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Panama Canal Watershed Experiment- Agua Salud Project

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ABSTRACT
In Panama, the graying of agriculture is accompanied by fallowed pasture that is either being reforested or invaded by an Asian wild sugar cane, *Saccharum spontaneum*. Does reforestation result in more or less dry-season runoff in the seasonal tropics? The Agua Salud project, managed by the Smithsonian Tropical Research Institute (STRI), aims to answer this question. Our study is being undertaken within the Panama Canal watershed, on leased lands adjacent to the Soberania National Park, which is the former U.S. Canal Zone. Over the past two years we have planted over 150,000 trees, both native timber species and teak, in catchments that were until recently grazed pastures. We have instrumented these plantation catchments as well as control catchments that consist of pasture, old-growth forest, old re-growth forest, early secondary succession, and *S. spontaneum*. Instrumentation installed to date includes 16 on-stream weirs in catchments that range from 8 to 400 ha, a triple rain-gage network, two eddy-covariance systems, surface-energy-balance station, 10 shallow groundwater monitoring wells, and automated water quality samplers. Studies completed to date include throughfall studies and soils analysis, a 25-year chronosequence in 108 secondary succession plots, and LiDAR overflights. Hydrologic works in progress include above- and below-ground carbon analyses, monitoring of all hydrologic and meteorological variables, and tracer studies using both natural and introduced tracers, as well as observations of shallow subsurface flow using electrical resistivity tomography at the hillslope scale. We are also educating large numbers of undergraduate, graduate, and post-doctoral students in the important field of tropical hydrology in collaboration with Panamanian universities. Data and observations will guide the development of conceptual and physics-based hydrologic models to enable predictions of the affect of reforestation on the water-balance at time scales ranging from single-events to annual. Models will be used to up-scale knowledge developed at the plantation and catchment scale to the entire Panama Canal watershed. Knowledge gained and models developed will help aid in land-use management decisions in Panama, the Caribbean basin, and much of the seasonal tropics. Our project is working in close cooperation with the Panama Canal Authority and the National Environmental Authority of Panama.

Introduction
Due to the construction of the Panama Canal, the Canal watershed has the distinction of being the only substantial watershed on the planet that discharges into two oceans. A second distinguishing feature is that it has the longest and most complete hydrological and land-use change record of any watershed of comparable size in the tropics. This makes it an appealing site for tropical research on hydrologic behavior, function, and ecosystem services. Our project builds upon a significant body of prior work in the Panama Canal Watershed, including the Panama Canal Watershed Monitoring Project,

which was a joint project between the Panamanian Government and the U.S. Agency for International Development (Heckadon Moreno, *et al.* 1999; Condit *et al.*, 2001; and Ibáñez *et al.*, 2001).

The largest river in the Panama Canal Watershed is the Rio Chagres, which was dammed to create Lake Gatun, and create the trans-isthmian water crossing at 26 m (85 ft) elevation. The upper Rio Chagres is a protected natural park that is 98% old-growth forest (Ibáñez *et al*., 2001). The Upper Rio Chagres watershed was studied by a multi-disciplinary group of researchers in 2002-2003, as summarized in Harmon (2005). The entire Canal basin is covered by a dense network of hydrological monitoring stations including approximately 30 streamflow gages, more than 70 rain gages, 20 meteorological stations, twice-daily weather balloon soundings, and S-band weather radar. The Panama Canal Authority (ACP) performs regular annual assessments of land cover within the Canal watershed.

