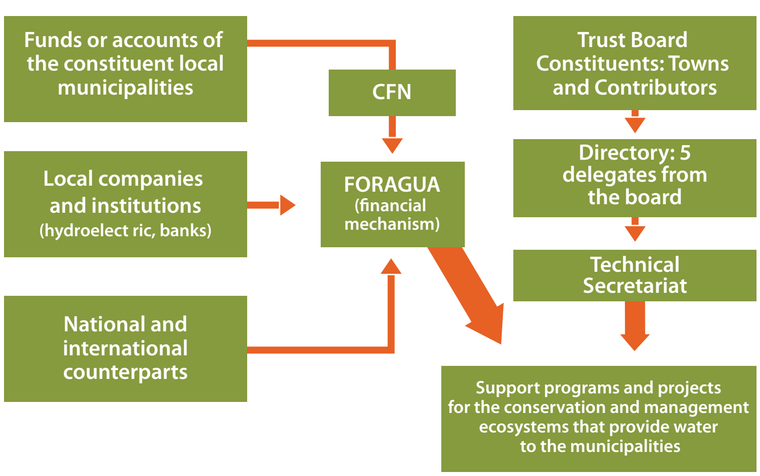


Figure 7.9 FORAGUA's Stakeholders

FORAGUA's Funding

FORAGUA is funded through an environmental services charge and through donor funding. The mechanism is based largely on the willingness of citizens to pay an additional amount on their water bill. As the total costs to implement protection and restoration measures as well as the costs of purchasing land were anticipated to be high, a classification of users following the same categories used by the municipalities was created (i.e. residential, commercial and industrial, and official users). Fees were set trying to average the charge with already existing ones (garbage collection, street lighting, etc.; See Table 7.3).

The municipality of Puyango mentions the following funding sources in its ordinance:

- Charges for environmental services created by the municipal ordinance;
- Financial resources that are allocated by the municipality of Puyango through its budget;
- Funds obtained on the basis of the voluntary donation of 25% of the income tax;
- Contributions, inheritances and donations; and
- Other sources (e.g. international cooperation).

In addition the ordinance assures that this funding cannot be diverted for other uses not related to watershed conservation and restoration activities. Article 14 of the ordinance states that "no official or municipal authority is allowed to assign these economic resources to a different use" (Constitutional Court of Ecuador, 2008).

FORAGUA is an endowment fund (Laurans et al., 2012); it is not the interest generated by the fund but a portion of the fund itself that is used to finance conservation activities in the watershed. Any interest that is generated is used to complement the

Table 7.3 Environmental Charges in FORAGUA's Constituent Municipalities

	Number of water users (households, businesses)	Environmental charge (US$)	Amount collected (US$/year)
Loja	30,000	3-8 cents/m^3	400,000
Celica	910	9 cents/m^3	15,000
Puyango	1,300	11 cents/m^3	18,000
Pindal	481	5 cents/m^3	8,000
Macará	2,683	8-10 cents/m^3	45,000
Zamora	11,000	1 dollar/property	11,000
Chinchipe	754	2-5 cents/m^3	4,000
Palanda	348	4-10 cents/m^3	5,000
El Pangui	1,500	10-15 cents/m^3	22,000
Centinela del Condor	823	4-10 cents/m^3	12,000
ZARUMA	2,162	4-10 cents/m^3	42,000
Total	**51,961**		**582,000**

Table 7.4 Total Additional Funds for FORAGUA Obtained To Date

Donor	Objective	Amount (US$)
Private donations	FORAGUA's establishment	50,000
Flemish forest fund	Setting up of the baseline, equipment, water monitoring	120,000
RARE International	Social marketing campaign and purchase of properties	30,000
Flemish forest fund	Compensation for environmental services	50,000
Private donations	Purchase of properties	500,000
USAID	Strengthening the technical secretariat of FORAGUA	37,000
AQUAYA Institute	Water quality monitoring	35,000
Tinker	Entry of new municipalities	237,000
Government of Flanders	Restoration of degraded areas in the micro-watersheds	114,000
RARE	Environmental awareness campaigns	130,000
NCI	Support for FORAGUA's activities	120,000
Municipality of Loja	International conference	30,000
Total		**1,453,000**

activities of the Secretariat. The annual amount for investment in the fund is approximately US$ 600,000 (Table 7.4).

The environmental charge is collected by the Ecuadorian Central Bank to ensure that funds are only used for activities related to watershed protection. Because the fund's financial resources are public they are invested by the CFN. Of the total funds raised by the environmental charge, 90% of the revenues are reinvested in the municipalities proportional to the amount each municipality collects, and 10% is used to run the Technical Secretariat of the fund (Figure 7.7). The mechanism is designed so that all

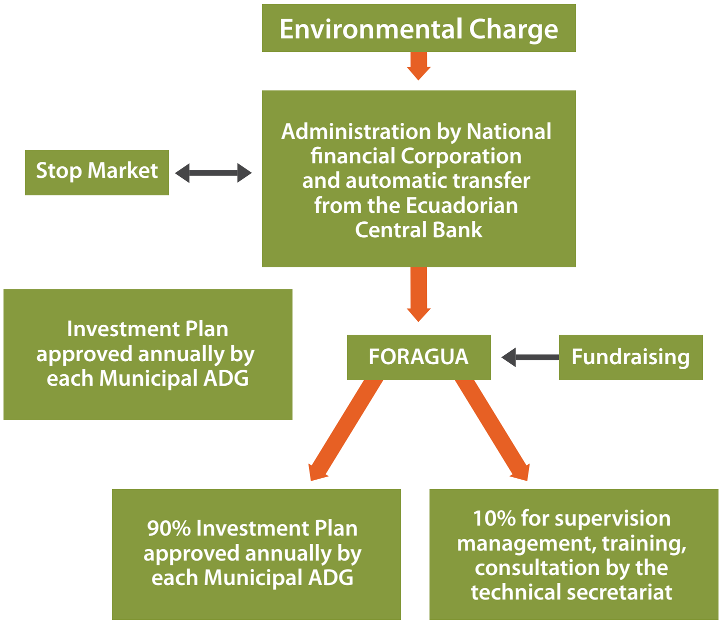


Figure 7.10 Flow of the Money Collected by FORAGUA's Members

municipalities provide their resources to the management of the fund's activities. Each municipality alone could not achieve this because in the case of small municipalities the resources would not be sufficient to manage a technical secretariat or to implement broad conservation activities.

In addition to the funds raised by the environmental charge, it is the task of the Technical Secretariat of FORAGUA to manage resources provided by national and international cooperation, public institutions, and donations (Table 7.4 and Figure 7.10).

Watershed Management Activities

The investment of the financial resources provided by the fund can only be done by implementing an individual investment plan that each FORAGUA municipality has to develop. These investment plans contain proposals for the destination of the funds and must be aligned with the ordinances. The investment proposals fall under the responsibility of the municipal water authorities, such as the municipal water company EMAAL-EP in Loja, and must be approved by FORAGUA and the Municipal Council on a yearly basis.

The start of a management plan is the zoning of the municipality and mapping of areas of hydrological importance (see section on Watershed Management Activities). For example, the municipal ordinance of Chinchipe states that areas that impact the water cycle, due to factors including location and vegetation cover, are considered priority for conservation. Watersheds, aquifer recharge and water supply sites are particularly important target areas for preservation. This municipal ordinance distinguishes between intangible or permanent protection zones, areas for the recovery of forest cover and the regeneration of natural ecosystems, and areas for agricultural, recreational and other sustainable uses (Constitutional Court of Ecuador, 2010).

The importance of specific areas for the provisioning of hydrological services is measured by the number of beneficiaries served by a particular watershed. The use of maps has been key. Aerial photographs and satellite images have facilitated the identification of current land uses, and provided a clearer picture of the state of the water catchments. Information such as soil types, slope, fertility, temperature and precipitation have also been collected to determine if the current land use is the best within the range of potential uses of that land (GCA, 2006). Natural ecosystems are seen as the best option for ecosystem service delivery. Using this information, it is determined which areas within the watershed are being over-exploited and which should be priority areas to be bought by the municipalities through FORAGUA.

Before the establishment of FORAGUA, some watersheds were already owned and protected by local governments. However, a majority of the watersheds were privately owned and primarily used for raising dairy cattle (Table 7.4). Land purchases are one of

Table 7.5 Area of Pastures and Number of Private Landholders within the Watersheds in 2013

Municipality	Watershed	Number of Hectares of Pasture	Number of Owners
Loja	El Carmen, San Simón, Pizarros, Puritroje, Jipiro y Shucos	No data	49
Macará	Mataderos	491	51
	Jorupe	207	23
Puyango	Luz de América	36	16
Celica	Quira	98	No data
	Matalanga	46	16
	Quillusara	118	51
Pindal	Papalango	247	50
Zamora	Limón	No data	20
Chinchipe	Los Rubies	300	No data
	Chaupe las Minas	70	No data
Zaruma	Giando-Mirmir	No data	25
Palanda	SUHI, Los Molinos	No data	23
Centinela del Cóndor	Zumbi	No data	15
El Pangui	Cayamatza	No data	No data

Source: FORAGUA, 2014

the main activities of the constituents of FORAGUA. The fund has bought approximately 15,000 hectares from 52 landowners.

Although a key component of FORAGUA's management plan is the purchase of land in areas of high importance for hydrological service provision, additional activities for watershed conservation and restoration have also been implemented. Such activities include management and monitoring, the recovery of natural vegetation, compensation for environmental services, protection of water sources, the conservation and protection of property declared as reserves, scientific research, environmental education, and other activities permitted within the municipal reserves. FORAGUA's constituents must provide receipts to guarantee that the funds are only used for acceptable activities (Constitutional Court of Ecuador, 2008; Kauffman and Echavarría, 2013).

When land is purchased it gets integrated into the municipal conservation reserves. However, as mentioned earlier, landowners within areas of high hydrological importance can also decide to establish a private conservation reserve, with the approval and regulation of the Ministry of Environment. In addition, the Ecuadorian national government has a payment program for conservation and restoration of forest and *paramo* on private lands called Socio Bosque. Currently it is not known if any landowners within the FORAGUA watersheds participate in this program. A type of indirect conservation incentives that has been implemented are payments to landowners in the form of rental contracts.

Within municipal protected areas, FORAGUA's members undertake restoration activities, mainly through reforestation with native tree species. For certain areas of hydrological importance, municipal ordinances also allow production systems, such as pastures and corn, to be replaced by other crops that cause less environmental impact and provide continuous forest cover, such as shade coffee and native fruits (Constitutional court, Ecuador, 2010).

For example, in Pindal there is a project for the promotion of coffee agro-forestry systems instead of intensive corn production. FORAGUA also finances environmental education projects.

To get a clear idea of the impact of the different activities it is necessary to monitor and measure the effects. The absence of monitoring activities can hinder the analysis of whether water funds are effective in providing services (Goldman et al., 2008). According to Farley et al. (2011), in Ecuador most programs financing ecosystem service provision did not conduct baseline ecological analysis. FORAGUA has now implemented a monitoring program to collect information about the watersheds of the municipalities. This baseline study includes maps of land use, vegetation cover, analysis of potable water systems (users, losses, payments, subsidies, cost analysis, water flows) and land tenure. So far all of the watersheds have been assessed in seven municipalities, and assessments are currently being undertaken in the other municipalities.

Challenges and Lessons Learned

A key challenge for many schemes that focus on ecosystem service provision is the fact that there is a need for more information on land uses that will in fact produce the services promised (Farley et al., 2011). Additionally the board of FORAGUA detected the following challenges:

- Slow transfer of revenues from municipalities to the CFN;
- Lack of enforcement of the ordinances by municipalities;
- Little citizen engagement;
- Low collection rates of the environmental services fee and high default rates;
- Lack of technical staff for the Secretariat;
- Limited budget of the Secretariat;
- Lack of political will of some constituents;
- Lack of a communication strategy that informs society of the value of the fund and raises public awareness, engagement and support, especially during periods of political instability;
- No implementation of investment plans;
- Heterogeneity in politics and political affiliation of the municipal autonomous decentralized governments;
- No connection with the National Secretariat for Water (SENAGUA);
- Conservation areas are excluded from land use plans. No representation of taxpayers and water users on FORAGUA's board (FORAGUA, 2013);
- The fund has thus far failed to achieve behavior change among landowners.

