Focus Article

The Galápagos archipelago: a natural laboratory to examine sharp hydroclimatic, geologic and anthropogenic gradients

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Poor understanding of the water cycle in tropical ecosystems has the potential to exacerbate water shortages and water crises in the region. We suggest that the Galápagos Islands provide an excellent proxy to regions across the tropics as a result of sharp hydroclimatic, anthropogenic, and pedohydrologic gradients across the archipelago. Hydroclimatic and pedohydrologic gradients are found across different elevations on single islands, as well as across the archipelago, whereas anthropogenic gradients reflect land use and land cover change across islands as population and growth in tourism have affected individual islands differently. This article highlights specific opportunities to further examine our understanding of the interactions between water and critical zone processes in tropical ecosystems, making connections between the Galápagos archipelago and much of the understudied tropics. The Galápagos archipelago offers a natural laboratory through which we can examine current threats to freshwater security as well as the dynamics of coupled natural and human systems.

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INTRODUCTION

In the past 50 years, global freshwater use has more than tripled.[1] Currently, the lack of potable water resources affects about half of the population in the tropics, and the proportion of people with access to safe drinking water is lower in the tropics than in any other region of the world.[2] Despite current water shortages facing tropical and subtropical latitudes, little research into tropical water cycling is carried out because of a limited research infrastructure coupled with lack of access to historical data, with the notable exception of Hawaii.[3–5] Projected population growth in the tropics combined with climate change and the lack of conservation efforts in many tropical countries is a growing concern amongst policymakers, economists, and defense analysts alike. However, sites like the Galápagos archipelago provide an opportunity for researchers to understand tropical water cycling across a set of inter- and intra-island gradients that cover microclimatic zones representative of many zones of the tropics. Furthermore, the well-described chronosequence,[6] climosequence,[7] and basaltic bedrock of Galápagos can lend further insight into prior hydrologic studies conducted at other tropical sites. Compared to Hawaii, for example, Galápagos has a much more complex eruption history, it is located right at the equator, it has a much narrower range of mean annual precipitation

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than does Hawaii.[8] Further, its population density is two orders of magnitude lower than Hawaii,[9,10] leading to limited urban and agricultural development in some of the Galapagos Islands.

Here, we focus on three gradients across the Galápagos archipelago that could serve as ideal proxies for tropical systems around the globe (Figure 1). Two of those are natural gradients that affect water cycling on the islands: a hydroclimatic gradient and a pedohydrologic gradient. The hydroclimatic gradient is elevation-dependent and results in microclimate zonation across the islands. A stark windward–leeward contrast across each island provides for an additional opportunity to compare vertical groundwater systems in wetter and drier environments. The second natural gradient is a pedohydrologic gradient, here defined as changing soil–water interactions across a chronosequence (islands of different age) and climosequence (temperature and precipitation variations with elevation). The third gradient is an inter-island, anthropogenic gradient driven by varying land use and land cover change. Although some islands are well-preserved and do not even allow tourist entry, over 70% of the landscape of San Cristóbal and almost 50% of Santa Cruz, the two most populated islands, have been dramatically altered by land use change and invasive species since 1987.[12]

Many environmental challenges in Galápagos are also present throughout the tropics, as growing populations and increasing tourism industries lead to water crises, or inadequate access to or management of freshwater resources.[13] This type of water crisis has been observed in numerous tropical systems, including agricultural zones,[14–17] mountainous areas,[18,19] coastal zones and islands.[20–23] These crises may be exacerbated by increasing tourism rates, which cause issues ranging from soil erosion and invasion by non-native biota[24–26] to poor water quality and high demands on groundwater systems.[27,28] We identify three particular challenges facing tropical hydrology that can be explored on the Galápagos: the importance of fog inputs into tropical systems, the effects of land use change on soil development and evolution, and the role of pedogenesis on hydraulic and hydrochemical fluxes through the soil column. We suggest that the identified gradients in Galápagos, coupled with the increasing human pressures, make the archipelago an ideal proxy for not just tropical and subtropical ocean islands, but for the continental tropics as well. The Galápagos as a natural laboratory for earth surface processes has been discussed previously[29] but the existing opportunities to understand the feedbacks between humans, the critical zone, and the water cycle place the

