Land-Cover / Land-Use Change Program

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Progress Report

Project Title: Vulnerability and adaptive management of tropical coastal wetlands in the context of land use and climate changes

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Abstract:

The tropical island of Puerto Rico leads the reforestation in the Central and South America, which supports the Forest Transition Model with the economic shift from agriculture to industry and service as the main driver. Upon agricultural abandonment, migration to urban and suburban areas led to urbanization and urban sprawl. While reforestation and conservation policies may enlarge and aggregate forest patches, urbanization and urban sprawl may do the reverse. While having strong interference with coastal development, tropical wetlands are becoming vulnerable to LCLUC and climate changes, such as drought and sea level rise. The key objective of this project is to answer the scientific question of "*How the land cover and land use changes, interacting with the climate change, impact the vulnerability of tropical coastal wetlands spatiotemporally?*"

In 2015, **1)** we further investigated the ecohydrological processes of the watersheds feeding the major wetlands in response to climate changes and LCLUC. Specifically, we emphasized how the changes in landscape composition and fragmentation, as found in our previous work, and the projected climate in the next 50 years will alter ecohydrological processes.

2) In addition to changes in climate and hydrological processes, sea level rise (SLR) poses another serious threat to the coastal wetlands, often confronting with coastal developments. Coastal infrastructure and agriculture just above the extreme high tide line may limit or even eliminate opportunities for wetland migration under SLR. In Puerto Rico coastal wetlands have been decimated by land use changes related to agriculture. Drainage canals were instrumented to drain coastal wetlands for agriculture. As a result of agricultural abandonment, extensive coastal areas have reverted to wetland. We applied the Sea Level Affecting Marsh Model to test the hypotheses of: a) the migration capability of coastal wetlands, especially the freshwater systems,

is limited by coastal development under SLR, thus the phenomenon of “coastal squeeze” will appear; b) the agriculture drainage canals will exacerbate the SLR effects on coastal wetlands.

3) Consistent mapping of tropical forest change is essential for Global Climate and Land Surface Modeling, but is highly restricted by persistent cloud cover. For example, the most recent land cover/use map available for Puerto Rico is for 2000, within which the El Yunque Forest was delineated using the images in 1980s. To detect recent forest changes in Puerto Rico, we start to fuse the ALOS PALSAR images with the Landsat TM images in 2010 for land cover classification.

Our results showed that:

1) The hydrological process in terms of water discharge per watershed area is significantly increased by mean annual rainfall and interestingly by the fractions of pasture in the watersheds, but significantly reduced by the fragmentation of the land cover. Most watersheds in Puerto Rico are characterized by reforestation in the price of pasture and agriculture. Pasture consumes less water than forest, so that the effect of the fractions of pasture in the watersheds on water yield is positive. The landscape fragmentation tends to facilitate the reuse of runoff in the downstream vegetation. In addition, more edges may induce more evapotranspiration. These may explain why the hydrological service is reduced by landscape fragmentation. The big discharge is significantly reduced by the forest cover and the edge-to-area ratio of pasture. Tropical forest has deep roots that enhance infiltration and increase soil water storage, so that the big flows significantly decrease with increase in forest cover.

2) Based on the downgraded climate models for Puerto Rico (Hayhoe 2013) for IPCC 3 emission scenarios A2 (isolated development, little collaboration), A1B (collaboration between countries with balanced energy use), and B1 (economic globalization with high technology development), the watersheds of Rio Grande de Loiza at Caguas in the mountains and Rio Culebrinas in the northwest both showed consistently decreasing discharge in the next 50 years. The average annual rate of decreasing is -0.64 and -1.27 M ton y^{-2} for Rio Grande Loiza and Rio Culebrinas watersheds, respectively.

3) Land-use/cover changes coupled with SLR will have a synergistic effect on wetland migration in our study area. The three freshwater wetland types, inland fresh marsh, swamp, and inland open water, lose areas under all SLR scenarios as estuarine and marine systems migrate inland. A 0.5 or 1 meter SLR will have very low effects on freshwater systems. However, under the 1.5 or 2 meter SLR scenarios the reductions in freshwater systems could potentially have an effect on the composition, distribution, and abundance of plant and animal species.

4) Historic and prevailing land use alterations related to intense agriculture may exacerbate the effects that SLR will have on the migration of wetlands. Existing drainage canals will facilitate the influx of salt water inland and hence, accelerate the migration of estuarine systems into areas of freshwater wetlands.

5) Future management to mitigating the effects of SLR on coastal systems should include the restoration of natural hydrological features such as the filling of manmade drainage canals in the coastal alluvial plains of Puerto Rico, as a precautionary measure to protect the wetlands.

6) Inclusion of SAR images in the land cover mapping contributed to higher accuracy than using the optical images alone. The texture parameter of homogeneity could be used to delineate cloud forests where clouds are persistent. Our preliminary results on the forest changes in 2000 – 2010 revealed the continuous reforestation in Puerto Rico.