With enough time, the intense weathering of igneous rocks in the seasonal humid tropics produces soils dominated by aluminum and iron sesquioxides (Stallard, 1988). Precursor soils are Acrisols and Ferralsols, with the latter typically older and dominant on continental cratons. The study area and much of the eastern Canal Basin are underlain mostly by basaltic and andesitic rocks of a Cretaceous island arc (Stewart, *et al.*, 1980, Wörner, *et al.*, 2005). The soils are broadly classified as Acrisols and are up to 20 m in thickness. These soils are dominated by the clay minerals kaolinite and halloysite, with small amounts of illite, smecitite, and interlayered illite/smectite (Harrison *et al*., 2005). Deeper weathering profiles with higher proportions of clay are present primarily in upper slope positions (Harrison *et al*., 2005). The soils of the tropics have been poorly mapped in general, so the exact coverage of these soils is uncertain. Together, Acrisols and Ferralsols cover 1,960,000 km^2 or 57% of the humid tropics (Fig. 1; Richter and Babbar, 1991; Kaufman *et al*., 1998). The main difference between these two soils is an increase in clay content with depth in the case of Acrisols. Near surface, Acrisols and Ferrisols have similar porosity and plant available moisture, and are frequently well drained and structured (Kaufman *et al*., 1998, Elsenbeer, 2001). Tropical vegetation, which we hypothesize is the major driver of the rapid flow capacity, is highly diverse across the tropics. Thus, we expect that our results will be applicable to some degree in areas of the tropics covered by Acrisols and Ferralsols.

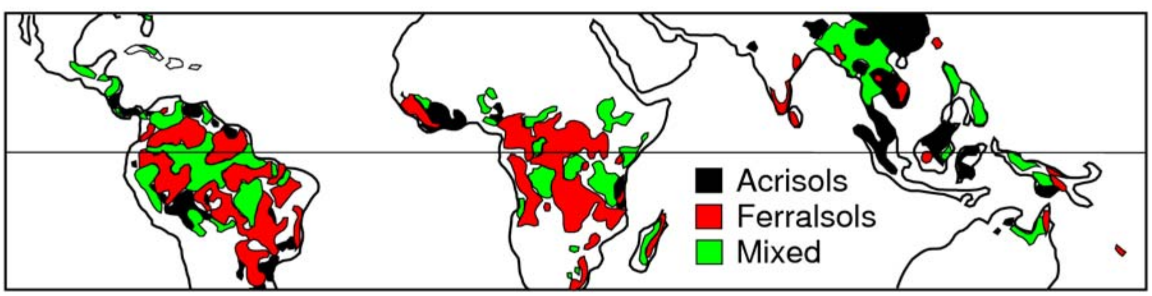

Figure 1: Distribution of Acrisols, Ferralsols, and dominant mixes of the two throughout the tropics (after FAO-GIS, 1998).

Macropores and pipes are produced by roots, soil fauna, or desiccation cracking. They provide pathways for water to bypass the soil matrix and to move downslope to the shallow aquifer at velocities of several mm/sec (e.g. Beven and Germann, 1982; Mosley 1979, 1982). Soil physics dictates that water will enter soil pipes or macropores only under positive pressure (Hillel, 1998). Once water is inside the macropore network, it can be transported downslope through otherwise unsaturated soils. Many studies indicate that the importance of macropore flow increases with the amount of event precipitation. An abundance of macropores (both desiccation and tension cracks) and pipes was observed in all soil pits opened at three sites in the Upper Rio Chagres watershed during a reconnaissance study conducted in 2002 (Harrison *et al*., 2005, Hendrickx *et al*., 2005), as well as those dug near Gamboa (Niedzialek, 2007; Niedzialek and Ogden, 2005). Subsurface pipes were observed by Hendrickx *et al*. (2005) with diameters up to about 10 cm. The abundance of macropores and pipes in the Upper Rio Chagres watershed is much larger than ever observed in soils in the more temperate regions of western Europe and New Zealand (J.B.J. Harrison and J.M.H.Hendrickx, pers. comm.). Señor P. Rojas, park ranger in the Rio Chagres watershed, has often observed jets of water from macropore pipes during heavy precipitation events (Hendrickx *et al*. 2005) indicating that the pipe network is hydraulically well connected. The exfiltration of water from pipes on tropical hill slopes has also been reported by Bonell *et al*. (1984) and Elsenbeer and Cassel (1991), and Niedzialek (2007) at a high landscape position at Cerro Pelado near Gamboa, Panama, during a 4-hour, 100 mm rainstorm in November, 2006.

