Using Remote Sensing to Discover Historic Context of Human-Environmental Water Resource Dynamics

*Zachary Brecheisen¹, Nicholas Hamp-Adams¹, Abigail Tomasek¹, Erika J. Foster¹, Timothy Filley¹, Martín Villalta Soto², Lucia Zuniga Reynoso¹, Andre de Lima Moraes¹, and Darrell G. Schulze¹

¹Purdue University, West Lafayette, IN, USA; ²National University of St Augustin of Arequipa, Arequipa, Peru; *Corresponding Author

Abstract: Analysis of historic and contemporary high-resolution imagery can help to fill knowledge gaps in land cover and management history in locations where documentation is non-existent or records are difficult to access. Historic imagery dating back to the 1960s can be used to structure quantitative investigation and mapping of land use and land cover change across space and time to enhance earth science, policy, and social science research. Imagery can further inform municipal planning and implementation in areas of natural resource allocation, infrastructure, and hazard mitigation. For management and public education, historic imagery can help people to understand environmental processes and the impacts of human activity in the local environment. Here we emphasize the value of high-resolution historic satellite imagery from the Corona and Keyhole satellite programs to inform environmental research, public education, and environmental management. Within the Region of Arequipa in southern Peru we highlight examples of urban development, agricultural expansion, river channelization, and glacial retreat via comparison of historic and modern satellite imagery. By incorporating these types of historic imagery data in formats accessible to non-professionals, public engagement as well as research into human-environmental investigations will be greatly enhanced.

Keywords: historic imagery, declassified, Corona, Keyhole, glacier melt, agricultural development, Arequipa Peru

n a world with increasingly complex humanmediated environmental changes, water Laccessibility is one of the leading causes of environmental social conflicts globally and particularly in Peru (Stark, Guillén, and Brady 2012). Anthropogenic activities are a dominant driver concerning water quality, abundance, and distribution. For instance, urban expansion leads to increased population density and a greater demand for water resources, while increased impervious surfaces and industrial practices lead to increased flows and contaminant transport to downstream areas (Carpio and Fath 2011; Wang et al. 2018). Additionally, agricultural modernization and expansion impacts water quality due to increased erosion, application of pesticides and fertilizers,

(Canfield, Glazer, and Falkowski 2010; Lu and Tian 2017; Li et al. 2020) and changing water availability (Stark, Guillén, and Brady 2012). Globally, land use change has caused drastic alterations of soil fertility (Khaledian et al. 2017) and stability (Diringer et al. 2020; Lacroix, Dehecq, and Taipe 2020), hydrology (Ochoa-Tocachi et al. 2016), loss of ecosystem services (Castello and Macedo 2016; Peng et al. 2017), and susceptibility to natural disasters such as flooding (Rogger et al. 2017) and drought (Bagley et al. 2014). While these issues are occurring at a global scale, research has shown that they disproportionally affect developing countries (Givens, Huang, and Jorgenson 2019), exacerbated by data scarcity in these regions (Hilbert 2016). This paper describes

how satellite imagery can be used as a resource to document and visualize anthropogenic changes in the context of the Arequipa Region of Peru, which has undergone extraordinary human-mediated environmental change over the last 60 years.

The Arequipa Region of southern Peru is approximately 63,000 km² and has tremendous variation in climate and topography, ranging from sea level along the Pacific coast to more than 6,000 m elevation in the Andes. Correspondingly, temperature varies across the Region from continually frozen glacial flows in the mountains to 30° C on the desert plateau (Moraes et al. In preparation for submission). Annual precipitation has similarly high variability from ~5 mm in the alluvial desert plateau of the Majes agricultural project (EcoUrbe Consultores 2013), a midelevation Andes rain shadow, to 800 mm at higher elevations. The Region is home to the city of Arequipa, Peru's second largest city with a population of 1,382,730 (INEI 2017). Within these topographic and climatic extremes exists a great diversity of human and natural environments including historic and modern agricultural areas, mountain top glacial ice and snow cover, sprawling cities, and large rivers inside huge canyons. Across the Region, there is a long history of human-environmental interaction dating back into Inca history and evolving into the present day (Sandor and Homburg 2017). Despite this richness in anthropogenic activity across the landscape, challenges arise when trying to locate precise records and documentation of where and when humans have shaped the landscape.