When small municipalities join together, they can create economies of scale that make a water fund possible. Collaboration also facilitates the transfer of knowledge and good management practices; it makes solidarity between smaller and bigger municipalities possible, and it strengthens the possibility of applying for national and international financial aid. Additionally, according to Kauffman and Echavarría (2013), a trust fund can make it easier to receive external donations as donors may be reluctant or forbidden from providing money directly to government entities. Private trusts provide a mechanism for overcoming these difficulties. Trusts can also provide protection against the changing priorities of elected officials and political instability that can lead to the diversion of funds.

Capacity Building for Watershed Management: Improving Watershed Management Capacity via Sustainable Ranching Systems in Panama's Azuero Peninsula

Introduction

The Republic of Panama is a privileged country in terms of water resources. The country has 52 watersheds, 18 on the Caribbean Sea and 34 on the Pacific Ocean and more than 4,000 kilometers in its major rivers alone (Castillo, 2011). Despite this natural wealth of water, some areas of the country experience recurrent water shortages for several months of the year as well as water contamination by agrochemicals.

This problem is especially evident in the Dry Arc region of the Azuero Peninsula of Panama, located in the province of Los Santos, an area of low rainfall and prolonged and marked dry seasons, during which the water level in the aquifer drops significantly and puts the region's quarter millions inhabitants at risk of potable water shortages(Castillo, 2011). Here as elsewhere in Panama, landholders deforest natural ecosystems to make space for agricultural and livestock production systems. Conventional cattle ranching is a common practice conducted in marginal, steep, upland areas which are unsuitable for agriculture but encompass important watershed areas where water sources originate. Ranchers in Panama cut and burn trees to plant exotic, aggressive grasses, which they manage by annual burning and extensive applications of herbicides (Slusser et al., 2014). The environmental impacts of these practices include loss of biodiversity and soil carbon, decline in soil fertility, soil erosion and compaction, reduced water infiltration and regulation capacity and watershed contamination (Steinfeld et al., 2006). One recent example, was the state of emergency that was declared in the Azuero after La Villa River, a source of drinking water for over 100,000 residents, was contaminated with an herbicide commonly used in agricultural fields, resulting in millions of dollars of costs to provide potable drinking water for multiple weeks (Rios, 2014).

Sustainable ranching practices, such as silvopastoral systems (SPSs), which combine trees, forage shrubs and grasses with livestock production, can increase biodiversity and ecological integrity while complementing livelihood practices (Palmer, 2014). SPS can increase the diversity of shrub and tree species through the establishment of living fences and wood lots, protect riparian zones and integrate trees in pastures, management practices which promote higher levels of biodiversity and connectivity between remnant forest patches (Harvey et al., 2005; Murgueitio et al., 2011). Increased vegetation cover also improves the provision and regulation of ecosystem services. SPS can decrease soil erosion, improve nutrient cycling, enhance soil fertility, reduce watershed contamination, improve hydrological cycling and increase carbon sequestration, crop pollination and pest management, all of which are vital to ecosystem services (Chazdon et al., 2009; Calle, Montagnini and Zuluaga, 2010; Murgueitio et al., 2011). Despite all of these benefits, SPSs are absent from the Panamanian landscape because farmers do not traditionally have trees in their pastures due to light competition with pasture grass. Further, SPS is not well known among research institutes, extension agents and farmers in Panama (Slusser et al., 2014). In order to address the lack of sustainable ranching systems and practices reaching land use decision makers in Panama, the Environmental Leadership and Training Initiative (ELTI - a program of the Yale School of Forestry and Environmental Studies (F&ES) in collaboration with the Smithsonian Tropical Research Institute (STRI)) provides capacity building opportunities and leadership support to land-holders,

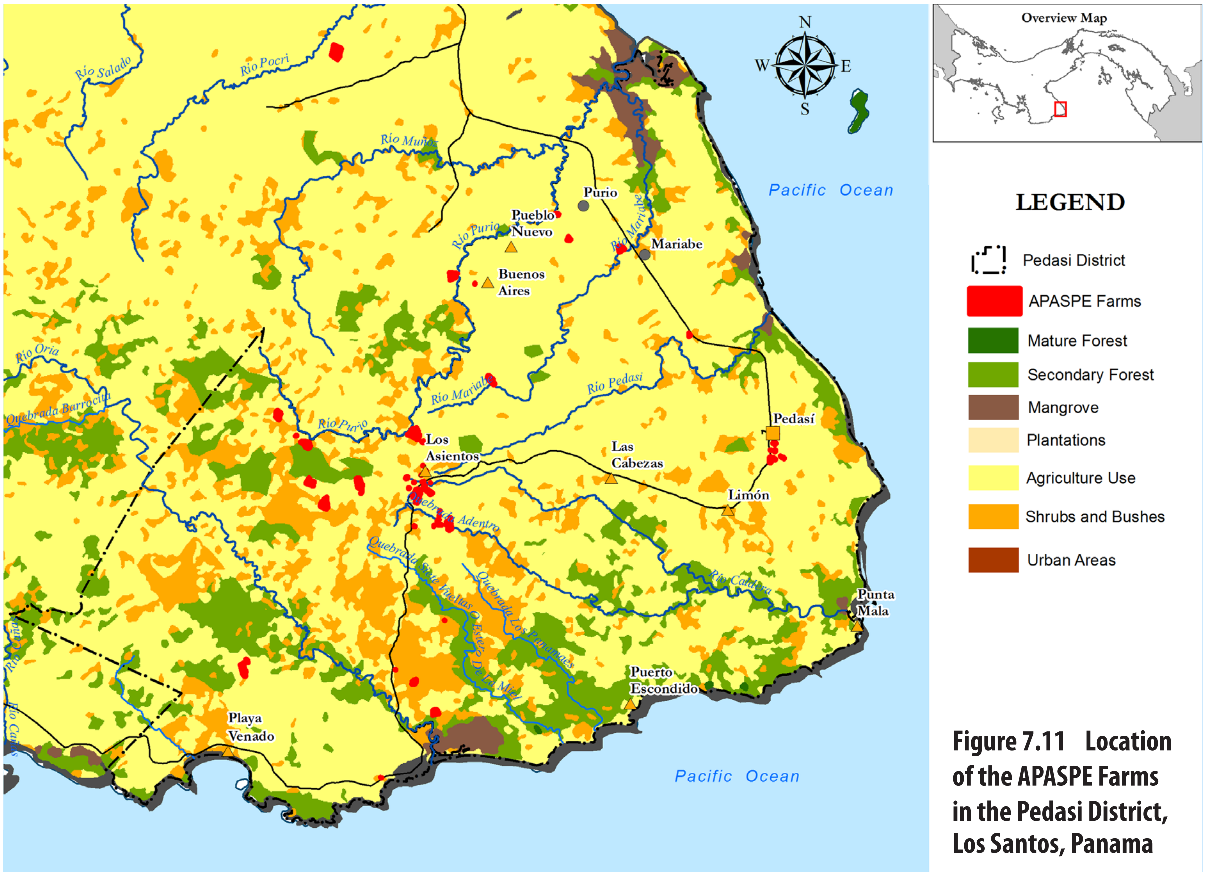


Figure 7.11 Location of the APASPE Farms in the Pedasi District, Los Santos, Panama

extension agents, local authorities, policy-makers and business leaders who make decisions about land use in multiple-use, human-modified landscapes. ELTI's goal is to conserve biodiversity and restore tropical forests using strategies that respond to the local needs and realities of landholders. ELTI also offers financial assistance for professional development and mentoring and technical assistance to develop and implement local projects.

To address the land and water degradation issues affecting farmers in the Dry Arc of the Azuero, ELTI, with the assistance of Colombia's Center for Research in Sustainable Agricultural Production Systems (CIPAV), implemented a number of field courses for land-holders and environmental authorities to improve their knowledge of native species reforestation, agroforestry and SPS.As a result, several farmers decided to incorporate tree planting and conservation practices into their farms. One group of farmers in particular, that reside in a critical watershed consisting of the four largest rivers of the District of Pedasi that provide water for potable and agricultural uses, decided to collaborate and create their own legally recognized association to implement these practices. In 2009, these farmers formed the Association of Livestock and Agro-Silvopastoral Producers of Pedasí (Asociación de Productores Pecuarios y Agrosilvopastoriles de Pedasí, or APASPE; Figure 7.11) and developed a grant proposal with the Global Environment Facility's (GEF's) Small Grants Program (SGP) to seek support for implementing SPS on their farms.

In 2010, APASPE received funding to implement the first SPS demonstration farms and watershed restoration in the region. The APASPE members have enjoyed many successes, including a second phase of funding (2014–16) to restore forests in watershed areas. While the watershed impacts of APASPE's efforts have not yet been scientifically quantified, their initial success (reforesting 10km of riparian areas with over 10,000 trees of 25 different native species and establishing 40 hectares of SPS) has inspired other landholders to also explore the production and conservation benefits that can be achieved via SPS. Towards this goal, APASPE members have hosted more than 700 local and international visitors to their model farms and currently serve as co-facilitators in ELTI training courses and aid in farmer to farmer learning. In an effort to share their experiences and replicate their success, APASPE has advised two farmer cooperatives in the preparation of sustainable ranching funding proposals and shared their experiences in more than 30 public forums. With continued support, these efforts could lead to a growing number of landholders working together at the landscape level to conserve and restore watersheds in ranching landscapes (Slusser et al., 2014).

Managing Watersheds Using Payments for Hydrological Services: Mexico's Experience in Central Veracruz

Introduction

"Payment for Hydrological Services" (PHS) programs, an approach to watershed management that provides compensation to upstream landowners for conserving forests or implementing other practices that protect water resources for downstream consumers, have quickly gained popularity worldwide in recent years. Mexico's PHS program, active since 2003, is one of the longest running PHS programs in the world, and thus provides an excellent case study for understanding both the opportunities and challenges of this policy instrument for promoting sustainable watershed management.

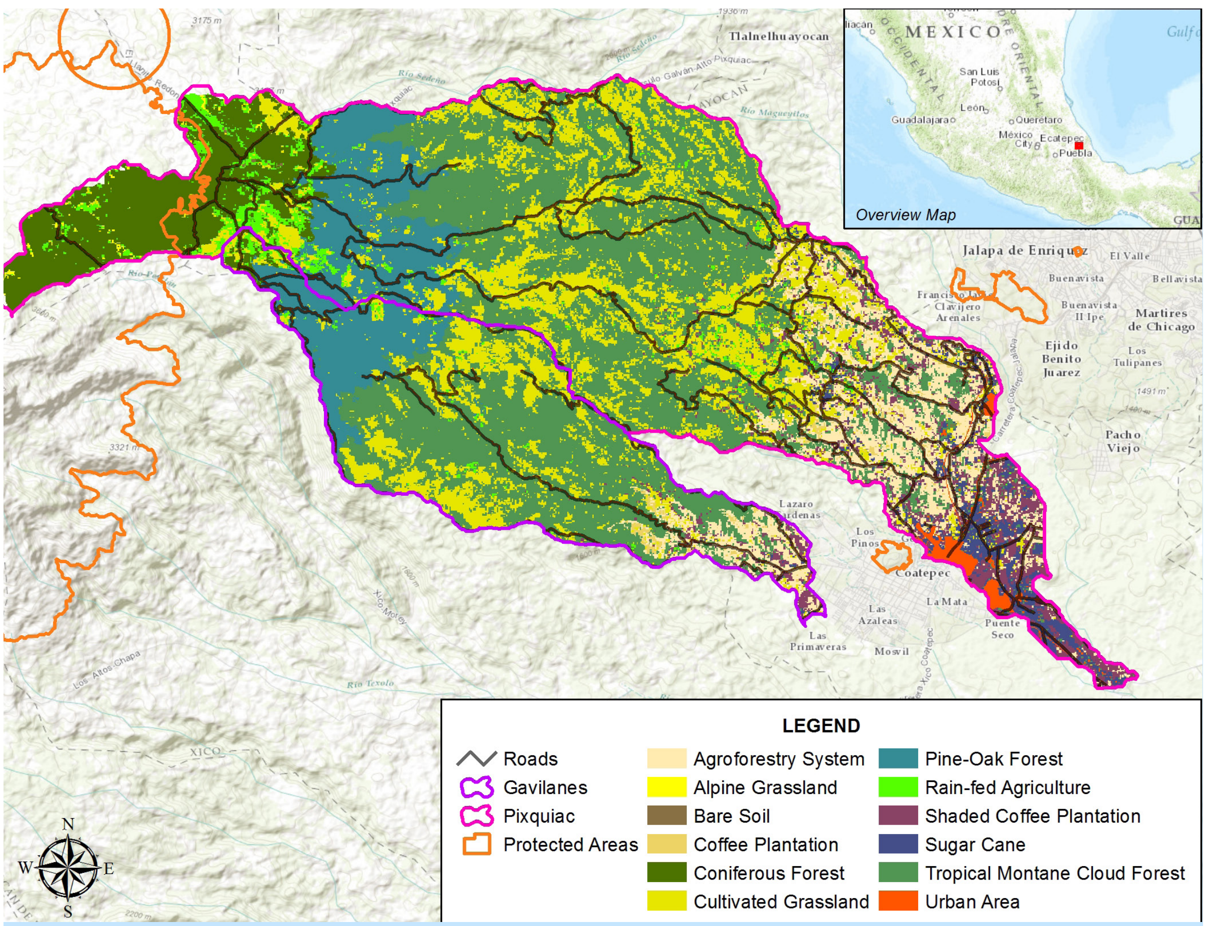


Figure 7.12 Vegetation Cover in the Los Gavilaes and Pixquiac Watersheds in the Mountainous Region of Central Veracruz, Mexico

In addition to this national PHS program, Mexico's experience with such payments includes multiple matching payment programs (over 70 throughout Mexico) that have emerged with the support of of local municipal and state governments as well as local non-governmental organizations. These diverse experiences provide a rich and varied context within which to analyze and compare different approaches and derive key lessons learned that can provide valuable information for other PHS programs worldwide.