Progress:

1) ***Ecohydrological processes of the watersheds feeding the major wetlands in response to changes in landscape composition and configuration and future climate***

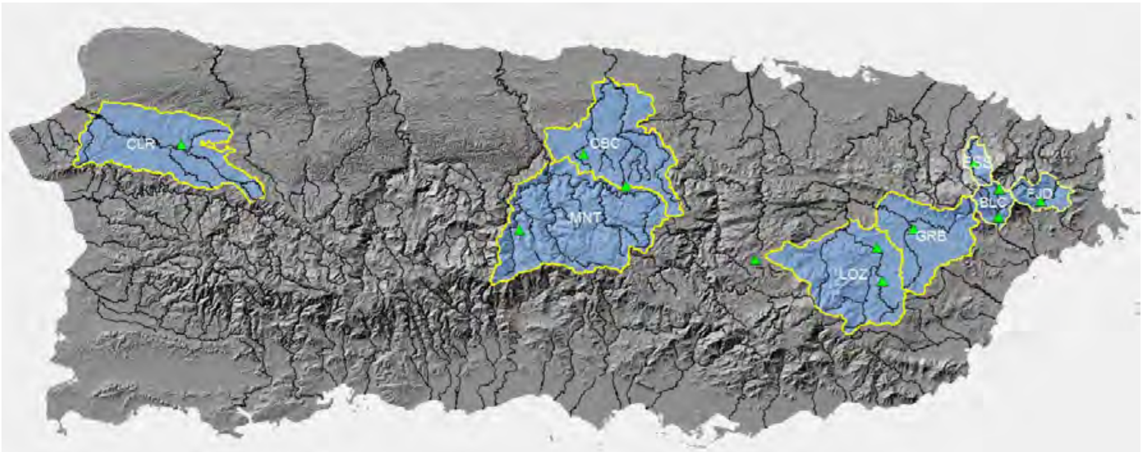

Figure 1 Selected watersheds feeding the major wetlands in this study. FJD, Rio Fajardo, ESS, Rio Espiritu Santo, BLC, Rio Blanco, GRB, Rio Gurabo, LOZ, Rio Grande de Loiza, CBC, Rio Cibuco, MNT, Rio Grande de Manati, and CLR, Rio Culebrinas.
Green points represent the locations of the meteorological stations.

Both land use and climate changes can alter the ecohydrological processes in coastal wetlands and their vicinity. Therefore it is important to analyze the vulnerability of coastal wetlands to changes in land use and climate at the watershed scales.
To investigate how hydrological processes respond to climate change and variation in land cover, we selected eight tropical upland watersheds in Puerto Rico feeding the major wetlands, to simulate the discharge in the past and in the future (Fig. 1). Daily rainfall and temperature from inside and nearby meteorological stations were used to drive the SWAT (Soil Water Assessment Tool) model. The selection of these eight watersheds is based on the criteria that there exist long-term discharge observations by USGS and corresponding rainfall and temperature observations. The simulated daily discharge is compared with the USGS discharge measurement, and we found the correlation between simulated and observed varies from 0.79 to 0.92 (Figs 2 and 3).

Ecohydrological processes in response to changes in landscape composition and configuration

Long term meteorological records of daily rainfall, maximum and minimum temperature are used to drive the model with land cover maps of 1977, 1991, and 2000. Averaged annual discharge and large discharge above 95% of the daily values during 1981 to 2014 are calculated and divided by the area for each watershed. At the same time, we calculate the landscape pattern indices such as area proportions and edge-to-area ratio of crops, urban, forest, and pasture. The edge-to-area ratios of the four land cove types are summed up to give a combined landscape fragmentation index.

