July 19, 2019

Dr. Garik Gutman
Room 3Y77
300 E Street, SW
Washington, DC 20546

Subject: Final Report for Contract # NNH15CN72C: Climatic and Socioeconomic Drivers of Land-Cover and Land-Use Change in Tropical Andean Alpine Wetlands

Dear Dr. Gutman,

In accordance with Clause H.3 – Additional Reports of Work – Research and Development of the subject contract, Science Systems and Applications, Inc. (SSAI) is pleased to submit the final report for the entire period of July 6, 2015through July 6, 2019.

If you have any questions, please contact the undersigned by phone at 301-867-2112 or via electronic mail at ankita.jindal@ssaihq.com.

Sincerely,

Ankita Jindal
Contract Administrator

Enclosure (1)

CLIMATE AND SOCIOECONOMIC DRIVERS OF LAND-COVER AND LAND-USE CHANGE IN TROPICAL ANDEAN ALPINE WETLANDS

Final Report: July 2015 – July 2019

Submitted: July 19, 2019

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Funded by: NASA ROSES 2013 Land-Cover / Land-Use Change Program

Project Period: July 7, 2015 – July 6, 2019

PROJECT ABSTRACT:

The goal of this project has been to investigate the relative importance of factors impacting the landuse and landcover of high-altitude peatlands systems ("bofedales") in the tropical Andes of Bolivia and Peru. These bofedales support a wide variety of important ecosystem and economic services, but in many areas are actively degrading. Hypothesized factors driving these changes include changes in climate, and changes in landuse due to socioeconomic pressures. Our objectives in this project include: (1) assess bofedal health with satellite imagery, by examining both vegetation characteristics, and site topography (as an indicator of geomorphic stability); (2) analyze 20th century climate and model likely 21st century climate scenarios to understand recent and future climatic pressures on these systems (shifts in rain rates, in particular, could be of critical importance); and (3) conduct socioeconomic studies in affected communities to understand where, how, and why landuse patterns may be changing.

BOFEDAL ASSESSMENT:

Observations at our field sites (made during our previous LCLUC funded project (2009), "The impact of disappearing tropical Andean glaciers on pastoral agriculture"), as well as reports from collaborators in Bolivia, suggest many of the bofedal systems were in decline. Our aim with this component of the project was to develop methods to assess bofedal health regionally using satellite imagery. We hypothesized that development of erosive channels in the bofedales may be directly undermining their hydrology, thereby leading to stress and degradation, and that such effects would be observable by their reflectance. Thus, two different approaches were taken: examining the geomorphology of bofedal sites (via elevation models generated from stereo satellite imagery) to evaluate the erosional state of the bofedales, and examining the spectral signature of the sites to evaluate the health of the vegetation.

To examine geomorphology, we developed digital elevation models (DEMs) from stereo imagery at 3 different sites, and from these measured the depth of observed channels, and the slope of the peatland (which generally fill valley bottoms, and so are fairly flat). Significant effort was expended on the DEM generation process, using both commercial tools (PCI's Orthoengine) and open-source tools (NASA Ames Stereo Pipeline (ASP)), because, for our case, we needed sharp and relatively accurate delineation of small channel features. DigitalGlobe imagery from either Worldview-2 or GeoEye-1 was sourced, both with nominal panchromatic resolution of 0.5 m or less. We also had limited high accuracy ground control information for these 3 sites, from differential GPS points taken during our previous project. We concluded that the best DEM results were obtained by active involvement of an analyst, and could not routinely be generated in an automated fashion. In other words, the best results were site and imagery specific; A particular GeoEye-1 image might work best in one location or date, using Orthoengine with SGM (semi-global matching) routine, while a Worldview-2 image might work better using NCC (normalized cross correlation) in another location. In most cases, the more automated ASP approach produced the least useful DEMs.

With the best DEMs, we then measured channel size (depth and width), using transects across the channels, bofedal slopes, and bofedal NDVI. Our preliminary results relating channel depths to simple NDVI measures did not show strong correlations, despite what appear to be clear observations in the field. For example, at the Manasaya site, which we have been working in since 2011, approximately half of the bofedal dried up and died around 2016, in the area of the bofedal adjacent to a deep channel (~2m deep and 2m wide). At the Tuni site, a wide and deep channel is adjacent to a large dry area, that was likely (at some point in the past) a dense bofedal, as it continues to be along its wet edges. We suspect the poor correlations between NDVI and physical morphology of these sites might be explained by several factors: (1) a difficulty in discerning, via these DEMs, streams within bofedales that do not have channels (e.g., are not cutting erosively down) from those that do, but whose channels are not being resolved in the DEM; (2) sensitivity of the NDVI measurement to time of year, and within season variability (see next section); and (3) insufficient number of samples. We still believe there may well be a useful connection between the geomorphology of these systems and their health, and future efforts might benefit from more extensive fieldwork, and use of drones to map these features in detail to help validate satellite-based measures.