This analysis focusses on two watersheds in the mountainous region of Central Veracruz: Los Gavilanes (~3,680 ha) and Pixquiac (~10,727 ha; Figure 7.12). The region provides an ideal case study for examing the potential for using PHS as a policy instrument for watershed management for several reasons. While the state of Veracruz occupies only 3.6% of Mexico's terrestrial area, it is considered the third-most biodiverse state, and its rivers channel 33% of the surface flow of rivers of the country. Nevertheless, Veracruz ranks first nationwide in the natural vegetation loss due to a long history of clearing forests to make way for agricultural expansion, with a concomitant loss of important ecosystem services. Only 4% of undisturbed natural vegetation remains in the state and it has the highest number of endangered species. Approximately 40% of its area is affected by high erosion rates and flood and drought cycles are ever more severe. In the face of these problems, numerous PHS programs have developed in the state, with the engagement of all three levels of the government and the private sector. These programs include local matching funds from the municipalities of Coatepec, "Public Trust for the Promotion, Preservation, and Payment of Environmental Forest Services" (FIDECOAGUA; the first PHS program in Mexico established in 2002) and Xalapa, "Program for the Compensation of Environmental Services and Integrated Rural Development" (PROSAPIX; established in 2006), as well as a federal PHS program operated by the National Forestry Commission (CONAFOR) since 2003. In addition, the State Environmental Secretariat in Veracruz plans to foster PHS programs through the recently created Environmental Fund of Veracruz. Given the emergence of so many actors and programs, the central region of the state of Veracruz is considered a laboratory for the creation and evaluation PHS programs.

The two study watersheds are the primary water sources for two large population centers: Coatepec (population = 53,621; receives 90% of its water from the Gavilanes River) and Xalapa (population = 424,755; receives 40% of its water from the Pixquiac River). The elevation ranges from approximately 1,000 to 3,000 m.a.s.l., and climate is temperate humid with average temperatures between 12 and 18 °C and annual precipitiation between 2,000 and 3,000 mm (Garcia, 1988). These watersheds are located in the upper headwater region of the larger Antigua river basin (Figure 7.12).

The dominant original vegetation in these watersheds was tropical montane cloud forest, with mixed pine-oak forests occurring at the highest elevations above the cloud forests (Rzedowski, 1978). However, more than 64% of the area has been deforested and converted to other land uses, primarily pasture for extensive cattle grazing (22%), but also including shaded coffee plantations (18%), agriculture (11%), and sugar cane (5%; Muñoz-Villers and López-Blanco, 2008). In the Gavilanes watershed, Coatepec has established a municipal reserve, "La Cortadura", to protect approximately 100 ha of tropical montane cloud forest. Nevertheless, a series of government-supported reforestation initiatives have used mainly *Pinus patula*, a species that is native to the higher elevation pine-oak forests, in abandoned pastures and cropfields, including those in areas that previously supported cloud forests. While the goal of this reforestation initiative has been aimed at protecting the provisioning and quality of water supply in the region, local actors have complained about the displacement of native tree species.

Provision of Ecosystem Services: Current and Future Trends

The ecosystem services provided by the forests, and particularly the dominant montane tropical cloud forests, within the Pixquiac and Gavilanes watersheds are described below, organized according to the four broadly recognized types of services: supporting, regulating, provisioning, and cultural (MEA, 2003).

Supporting Services

Despite occupying only ca. 1.4% of the world's tropical forests, montane tropical cloud forests harbor exceptionally high levels of species diversity and endemism (Doumenge et al., 1995; Aldrich et al., 2000). In Mexico, these forests occupy < 1% of land area but are home to 10-12% of all plant species in this megadiverse country (Ramamoorthy et al., 1993). Nevertheless, over half of these forests have been transformed to other land uses in recent decades (Challenger and Caballero, 1998). The Antigua River basin in Veracruz, where the Pixquiac and Gavilanes watersheds are located, has been declared a zone of high prioritiy for biodiversity and hydrological services, largely due to the strong pressure on remaining fragments of cloud forest (Arriaga et al. 2000, 2002; Cotler, 2011). Important supporting services provided by the high levels of biodiversity and structural complexity in cloud forests in this region is maintaining nutrient cycling processes and stabilizing soils on steep slopes, which contribute to the provisioning of other ecosystem services. Conversion of cloud forests and associated shade coffee farms to other more intensified land uses has contributed to diminishing overall biodiversity in the region.

Regulating Services

Cloud forests are widely considered to be especially important as 'water producers', due to their ability to capture additional water inputs from the interception of cloud water by the canopy (referred to as 'fog drip' or 'horizontal precipitation'), and low evapotranspiration losses (Bruijnzeel et al., 2011, and references therein). In addition to potentially having higher total water inputs, cloud forests may also help regulate water flows promoting infiltration and soil and groundwater storage, thereby ensuring high dry season baseflows and minimizing peak flows during high rainfall events (Bruijnzeel, 1989). Lastly, because cloud forests often occur on steep slopes, they are important for stabilizing soils and reducing erosion. Conversion of cloud forest to pasture was found to lead to increased peak flows and reduced dry summer baseflows (Muñoz-Villers and McDonnell, 2013). In addition to land use conversion, climate change may also be affecting the hydrology and climate of cloud forests, including increasing the level of cloud condensation and potentially reducing the frequency and duration of fog at lower elevations. Other important regulating services provided by cloud forests include carbon sequestration and storage and maintaining regional climate patterns. Additionally, high levels of biodiversity in cloud forests have been shown to contribute to regulation of pests and disease occurrence in coffee plantations and other agricultural crops (Soto-Pinto et al., 2002).

Provisioning Services

Maintaining a reliable supply of high quality water to lower-lying areas, especially to the main urban centers of Xalapa and Coatepec (see details above), is considered a critical provisioning service of headwater cloud forests within the Gavilanes and Pixquiac waterhsheds. For example, Mokondoko-Delgadillo (2012) studied 10 catchments in central Veracruz and showed strong relationships between vegetation cover in riparian zones and water quality (E. coli concentration), and the level of gastrointestinal illness in the nearby communities. A conservative estimate of the value of this ecosystem service of riparian forests in maintaining water quality was $90/ha/yr, very similar to the amount of PSH payments at the time. Additionally, water from streams and rivers originating from cloud forests is important for local agricultural production (e.g., potatoes, sugarcane, vegetables, coffee, fruit trees), and local fisheries (trout farms; CNA, 1998; Muñoz-Villers and Lopez, 2008). Finally, cloud forests provide numerous timber and non-timber forest products that are collected by local people, including fuelwood, timber for construction, orchids, palms, wildlife, and medicinal plants.

Cultural Services

Cloud forests in Veracruz are widely recognized for their important cultural services, as prominently reflected by the region's designation as belonging to the "Ruta de Los Pueblos Mágicos" ("Route of the Magical Towns"). This route consists of a series of small towns (including Coatepec) in the upper mountains of the Antigua Watershed, and is a program established by Mexico's Secretary of Tourism, in which sustainability and cultural history and traditions are important criteria in the evaluating and selecting eligible participants (http://www.sectur.gob.mx/es/sectur/sect_Pueblos_Magicos). An important aspect of the cultural values of this region comes from the mystical atmosphere created by the fog-immersed cloud forests, with their abundant mosses and epiphytes. Recreational opportunities, including river rafting, hiking, wildlife viewing, and other outdoor activities and nature experiences, are also important cultural services provided by cloud forests.

Socio-Economic Dimensions

Both Coatepec and Xalapa have high rates of population growth and urban expansion (INEGI). Coatepec's income depends mostly on tourism and agricultural production (coffee), whereas Xalapa is the capital of Veracruz and therefore the location of many state agencies, universities and an active tourism sector (For more details, see: http://www.veracruz.gob.mx/finanzas/informacion-socioeconomica-por-municipio/cuadernillos-municipales/).

Watershed Governance

PHS programs in Mexico have been operating for more than a decade and have used different approaches for financing and administrating hydrological service payments. FIDECOAGUA was established as a public trust administered by the municipal authorities in Coaptepec with fixed payments from local water users. In 2003, CONAFOR establishing the Mexican Forest Fund as a similar trust fund for managing the 2.5% of all water concession payments in the country and channeling the funds towards areas eligible for PHS nationally. Such trust funds have been critical in the acceptance of PHS programs in Mexico since they increase transparency and provide continuity in payments across changes in government administrations. This latter program has undergone continuous modifications and expansions, the most important of which is the creation of a matching funds programs in 2008 that allows local partnerships and has since fostered the establishment of over 70 local PHS initiatives to date. One of those partnerships resulted in the creation of PROSAPIX, which consists of a collaboration between the CONAFOR, state government of Veracruz, the municipality of Xalapa, and a local NGO, SENDAS. One of the major challenges faced by these programs is ensuring consistent funding and continuity, in part due to a lack of formal structures for managing program funds and relatively frequent turnover of public officials and hence changing priorities and approaches to managing water resources.

Designing the Watershed Management Plan

This section provides a brief overview of the structure, history, and impacts of each of the three PHS programs mentioned above: FIDECOAGUA, CONAFOR, and PROSAPIX.

COATEPEC: FIDECOAGUA (Public Trust for the Promotion, Preservation, and Payment of Environmental Forest Services)

The municipality of Coatepec established the first PHS program in Mexico in response to a drought in 1998 that resulted in the restriction and scarcity of drinking water to the residents for the first time in their history. In reponse this this crises, and after noting problems with increased water demand and deforestation, the municipality established a 100 ha community reserve, "La Cortadura", dominated by intact cloud forest vegetation in the upper watershed. In November 2002, the public trust FIDECOAGUA was created, with the objective of promoting the protection of forests and water supplies in the Gavilanes watershed through the establishment of a payment for hydrological services program (Saldaña Herrera, 2013). One advantage of FIDECOAGUA's operation is that the municipal boundaries of Coatepec largely correspond to the limits of the Gavilanes watershed, which greatly facilitated its ability to invest program funds to directly benefit inhabitants of the municipality.

FIDECOAGUA is comprised of this trust fund, a technical committee, and an operational team. The technical committee develops work plans and decides how the resources will be distributed, and consists of the municipal president, the director of the local water operator (CMAS), and prominent stakeholders in the region. The operational team is comprised of a director, an administrator, and an assistant, all of whom receive support and technical training from CONAFOR for the monitoring of compliance in parcels receiving payments (Fuentes-Pangtay, 2008).

Although initially conceived as an autonomous trust, in practice, the municipal government maintains considerable power over FIDECOAGUA's administration, given that it appoints the president and secretary of the technical committee, as well as the director of the operational team. The municipal government also administers funds obtained from water users in the city, who pay $1-2 pesos per month for domestic or private sector water use. By 2008, a total of 668 ha had been enrolled in the program, of which 135 were paid through a combination of CONAFOR's PHS program and FIDECOAGUA. In 2008 FIDECOAGUA established an agreement with CONAFOR's new "Matching funds program", which effectively doubled payments for water providers in the region. More recently, local citizens and companies including Coca-Cola and Nestle have become supporters through the creation of an "adopt-a-hectare" program in 2012. This program effectively doubled the area receiving payments from 800 to over 1600 ha between 2011 and 2012, most of which consisted of shade coffee farms in the lower portion of the watershed. In addition to the payments made directly to upstream landowners, FIDECOAGUA also includes a mechanism for providing scholarships ($1,200 pesos/year) to support the education of the children of landowners enrolled in the program.