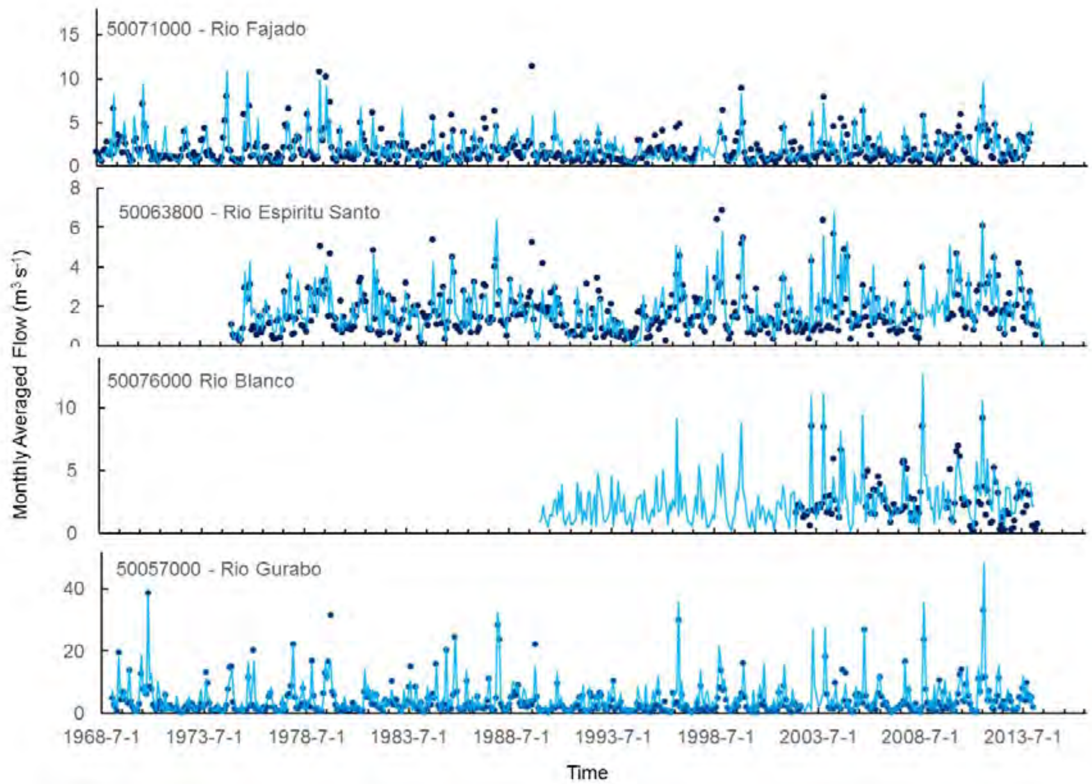

Figure 2 Simulated versus observed annual discharge for FJD, ESS, BLC, and GRB.

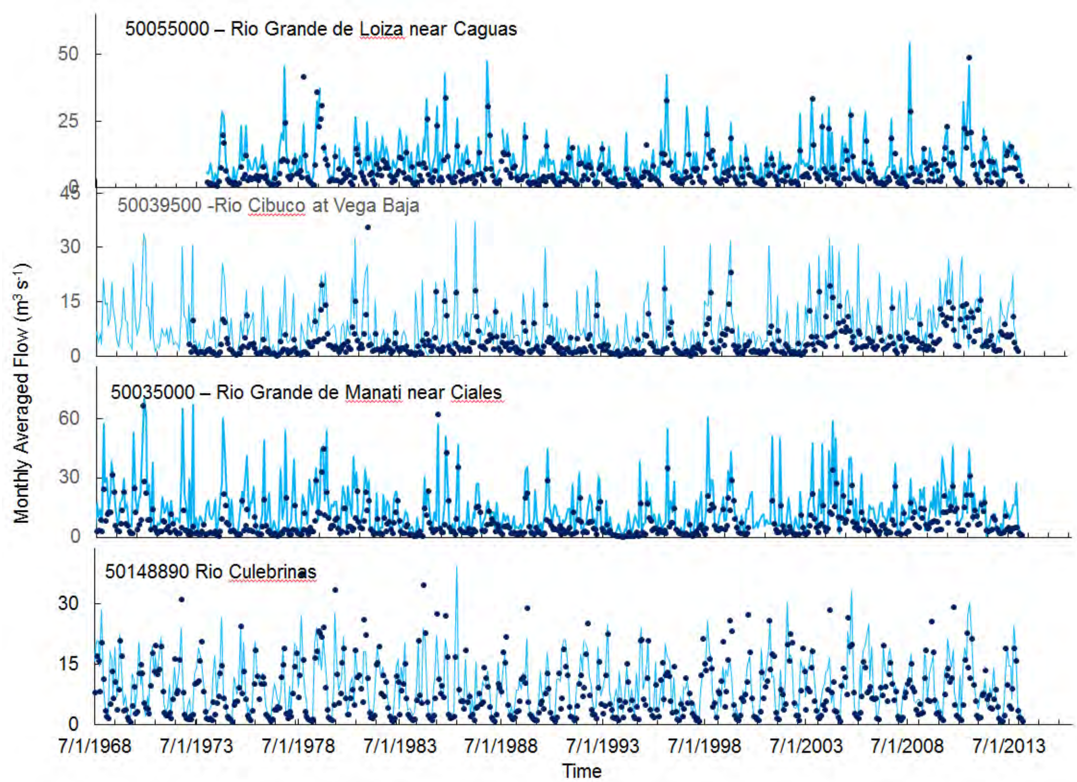

Figure 3 Simulated versus observed annual discharge for LOZ, CBC, MNT, and CLR.

To obtain the relationship between the hydrological processes of tropical watersheds and climate and land cover changes, we apply linear mixed effect model to regress the mean annual discharge per watershed area, F in Mt y^{-1} km^{-2}, on mean annual rainfall, R in mm, and landscape indices. The following significant relationship among the watersheds was found (Equation 1).

$$F_{fixed} = -0.553 + 0.00886R + 0.0569A_g - 0.0138P \qquad (1)$$

where F_{fixed} is the component of F explained by variation among the watersheds. This relation indicates that the hydrological process (water discharge) per watershed area is significantly increased by mean annual rainfall (R) and interestingly by the fractions of pasture in the watersheds (A_g), but significantly reduced by the fragmentation of the land cover (P). Forest cover does not appear in this equation. However, most watersheds in Puerto Rico are characterized by reforestation in the price of pasture and agriculture. Pasture consumes less water than forest, so that the effect of A_g is positive in Equation (1). The landscape fragmentation actually facilitates the reuse of runoff in the downstream vegetation. In addition, more edges may induce more evapotranspiration. These may explain why the hydrological service is reduced by landscape fragmentation.