The second effort to assess bofedales was focused on taking advantage of the Landsat archive, reaching back to the 1980s, to track trends in bofedal extent and health. Previous efforts had relied on performing individual classifications of 'best available' imagery, to look for changes. But we found much more substantial intra-seasonal variation in the apparent greenness (as measured by NDVI) of these systems than we had expected. Thus, the specific dates used to track change in landcover across years can influence trends. We therefore revised our work plan to include much more Landsat imagery, to better characterize within-year variation, and thus improve the interpretation of longer-term trends.

We extensively explored different machine learning algorithms, using test data provided by a selection of manually classified images. Although the optimal algorithm varied, in general we found support vector methods (SVM) to perform best. We then trained a support vector machine, and applied it to ~150 Landsat images, which had been selected from the dry-season (June – October), and manually verified to be free of snow or other anomalies. The results indicated additional sources of variation may be confusing matters, including, perhaps, BRDF (bidirectional reflectance distribution function) of some of the vegetation and the surrounding material, along with more extensive intra-seasonal variation than we had expected. Without time to fully explore these effects, we instead consolidated the SVM results to ~75 images that did not exhibit these effects, and developed a decadal stability index to evaluate and map change from those results. The purpose of the stability index is to provide a measure of vegetation change that is less susceptible to normal intra-annual variations, and yet can capture longer-term change. The preliminary results were presented to local community members in our last meetings in June 2019, and well received. Final results are being compiled for publication later this year.

CLIMATE MODELING:

The goal of the climate modeling component was to apply a regional climate model to analyze projected changes in precipitation climate characteristics (coverage, intensity, wet season duration, diurnal cycle) in the Central Andes during the 21st century associated with land cover and land use modifications and climate change. By using a regional climate model, we are able to look at features at scales relevant to landcover processes in this region (~9km grid cell).

Our approach uses the Coupled Ocean Atmosphere Wave Sedimentation Transport modeling system (COAWST) regional climate model (RCM), operating at convective system resolving scale (9-km grid spacing), to dynamically downscale the results from four fifth generation Climate Model Intercomparison Project (CMIP5) global climate models (GCMs). These four GCMs used as input included CCSM4, GFDL-ESM2M, IPSL-CM5A-MR, and MIROC5. The first three GCMs are weakly, highly, and moderately sensitive to climate forcing, respectively, whereas MIROC5 is known to be one of the best GCMs for simulating monsoon patterns (as occur in the Central Andes). These and all CMIP5 GCMs natively lack sufficient spatial resolution (90 km +) and temporal resolution (daily) to adequately capture regional orography and sub-daily weather phenomenon and are overly dependent on their parameterization schemes. The COAWST RCM addresses these inherent weaknesses of GCMs by operating at an order of magnitude higher spatial resolution and with hourly model output, which is sufficient for characterizing the diurnal cycle and explicit simulations of convective systems. Such capabilities are particularly important for the pastoral-based economy, water resources, and ecosystem of the Central Andes, as these are all dependent on regional precipitation climate characteristics.

However, running COAWST is computationally intensive (orders of magnitude greater than a GCM), and so we took a "snapshot" approach, where we ran four, year-long COAWST simulations spaced roughly thirty years apart (2003, 2031, 2059, 2087) for each of our four CMIP5 ensemble members. We adjusted the associated land cover characteristics (forest cover and glaciers) for each snapshot year using projections provided by Instituto Nacional de Pesquisas Espaciais in Brazil and PI Dan Slayback. To further manage computational expense, we opted to focus our simulation ensemble on the regional climate pathway (RCP) 6.0 CMIP5 scenario (mid-range future climate projection) as a compromise between the more aggressive RCP 8.5 and more modest RCP 4.5 CMIP5 scenarios.