Despite its growth and trust fund mechanism, a major interruption in FIDECOAGUA's operation occurred in 2007, when a new municipal president who was not convinced of the importance of the program decided to channel the program's financial resources and physical assests elsewhere in the municipal government. This experience underscored the vulnerability of FIDECOAGUA to changing political and economic interests within the local government that has primary responsibility for decision-making processes affecting its operation. It also highlights the risks of focusing too much on water providers versus water users and not creating a core group of supporters who can defend the program during changes in administration.

CONAFOR – PHS (Pagos para Servicios Ambientales Hidrológicos) & Matching/Local Program

CONAFOR's national PHS program was created in 2003 as part of modifications of Article 223 of the Federal Rights Law, which established a permanent source of funds (USD 15.4 million/year) to support the PHS program through the transfer to CONAFOR of 2.5% of the tax concessions collected from water users nationally by the National Water Commission (CONAGUA). The Fondo Forestal Mexicano (FFM) was created to serve as the financial instrument to receive and administer the funds, and made it possible to distribute the same funds to landowners enrolled in the PHS over a 5-year period. Based on scientific information and advice from experts, the decision was made to pay a higher amount (USD 30.8 ha/yr) to lands supporting cloud forest, and a slightly lesser amount ($23.1 ha/yr) to all other forest types (Muñoz-Piña et al., 2008). Initially there were relatively simple eligibility requirements established for enrolling in the PHS, including: a minimum of 80% forest cover; documentation of legal land ownership; location near over-exploited aquifers; proximity to population centers with greater than 5,000 inhabitants; no active timber extraction occurring on the land unless it is certified; and a total surface area between 50 ha and 4,000 ha.

However, in 2004, a more targeted approach was developed that established detailed eligibility criteria intended to reflect different program priorities, including not only hydrological sevices but also other ecosystem services (e.g., biodiversity, carbon), as well as reconversion and improvement of agroforestry systems. Between 2005-2008, other criteria and modifications were incorporated, such as reducing the minimum forest cover to 80%, location within or near a National Protected Area or within the 60 Mountain Regions identified by CONAFOR, level of deforestation risk, and zones with surface water scarcity. Gradually, socioeconomic criteria were also added, such as the degree of marginalization, the presence of indigenous populations, gender considerations, and the existence of a contract with a buyer of ecosystem services. These social criteria reflect the political interests and pressures to address issues of poverty alleviation, equity, and social justice, and therefore are a movement away from basing PHS on solely technical criteria (e.g., forest cover and its relationship to hydrological services) and economic goals (e.g., creation of markets) that may affect the efficiency of the program in the future (Muñoz-Piña et al., 2011)

Calls for applications are announced annually, and once received, applications are reviewed and evaluated based on the PHS program's eligibility criteria and priorities. Landowners invited to enroll in the program must sign an agreement to conserve the designated forest area and implement best management practices on the land. In order to facilitate monitoring (see below) and enhance program efficiency, the minimum land area for enrollment is 250 ha and each hectare must support at least 80% forest cover. Consequently, coordination among neighbors or within the entire community is often necessary for an application to be successful, especially in areas like Veracruz where landholders are often small (Manson et al., 2013).

In 2008 CONAFOR expanded the PHS program to include a program to promote local mechanisms of PHS, referred to as "Fondos Concurrentes" ("Matching Funds"). Creation of this mechanism was largely a response to concerns about the lack of local contributions to PHS funds and participation by diverse stakeholders, potentially due to the top-down approach of the original PHS program, in addition to concern about long-term financing, since there appeared little likelihood that current funding sources could be convinced to increase their contributions to the program. The goal of this program is to directly engage the local users of the hydrological-environmental services, thereby making them co-responsible for maintaining the ecosystem benefits and promoting more sustainable land use activities. Additionally, there was an expectation that this approach would motivate the users of the hydrologic services, including private companies, to establish contractual agreements with the service providers to increase the sources and total amounts of local funding available to support the PHS program (Saldaña-Herrera, 2013).

The initial CONAFOR PHS program operated on the concept of providing payments to landowners in exchange for conserving (e.g., not using) their forests. Part of the vision and motivation for establishing the "matching program" was a desire to engage landowners in the development and implementation of best practices for forest conservation and land use management. Another important goal of the matching program was to increase the flexibility of program operators to include restoration and monitoring activities, and establish payment amounts that better reflect local opportunity costs. However, the transition from a more passive approach to a more active approach presents certain challenges, especially since landowners' perceptions and expectations related to their participation and benefits from the PHS program also required changes.

XALAPA: PROSAPIX (Programa de Compensación por Servicios Ambientales y Desarrollo Rural Integral del Pixquiac)

Support for the PHS program in the Pixquiac (referred to as "PROSAPIX") watershed initially came from the municipal government of Xalapa in 2006, as a means to partially justify 30% increases in water user fees that were necessary to insure the solvency of the city's water treatment and distribution system. A local NGO, SENDAS, had recently moved to the area and was promoting the integrated management of watersheds, along with the regional and inter-community relationships needed to develop technical, organizational, and financial mechanisms for sustainable natural resource management. SENDAS was selected by the Xalapa government to administer the PROSAPIX program. In the interest of empowering local actors, SENDAS helped create the Committee of the Pixquiac River Watershed (COCUPIX) to oversee the PROSAPIX program. This committee is comprised of representatives of the communities that supply and use the ecosystem services within the watershed, as well as several universities, state and federal government agencies, ejidos, and NGOs. In 2008, COCUPIX appointed SENDAS as the technical service provider responsible for administering PROSAPIX program. Environmental and social studies of the watershed were performed to identify priority areas for PHS and associated technical assistance.

In subsequent years, the PROSAPIX program was supported by a mix of state and local funding sources in conjunction with CONAFOR (starting in 2008 when the matching funds program was established, see further details below). Notably, in 2008, newly elected government officials in Xalapa City withdrew funding from PROSAPIX, a decision primarily due to lack of convinction by decision makers and local water users about the program's effectiveness. As in the case of FIDECOAGUA, the primary focus of SENDAS has been on working directly with water providers (upstream landowners), with much less emphasis given to outreach with downstream users, which may have contributed to the lack of political will to continue financing the program. Overall, the PROSAPIX program has consistently suffered from an irregular and unpredictable array of funding sources that reflect a lack of a clear legal structure or trust fund for managing payments, which consequently has limited its growth.

In addition to providing payments to landowners for conserving intact forest parcels ($1,000/ha), PROSAPIX also directly supports restoration activities and sustainable land use practices through technical assistance and financing. PROSAPIX's approach to program implementation is based on a series of progressive steps that are meant to foster a new relationship between the watershed and landowners and to avoid the subsidy culture that has plagued other PHS programs in Mexico. In the first year, the landowner conducts reforestation or forest conservation activities. In the second year, a sustainable production project is developed and implemented with interested landowners, with the goal of achieving a long-term sustainable production system that is compatible with watershed protection within the 5-year period of the program the project. After the first three years of operation, PROSAPIX achieved the reforestation of 132 ha with native forest species, the conservation of 114 ha of intact cloud forest, the creation of two community nurseries for native tree species, and participation by 57 landowners in sustainable land use activities.

The Science Behind the Management Plan

Cloud forests play an important role in providing important regulatory, supporting, cultural, and provisioning ecosystem services to society, and that these services have been a strong motivating factor underlying the design and implementation of PHS programs in cloud forest regions worldwide. This is especially the case for hydrologic services, as cloud forests are perceived as important 'water producers' and therefore often targeted for conservation as part of PHS programs. However, very few studies have conclusively documented contributions of cloud forests to streamflow, and especially to dry season flows, which are usually the most critical in terms of sustaining lower-lying population centers. Moreover, there is an overall lack of monitoring and evaluation of the effects of PHS programs on influencing water quantity and quality over time, as most assessments focus on determining forest cover and assume a positive relationship between forest cover and hydrologic services (Brouwer et al., 2011). Notably, because tall stature forests inevitably use more water (e.g., have higher transpiration rates) than the shorter stature grasslands and agricultural crops that often replace them following deforestation (Zhang et al., 2004), water yield is often lower from watersheds dominated by forests. However, because cloud forests may have additional water inputs due to frequent immersion in cloud and consequently high canopy interception of fog combined with low evapotranspiration rates, water yield is predicted to be higher from cloud forests than low stature vegetation. Nevertheless, cloud forests are highly variable in the amount and frequency of cloud immersion, and therefore it is important to collect field measurements to determine the actual role of cloud forests in influencing water balance and streamflow dynamics at a particular site in order to assess their contribution to hydrologic services. Additionally, even if total (annual) water yield may be less under forests (including some cloud forests), the critical target for hydrologic services is usually the amount of *dry season streamflow*, since water availability to low-lying regions is generally more important during the dry months than during the rainy months. Because forests generally have high infiltration rates and soil and groundwater recharge, they are generally able to continue providing water to streams for longer periods of time (i.e., into the dry season), compared to pastures and agricultural crops, which often have low infiltration rates, high runoff rates, and therefore higher peak flows during the wet season and lower baseflows during the dry season. Consequently, field evaluations of the impact of cloud forests and land use conversion on hydrologic services should include a site specific assessment of the *distribution of streamflow* during the entire year, as well as over several years, in order to determine impacts on dry season flows.

As part of our Veracruz cloud forest study, the water balance and streamflow dynamics for three land cover types occurring within the cloud forest zone in the Xalapa-Coatepec region: mature cloud forest, naturally regenerating 17-year old cloud forest, and a degraded pasture was assessed. The water balance of a young (10-year old) and old (30-year old) pine plantation was also assessed. The results showed that the amount of additional water inputs due to interception of cloud water by the canopy was less than 2% of annual precipition (or 640 mm; Holwerda et al., 2010), which is much lower compared to many cloud forests worldwide, where canopy interception rates can reach up to 75% and more than 1,280 mm (Bruijnzeel et al., 2011 and references therein). Additionally, estimated evapotranspiration for this site (1,400 mm/yr; Muñoz-Villers et al., 2012) was much higher than most other cloud forest sites. Combined, these results suggest that water yield would most likely be less under cloud forest compared to shorter stature vegetative cover types, such as pasture or pine plantations. This was confirmed by the streamflow measurements, which showed that annual stream water discharge from a pasture-dominated watershed was 12 and 9% greater compared to watersheds dominated by mature cloud forest or 20-year old regenerating cloud forest, respectively (Muñoz-Villers and McDonnell, 2013). However, late dry season baseflow – *which is a more important hydrologic service than annual streamflow in this region* – was 35 and 75% higher in watersheds with mature and regenerating cloud forest, respectively, compared to the pasture watershed (Muñoz-Villers and McDonnell, 2013). Thus, in the case of cloud forest regions in Veracruz, Mexico, targeting PHS payments to areas supporting mature and regenerating cloud forests should help maintain water availability to lower-lying towns and cities during the dry season, and may also help protect against flooding during high rainfall events in the wet season.

Monitoring and Evaluation

The primary form of monitoring and evaluation of the effectiveness of both Mexico's national PHS and matching programs has been based on assessment of forest cover using satellite imagery (IKONOS or Quickbird, 1m2 pixel size). In the case of all three programs, the field technicians/extensionists also work directly with PHS participants to assist them with preparing and submitting their applications and implementing their management plans. Additionally, for CONAFOR's "matching program", a field technician is also responsible for visiting the PSH participants regularly to verify that they are implementing activities established in their management plan (e.g., planting and/or protecting trees, establishing fire breaks); such restoration and reforestation activities are not included in the national PHS program. The approach used for the field techicians of PROSAPIX is to visit all enrolled landowners the first year, thereby setting a strong precedent for strict enforcement, followed by a gradual scaling back in in the number of visits to a random subgroup of 50% and, eventually, 30% of the total number of participants. Monitoring criteria include limiting extraction of wood for domestic uses, establishment of signs in conservation areas, excluding livestock from reforestations, and participation in sustainable productive projects. Additionally, monitoring of water quality in the Pixquiac has been conducted through a participatory community monitoring network in collaboration with Global WaterWatch-Mexico since 2005 (Fuentes-Pangtay, 2008).