Similarly, we apply linear mixed effect model to regress the mean annual big discharge F_b (daily discharge greater than 95% based on land cover in 1977) per watershed area on rainfall and land cover indices, and found the following relationship (Equation 2).

$$F_{b,fixed} = 0.772 - 0.187A_f - 0.302P_g \qquad (2)$$

Surprisingly, the big discharge does not depend significantly on rainfall, but is significantly reduced by the forest cover and the edge-to-area ratio of pasture. Tropical forest has deep roots that facilitate infiltration and increase soil water storage, so that the big flows significantly decreased with increase in forest cover. Again the big flow is also reduced by the pasture fragmentation during the forest expansion.

Ecohydrological processes in response to future climate

Based on the downgraded climate models for Puerto Rico (Hayhoe 2013) for IPCC 3 emission scenarios A2 (isolated development, little collaboration), A1B (collaboration between countries with balanced energy use), and B1 (economic globalization with high technology development), we simulated annual discharges of two watersheds, i.e. Rio Grande de Loiza at Caguas in the mountains and Rio Culebrinas in the northwest. Average discharge rate and standard deviations were illustrated in Fig 4. Both watersheds showed consistently decreasing discharge over the period from 2011 to 2060. And the average annual rate of decreasing is -0.64 and -1.27 M ton y^{-2} for Rio Grande Loiza and Rio Culebrinas watersheds, respectively.

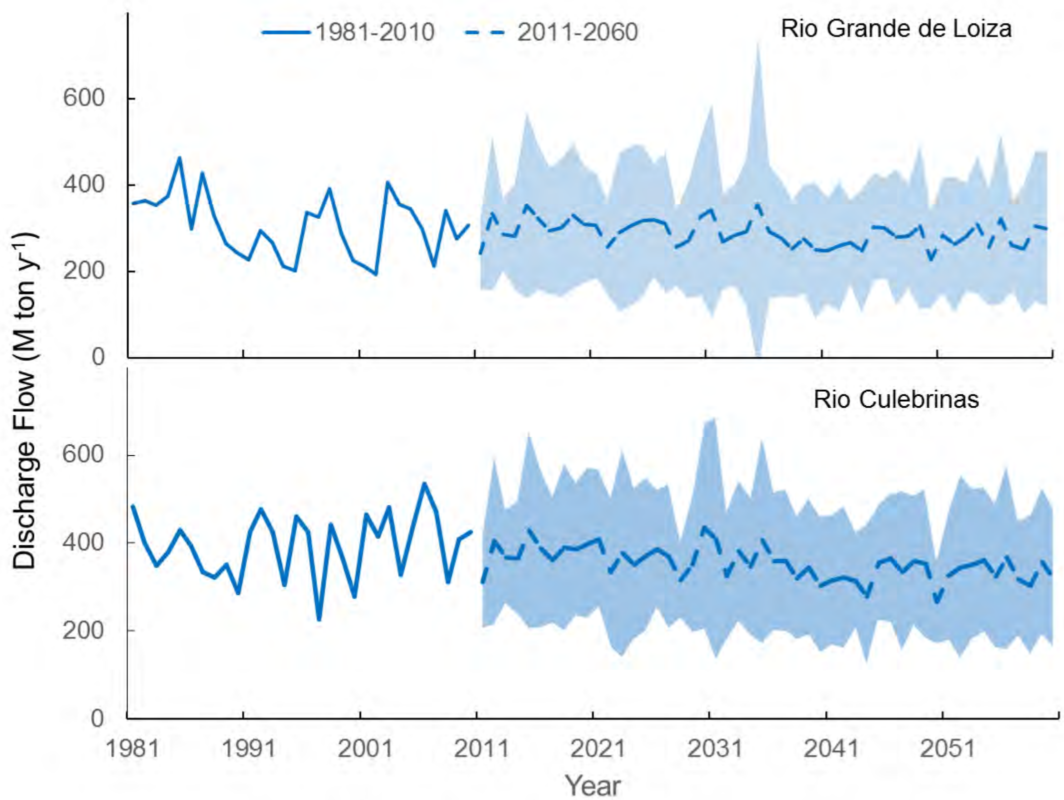

Figure 4 Average and one standard deviation of the projected average trends of annual discharge for Rio Grande de Loiza and Rio Culebrinas.

2) *Sea Level Rise Effects on Coastal Wetlands Systems*

Global climate changes are mainly characterized by warmed atmosphere/oceans, rapidly diminished snow/ice, and risen sea level (SLR). Current projections suggest SLR scenarios over one meter are possible by 2100, posing potential serious threats on coastal wetlands and human infrastructure. The migration of coastal wetlands to inlands might be blocked by coastal developments and agriculture right above the high tide line.