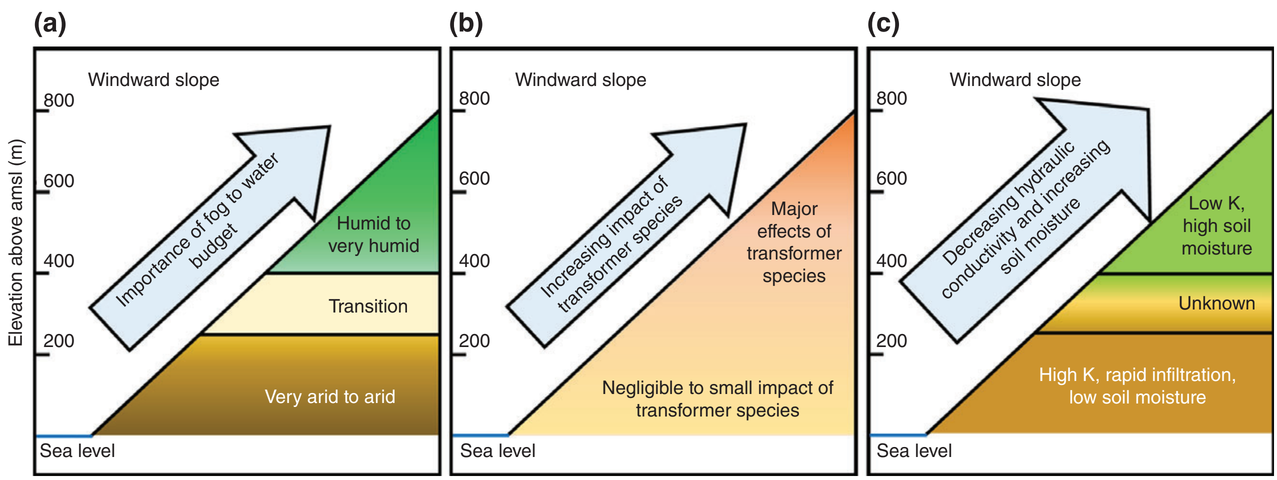

FIGURE 1 | Conceptual diagrams illustrating our hypotheses regarding elevation-controlled gradients across the Galápagos. (a) With an increase in elevation, the importance of fog-water input into the water budget will increase, with a large proportion of annual water input in the highlands coming from occult precipitation. At the dry coastal elevations which receive water from convective rainfall, the importance of fog water as an input into the groundwater system decreases to zero. (b) As a result of land use change on the archipelago, we suggest that invasive (i.e., 'transformer') species in the Galápagos have affected the highland areas more than they have the lowlands, largely due to greater water availability with higher elevations.[11] (c) The increase in the amount of water inputs to the system results in soils with a lower hydraulic conductivity and higher soil-moisture retention due to high concentrations of hydrated clays at high elevations, and high hydraulic conductivity and low soil-moisture retention at low elevations due to the limited amount of water received along the coast, the nature of the precipitation at low elevations, and the structural differences in the soil.

Galápagos in a unique position beyond its historical importance.

PHYSICAL AND ANTHROPOGENIC VARIABILITY

Hydroclimatic Gradients

Hydroclimatic gradients are significant because they affect the spatial and temporal distribution of freshwater cycling. The Galápagos Islands, for example, experience strong gradients in temperature and precipitation by elevation, and different behavior of precipitation, runoff, and groundwater–surface water interactions in each unique microclimatic zone (Figure 2). In addition to the presence of microclimates, the oscillation of the intertropical convergence zone (ITCZ) results in annually different seasons in the archipelago,[31] similar to other tropical sites that are also influenced by decadal-scale climate anomalies.[32] Because of the small spatial extent of the islands, the impact of climate on the hydroclimatic gradients can be constrained.

The effect of the precipitation–elevation gradient on island-wide recharge and discharge zones in the Galápagos has been hypothesized, although success in the identification of these zones is varied. A recent review article comparing the hydrology of San Cristóbal and Santa Cruz proposed groundwater systems that include perched aquifers, impounded dike aquifers, and a low-gradient basal aquifer[3] (Figure 3). A helicopter-borne time-domain electromagnetic sounding equipment (SkyTEM) survey carried out on San Cristóbal and Santa Cruz identified units comparable to those in other basaltic systems, shown in Figure 3.[33,34] Additional evidence for the hydrogeological units comes from surface water flow patterns[35,36] and geochemical studies of the groundwater.[37] This type of work in the Galápagos may be used as the basis for comparison in other tropical systems with highly fractured bedrock and high precipitation rates, including the Hawaiian islands.[3]