Study Sites

The STRI Panama Canal Watershed Experiment takes advantage of new and existing hydrologic infrastructure. The weirs shown at Ciudad del Arbol on Figure 2 where built in the 1920's. We located these long-neglected weirs and re-activated them in support of our project. We have also installed over thirty rain gages at ten locations across the study area.

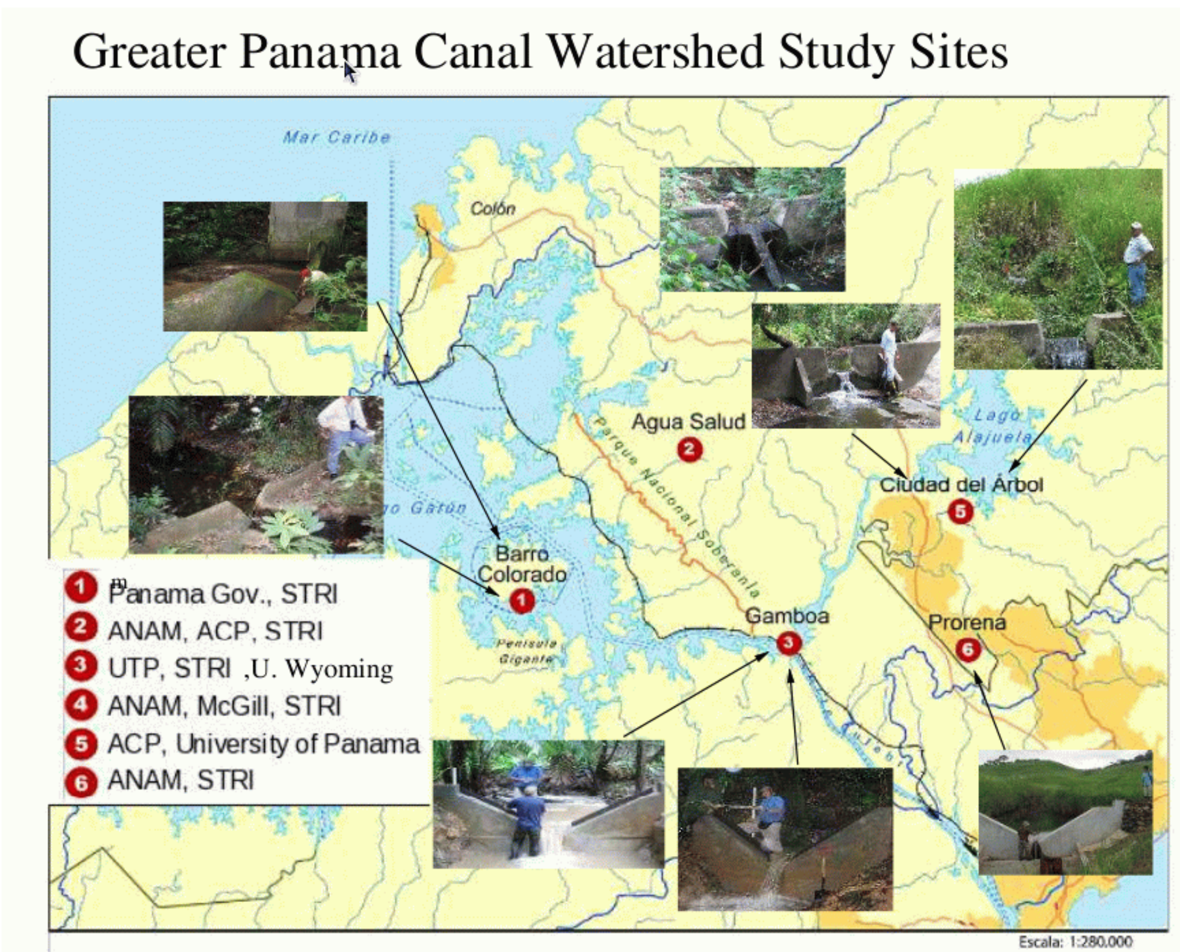

Figure 2: Study sites and weirs in the greater Panama Canal Watershed

The plantation, old-regrowth and pasture study sites of the Agua Salud project are shown in Figure 3, together with a background of land-use. The forest in the catchment labeled 50% deforested is