The land use history of Puerto Rico in the coastal area involves intensive agriculture which drained wetlands before 1940s and then agriculture abandonment followed by wetlands recovery and coastal development. The land use legacy in intensive coastal agriculture may modulate wetlands migration and exacerbate the SLR effects.

Our objectives are to test the hypotheses of: a) the migration capability of coastal wetlands, especially the freshwater systems, is limited by coastal development under SLR, thus the phenomenon of "coastal squeeze" will appear; b) the agriculture drainage canals will exacerbate the SLR effects on coastal wetlands.

We selected the wetlands in the northern coastal plain of Puerto Rico, west of the San Juan Metropolitan area, as our study area (Fig. 5). The coastal area was heavily drained in the agricultural era and now has wetlands recovered, together with intense urbanization (Fig. 6).

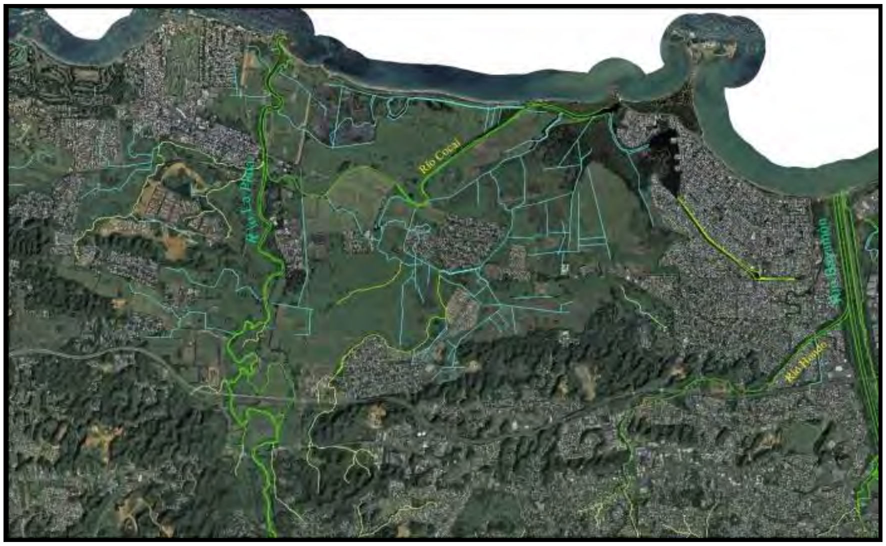

Figure 5 Hydrological systems of the study area in Northern Puerto Rico.
Green, rivers, yellow, ravines, light blue, drainage canals.

We applied the Sea Level Affecting Marshes Model (SLAMM) to assess the SLR effects on the coastal wetlands migration. SLAMM simulates the dominant processes involved in the conversion of wetlands and coasts as well as the long-term changes caused by SLR (Park et al, 1989; Clough et al, 2010). The processes of inundation, erosion, over-wash, saturation, and accretion are simulated to project wetland type migration. We choose the SLR scenarios of 0.5, 1, 1.5, and 2 meters for the year 2100.

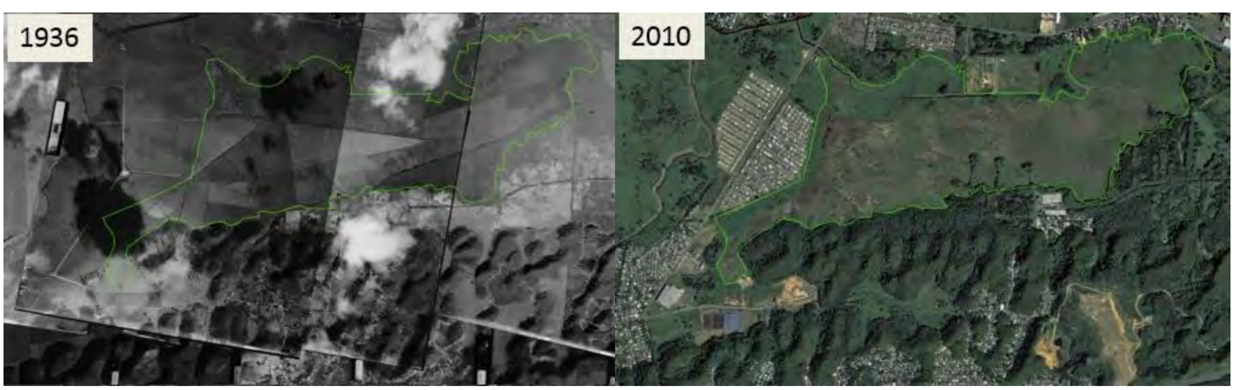

Figure 6 Historical land use changes in the coastal plain
(from agriculture to wetlands recovery and urban development).