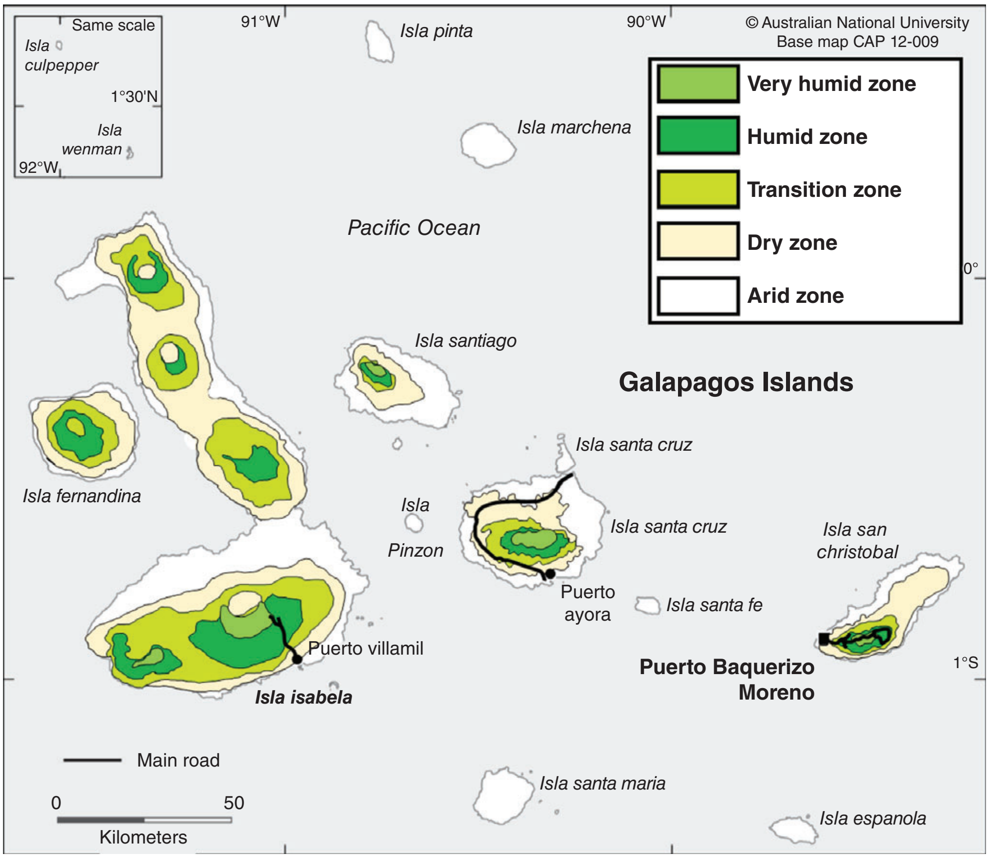

FIGURE 2 | Map of climate zones on Galápagos (after Huttel[30]) illustrating how climate zones are distributed based on elevation above sea level and wind direction. Note that several volcanoes on Isabela and the primary vent on Fernandina are calderas, and thus, have different climates because of an orographic effect, where the high walls of the caldera shield the inside of the caldera. Older islands with weathered topography no longer have distinctive calderas, so the orographic effect is felt across the entire island.