Impacts and Outcomes of Management Activities (Social, Economic, Ecological Benefits)

Recent studies in Mexico (Muñoz-Piña et al., 2011; Scullion et al., 2011) and elsewhere (Kosoy et al., 2007; Van Hecken and Bastiaensen, 2010; Garcia Amado et al., 2011; Newton et al., 20120) suggest that the amount of PHS received by land owners is not considered to be economically significant, nor a primary motivating factor for landowner participation in PHS programs (Scullion et al., 2011). This applies to the national program run by CONAFOR, as well as to the local matching programs operating in individual watersheds although the amounts paid in the latter tend to be somewhat higher. In part this may be due to the strong focus on forest conservation in these programs and the low additionality achieved by them, since participating land owners were mostly planning on conserving their forest cover anyway and view these payments as a "reward" for their environmentally-friendly decisions (Scullion et al., 2011). Restoration of forest cover in local matching programs, while allowable, is complicated by the much higher opportunity costs associated with converting agriculture or croplands to forest cover. Nevertheless, the novel approach used in the PROSAPIX program, that combines PHS with technical assistance to strengthen alternative, more sustainable, land use practices does seems to have had some success in improving farmer livelihoods, changing community perceptions, and increasing forest cover (Asbjornsen et al., in review). This approach attempts to move beyond the subsidy-based culture that dominates in rural communities in Mexico and promote co-responsibility in the management of local natural resources. Another factor influencing the economic impact of PHS is the stability of the program provided by a legal framework and trust fund for managing funds and that permit program beneficiaries to make longer-term plans on how these payments could be best used to improve livelihoods.

In general, the impacts of PHS program activities on perceptions and behaviors of participants appear to be greater for the matching versus the national PHS program, due in part to the stronger relationship between program operators and the landowners receiving payments (Asbjornsen et al., *in review*). Although originally conceived as a mechanism for strengthening relations between water users and providers, the experience in the upper Antigua basin suggests that matching fund operators tend to largely ignore the former group in these programs at their own peril. This decision affects the long-term support and therefore stability of the program through successive municipal administrations. Another factor affecting the operability of matching PHS programs is whether the target watershed is within the political boundaries of the municipality supporting the program (FIDECOAGUA) or includes neighboring municipalities as well (PROSAPIX) since politicians tend to favor activities that directly favor their constituents. Except for the technical assistance in the Pixquiac and work with primary schools in the Gavilanes, the outreach efforts of both programs to help foster changes in perceptions and generate longer-term impacts and support have been fairly limited, particularly amoung water users (Asbjornsen et al., in review).

The environmental impacts of these programs has been harder to gauge due to the almost exclusive reliance on forest cover as the indicator of PHS program performance. While all three programs appear to have limited forest loss within areas receiving payments, the additionality of these payments appears fairly low and there are very few attempts to explore issues such as leakage (Alix-Garcia et al., 2005). Even more rare are attempts to actually evaluate the impacts of PHS programs on target hydrological services (e.g., Locatelli and Vignola, 2009, Brouwer et al., 2011). While changes in the rules governing matching programs has allowed for monitoring of ecosystem service provisioning since 2010, to date only a few of the >70 PHS programs operating in Mexico have actually set up monitoring programs. The evaluation of water quantity and quality in target watersheds should be peformed prior to the establishment of PHS programs and regularly thereafter so that a baseline can be established for evaluating program performance and making adjustments to ensure that their environmental impacts are maximized in the future. Too often these programs are considered as outreach or public relations campaigns by municipal governments rather than science-based approaches to ensuring the effective management of water resources or as real contracts between water providers and users that require hard evidence of their effectiveness in achieving the desired results. To date the PROSAPIX program is the only one of the three programs that, since 2005, has attempted to monitor water quality using community-based methods developed by the NGO Global Water Watch. Nevertheless, this monitoring has not been used to evaluate program performance and is still to coarse (only monitoring the main river channel in the lower portion of the watershed) to provide much information on specific program activities. SENDAS is currently planning to establish a much more fine-scale network of monitoring points in the near future that should help address this issue.

Strengths, Challenges, and Lessons Learned

General Points

Both the national and matching PHS programs in the Pixquiac and Gavilanes watersheds have similarly experienced a few key challenges. First, they have both had difficulties maintaining continuous economic and political support for program operation, and have at different times and circustances faced uncertainty regarding their long-term sustainability. Consequently, they have both been pushed to diversify their sources and mechanisms of funding, ranging from charging water users (including both industrial and residential) to offering incentive mechanisms such as 'adopt-a-hectare' programs whereby interested citizens or organizations can voluntarily support forest conservation. Both programs have also, over time, expanded their range of operationt oinclude other ecosystem services besides water, particularly biodiversity and carbon. Finally, both PHS schemes have faced challenges related to creating effective monitoring and evaluating systems to assess the direct impacts of PHS payments on target outcomes related to maintaining or improving hydrologic services, as well as indirect impacts on other non-target social and economic dimensions, such as poverty alleviation, social conflict, and equitable distribution of and access to resources. Some of the unique strengths and challenges faced by the different programs are sumerized below.

FIDECOAGUA - Coatepec

FIDECOAGUA was conceptually designed as a government supported and operated program in order to simplify its operation through a focus on paying land parcels with the greatest amount of forest cover. This simplicity has enabled it to be broadly disseminated and provides an innovative idea among local actors while maintaining relatively low operational costs. In practice, landowners are paid to conserve the forest, but no additional funds are provided for other activities such as reforestation, conservation activities, or sustainable land use practices, making it a natural extension of traditional government subsidies. Moreover, those landowners that had contacts, lived near major roads, or had initiative were often the ones that managed to be included in the program. Additionally, monitoring compliance using only satellite imagery is also challenging and requires constant support from CONAFOR (Fuentes-Pangtay, 2008). Finally, the program did not explicitly establish a direct relationship between the extent of forest cover and the main program objective of securing the sustainable supply of drinking water for the urban population, as there are many complex factors besides forest cover alone that may influence water resources (see details above; Guzman, 2005, Fuentes-Pangtay, 2008).

Strengths:

- Constant support from a surcharge (1$ peso for domestic users; 2 pesos for commerial users) on bi-monthly bills of local water users;
- The municipality encompasses the geographic boundaries of the watershed that provides water to lower-lying urban center thus avoiding complications of making payments to land owners in other municipalities;
- Relatively simple structure and operation as a quasi government entity with a public trust and a technical committee comprised of local decision makers and stakeholders;
- International recognition of the program as the

first of it's kind in Mexico has been an important factor in minimizing political influences from making large changes to the program;

- Society willing to participate and rapid growth of the program as it meshes well with the country's history of subsidy payments to rural areas of the country; companies are contributing (Coca Cola, Nestle), good relationships maintained by FIDECOAGUA.

Challenges:

- Directly dependent on the local municipal government, making it vulnerable to the loss of institutional memory (changes in staff) with changes in the mayor every three years and the assignation of staff based on political considerations and often lacking the needed skills, knowledge, and experience related to PHS;

- Stagnant funding ($2 peso surcharge on water users) that has limited the area of forest that can be included in the program. However, the total area was recently more than doubled by an innovative "adopt-a-hectare" program in 2010. Finally, the fact that payments are the same for all users means that domestic users provide a disproportionate amount of funding for the program versus private and industrial users;

- Lack of a scientific foundation for strengthening the program. Continued use of forest cover as the sole criterion for selecting priority areas for enrollment in the PSA program, despite the identification of hydrologically vulnerable areas from an early study of the microwatershed (PLADEYRA, 2003). Evaluation of program impacts is also limited by a focus on forest cover using remote sensing instead of in-stream monitoring of water quantity and quality;

- Less attention has been given to outreach activities among water producers/landowners in the upstream areas of the watershed; consequently their knowledge and support of the program tends to be less compared to downstream users (mainly school children have been the focus of the program to date).

PHS-CONAFOR (National and Matching Programs)

This program started in 2003 with a focus on hydrological services and support from 2.5% of the recources captured in water concesion payments nationally to CONAGUA. In 2004, payments for biodiversity conservation, and carbon sequestration were included. In 2008, the federal congress started making an average of $US 50-60 million in extra payments so that the program could renew five-year contracts with existing beneficiaries and still add new land owners to the program. Monitoring is done via high-resolution satellite imagery. Given the high demand for PES payments, the limits in financing, and the weak relationship between water providers and users in the national program, in 2008 CONAFOR created the local matching funds program in which it provides up to 50% of the financing provided by a local source. In addition, this program allows funds to be spent on restoration and monitoring instead of just forest conservation and the training of landowners as is the case for the national PHS program. Although this program now includes over 80 local programs, monitoring is still largely done by satellite imagery as in the national program.

Strengths:

- Clear structure, selection criteria, and rules of operation with the federal government as the main user supporting the system through tax revenue nationally;

- Establish obligations for economic contributions by the municipal and state governments; greater involvement of local citizens (applies to the matching program only);

- At the national level, the operation of the PHS is less vulnerable to the vissisitudes of the interests and pressures of local political parties and politicians, which helps to balance or mitigate the changing local political and economic environment. Helps to prevent the selection criterias for PHS enrollment becoming political rather than technical;

- Having a centralized national program is also more cost effective, because the human capacity building and infrastructure for managing the operational of the program can be integrated into a single centralized unit with costs distributed across the entire program/country;

- The matching program allows for a tighter relationship between water providers and users stimulates the participation of more people/properties including the private sector;

- The matching program is more flexible compared to the national program and can be better adapted to local conditions and a wider range of landowners (i.e., can be smaller in size), types and amounts of payments, and target watersheds.

Challenges:

- Top-down approach sometimes poses challenges with regard to achieving acceptance and trust by local stakeholders and participants (there is often little incentive locally given that fact that resources are distributed nationally); this approach also limits innovation to central offices of one government agency versus involving other sectors of society;

- The lower limit of 250 ha required for enrollment in the program, requires coordination between landowners and can exclude those in regions where land holdings tend to be relatively small (such as in Veracruz where much of the land ownership is ejido or small private properties). Combined, these small land holdings can be extremely important for maintaining watershed functions, while the landowners are the ones that live in the watershed and directly manage the natural resources (Fuentes-Pangtay, 2008);

- The payment levels often fail to reflect local opportunity costs, resulting in low program participation, while those landowners who do enroll are often those who live in the city and therefore do not actually manage the natural resources in the watershed. (Note: starting in 2010, the approach of linking payment amount to deforestation risk as a surrogate for opportunity costs has attempted to deal with this issue.);

- Low degree of ownership among program participants, with program benefits often not being distributed equitably and/or not being utilized in ways that contribute to watershed sustainability (e.g., for personal consumption, etc.), which is especially a problem when payments are give to ejidos and not those responsible for individual parcels, or when given in the form of cash payments versus technical assistance (Fuentes-Pangtay, 2008);

- Lack of the creation of a true regional ecosystem services market where other water uses within the watershed also contributes to the payments;

- Insufficient monitoring of hydrological services to demonstrate program effectiveness in maintaining water quality and quantity;

- National PHS programs where the government is the only buyer (like Mexico's PHS) are often more vulnerable to political tensions; for example, over time, there's been a tendency to increase the number of socioeconomic variables and therefore reduce the weight given to hydrological priorities when evaluating applications (Muñoz-Piña et al., 2011);

- Mechanism for identifying large priority watersheds but not priority microwatersheds or key areas of hydrological recharge within them (problem of scale).

PROSAPIX - XALAPA

Strengths:

- Vision of promoting co-responsibility rather than dependency on subsidies by combining cash payments with technical assistance to foster productive projects that utilize sustainable practices;

- The multi-sector organization responsible for overseeing the operation of the program (COCUPIX) ensures that there is good communication and coordinations between diverse stakeholders, participants, and program administrators;

- The program has a strong scientific foundation using previous watershed-level studies to identify priority areas for conservation / restoration, as well as monitoring of water quality since the inception of the program;

- Program administrators (SENDAS) have increased program transparency and built a strong relationship with communities of water providers.