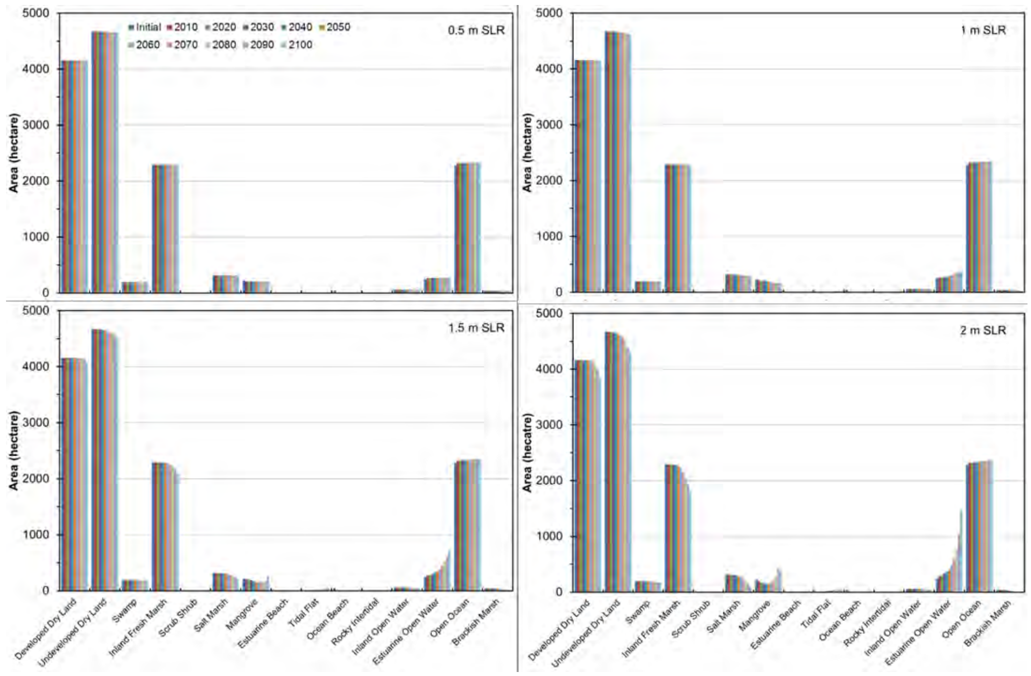

Figure 7 Changes in the distribution area of wetland types
under 0.5, 1, 1.5, and 2 m SLR scenarios.

The freshwater systems (i.e. swamp, inland fresh marsh and open water), irregularly flooded marsh, salt marsh, ocean beach, and rocky intertidal would lose area under all scenarios at the end of the simulation (Fig. 7). Estuarine open water, tidal flats, and open oceans increase in area under all scenarios. Mangroves have various responses to different SLR scenarios. A 0.5 or 1 meter SLR will have very low effects on freshwater systems and the loss of their total area as a result of the migration of estuarine wetlands is low. Under the 1.5 or 2 meter SLR scenarios the reductions in freshwater systems could potentially have an effect on the composition, distribution, and abundance of plant and animal species.

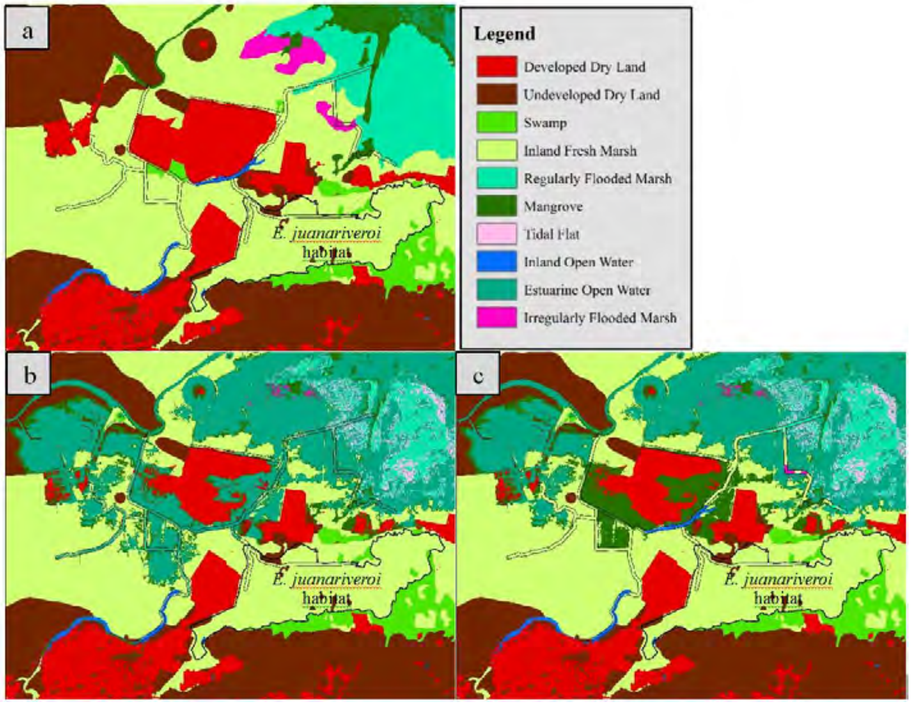

Figure 8 Drainage Canal Effect on wetlands migration at a 2 meter SLR scenario. Wetlands distributions under a) initial condition, b) not-filled canals, and c) filled canals