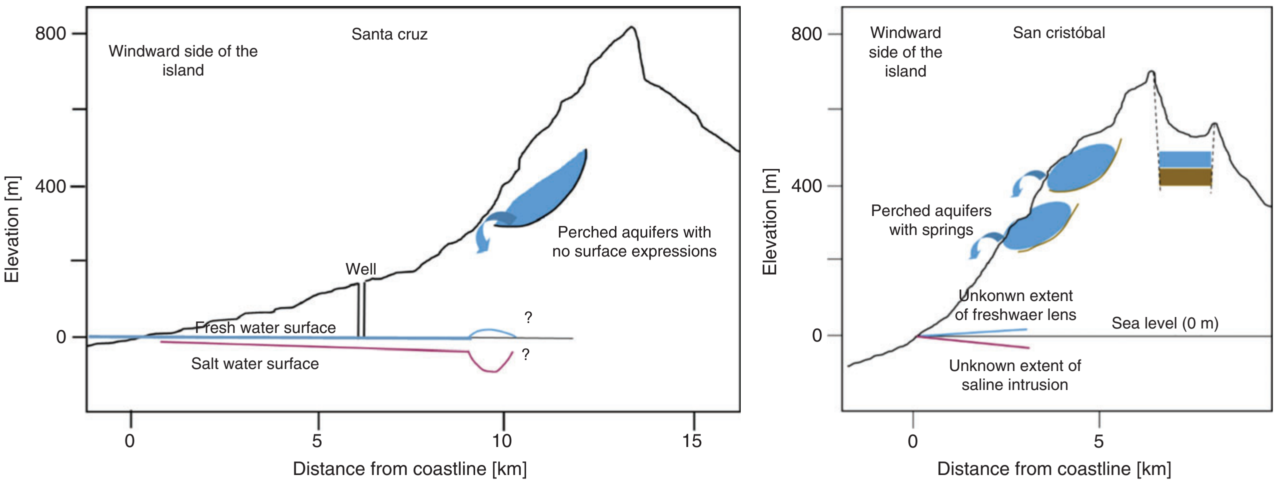

FIGURE 3 | Conceptual models of the hydrogeology of Santa Cruz and San Cristóbal, the most highly populated islands, based on SkyTEM surveys,[3,31,32] geochemical validation,[33] and our interpretation of work by Violette et al.[29]

In addition, because of its location in the central Pacific, changes in the strength and frequency of El Niño events, and the effects that extreme El Niño events can have on areas around the tropical Pacific, can be readily studied in the Galápagos. Recent investigations suggest that global climate change will result in higher convective precipitation rates on the islands than that has been observed in the past,[38] whereas other studies argue that climate change is already causing more distinct seasons on the archipelago.[39] Climate data from the Galápagos will complement previous work on the El Niño Southern Oscillation (ENSO) cycle completed throughout the tropics,[31,40] with the added advantage of providing insight into the manifestation of the ITCZ.[41,42]

This information highlights several themes to be studied in the Galápagos and applied across the tropics. First, understanding inputs into the tropical water cycle is key to understanding how climate change may affect surface water and groundwater storage and volume, and how precipitation regimes may change in the future. As a first step, we compiled rainfall isotope data (Figure 4) collected on Santa Cruz Island that show a clear seasonal difference associated with convective rainfall (January–June) and fog (June–December). However, these data highlight our knowledge gaps, as we do not yet understand the effects of ENSO or the spatial variability of precipitation inputs across the archipelago. In addition, the different microclimates across the Galápagos provide an opportunity to investigate how climate influences the partitioning of surface and shallow subsurface water fluxes into groundwater systems, thus offering proxies for larger groundwater–surface water systems throughout the tropics.

Anthropogenic Gradients

Land-based tourism destinations such as the Galápagos, and many other sites in the tropics, rely on a healthy natural ecosystem to attract tourists. However, strong pressures on native species as increasing demands by the growing native population and tourists can overburden tropical ecosystems. Although globally tourism does not directly use more than 1% of global water resources,[43] the residual effects of tourism in ecologically sensitive areas, including larger native populations to support the tourism industry[44] necessitates the importation of food, potable water, and supplies[45] to sustain human demand. Such indirect effects of increased tourism in tropical systems can be studied in a spatially constrained system like the Galápagos, and the implications can be applied to regions across the tropics.

Permanent human colonization of the Galápagos Islands first took place in the 1800s.[46] Between 1985 and 2005, the native population of the islands almost tripled and tourism to the islands exhibited a sixfold increase.[47] Both increases have placed pressure on the natural systems and infrastructure of the islands, as the archipelago has become an ecotourism hotspot for its biological significance,[30] natural beauty, and undisturbed nature. Because of the population growth on the archipelago, the land use/land cover change is evolving at higher rates than ever before in the Galápagos, as it has in the rest of the tropics.[48] There is much local concern for the fragile island ecosystem that is being impacted in both direct and indirect ways