The final COAWST RCM dataset includes 16 RCP 6.0, 2 RCP 4.5 (MIROC only), and 2 RCP 8.5 (MIROC only) simulations with hourly surface data, and both surface and 3D meteorological data at six-hourly, daily, and monthly time scales. This final dataset represents the second run of the COAWST simulation set. The original set of 20 COAWST model simulations completed earlier in the project helped identify a previously unknown COAWST bug, where upwelling in equatorial regions and ocean-to-atmosphere fluxes were too strong, resulting in a significant cold bias in equatorial sea surface temperatures, a corresponding dry bias in precipitation over the Amazon, and notable reduction in precipitation in the Central Andes. After we fixed the bug in COAWST, we re-ran the 20 simulations, which we found generated much improved and more realistic model results. As of this date, all but one of the new COAWST simulations are complete, and the final simulation is nearing completion. Results thus far suggest that precipitation in the Central Andes is expected to decrease by 11-18% (up to 500 mm/year) by 2087 with 15-25 fewer days with precipitation and an increase in precipitation rates (0.5 mm/hr on average). Despite these changes, the spatial coverage and diurnal cycle timing of precipitation are not expected to change.

We find the increase in precipitation rates to be the most significant result from this work, as this will likely contribute to even further degradation of bofedales due to increased erosive action.

Socioeconomic:

The goal of the social science component of the project was to: (1) assess the socioeconomic factors affecting landcover and land-use change in bofedal (alpine peatland) systems; and (2) combine socioeconomic, land cover change, and climate data to provide likely future trajectories for bofedal systems. The aim of this research is to understand change in bofedales and consider the socio-ecological dimensions, or "drivers" (both natural and human), which influence bofedal condition and change.

In order to collect socioeconomic data on land cover and land use change, a mixed method approach was applied and included focus groups, participatory mapping, vegetation survey, and household survey. Two primary regions of study were selected including Sajama National Park (PNS), located in the western Cordillera, and Chuñavi (near field sites of Tuni-Condoriri), located in the eastern Cordillera Real. A team of facilitators in the social sciences was identified and trained, and the materials were developed, and IRB approval was obtained. Focus groups were held in 2016 at the national park scale, and in 2017 in each community. The first focus groups were convened to learn about the conditions of the bofedales, how community members classified their bofedales, their main economic activities, how they relied on the bofedal resources, and to recall major climate events that have impacted their land management, water and bofedal resources. The event took one day at each site, maps and pictures were prepared with the communities, and the focus group facilitators transcribed the discussions. This protocol was applied in Sajama with the participation of 46 community members, and in Chuñavi with the participation of 34 members. Drawing on these results, a series of workshops was held in July 2017 to identify local perspectives of bofedal change within each community and in relation to landcover maps of bofedal condition in 1986, 1996, 2006, and 2016. A total of 73 community members from the park participated. The results of these focus groups and the participatory mapping combined with vegetation analysis are published in Yager et al., 2019. In addition, an online ArcGIS Storymap of results was generated for students and educational outreach: https://arcg.is/05Wq5n.

At the park level, the landcover change maps indicate a decrease in total area of healthy bofedales from 33.8 km^2 in 1986 to 21.7 km^2 in 2016, and an increase in dry bofedal/mixed pastures from 5.1 km^2 in 1986 to 20.3 km^2 in 2016. At the community level, two communities (Papelpampa and Caripe) maintain or increase the area of healthy bofedales, and three communities (Sajama, Lagunas, and Manasaya) show a loss in area of healthy bofedales. An increase in dry bofedal/mixed grasses is found in all communities (see Table 1).

Vegetation data was collected to groundtruth image results and classify land cover properties of peatlands of study. Forty-three ground truth points (GTPs) and vegetation sampling sites were randomly selected across multiple classes. We surveyed 110 quadrats in all bofedal classes and registered a total of 16 families, with the Juncaceae family as most abundant (~29% average total cover), followed by Cyperaceaea (~24%), Poaceae (~18%), and Plantaginaceae (~13%) in pasture areas characterized by more arid and salinized conditions. A total of 54 vascular plant species were found in all pasture classes[1]. The vegetation survey was conducted during the dry season to correlate with the dates of satellite image analysis, and represent pasture grasses that are available at this critical time of year for animals when forage is limited. The vegetation survey results provide field verification of the classification results, and confirm that the healthy bofedal class is dominated by peat forming vascular plants from the Juncaceae family, and the drying bofedal/mixed pastures class is dominated by dry grasses (e.g. *Deyuexia* spp.) and other mixed meadow species (e.g. *Plantago tubulosa*) with less presence of Juncaceae.