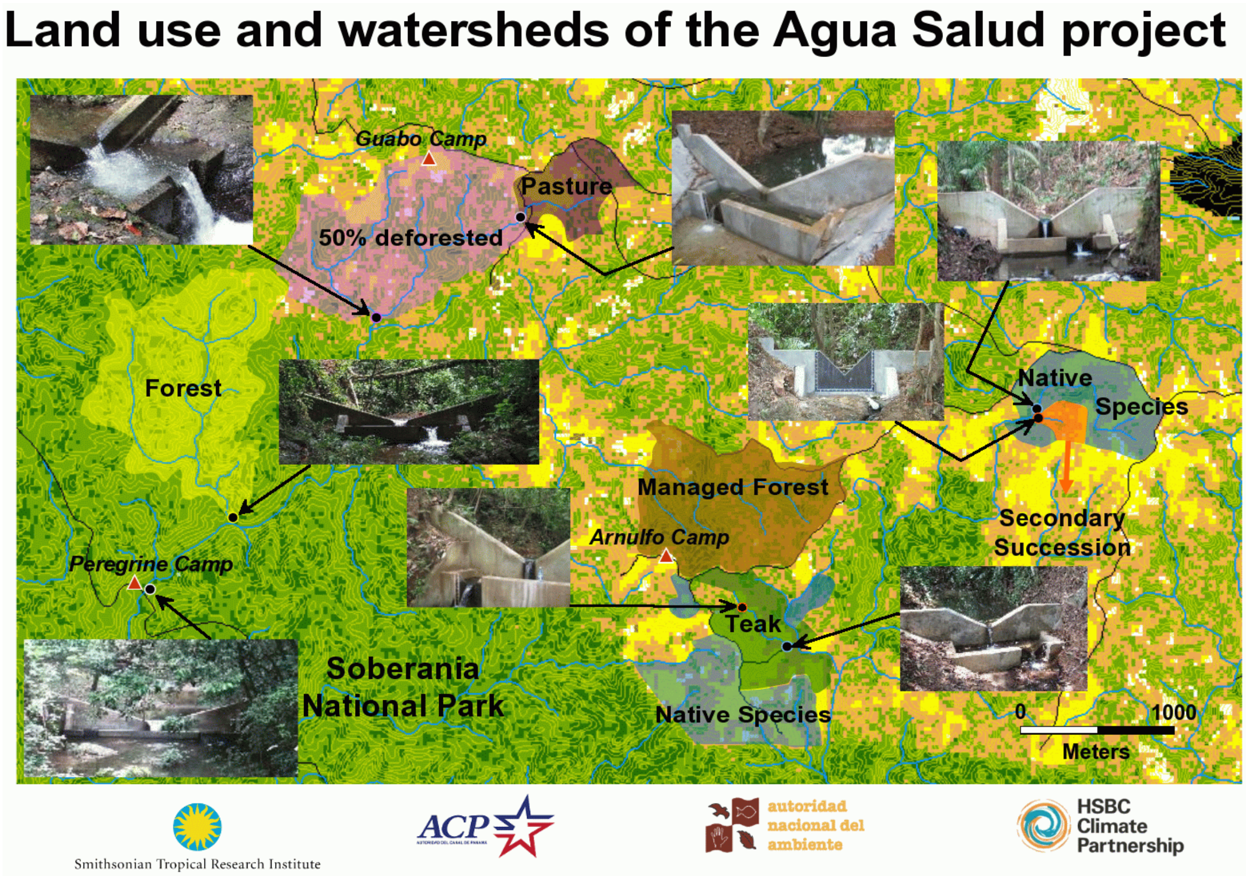

Figure 3: Study catchments in the Agua Salud project showing land-use, plantations and weirs. Darker greens are forest.

regrowth due to non-interventional succession. The pasture catchment is being maintained in active grazing. The teak and native-species plantations are being fertilized annually and the grass and competing native vegetation are being manually trimmed on a regular basis.