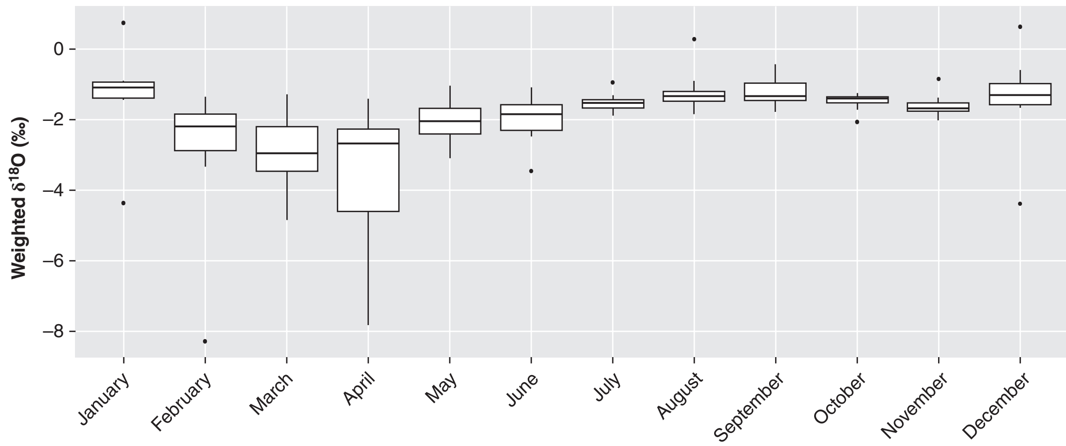

FIGURE 4 | Thirteen-year (1995-2008) averaged monthly means for δ18O in precipitation. Data in this original figure are derived from the Global Network of Isotopes in Precipitation dataset at a single coastal station located ~200 M.A.S.L., Santa Cruz Island, Galápagos. A seasonal shift in the δ18O is hypothesized to represent the different types of precipitation contributing to the ecosystem. Between December and May of non-El Niño years, the islands are dominated by convective rainfall events; between June and November, the lowlands are extremely dry and the highlands experience a nearly constant fog. Note that the ranges of δ18O values in the precipitation are smaller for fog inputs than for the convective rainfall inputs.

by the growing permanent and tourist populations, described as 'the main driver of change' on the islands in recent decades.[49] Recent work indicates that stakeholders across different sectors of the economy recognize that growing population and increasing tourism are driving increasing negative pressures on the environment.[50] Because Hawaii and other tropical islands have faced similar challenges,[8] the Galápagos can serve as a testing ground for best practices applied in other tropical island systems.

Numerous changes to the islands as a result of human population growth have been studied through on-island surveys of land use change and via remote sensing.[51] One of the current threats to the environment identified by surveys include the expansion of built area and infrastructure on the inhabited islands to accommodate the increase in tourism (Figure 5). The extension of built area has not only led to degradation of the landscape from construction and from encroachment on native plant habitat but has also led to an increase in the energy and fresh water demands of the islands. As a result of land use changes, the Galápagos archipelago is severely affected by invasive species that threaten native flora and fauna.[52] Because of the growing human population, the importation of food, oil, and water has provided a means for the introduction of these invasive species. Nearly 1500 new species are known to have been introduced to the Galápagos in the past 40 years, many of which are a direct result of the increased reliance on imported goods.[47] Remote sensing studies have quantified degradation along anthropogenic gradients in many ways (e.g., mapping distinct vegetative zones across the human-inhabited islands,[53] visualizing the spread of the invasive guava plant on the inhabited islands via the use of high spatial resolution imagery[54]). These disturbances all have direct and indirect impacts on hydrological processes and the partitioning of precipitation into evapotranspiration, runoff, and groundwater recharge.

Research into human impacts on the Galápagos has implications for other sites across the tropics experiencing increases in tourism and growing permanent populations. The propagation of invasive species and the spatial patterns of anthropogenic degradation observed on these islands may reveal patterns that provide insight into land use and land cover change across the tropics, as well as how conservation efforts may reverse the effects of overuse of natural resources. For example, several studies have shown the effects of remediation efforts in the Galápagos,[53] whereas others have shown the value in active control of invasive species.[54] Management practices developed in the Galápagos may become models for other ecologically fragile systems across the globe, especially because entire islands remain off-limits to tourists, rather than tropical systems like Hawaii or continental landmasses, where humans have left large environmental footprints.

Pedohydrologic Gradients

Similar to the Hawaiian islands, the Galápagos archipelago formed on a hotspot, resulting in a