Challenges:

- The prevalent culture in rural areas to expect 'hand outs' in the form of subsidies (subsidy mentality) as part of the political environment, which makes it difficult to establish agreements that are based on payments in exchange for participation in activities;

- Financial sustainability of the program is a major challenge, because i) the operational costs of the technical team (SENDAS) has thus far not been integrated as part of the program's transaction costs; ii) financing integrated rural development/sustainable land use projects is much more expensive than simply providing subsidies for forest protection and will require additional mechanisms to generate the necessary funding (e.g., projects for technical assistance from other sources than PES); the program has lacked a leagal framework for generating and receiving constant payments from local water users;

- Lack of stable long-term institutional support from the Xalapa government/administration, which is also the major beneficiaries of the PES program;

- Contributions are not received directly from the water users (they are distributed through CMAS-Xalapa and the municipality of Xalapa); this has posed a challenge for SENDAS to engage the interest and participation of both the upstream water producers and downstream water consumers (e.g., the link connection between producers and users is not as direct/strong as with FIDECOAGUA). It has also been difficult to finding "matching funds" for participation in CONAFOR's matching program, possibly due to a lack of confidence/trust in the local administration (lack of transparency; it's not clear how the program is charging the water users);

- FIDECOAGUA has had a stronger but still very limited (school children) with water users, whereas PROSAPIX's relationship with water providers is much stronger. Both programs would benefit greatly from strong relationships with local water users and events designed to foster a dialogue between water providers and usters;

- Lack of transparency by CMAS-Xalapa and a lack of trust by water users in this water operator. This has made it very difficult to replicate the system in Coatepec where water users receive a surcharge to support FIDECOAGUA. As a result, SENDAS is contemplating a system of voluntary payments.

Summary and Conclusions

Factors that lead to a high likelihood of success of PHS programs

- Political and financial stability through institutional frameworks and agreements;

- Good relationships between water users and providers that support the program during periods of political transition;

- A strong operational struction (e.g., at the municipal or NGO level);

- Clear and transparent system for charging water users that provides information on program impacts and how program money has been spent;

- Monitoring of target ecosystem services to improve performance; use of other scientific information (hydrological balance, socioeconomic studies) when available;

- Co-responsibility; Combination of cash payments and technical assistance to promote sustainable alternatives that maintain ecosystem service provisioning;

- Good understanding and ownership of the program by the citizens.

Remaining gaps in knowledge: recommendations for future directions

- Assessment of the impacts that PHS programs have had on local people (both users and consumers);
- How to achieve a true market-based approach to PHS with little intervention by government and the participation of many ecosystem service users and providers;
- Consideration of multiple ecosystem services;
- Payments adjusted accordingly and that don't just relly on opportunity costs (these tend to be very low);
- Determine the primary motivations of landowners for participating in PHS programs.

The Cuitzmala Watershed on the Pacific Coast of Mexico

Introduction

This watershed is unique because of its biotic characteristics, the wealth of information available on it, and for the team of researchers working there. The tropical dry forest of the Pacific Coast of Mexico holds a large biodiversity that is unique to this region. A portion of this forest located in the state of Jalisco has been protected since 1971 by the Universidad Nacional Autónoma de México, and in 1994 as a Biosphere Reserve. Since, a very large body of research has developed in this area to study its biodiversity and the functioning of the ecosystem. Research on the way this ecosystem is managed around the protected area started as early as 1980, and the study area was enlarged to the whole watershed in 2000. An interdisciplinary team working on the reserve and the watershed as a social-ecological system has been expanding since.

The Cuitzmala watershed is located on the Pacific Coast of Mexico in the state of Jalisco. Its total area is

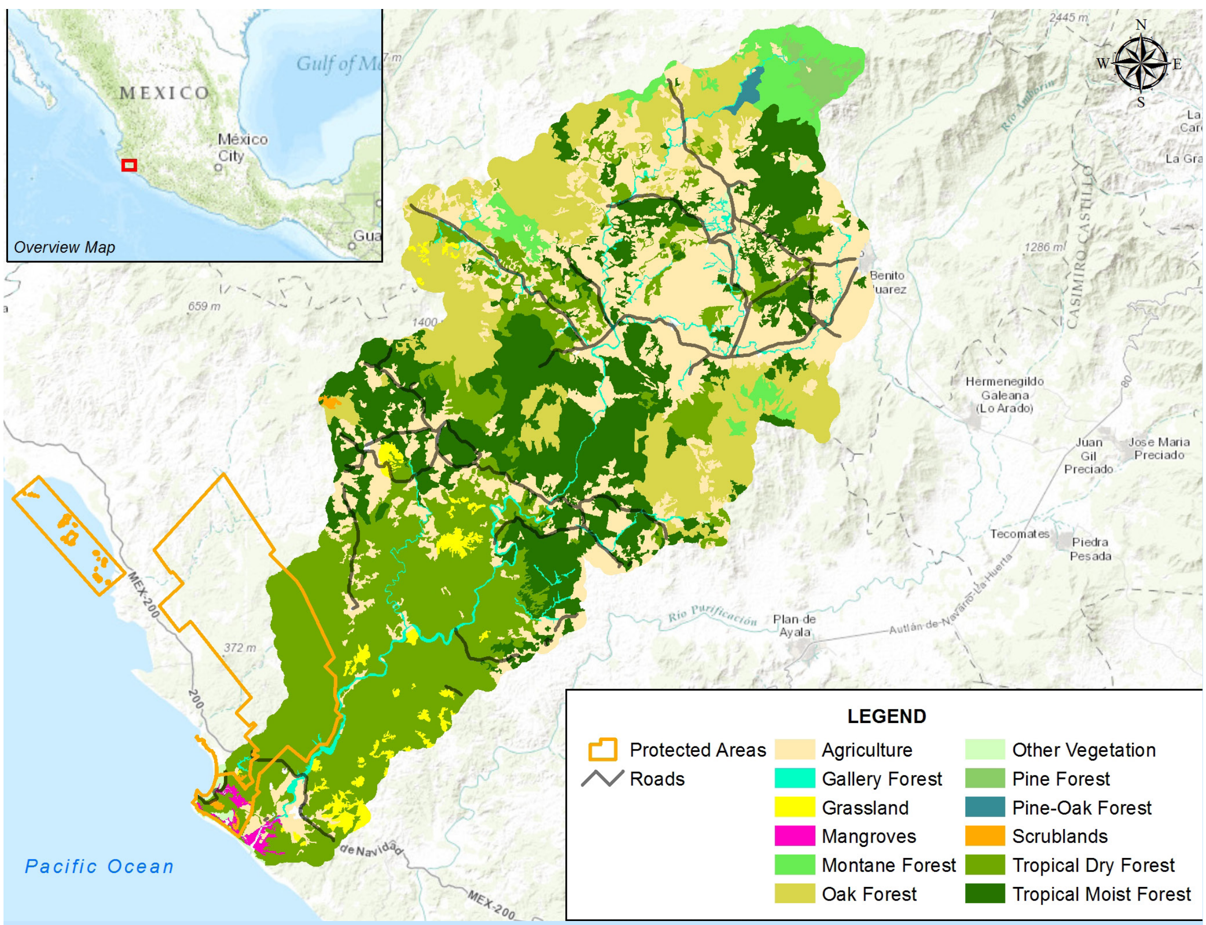


Figure 7.13 Vegetation Cover of the Cuitzmala Watershed in the State of Jalisco, Mexico

1,090 km2, ranging between 19° 29' - 19° 34' North and 104°58'- 105°04' West (Figure 7.13). The maximum altitude is 1730 m and the river discharges in the Pacific Ocean (Martinez-Trinidad, 2007).
The watershed is dominated by mountains (70% of the watershed) and hilly areas (24%), with moderate slopes (12°to 24°) making up 44% of the area (Martinez-Trinidad, 2007). Its geological origin is volcanic, with large areas dominated by granite (85%). Varied topography and land uses create high edaphic heterogeneity, but soils are largely dominated by Regosols (73%).

Local climate is strongly seasonal with precipitation, including cyclones, concentrated between June and December (García-Oliva et al., 2002). In the upper parts of the watershed the climate is temperate, with up to 1,600 mm rainfall per year, potential evapotranspiration below 100 mm per month, and runoff up to 400 mm average for July, August and September (Piña, 2007). In contrast, the lower part of the watershed has a hot sub-humid climate, with 750 mm rainfall per month and average temperature of 24.6° (García-Oliva et al., 2002).

The watershed is largely forested, with 15-38% converted to pastures and croplands (data sources and definitions of types of land use and land cover categories can be found in Larrazabal, 2008; Piña, 2007). Overall, the dominant vegetation type is semideciduous tropical forest (40% of the area), followed tropical dry forest (25%). Temperate forests (oak, pine-oak) are only found in the upper part of the watershed (20% of the area), while a semi-deciduous tropical forest is found in the transition between the temperate and the tropical dry forests as well as along the margins of the larger rivers.

Land tenure of the watershed is a patchwork of private and community lands, dominated by private owners including the Fundación Cuixmala (50%), ejidos, which are areas of communal land used for agriculture (35%), and two indigenous communities (10%). The Chamela-Cuixmala Biosphere Reserve (http://www.ibiologia.unam.mx/ebchamela/www/reserva.html) is owned (by sections) by National (the Universidad Nacional Autónoma de México) and state (the Universidad Autónoma de Guadalajara) universities, a private foundation (Fundación Cuixmala). Federal lands (5%) include a section of the Reserved as well as the riparian zones along river edges (5-10 m strips extending from the maximum water level; Warman, 2001; Flores-Diaz et al., 2014).

Sixty two small communities are found across the watershed. Many regional management decisions are made by the local authorities of the municipalities of Villa Purificación and La Huerta, although the main cities of these municipalities are outside the watershed (Flores-Diaz et al., 2014). Paved roads link these cities to the coast. A low density network of non-paved roads is found outside the Reserve.

The watershed has undergone several different periods of transformation (Castillo et al., 2005; Lazos Chavero, in press). Before Spanish colonization, the region was occupied by diverse Nahuatl indigenous populations that were sparsely settled. Nearby to the south of this area, the area was occupied by Spaniards shortly after their arrival in the Americas and the best lands were taken from the indigenous populations. Villa Purificación was founded in 1556 (Regalado, 2000). Sugar cane plantations and later those of añil (*Indigofera tinctoria* and *Indigofera suffruticosa*) and rice were promoted. Goods were exchanged through several rural roads between "la Villa" and the lower part of the watershed. Large private properties called Haciendas were gradually created and fostered at the onset of Mexican independence (1859) on former indigenous lands. The big landowners introduced cattle ranching as a way to access large territories. The Mexican revolution (1910) initiated land distribution to peasants but lands were also given to military officers. Exploitation of both temperate and tropical forests began during this time. In 1943, the "March to the Sea" program promoted additional land distribution in the lower coastal lands. Ejidos in the southern part of the watershed were mostly created during the 1950s through the middle of the 1970s. Around the 1970's, credit started to flow to the ejidos and local communities through the federal bank Banrural, first to grow maize for the big cities of Jalisco, and later on to establish cattle ranches. These development programs brought important social, economic and environmental transformation to the region. Tourism, while present in governmental discourse since the 1940s, has grown slowly since the first decade of the XXI century (Castillo et al., 2009).

At present it is becoming an important activity which may have important effects on ecosystem services in several of the watersheds of the southern part of the Jalisco coast (Riensche et al., 2015).

Today, direct water users in the watershed are largely farmers, industry, mining (increasing recently) and tourism as well as residents of the municipalities of Villa Purificación and La Huerta and other smaller, dispersed communities. Farmers include small farmers, commercial specialized farmers (growers of sugarcane, watermelon, tomatoes, chili, papaya, and mangoes), large and small cattle ranchers, and pig ranchers. Industry includes bottled water companies. Most water users in the basin (private, ejido or indigenous) are subsistence farmers. The exception (on less than 5% of the land area) is a group of wealthier residents who own a narrow strip of land (about 1 km wide) along the coast where the tourism industry is located (Flores-Diaz et al., 2014).

Ecosystem Services

The Cuitzmala region has been managed to foster the supply and delivery of various provisioning ecosystem services (Maass et al., 2005). Wood has been extracted largely from tropical semi-deciduous forests (TSF) and temperate forests. All vegetation types have been extensively transformed first into cornfields, and subsequently to pastures for cattle ranching. The alluvial plains have been used for intensive commercial agriculture. Some hilly areas are still being used for subsistence milpa cultivation (an agricultural system in which maize, squash, and beans are grown). People extract useful plants and animals from all types of ecosystems. The dominant low hills, dominated by tropical dry forest (TDF), are highly productive with a Net Primary Productivity (NPP) of 12-14 Mg ha^{-1} yr^{-1} (Maass et al., 2005). The TDF is very diverse for both its plants and animals, many of which (approximately 70%) are endemic to the western coast of Mexico (Durán et al., 2002; Noguera et al., 2002).