One of the hypotheses being examined in the Agua Salud project is that reforestation from pasture results in increased biological activity in the near-subsurface bioturbation layer, which will increase infiltration and ground water recharge. Increased ground water recharge will increase dry season river flows. One of the tools being used to test this hypothesis is electrical resistivity tomography (ERT). Figure 4 shows results of an ERT test using slightly salty water, for a 400% conductivity contrast, applied at the upslope end of the graph. Five hours after the start of the test, the electrical conductivity in the active layer showed approximately 20% increase in conductivity.

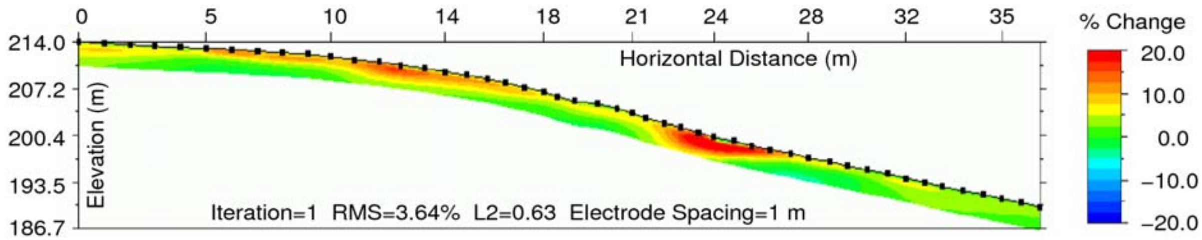

Figure 4: Results of ERT study conducted using downslope flowing salinity contrast applied in the teak plantation in July, 2009, showing percent change in electrical conductivity 5 hours after application at x=0. The active layer is readily visible.

Conclusions

The STRI Agua Salud project aims at improving our understanding of the ecosystem services provided by tropical watersheds including production of consistent high-quality supplies of water for human consumption and Canal operations. Figure 5 shows significant differences between dry-season streamflow behavior as a function of land-use in closely paired catchments. Our experiment is fully operational and beginning to yield interesting results. Better yet, the project infrastructure is positioned to observe a significant period of aforestation in a tropical watershed.

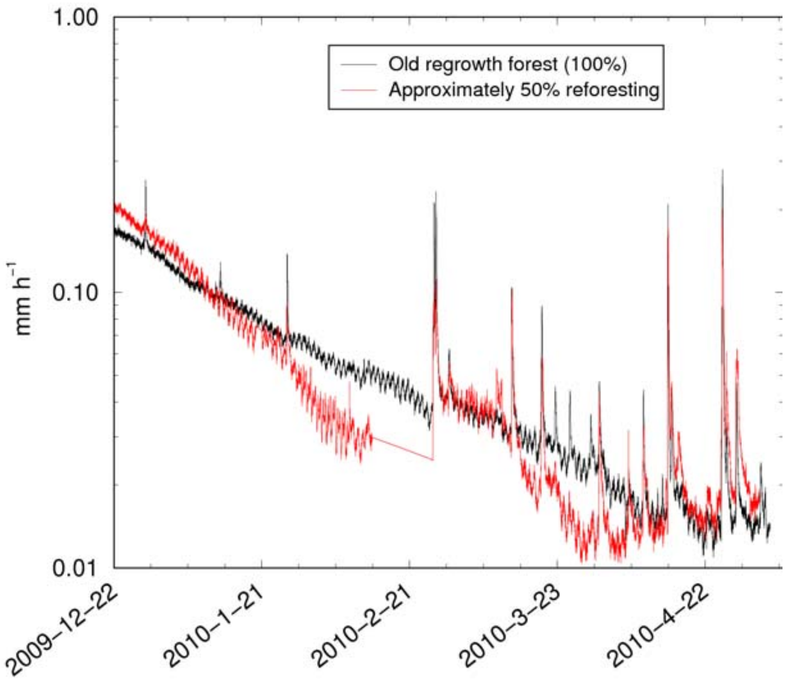

Figure 5: Significant dry-season flow differences between old-regrowth forest and approximately 50% reforesting watersheds shown on Figure 3.

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