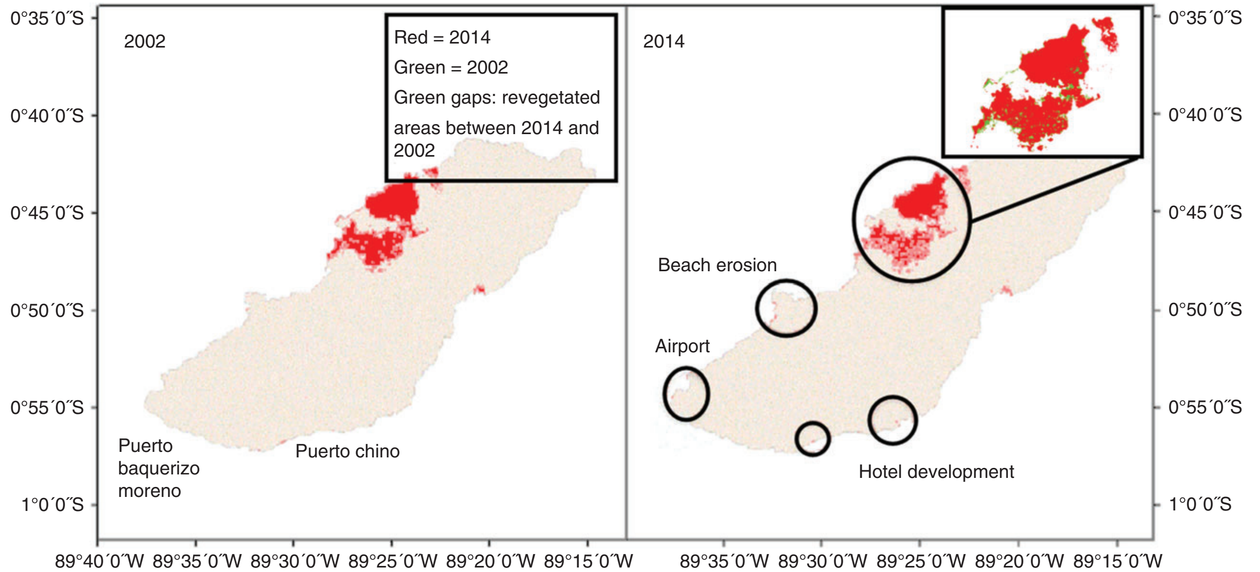

FIGURE 5 | Preliminary calculation of the normalized difference built-up index (NDBI) from Landsat imagery captured in 2002 and 2014 on San Cristóbal Island. Red indicates built-up/barren areas in 2002 and 2014, respectively, and green in the 2014 image indicates revegetated areas in the 12-year span. Note that cinder cones and younger lava flows exist in the NW portion of the island that has a notable barren appearance in both images. Circles indicate principal areas of change of barren/built-up land area over the intervening 12 years—such changes in NDBI are a result of increased infrastructure development and beach erosion.

chronosequence[55,56] in which different islands have well-constrained and different ages over the same bedrock type. Earth scientists have the opportunity to isolate the influence of soil development (pedogenesis) across different aged bedrock with similar land use histories,[57] providing an ideal experimental setting with findings pertinent to many parts of the tropics where land use histories are more complex. Several notable studies have already shed light on 'pedohydrologic', or soil–water interaction,[58] gradients across different elevations, which can be typified and then used to describe systems beyond the Galápagos archipelago.

On windward slopes of San Cristóbal (oldest) and Santa Cruz (younger), similar distributions of clays were observed throughout the soil column.[59] However, because of the microclimates present across different elevations, clays at high elevations are generally exposed to more meteoric water as a result of the fog, which results in swelling of the inter-sheet layers and lower hydraulic conductivity than soils at lower altitudes.[59] On other tropical islands, like Bali,[60] researchers found that the overlying soil type was an excellent predictor of groundwater behavior. The difference in the soil water content across elevations on Galápagos not only has implications for agricultural practices on the islands but also provides an excellent opportunity for an analogous site in the tropics of spatially intensive soil moisture observations (e.g., those carried out at the Tarrawarra catchment in Australia[61,62] or across the Appalachians and Piedmont in the United States[63,64]). In addition to understanding soil moisture distribution, the Galápagos provides a proving ground for understanding different island aquifer structures as a result of different eruption and structural histories.[3,65]

The limited research on the vadose zone in the Galápagos leaves many questions still to be resolved, including how changes in the hydraulic properties of soils across different microclimates affect soil moisture distribution, and whether the variables affecting soil moisture change with elevation. Findings could reveal connections between plant types, soil moisture, and aquifer recharge, as well as providing tropical hydrologists with the opportunity to test pedotransfer functions developed in more temperate climates.[66,67] On a theoretical level, the Galápagos provides an opportunity to study pedogenesis across the aforementioned hydroclimatic gradients on nearly homogeneous bedrock. Understanding soil formation processes, especially with regards to sources of soil material (e.g., atmospheric deposition, chemical weathering of bedrock) could aid in better understanding bedrock weathering rates and element depletion across a range of climates.[11,68]

CURRENT CHALLENGES AND OPPORTUNITIES

The Galápagos archipelago provides a unique environment for studying interactions between hydroclimatic, anthropogenic, and geologic gradients within a limited spatial extent (Figures 1, 2, and 5). Despite the islands' biological significance, research into the critical zone between the groundwater and the atmosphere is needed to enhance our understanding of how a variety of natural and anthropogenic stresses may impact the islands. The following section outlines several knowledge gaps in Galápagos that, when filled, could provide perspective to issues faced not only in these islands but throughout much of the understudied tropics.[69]