The persistent drainage canal system is effectively accelerating the migration of estuarine systems into the freshwater marsh region by facilitating the influx of saltwater at a faster pace than that allowed by the natural topography of the alluvial plains (Fig. 8). Filling drainage canals reduces the net loss of two types of palustrine systems. The loss of inland freshwater marsh is reduced by 46.6 ha and inland open water loss is reduced by 4.3 ha. When the drainage canals are not managed, the model predicts a significant portion of wetlands in this area, 339.2 ha, will ultimately convert into open estuarine water. Filling drainage canals arrests the transformation by protecting 46.6 ha of the inland freshwater marsh in the southern limits of its range and increasing the mangrove coverage at the end of the century by 130 ha.

Our analyses suggest that future management to mitigating the effects of SLR on coastal systems should include the restoration of natural hydrological features such as the filling of manmade drainage canals constructed in agricultural era, as a precautionary measure to protect the wetlands.

3) <u>*Fusing Landsat TM and PALSAR images to detect forest transitions in the tropics*</u>

Changes in tropical forests and their feedbacks to climate are major components of the interactions between terrestrial systems and climate. Consistent mapping of tropical forest change is essential for Global Climate and Land Surface Modeling, but is highly restricted by persistent cloud cover. For example, the most recent land cover/use map available for Puerto

Rico is for 2000, with the El Yunque National Forests delineated using the images in 1980s. This greatly hinders the LCLUC research in the tropics, such as Puerto Rico. To complement optical remote sensing in cloudy tropics, recent efforts have been made to fuse the optical data with the data from radar, such as the Synthetic Aperture Radar (SAR) in L-band (e.g. ALOS PALSAR) and C-band (e.g. RADARSAT). Considering lacking of recent land cover/use maps in Puerto Rico, we start to try the fusion of optical and radar images to detect recent LCLUC in Puerto Rico.

For our preliminary study, we choose the Landsat TM images between January 2009 and January 2011 and the ALOS PALSAR images in 2010 (https://www.asf.alaska.edu/sar-data/palsar/terrain-corrected-rtc/). We use the Google Earth Engine as the platform and the random forest classifier for land cover classification.

The results indicate that the SAR images (when combining with TM and terrain data) contribute to higher classification accuracy than that using TM and terrain data alone. The texture parameter of homogeneity can be used to delineate forests, especially cloud forest, to reduce the effect of persistent clouds in that region. Forest and water types have the highest classification accuracies. However, the pasture is likely to be misclassified with crops.

Current results show the total forest cover of 49% (including woody agriculture and shrubs) in 2010, higher than that in the land cover map of 2000 (Fig. 9). We'll use the Sentinel-1 SAR data and the NASA Landsat-8 images to detect forest changes in 2015.

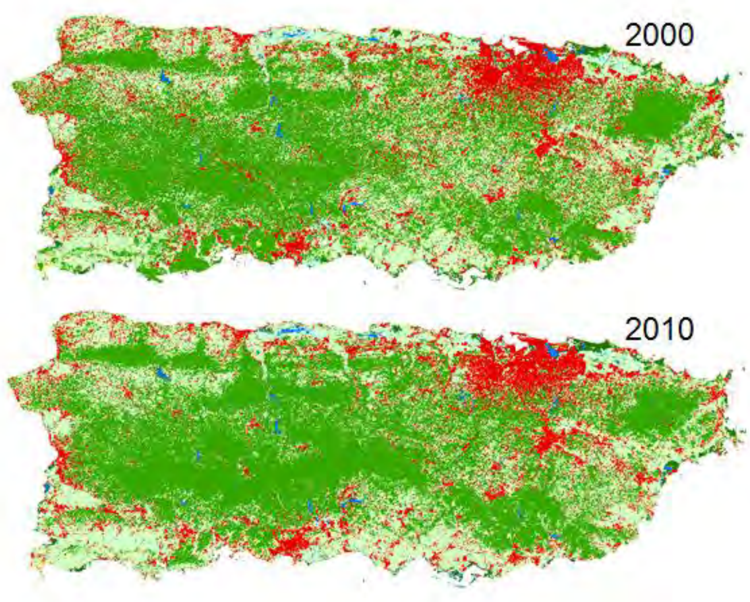

Figure 9 Preliminary results on land cover changes in 2000 – 2010 (land cover in 2000 is from Kennaway and Helmer, 2007). Dark green, forest cover including woody agriculture; Light green, herbaceous cover including pastures and herbaceous agriculture; Red, urban development

Manuscripts published, completed, and in preparation:

Gao, Q. and Yu, M. 2014. *Discerning the fragmentation dynamics between tropical forest and wetland in the context of reforestation, urban sprawl, and policy change*. PLOS ONE doi:10.1371/journal.pone.0113140

Villanueva, L. and Yu, M. 2015. *Legal and Policy Framework as it pertains to Puerto Rico Coastal Vegetative Wetlands, and its effects on Land-Cover/Land-Use Change*. Completed