The key provisioning services of the region are water, timber, wood, fuelwood, cattle, crops, and useful plants and animals (Maass et al., 2005). Water is a scarce resource and greatly in demand. Nearly 90% of the precipitation returns to the atmosphere through evapotranspiration; in areas dominated by TDF, monthly precipitation is lower than the potential evapotranspiration during most of the year (Maass and Burgos, 2011). Water is drawn from streams and wells (Solorzano Murillo, 2008) and while water quality is good in proximity to the reserve, it deteriorates closer to towns as a consequence of sewage that is discharged directly into streams. The lower part of the watershed shows high incidence of coliform bacteria associated with the high density of fauna (Lopez, 2008). Small communities were highly dependent on river access for household water consumption until the 1990's; after which people started to boil water. As of 2004, the inhabitants started to consume bottle water (Lazos Chavero, in press).

Low intensity agriculture in hilly areas provides maize for local consumption and calves for regional and national trade (Cohen, 2014). During the 1990's, calves were even exported to the USA (Lazos Chavero, in press). Along the alluvial plains, sorghum, maize, papaya, mango, tamarind, lime, chili peppers, watermelon, and squash are cultivated intensively (Cohen, 2014; Monroy Sais, 2013). Approximately 16,000 m^3 $year^{-1}$ of wood is obtained from the TDFs and TSFs in the state of Jalisco, where the watershed is located (Cohen, 2014; SEMARNAT, 2010). Timber species such as *Cordia* spp., *Enterolobium cyclocarpum*, *Tabebuia* spp., and *Pirhanea mexicana* are among the most valued (Godínez Contreras, 2011). Close to 200 plants species from the TDF and TSF are, or have been, used for medicine, timber, wood fuels, materials, food, beverages, and spices (Godínez Contreras, 2011). They are commercialized at local, regional, national, and international markets. *Croton* spp. stems in particular are removed from the TDF and transported to the northern part of Mexico for tomato agriculture (Rendón-Carmona et al., 2009). Vertebrate animal species used for food (Monroy Sais, 2013) include deer (*Odocoileus virginianus*), collared pecari (*Tayassu tajacu*), coati (*Nasua narica*), chachalaca (*Ortalis vetula*), and iguanas (*Iguana iguana*). Other animals (e.g., parrots - *Amazona finschii, A. orathryx*), are caught and sold as pets (Renton, 2002).

Native TDF species are adapted to low and seasonal water availability. Predictions for climate change in the tropics include increasing temperatures and decreasing water availability, making TDF species to likely be important sources of germplasm readily adapted to these conditions In addition, many of these species can be propagated vegetatively (Maass et al., 2005). Wild relatives of crops, such as those of squash (Cucurbita) and other TDF species, are likely to be important sources of genetic diversity for present crops and novel future products (Lott, 1993).

Global and micro-climate regulation, maintenance of soil fertility, flood control, erosion control, pest and pollination regulation, and resilience are the most important regulating services of the Cuitzmala watershed (Maass et al., 2005). Mexican TDFs store 2.3 Pg carbon (C), which is about equal to the carbon stored by the evergreen forests in the country (2.4 Pg C). Potential carbon emissions to the atmosphere from the burning of biomass (as a result of slash and burn agriculture) in the TDF landscapes of México may amount to 708 Tg C, as compared to 569 Tg C from evergreen forests (Jaramillo et al., 2003). At a local scale, the forest provides shade and moisture to farmers and their animals (Castillo et al., 2005). The regulation of soil fertility in the hilly lowlands is particularly critical given that soils are shallow and rocky, slopes dominate, and rainfall is strongly seasonal, creating a high leaching potential for this ecosystem (Maass et al., 2005). The TDF has evolved tight recycling mechanisms to avoid nutrient loss from the system, such as the maintenance of a dense leaf litter layer of up to 8.2 Mg ha^{-1}, microbial immobilization of nutrients during the dry season, nutrient resorption prior to leaf abscission, forest resistance to fires and high soil aggregate stability. Fires induced by farmer to promote pasture growth and woody vegetation encroachment consume up to 80% of the aboveground biomass, with forest-to-pasture conversion resulting in 77% and 82% losses of carbon and nitrogen, respectively, from aboveground biomass. TDFs also regulate soil erosion; erosion and sediment transport downstream due to maize cultivation can be several orders of magnitude above the natural rates (up to 130 Mg^{-1} ha^{-1} yr^{-1}), while nutrient losses can account of up to 179 and 24 kg ha^{-1} yr^{-1} of nitrogen (N) and phosphorus (P; Maass et al., 1988). Forests play a critical role in regulating floods given that the region is constantly exposed to cyclonic events with highly erosive storms. Vegetation and litter leaf cover help keep high infiltration rates in the soil, avoiding runoff and soil erosion, therefore reducing floods (Colter et al., 2002; Maass et al., 1998).

Both native and introduced pollinators are important for many of the agricultural crops in the region that, in 2000, accounted for US $12,000,000 (Maass et al., 2005). For example, squash (*Cucurbita* spp.) is pollinated by the native solitary bees *Peponapis* spp. and *Xenoglossa* spp., and also is visited by the introduced *Apis melifera*; however, native pollinators arrive at the flowers earlier and are more efficient pollinators, both removing and depositing pollen on the flower stigmas (Mariano-Bonigo, 2001). Thus, a reduction in native pollinator populations through the fragmentation and transformation of TDF and TSF, may affect the yield and quality of many crops including squashes, with negative economic impacts. Flying vertebrates, such as nectarivorous and frugivorous bats (*Glossophaga soricina, Leptonycteis curasoae,* and *Artibeus jamaicensis*) are also essential pollinators of wild and domesticated species of cactus and agave, as well as trees of the family Bombacaceae that are endemic to the Coast of Jalisco Region and have aesthetic and economic value (Quesada et al., 2013).

The resilience of TDFs seems to be quite high despite major disturbances associated with cyclones and drought (Martinez-Ramos et al., 2012; Maass et al., 2005). Its coppicing capacity plays an important role in its recovery, and basal area has been shown to reach levels observed in mature forests only ten years after pastures are abandoned. The TDF found here is resistant to fire, even in very dry periods. Human disease regulation and pest regulation depends on the dynamics of vectors and parasites, and might rely on the maintenance of the diverse communities of their natural enemies in the TDF and TSF, but further research is needed to validate these likely links.

The most important cultural services of the watershed are its scenic beauty, its potential for ecotourism, and spiritual fulfillment (Castillo et al., 2005; Maass et al., 2005). The rugged nature of the coastline, with multiple small creeks and some wider bays, the clear-colored fine sands contrasting with the green (rainy season) or grayish (dry season) vegetation, and the presence of streams, rivers, and wetlands are deeply appreciated by national and international tourists (Castillo et al., 2009; Godínez 2003). The high diversity of birds and other organisms found in wetlands can provide a focus for the development of ecotourism for international tourists and local inhabitants are currently exploring this option. Local inhabitants also value the beauty of the shore, wetlands, water bodies, and the preserved TDF, and consider that they contribute to their spiritual well-being (Castillo et al., 2005).

Watershed Governance

Watershed governance is complex as there are numerous stakeholders in the region; the three main types of land ownership are: private, ejidos and indigenous communities. Owners of private properties can decide the land use and vegetation cover. In the Ejido and indigenous communities, the Assembly (a plenary session of all members) is the main agrarian authority and makes broad land-use decisions, but the individual farmers make their own management decisions regarding what, when and how their land is used (Schroeder and Castillo, 2012).

Water in Mexico, by law, belongs to the whole nation (Carpizo, 1917) and its management is conducted by the National Water Commission (CONAGUA for its acronym in Spanish). For example, CONAGUA is in charge of granting authorizations and water use permits. Several studies have shown, however, that most local people are not aware of CONAGUA water regulations although they have constructed informal institutional arrangements to regulate water use either for domestic purposes or for agricultural activities (Flores-Diaz et al., 2014; Solorzano Murillo, 2008). Local water committees often exist in rural communities to organize water access, where most water is pumped from wells and payments include only electricity costs (Solorzano Murillo, 2008). Drug dealers also play an important role in water access and distribution.

There are currently no major dams in the Cuzmila watershed; however, there has been a plan to construct one in the upper watershed for eight years. Similarly, there are no water institutions that regulate water access for irrigation systems. Farmers near rivers have appropriated the rights to irrigate small plots along rivers and streams and do so during the rainy season.Temporary structures for water retention are also used by local ranchers to water their cattle. Farmers value their access to water and recognize the rights of others to access it as well. They also understand the need to keep riparian vegetation for the purpose of controlling erosion, providing shade to cattle, and for recreational use (Flores-Diaz et al., 2014).

Little is known about water conflicts in the region. Recent conflicts around the development of extensive tourism facilities along the coast have highlighted conservation needs such as protection of biodiversity and the appropriate use of freshwater and beach resources in the area (Castillo et al., 2007). Tourists, largely high-end, are attracted to the beauty, cleanliness and privacy of the beaches; yet, on the other hand, big tourism developments have been recently been approved for the area neighboring the Reserve including a Marina and a Golf Club. As tourism infrastructure develops, and so does the urban sprawl of the growing population working for it, and water demand for irrigation, pools and tourist's showers increases conflicts are likely to escalate in the near future (Riensche et al., 2015).

No watershed management plans presently exist for the Cuitzmala River Basin. However, diverse regional associations have been created in the last 10 years, joining municipal, state and federal agencies with citizen and private institutions to address environmental issues focused on watershed programs (Flores-Diaz et al., 2014). Based on the 2004 decree of the Rural Development Law, municipal and regional councils were created as platforms where governmental agents and citizens (including academics) discuss and take recommendations regarding productive, health, educational and environmental issues to the appropriate authorities. These associations are becoming important stakeholders. In addition, an NGO named JICOSUR (Junta Intermunicipal de Medio Ambiente de la Costa Sur- Intermunicipal Board for the Environment in the Southern Coast of the State of Jalisco) was formed (Arellano and Rivera, 2011). One of the main aims of JICOSUR is to promote watershed management plans for the entire coastal region to maintain its long-term conservation. Interactions between this organization and academics are underway (Castillo et al., 2007; Lazos Chavero, in press). Finally, a community water monitoring program has been conceived (Carrara Castilleja, 2009; Jiménez Belalcázar, 2014; Russildi Gallego, 2010) and is in the process of being implemented as a educational tool and a way to empower the communities with their water resources management. If an inter-municipal association truly had the support of the municipal authorities and the federal water authorities, there could be a great improvement in local water governance.

Lessons Learned

The Cuitzmala River watershed provides key ecosystem services to a variety of users both within and outside the watershed. Long-term ecological research in the area has contributed to understanding these services, particularly the contribution of ecological processes to the delivery of ecosystem services. However, watershed management requires communication and institutional interventions as well as sustainable practices. Additional trans-disciplinary research and co-design of watershed management plans between researchers and local stakeholders is necessary.

Appendices

Appendix 1: Bibliography

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Appendix 2: Conference Agenda

Watershed Management for Ecosystem Services in Human Dominated Landscapes of the Neotropics

Earl S. Tupper Conference Center,
Smithsonian Tropical Research Institute
Panama City, Panama
March 19-22, 2014

A conference organized by

The Environmental Leadership & Training Initiative (ELTI) and TheNative Species Reforestation Project (PRORENA)

With support from

The Inter-American Development Bank (IDB)

MARCH 19
Field trip to Agua Salud Project for conference presenters

The conference activities began with presentations about STRI's Agua Salud Project and ELTI's Permanent Training Site Initiative within the Agua Salud Project, in order to familiarize the conference presenters with the Agua Salud Project site before the field trip. At the site, Dr. Jefferson Hall and Dr. Bob Stallard of STRI explained the objective of the research site: to understand the ecosystem services provided by forests in a seasonal climate and how they change with land use and climate change.

Dr. Hall explained the following three different pillars of research at Agua Salud: (1) the hydrology component, which tests for the forest "sponge effect" and whether forest soils moderate stream and river flow; (2) secondary forest dynamics and their ability to replace the services lost from mature forests; and (3) native species plantations and their ability to meet the increasing demands of humans while also providing and regulating ecosystem services. In addition, Dr. Hall described the publications and ongoing research conducted by scientific collaborators in the site and their importance for applied ecology.