Fog as an Input into the Hydrologic System

Fog is a principal water source in many tropical and subtropical ecosystems,[70,71] especially those in high topographic positions where soil moisture is low. Studying fog and its relationship with the terrestrial system is paramount to understanding overall water availability under current conditions, and under future conditions of climate change.[72] Understanding the importance of fog as an input into the water budget of the Galápagos will provide insight into not only sources of water in the local groundwater system but also to understand the behavior of inputs into hydrologic systems across the tropics. The advantage of working with fog as an input into a system's water budget is that fog is often isotopically enriched in ^{2}H and ^{18}O compared to rain as a result of fractionation processes.[73–75]

Despite the importance of fog in the Galápagos, few studies have sought to understand the input of fog into the water budget of the islands. One study compared water inputs at humid high altitudes and arid low altitudes,[76] and the other used isotopes to trace sources of groundwater by elevation.[37] The use of stable isotopes of water as a tracer has been successful in tracing sources of groundwater[77–79] and sources of water for ecosystems.[80–82] In Hawaii, for example, evidence for highland fog contributing to perched aquifers that discharge into high elevation streams was determined through the use of stable isotopes.[4] Similar studies have been carried out in Puerto Rico[73,83] and mainland South America.[84,85] Because of the complex drainage and perched aquifers in fractured basaltic systems,[86] stable isotopic analyses of spring water leaving the groundwater system at varying elevations may provide evidence of variable flow paths within the bedrock. Such studies have proven useful on Easter Island,[87] Tahiti-Nui,[88] La Reúnion,[65] Gran Canaria,[89] and Hawaii.[5] Along with implications for understanding groundwater flow, non-rainfall atmospheric water inputs are a major source of water for plants throughout the tropics and into the mid-latitudes.[90–92] There have been a variety of studies that have used different collectors to understand the amount of water entering a system as a result of fog,[93] which is recognized as a significant precipitation input into ecosystems in both montane forests[81,94–98] and arid climates.[82,99–101] The Galápagos archipelago offers potential for understanding systems across the tropics for which fog is an input into the water budget. In addition, the small area of the islands and the well-defined microclimatic zones allows for the design of experiments that include high-frequency sampling of precipitation.

Rooting Depth and Soil Development in Stands of Native versus Invasive Species

Land use and land cover change in the Galápagos is mostly driven by the ever-increasing rate of invasion by non-native plant species. On San Cristóbal, 71% of the total agricultural area in 1987 was invaded by invasive species by 2006; on Santa Cruz, over 50% of agricultural land has been invaded by invasive species when no significant patches of invasive plant stands were even recorded in 1987.[12] The humid uplands of the Galápagos Islands (>400 m) are particularly impacted by invasive plants.[53] The most threatening of these non-native species are the trees *Psidium guajava* (guava) and *Cinchona succirubra* (quinine), the shrub *Lantana camara*, and the grass *Pennisetumun purpureum*.[102] Guava in particular exemplifies characteristics of a 'transformer species, an invasive species that changes character, condition, form or nature of ecosystems over substantial areas relative to the extent of that ecosystem'[103] because it is both drought- and flood-tolerant, grows well in a range of soil types and light availability regimes, and produces numerous seeds that are dispersed by a number of animal species.[54]

Despite the knowledge of the extent of invasive plant species in Galápagos[12,46,50,53,104,105] and across the tropics, the impact of invasive species on rooting depth, soil development, and unsaturated zone fluxes has not been investigated in many places beyond recent studies on the island of Maui, Hawaii.[106,107] The hydrologic and pedologic implications of invasive species remain poorly characterized across many tropical and subtropical regions, severely impairing remediation efforts. Studies of rooting depth in southern Florida demonstrated that *Melaleuca quinquenervia*, an invasive tree, was more competitive than the native species due to its ability to develop roots in the soil surface during soil-drying periods, its capacity to develop a deep root system at an early age, and its effectiveness as a rooter in wet and dry soils subject to a fluctuating water table.[108] Another study in the semiarid California coastal shrub revealed similar competitive capacities of invasive shrubs, as the removal of the invasive species resulted in more efficient water utilization by the native stands.[109] The ability of invasive understory plants to change soil functions has been investigated in other systems, and soils beneath the exotic plants were found to have higher pH and higher nitrification rates than soils below native plants.[110] A recent meta-analysis suggests that in terrestrial systems subject to plant invasions, litter decomposition rates are ~117% higher in the exotic species than in co-occurring native species, thus having a notable impact on soil nutrient cycling and development.[111] Furthermore, global climate models often lack information regarding rooting depth and root functioning,[112] as do regional primary productivity models in the tropics which lack spatially distributed data.[113] A better understanding of plant rooting depth in tropical systems and root responses to soil water availability could better inform ecohydrologic models of the redistribution of soil water by rooting systems and make them more representative of actual water balance parameters.[114] Measuring rooting depth across hydroclimatic and land use gradients would be informative of native and invasive vegetation dynamics across a range of climatic conditions, many of which are comparable to other areas in the tropics.