For this study, declassified, high-resolution satellite imagery from 1966 was compared to current imagery to determine the anthropogenic impacts on environmental systems in the Region of Arequipa. The Corona satellites, which flew from the 1960s to early 1970s, produced the 1966 imagery and Keyhole satellites, which flew from the later 1970s to 1980s, produced the 1978 and 1980 imagery used in this study. The Corona program was the first United States reconnaissance spy satellite program and took over 800,000 images of the Earth's surface from 1959 to 1972 (Perry 1973). The first successful mission took place on August 18, 1960. It was a highly classified program under the management of the Central Intelligence Agency and the United States Air Force, which together would go on to form the National Reconnaissance Office (McDonald 1995). Since declassification in 1995, Corona imagery has played an instrumental role in archeological investigations (Ur 2003; Fowler 2004; Goossens et al. 2006; Alizadeh and Ur 2007; Casana and Cothren 2008; Fowler 2013; Sevara et al. 2018). Corona imagery is available for public purchase from the United States Geological Survey (USGS) Earth Explorer (USGS 2016). Keyhole is the satellite reconnaissance program that followed Corona and it ended in the 1980s (Perry 1973). Despite its potential value for enhancing research, environmental scientists have not yet fully utilized the historic imagery of Corona or Keyhole (Schlesinger and Gramenopoulos 1996; Shroder, Bishop, and Overton 2005; Boyle et al. 2014; Pope et al. 2014; Guan et al. 2017; Lacroix, Dehecq, and Taipe 2020).

In this article, we explore several case studies from the Arequipa Region showing the utility of remote sensing for large scale multidisciplinary research like that done by the Arequipa Nexus Institute (Filley and Polanco Cornejo 2018). Such collaborative research endeavors can assess sustainability challenges via delineation of humanenvironment interactions in historic and modern satellite imagery. The case studies presented in this investigation include urbanization, agricultural development, river channelization, and loss of snowpack and glaciers. These examples provide an introduction to the capacity of satellite imagery, particularly historic imagery, to capture environmental history pertaining to water resource risks. We will conclude with an example of how high-resolution imagery can be shared with and used by the public via the Soil Explorer application (Isee Network 2015-2020; Schulze 2018). Soil Explorer allows non-specialist stakeholders to interact dynamically with remotely-hosted geospatial data across landscapes. Raster and vector spatial data can be explored at different scales and users are geolocated if they are within the map display boundary. Technologies like this could be incorporated in strategies to enhance public adoption of water management policies addressing challenges like climate change.

Methods

This study used historic images from two satellites, KH-40 (Corona J-1) and KH9-14, to investigate examples of human-environmental change in water resource contexts across the 63,000 km² Region of Arequipa, Peru (Figure 1). Both satellites captured imagery onto photographic film. KH-40 flew from August 1963 to October 1969, collecting imagery with an approximate pixel resolution of 2.75 m, and KH9-14 flew from March 1978 to September 1978, collecting imagery with an approximate pixel resolution of 6 m (Goossens et al. 2006; Hamandawana, Eckardt, and Ringrose 2007). It would not be until 1999, with the launch of the IKONOS satellite which collected ~1 m resolution panchromatic imagery in addition to ~4 m multispectral imagery, that imagery with such high-resolution would be available again, due to technological advances in the intervening 20-30 years (Pope et al. 2014). The historic imagery was compared with multispectral Sentinel satellite imagery obtained via Google Earth Engine (Gorelick et al. 2017) or 3 m PlanetScope satellite multispectral imagery via Planet Labs, Inc. (2020). This was done in order to update and edit existing land cover vector polygons from the Ecological and Economic Zoning (ZEE) project (Gobierno Regional Arequipa 2016) to conduct analyses of changes in land cover through time. PlanetScope data were employed when image resolution finer than 10 m (as in Sentinel imagery) was required, such as for detailed polygon delineation around small urban areas.

The 1966 Corona images and 1978 Keyhole images were purchased for 30 United States Dollars (USD) per image strip via USGS Earth Explorer (USGS 2016), within the declassified dataset listings. Both Corona and Keyhole image strips were exported as 7 micron digital scans of the film. Each 1966 Corona image strip was provided in four split components (a, b, c, and d) (~220 MB each), whereas the Keyhole image strips were supplied in two image components (a and b) each ~1.1 GB in size. The five-fold difference in file sizes between the two historic image types is due to the fact that the later Keyhole images individually cover a much larger spatial area than do the Corona images. Prior to georectification in GIS software, all of the historic satellite images were processed in Adobe Photoshop to crop out the film edges of the photographs. The next pre-georectification task was to mosaic the components of each image together. The image components were lined up, from right (a) to left (d) for Corona or top (a) to bottom (b) for Keyhole imagery, and mosaicked into image strips.

Following the completion of this process for all of the historic imagery, the image strips were then georeferenced to the high-resolution ArcGIS aerial basemap and to other image strips. The accuracy of the ArcGIS basemap was checked frequently against 10 m resolution Sentinel satellite data across the Region of Arequipa, to ensure that the basemap accurately accounted for dynamic topography. Because the image strips cover extensive areas, the Corona images required at least 200 ground control points to be precisely georectified to the contemporary surface. Due to optical lens distortion, the angle at which the images were taken, and very extreme elevation relief between valley bottoms and mountain or hilltops, distortion of these historic images was challenging to address, especially in montane parts of the Region (Goossens et al. 2006). Pincushion optical distortion also led the georectified Corona image strips to have a distinct horizontal hourglass shape. Approximately 200 control points were placed equidistant from each other around the border and within each of the Corona strips, especially in areas with complex topography and in areas of research interest for the topics discussed in this paper. Visible features used for georectification included town centers, roadway intersections, mountain peaks, river confluences, stone livestock corrals, and drainage features.