Davila Casanova and Yu, M. 2015. *Land use legacy of wetland drainage for agriculture exacerbates impacts of sea level rise on coastal wetlands in tropics.* Completed

Yu, M, Gao, Q., Gao, C., and Wang, C. 2015. *Topography differentiates vegetation growth trend under climate and land cover/use changes*. Completed

Gao, Q. and Yu, M. 2015. *Changes in land cover composition and configuration greatly altered ecosystem hydrological processes*. Completed

Yu, M. and Gao, Q. 2016. *Simulation of Land Use Changes in a tropical island in the era of agricultural decline, urban expansion and sprawl, and reforestation*. In preparation

Yu, M., Davila, D., Villanueva, L., and Gao, Q. 2016. *Policy change led to expanding and aggregating vegetative wetland in 1977 – 2010 despite coastal development*. In preparation

Wang, C., Yu, M., and Gao, Q. 2016. *Fusing Landsat TM and PALSAR images to detect forest transitions in the tropics*. In preparation

Presentations/Posters:

Gao, Q. and Yu, M. Aug. 10 – 14, 2015. The 100th Annual Meeting of the Ecological Society of America, Baltimore, MD. *Ecohydrological dynamics of tropical watersheds in response to land use and climate changes*

Davila Casonova, D. and Yu, M. April 20-24, 2015. The Annual Science Meeting of NASA Land Cover and Land Use Change Program and 2015 NASA Carbon Cycle & Ecosystems Joint Science Workshop, College Park, MD. *Understanding the past to predict the future: sea level rise, wetland migration and impacts to the habitat of a critically endangered frog*

Villanueva Cubero, L. and Yu, M. April 20-24, 2015. The Annual Science Meeting of NASA Land Cover and Land Use Change Program and 2015 NASA Carbon Cycle & Ecosystems Joint Science Workshop, College Park, MD. *Policy shifts and their impacts on coastal wetlands protection*

Gao,Q. and Yu, M. April 20-24, 2015. The Annual Science Meeting of NASA Land Cover and Land Use Change Program and 2015 NASA Carbon Cycle & Ecosystems Joint Science

Workshop, College Park, MD. *Ecohydrological dynamics of tropical watersheds in response to land use and climate changes*

Gao,Q. and Yu, M. April 20-24, 2015. The Annual Science Meeting of NASA Land Cover and Land Use Change Program and 2015 NASA Carbon Cycle & Ecosystems Joint Science Workshop, College Park, MD. *Discerning the fragmentation dynamics between tropical forest and wetland in the context of reforestation, urban sprawl, and policy change*

Yu, M. and Gao, Q. Nov. 1 – 6, 2014. The 7th National Summit on Coastal and Estuarine Restoration and 24th Biennial Meeting of The Coastal Society, Washington, DC. *Distribution Patterns of Tropical Wetlands in the course of Reforestation and Urbanization*.

Villanueva, L. and Yu, M. Nov. 1 – 6, 2014. The 7th National Summit on Coastal and Estuarine Restoration and 24th Biennial Meeting of The Coastal Society, Washington, DC. *Legal and Policy Framework as it Pertains to Puerto Rico Coastal Vegetative Wetlands*.

Villanueva, L. and Yu, M. Sep. 26, 2014. The Ambientis Symposium at University of Turabo, PR. *Legal and Policy Framework Pertaining Puerto Rico Coastal Vegetative Wetlands*.

Gao, Q. and Yu, M. Aug. 9 – 15, 2014. The 99th Annual Meeting of the Ecological Society of America, Sacramento, CA. *Land pattern dynamics of a tropical island in the context of urban sprawl and forest regrowth*.

Yu, M. and Qiong Gao. Apr. 2, 2013. The Annual Science Meeting of NASA Land Cover and Land Use Change Program, Washington, D.C. *Vulnerability and Adaptive Management of Tropical Coastal Wetlands in the context of Land Use and Climate Changes*

Villanueva, L. and Yu, M. Apr. 2, 2013. The Annual Science Meeting of NASA Land Cover and Land Use Change Program, Washington, D.C. *Changes in Vegetative Wetland and Coastal Forest Cover in the Northeast Ecological Corridor after Agriculture Decline in Puerto Rico*

Davila, D. Apr. 2, 2013. The Annual Science Meeting of NASA Land Cover and Land Use Change Program, Washington, D.C. *Vulnerability of the coqui llanero, Eleutherodactylus juanariveroi, habitat to sea level rise*

Villanueva, L. and Yu, M. Nov. 3, 2013. The Coastal and Estuarine Research Federation Conference, San Diego, CA. *Puerto Rico's Coastal Vegetative Wetlands in the context of Socio-Economic and Climate Changes*

Yu, M. and Qiong Gao. Apr. 3, 2012. The Annual Science Meeting of NASA Land Cover and Land Use Change Program, Washington, D.C. *Vulnerability and Adaptive Management of Tropical Coastal Wetlands in the context of Land Use and Climate Changes*.