[1] Species abundance by community is Caripe (30), Sajama (35), Lagunas (22), Papelpampa (22) and Manasaya (32).

Table 1 Total area of healthy bofedal, drying bofedal/mixed pastures, and *collpares* at decadal intervals (1986, 1996, 2006, 2016) in PNS and in pasture sectors corresponding to the five communities of study

Sectors			**Total area (km²)**			
			1986	**1996**	**2006**	**2016**
Healthy Bofedal	Sajama	6, 7, 8, 14a-e	15.5	9.4	13.8	7.8
	Caripe	1	1.9	2.3	2.5	2.6
	Lagunas	11,12,13	4.2	2.2	3.2	1.8
	Manasaya	2,3,4,5	5.6	2.8	4.8	3.0
	Papelpampa	9, 10	6.6	6.4	6.9	6.5
	Park Total		33.8	23.0	31.2	21.7
Dry Bofedal/Mixed Pastures	Sajama	6, 7, 8, 14a-e	1.5	8.0	4.0	9.6
	Caripe	1	1.5	1.5	1.6	2.8
	Lagunas	11,12,13	0.8	2.3	1.2	2.6
	Manasaya	2,3,4,5	1.0	3.6	1.7	3.5
	Papelpampa	9,10	0.3	1.4	0.9	1.7
	Park Total		5.1	16.8	9.4	20.3
Collpares (Salt Flats)	Sajama	6, 7, 8, 14a-e	6.3	7.7	4.0	2.5
	Caripe	1	2.6	2.6	2.6	2.0
	Lagunas	11,12,13	0.1	0.0	0.0	0.0
	Manasaya	2, 3, 4, 5	1.0	0.9	0.9	0.2
	Papelpampa	9,10	0.3	0.3	0.1	0.1
	Park Total		10.3	11.4	7.7	4.8

Based on the results from community workshops, a household survey of relevant land use variables and drivers was developed and tested, and implemented in 100 households (83 in Sajama, and 17 in Chuñavi). The household survey posed direct questions regarding land use decision-making and socio-economic data that influence livelihood strategies. These data were then evaluated applying cluster analysis to identify key variables that define differing livelihood strategies, such as access to labor, age of household head, land management decisions, and variables of social and economic capital[2]. The household data reports that the majority of households (90%) experience difficulty in accessing water. In addition, we constructed a vulnerability index (scale of 1 to 3) in relation to access to water. The combined social science data was analyzed using cluster analysis to identify distinct livelihood strategies and how these relate to the conditions of the bofedales, and access to water. The results of the cluster analysis data

[2] Social capital is access to networks of support, of information, and of labor and other resources through reciprocity and kin relationships. Economic capital is captured in the investment and savings, as well as the animals, llamas and alpacas, the household owns.

currently identify four key groups that are being analyzed and manuscript submission is expected by end of year.

The results of our focus groups, participatory mapping, and household surveys indicate five thematic conclusions: (1) There is a degradation of bofedales due to lack of irrigation; (2) Water levels and water access is hindered by climate change and social factors; (3) There is a deterioration of communal management that challenges bofedal management; (4) Climate change and extreme events have a negative impact on water levels and bofedal health; (5) Bofedal management is challenged by changes in land fragmentation and out-migration; (6) Adaptive actions must be diversified and include multidimensional sustainable livelihood outcomes.

The identification of pathways on an institutional scale to support the implementation of identified adaptive actions is needed. The following possible adaptive actions were identified: (1) increased technological access to manage water resources (including canals, installation of wells, and identification of usable springs and groundwater), (2) increase the productivity and management of bofedales by irrigation, coordinated across the community, (3) support of collaborative community-based policy actions at the local level over individualism, and (4) diversification of economic activities related to pastoral and non-pastoral production.

The final activity was a closing workshop to deliver the results of the research activities to PNS. We delivered reports of all social science data collected and land cover and land use change maps of bofedal change. Participants included key stakeholders and land management decision makers including 35 community members, key leaders from each of the five communities, and national park management representatives. Final results from our study, currently being compiled, will be used to inform conservation management strategies at the park level, and directed towards identifying priority development projects in water and bofedal management at the municipal level.