Soil Development across Precipitation Gradients

Hans Jenny's classical work[115] on pedogenesis introduced the concept of five soil-formation factors: the *climate*, the underlying *parent material*, the depth of *time* over which a soil has developed, the *biological activity* through and above the soil, and the *topography* upon which a soil develops. Although the Galápagos has not been a site of long-term soils research, it is an ideal place to understand how tropical soils develop across the same geologic setting,[116–118] with stable topography on shield volcanoes,[119] and well-constrained bedrock ages,[120] but under strong hydroclimatic and land-cover gradients. Climate varies greatly across the islands with the well-defined precipitation and temperature gradients with elevation, and land-cover changes include patches of diverse native and invasive species. Because of the stability of three of the five variables affecting soil formation, the Galápagos provides a natural laboratory in which watersheds can be used as 'controls' and single pedogenetic variables (climate, biota) can be studied at greater depth than in previous work.

There are very few studies of the Galápagos' soils, but numerous sites across the tropics and humid subtropics have been the focus of previous research. The Hawaiian islands, with the well-constrained chronosequence as one moves from the southeast (young) to the northwest (old), have been studied to understand how geologic age affects nutrient cycling and clay development[56,68,72] and how precipitation and temperature gradients in the subtropics affect soil carbon cycling, nutrient use, and the success of plant growth.[32,55,121] In Australia, the bedrock and climate variables were held 'constant' and nutrient cycling and isotopic fractionation as a result of changing biota were described.[122,123] In the Amazon, studies of soil change and differences in pedogenesis as a result of human disturbance have been extensively studied, while climate, bedrock, and age of the soils are held constant.[124,125] Additional studies into nutrient cycling in the Amazon have been successful because three of Jenny's factors of soil formation have been held constant.[126–128] The Luquillo Critical Zone Observatory in Puerto Rico has yielded many studies on rates of weathering and erosion in a climatic setting comparable to the highlands of the Galápagos, although the bedrock is less uniform.[129–132] The work done at Luquillo has implications for hypothesized weathering rates and modes of weathering in the Galápagos, and we suggest that many of the phenomena observed at Luquillo will be seen on the archipelago; we can test this hypothesis using a mass balance approach[133] to soil elements. Additional studies on soil gradients in which some of the factors of soil formation are held constant have been completed in areas undergoing land use change in China[134,135] and Hawaii,[136] where changes in nutrient concentrations in soils have long-term effects on the success of future generations of native species. Dust inputs as additional parent material for soils have been studied in California,[137] the Atlantic coast of the Americas,[138] and through surveys across the globe.[139–141] The Galápagos archipelago exhibits an ideal combination of stages of soil development and precipitation rates across which many gaps in our understanding of pedogenesis in tropical regions can be filled.

CONCLUSION

Coupling individual, spatially explicit processes with the knowledge of hydrologic processes throughout the understudied tropics is paramount in advancing knowledge of tropical hydrology and datasets that can be used as to constrain hydrologic models. There are several biome-wide mechanisms known to influence water availability in the tropics. Vegetation, for example, is known to moderate climate in the tropics by cooling the earth's surface through enhanced latent heat fluxes.[142] Furthermore, it is established that the hydrology of nonimpacted (near-natural) tropical montane forests is characterized by high rainfall, potential water input by cloud interception by plants, low transpiration rates, high streamflow and high rainfall interception rates, all of which could be lowered as forest use intensity by humans increases.[143] Changes in precipitation volume and type can also impact soils by affecting weathering and erosion rates, influencing the hydration of clay minerals, and ultimately changing the hydraulic conductivity of soils. With changing hydraulic properties, current water budget inputs of runoff, infiltration, and baseflow could change, resulting in more variable water resources and greater susceptibility to landslides and flooding. Because of the spatial variability of climates, biota, and soils on the Galápagos, we suggest that the islands can serve a useful site in concert with Hawaii to investigate the influence of hydrologic gradients in the tropics, and can provide valuable insight into how changing climates and growing populations may affect water resources around the world.

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