Panama Coordinator of the Neotropics Training Program for ELTI, Jacob Slusser, discussed how ELTI has utilized the infrastructure of Agua Salud to develop interpretative trails and demonstration areas to facilitate forest restoration courses for practitioners. He also explained how ELTI has developed training materials based on Agua Salud research to create capacity building courses on forestry ecology, ecosystem services and restoration strategies that have a strong scientific foundation and that highlight the importance of using science to make informed land use decisions.

Throughout the day, the participants visited the following five key sites within the Agua Salud Project:

- The ridge top, which provided a view of the Agua Salud property including the landscape mosaic of forests and agricultural systems established as part of the study and each system's associated watershed catchments where measurements are taken;

- The mature forest, where ELTI established a demonstration plot and a soil profile used to teach concepts of forest ecology and methods to quantify ecosystem services;

- A poorly growing teak-wood timber plantation, which illustrates the importance of conducting site analysis before reforesting with a particular species as well as the limited provision of ecosystem services provided by an exotic monoculture plantation;

- The native species plantations, which demonstrates STRI's Smart Reforestation® model of planting appropriate native species that perform well in degraded conditions and produce both timber and other ecosystem services. ELTI has developed an interpretative trail through these plantations to illustrate the range of forest restoration strategies and experiments conducted by researchers; and

- The silvopastoral system (SPS) which demonstrates a productive agricultural landscape where native tree species and shrubs are integrated into a cattle pasture. A local rancher manages the SPS using a pasture rotation system and provides participants with the local perspective of using new technologies and practices to improve rural livelihoods. In addition, SPS highlights the socio-economic benefits of forest restoration in productive landscapes, as farms become more productive and generate more economic opportunities in impoverished rural areas.

The field trip concluded with a visit to the Madden Dam of the Panama Canal Authority located on Alajuela Lake, which serves as a reservoir for Panama City's water and generator of electricity needed for Canal operations during the pronounced dry season. Dr. Stallard reiterated the importance of practicing sustainable forest management within these watersheds, especially due to importance of the region´s forests for mitigating storm and flood risks that can potentially destroy the Panama Canal infrastructure and disrupt the Panamanian economy and world commerce.

MARCH 20
Day 1 of Conference

The first day of the conference introduced participants to the goal of the conference as a forum to present and discuss the state of scientific knowledge (biophysical and social) related to watershed management in the Neotropics for the production of different goods and services and specifically those related to water. The presentations of the day focused on the first two panels; land-use effects on ecosystem services and the importance of watersheds for ecosystem services. Speakers and the titles of their presentations are listed below.

Panel 1
Land-Use Effects on Ecosystem Services

Robert Stallard, PhD., US Geological Survey & Smithsonian Tropical Research Institute. *Land-use effects on stream flow and water quality: experiences from Agua Salud and Eastern Puerto Rico*

Michiel van Breugel, PhD., Yale NUS. *Land-use effects on carbon sequestration and diversity in a tropical landscape*

Heidi Asbjornsen, PhD., University of New Hampshire. *Eco-hydrological impacts of land use and climate change in tropical montane cloud forests and implications for payment for hydrological services policies: A case study from Veracruz, Mexico*

Sunshine Van Bael, PhD., Tulane University. *Tropical biodiversity and ecosystem services in fragmented landscapes*

Panel 2
Importance of Watersheds for Ecosystem Services

Esteban Payan, PhD., Panthera. *The conservation of the Magdalena River Watershed of Colombia, as strategy for promoting the connectivity of jaguar populations and its related biodiversity*

Carlos M. Padín, PhD., Metropolitan University of Puerto Rico. Watersheds: *The green infrastructure*

Ciara Raudsepp-Hearne, PhD., Independent. *Minimizing trade-offs among ecosystem services in multi-functional landscapes*

Marco Tschapka, PhD., University of Ulm. F*orest fragmentation influence on ecosystem health: the ecosystem services of bats*

Keynote Speaker

Patricia Balvanera, Ph.D., Autonomous University of Mexico. *Ecosystem services provided by Neotropical forests: advances and perspectives from Latin America*

MARCH 21
Day 2 of Conference

The second and final day of the conference focused on approaches to the management of watersheds and the policies and socioeconomic drivers from within and outside the watershed that impact and drive management decisions (speakers and the titles of their presentations are listed below). The objective of these panels was to recognize the complexity of managing ecosystem services amongst diverse stakeholders. Organized as a round table discussion, the second panel of the day gave the audience the opportunity to interact with the presenters, which led to a stimulating dialogue about management responsibilities for decision makers with varying interests.

Panel 3
Approaches to the Management of Watersheds

Zoraida Calle, MSc., Center for Research in Sustainable Systems of Agriculture (CIPAV). *Participatory research for sustainable agricultural production and ecological restoration*

Jefferson Hall, PhD., Smithsonian Tropical Research Institute. *Reforestation and restoration for ecosystem services in watersheds of the humid tropics in Latin America*

Enrique Murgueitio, DVM., Center for Research in Sustainable Systems of Agriculture (CIPAV). *Sustainable livestock in watersheds*

Arturo Cerezo, Panama Canal Authority (ACP). *Approaches in productive landscapes: The Panama Canal Authority's Program for Environmental Economic Incentives*

Edgar Araúz, Natura Foundation. *NGO experiences in the management of watersheds*

Panel 4
Beyond the Watershed

Jorge Maldonado, PhD., University of the Andes. *Economic tools for valuing conservation and ecosystem services*

Daniel Moss, MSc., Daniel Moss Consulting. *Watershed management and governance: How can we get it right?*

Raisa Banfield, Sustainable Panama Foundation (PASOS). *The importance of integrated management of Panamanian watersheds*

Vidal Garza, PhD., Mexican Economic Development (FEMSA). *Scaling models of sustainable conservation through coordination between sectors: the case of the Latin American Water Funds Partnership*

Keynote Speaker

Carlos Vargas, Panama Canal Authority (ACP). The *Panama Canal: The Green Route of the 21st Century*

MARCH 22
White paper workshop and field trip to Agua Salud Project for invited guests

The activities during this day involved the following two separate events that occurred simultaneously:

- Dr. Hall and Vanessa Kirn, ELTI Intern, facilitated a workshop with the conference presenters focused on developing the "white paper" report to cover best practices of watershed management in the Neotropics. The goal of the white paper is to translate the scientific body of knowledge on watershed management into a document that policy makers, practitioners and other decision makers are able to understand and use. The publication of the white paper will facilitate further dissemination of watershed management science to other audiences. The workshop focused on developing a strategy for writing the publication by discussing the scope and content for the paper and determining the authors responsible for writing text for each component. Experts contributed their knowledge for each section and their specific research on watersheds in the Neotropics to highlight regional case studies. The session concluded with the production of a work plan and timeline to provide direction to the contributors over the next six months.

- Estrella Yanguas, Manager of the Agua Salud Project, and Jacob Slusser (ELTI) facilitated a field trip for invited guests. The Inter-American Development Bank (IDB) selected the guests for this field trip since they are important practitioners involved with watershed management in Latin America. In addition, ELTI identified and invited two influential Panamanian land-use decision makers from a private environmental consulting firm and the National Assembly of Legislators. The content of the field trip included: (1) an explanation of Agua Salud's research objectives; (2) a review of past and current research and results and their influence in land use decision making; and (3) a visit to the ELTI permanent training areas to understand how they are utilized to teach applied ecological restoration concepts to course participants.

Appendix 3: Diagnostic Tools for Assessing Watershed Governance

1. Inventory of Watershed-Related National Laws and Regulations

Name of Law or Regulation	Implications for Watershed Governance
General Water Law	
Water Tariff Law	
Strategic Economic Sectors Law	
Climate Change Legislation	
Disaster Risk Management Legislation	
Biodiversity Laws	
Etc.	

2. Inventory of Watershed-Related Institutions

Name of Public Entity	Responsibility for Watershed Governance	Cooperates with which agency?
Ministry of Agriculture		
Ministry of Energy and Mines		
Watershed Councils		
Municipalities		
Etc.		

3. Inventory of Watershed-Related International Rules, Regulations and Agreements

Rules, Regulations and Agreements	Impact on National Watershed Governance
Name of trade rule	
Name of bilateral agreement	
Name of multilateral agreement	
Loan conditionalities, e.g, IMF, IADB and WB	
Name of treaty	
Name of international regulation	
Name of Development Bank program	

4. Inventory of Watershed Policing Authorities

Policing Authority Name	Jurisdiction in Watershed	Real Enforcement Power

5. Inventory of Economic Development Incentives and Environmental Impact		
Government level	**Subsidy and Incentive Programs per Sector**	**Corresponding Environmental Requirements**
Municipal		
State		
Federal		

6. Inventory of Watershed Restoration Programs				
Program type	**Public Entity Designing**	**Public Entity Administering**	**Civil Society involvement**	**How financed**
PES programs				
Contamination Control				
Tax incentives for conservation and land use				
Water Funds				
Etc.				

7. Territorial Planning - Decision Tree				
Type of Territorial Planning	**Who decides**	**Who implements**	**Who enforces**	**Public hearings and accountability mechanisms**
Zoning				
Water extraction permits and water rights assignment				
Parks and green space				
Mineral extraction permits				
Agricultural subsidies				
Etc.				

8. Inventory of Available Territorial Planning Information			
Type of information	**Who collects?**	**Who controls?**	**Publicly available?**
Water balance maps			
Map of water and mineral concessions			
Territorial plan/zoning map			
Map of watershed health			

Appendix 4: Acronyms, Abbreviations, and Symbols

A	Annual total
ANA	National Water Agency of Brazil
a	Average
b	Base flow
ACP	Panama Canal Authority (Autoridad del Canal de Panama)
CAC	Central America and the Caribbean
CEPAL	United Nations Economic Commission for Latin America and the Caribbean
CIFOR	Center for International Forestry Research
CITES	Convention on International Trade of Endangered Species
cm	Centimeters
CONAFOR	National Forest Agency of Mexico (Comisión Nacional Forestal de México)
EJOLT	Environmental Justice Organisations, Liabilities and Trade
ELTI	Environmental Leadership and Training Initiative
ENSO	El Niño Southern Oscillation
EPMAAPS	Quito Municipal Water Utility (Empresa Pública Metropolitana de Agua Potable y Saneamiento, Quito)
ES	Ecosystem Service
FIDECOAGUA	Fund for the Promotion, Preservation, and Payment for Forest Environmental Services
FAO	Food and Agriculture Organization of the United Nations
FAV	Veracruz Environment Fund (Fondo Ambiental Veracruzano)
FONAG	Fund for the Protection of Water, Quito (Fondo para la Protección del Agua, Quito)
FORAGUA	South Ecuador Regional Water Fund (Fondo Regional del Agua)
Gt	Giga tons
GWP	Global Water Partnership
Ha	Hectare
IDB	Interamerican Development Bank
IEA	International Energy Agency
ITCZ	Inter-Tropical Convergence Zone
IUCN	International Union for Conservation of Nature
MA	Millennium Ecosystem Assessment
NADP	National Atmospheric Deposition Program (U.S.)
NAO	North Atlantic Oscillation
NGO	Non-governmental organization
NOAA	National Ocean and Atmospheric Administration (U.S.)
NPP	Net annual primary productivity
NTFP	Non-timber forest product
NYC	New York City
p	Peaks during storms
Paramo	Andean Grasslands
PCJ	Piracicaba, Capivari and Jundiaí Basins Inter-Municipal Consortium
PES	Payment for Ecosystem Services
PRORENA	Native Species Reforestation Project
PSA	Pacific South America
Q	The primary measurement of discharge or water leaving a watershed
R	Instantaneous runoff
S	Water depth
SACZ	South Atlantic Convergence Zone
SAM	Southern Annular Mode
SAMS	South America Monsoon System
SPS	Silvopastoral System
STRI	Smithsonian Tropical Research Institute
UNEP	United Nations Environment Program
TEEB	The Economics of Ecosystems and Biodiversity
TESSA	Toolkit for Ecosystem Service Site-based Assessment
TDF	Tropical dry forest
TMF	Tropical montane forest
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNSD	United Nations Statistics Division
USD	United States dollar
USDA	United States Department of of Agriculture
USGS	United States Geological Survey
WEBB	Water, Energy, and Biogeochemical Budgets
WWF	World Wildlife Fund

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IDB