KEY RESULTS:

- Development of a decadal stability index to evaluate and map bofedal change. The purpose of the stability index is to provide a measure of vegetation change that is less susceptible to normal intra-annual variations (e.g. NDVI), and yet can capture longer term change and areas of high vulnerability to desiccation.
- Precipitation amounts expected to decrease upwards of 500 mm/year by 2087 (18% decrease) over Altiplano and 300 mm/year (11% decrease) in Sajama. Decreased precipitation occurs year-round and shows no pronounced seasonal bias.
- Between 15 and 25 fewer precipitating days during the wet season by 2087 over the Altiplano. Precipitation rates are expected to increase (0.5 mm/hr), suggesting a tendency towards fewer, but more intense events. Greatest precipitation rate increases near diurnal peak (18:00 local)
- Land cover change maps in Sajama National Park show a decrease in bofedal condition over the past 30 years, influenced by decreased water availability tied to climate shifts, erosion increase, drop in water table, and socio-economic variables that are driving an increase in land fragmentation, out-migration, and greater vulnerability to impacts of extreme climate events.
- Analysis of socio-economic data currently identifies four clusters of livelihood strategies that impact land use and land cover decision-making related to bofedales.
- See Appendix for Supplemental Figures

PUBLICATIONS:

Accepted / in press:

Yager, K. and Valdivia, C. (in press). Cambio Temporal de Bofedales y Collpares en el Parque Nacional Sajama. Chapter 5 in *Bofedales del Parque Nacional de Sajama*. The Nature Conservancy and The National Herbarium of Bolivia, La Paz.

Yager, K., Valdivia, C., Slayback, D., Jimenez, E., Meneses, R. I., Palabral, A., … Romero, A. (2019). Socio-ecological dimensions of Andean pastoral landscape change: bridging traditional ecological knowledge and satellite image analysis in Sajama National Park, Bolivia. Regional Environmental Change, 19(5), 1353–1369. https://doi.org/10.1007/s10113-019-01466-y

Cooper, D. J., Sueltenfuss, J., Oyague, E., Yager, K., Slayback, D., Caballero, E. M. C., … Mark, B. G. (2019). Drivers of peatland water table dynamics in the central Andes, Bolivia and Peru. Hydrological Processes, 33(13), 1913–1925. https://doi.org/10.1002/hyp.13446

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Submitted / in preparation:

Nicholls, S.D. and Mohr, K.I. (in prep 2019). Validation of Weather Research and Forecasting (WRF) model simulations of the South American Climate during the Austral Summer of 2003-2004. JAMES (Journal of Advances in Modeling Earth Systems).

Nicholls, S.D. and Mohr, K.I. (in prep 2019). Projected Precipitation Characteristics of the Central Andes during the 21st Century from Projected Land use and Climate Change. Journal of Climate.

Mohr, K.I., Slayback, D., Yager, K, Mark, B. (in prep 2019). Decadal and Bi-Decadal Variability in Seasonal Precipitation in the Central Andes (1946−2012). (potentially: Journal of Hydrometeorology).

Conference presentations:

Valdivia, C., K. Yager, E. Jimenez and S. Rojas. 2019. Socioeconomic and Ecological Outcomes in the Context of Climate Change in Andean Landscapes: Livelihood strategies, Capitals and Adaptation in the Bolivian Altiplano. Agricultural and Applied Economics Association AAEA Session: Strategies to adapt to and mitigate the effects of climate change in Latin America, July 23, 2019, Atlanta GA.

Valdivia, C., K. Yager, A. Romero, K. Bedregal, and S. Rojas. 2019. Sayañas, Peatlands and the Sajama National Park: Climate Change Adaptation in the Bolivian Andes. Panel on

Governing Mountain Commons: Challenges and Opportunities for Sustainability in the Context of Change. International Association for the Study of the Commons, July 1-5, Lima, Peru.

Valdivia, C., E. Jimenez, and K. Yager. 2018. Livelihood strategies and climate change adaptation in three landscapes of the Bolivian High Plateau. Climate Change Issues and Adaptations in Latin America. Environment Section LASA2018 Congress May 23 – 26, 2018, Barcelona, Spain.

Hubbard, A. and Slayback, D. 2018. Measuring peatland channel erosion in the high Andes from very high-resolution DEMs. In session B082: The resilience of wetland ecosystems to multiscale environmental changes. AGU Fall Meeting, Dec 10-14 2018, Washington DC.

Nicholls. S.D. and Mohr, K.I. 2017. Simulating Future Precipitation Characteristics of the Central Andes with a Coupled, Ocean-Atmosphere Regional Climate Model. 97th American Meteorological Society Annual Meeting, Seattle, WA.

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