The complete collection of 1966 Corona strips combined form a high-resolution image across the Region of Arequipa. The same methodology was used for a 1978 imagery strip (satellite KH9-14), which required more than 900 control points to achieve comparable accuracy because of the much larger spatial extent of that imagery. The georectified 1978 Keyhole image strip had vertical pincushion distortion due to the fact that it was oriented roughly north-south whereas the 1966 Corona images were oriented east-west. Lastly, upon discovering unique evidence of salinization in the San Camilo area we georectified a small portion of a Keyhole image from 1980 (satellite KH9-16).

In order to estimate land cover change between one to two periods in the past via Corona and Keyhole imagery (1966-06-30 and 1978-05-16) and modern times we employed a combination of vector shapefile delineation and raster image analyses. Vector shapefile analyses were based on subsetting and manually updating the delineations of the land cover polygon dataset, published in the ZEE project (Gobierno Regional Arequipa 2016), for different time periods across the Region. To estimate changes in urban and agricultural area and river channelization, the areas of multipolygon features were tabulated and summed to estimate total area coverage at different times. Basic raster image manipulation prior to shapefile generation was used to estimate change in snow and ice cover on the peak of the Coropuna Volcano. Because ice and snow cover were mapped only as barren land in the ZEE land cover dataset, area coverage was estimated via panchromatic raster pixel value thresholding on 1978-05-16 Keyhole and 2019 May median-value Sentinel imagery generated via Google Earth Engine (Gorelick et al. 2017) to isolate ice and snow.

Land cover changes in the areas around the city of Arequipa necessitated more complex analyses. Both vector delineation and raster analyses were used to estimate land cover change among barren, agricultural, and developed urban coverage between 1966, 1978, and 2019. In these analyses the ZEE (Gobierno Regional Arequipa 2016) polygon delineations for 2015 were updated to match slight changes for 2019, as well as the much larger changes needed to map these land covers for 1966 and 1978. This entailed deletion of some polygons, changes in the border delineation of others, and the delineation of new polygons via manual digitization of features visible in the historic imagery. For each year (1966, 1978, and 2019), polygons were assigned classes of either urban development ("U") or agricultural development ("A"), with the non-delineated background considered to be barren ground ("B"). This is a slight simplification of the system, but barren ground does and did cover much of the undeveloped area around the city of Arequipa.

Following the completion of polygon editing and delineation for U and A classes for each year, the vector datasets were merged in R and converted to 30 m pixel resolution rasters aligned to Landsat 8, as exported via Google Earth Engine, using the sf ("simple features"), raster, and fasterize packages (Gorelick et al. 2017; Pebesma 2018; Hijmans 2020; R Core Team 2020; Ross and Sumner 2020). In cases of slight polygon overlap between U and A classes, the U class was chosen to ensure that the delineations of small town centers in the midst of large agricultural areas were preserved. This land cover change among B, U, and A classes from 1966 to 1978 to 2019 was analyzed in terms of area in km² and percent cover, using the SDMTools package (VanDerWal et al. 2019).

Results and Discussion

Following georectification, each of the 11 horizontal 1966 Corona image strips was ~330 km by \sim 22 km and covered an area of \sim 8,000 km², accounting for image warping and pincushion distortion. This comes to a cost of ~0.0037 USD km⁻² or 270 km²USD⁻¹ for the 1966 Corona imagery. The later 1978 Keyhole image processing resulted in an image that covers ~43,000 km² at 1,400 km² USD⁻¹, following mosaicking and georectification. In the case of the 1966 Corona imagery, there is ~2.5 km of image overlap between image strips near the center and ~7 km of image overlap near the ends of the strips, due to pincushion distortion. In areas of overlap like this, stereo imagery analysis could be used to generate historic Digital Elevation Models (DEMs) (Casana and Cothren 2008).

Relative to modern high-resolution imagery, this historic imagery at 3-6 m pixel resolution is a low-cost data source. Considered in terms of cost per unit area (km² USD⁻¹), early Corona or later Keyhole imagery is available at 270 km² USD⁻¹ and 1,400 km² USD⁻¹, respectively. In comparison, for the 1990s to 2000s, SPOT2 (10 m pixel resolution) and IKONOS (80 cm pixel resolution) can be purchased at 2.22 km² USD⁻¹ and 0.14 km² USD⁻¹, respectively (Land Info 2020). The two to four order of magnitude difference in cost per unit area does not factor in the time and effort needed to georectify the historic imagery nor the fact that more modern imagery derived from IKONOS,

SPOT, and other satellites may be available in multispectral format and at sub-meter resolution. in some cases. Nonetheless, the potential value of hundreds to thousands of square kilometers of satellite imagery per USD at finer than 10 m spatial pixel resolution is high. With this data we explored four examples of human-environmental water resource issues across the Region of Arequipa, proceeding east to west: urban development near the city of Arequipa (-16.4°, -71.5°); rural agricultural development near Santa Rita de Siguas $(-16.5^\circ, -72.1^\circ)$ and the Majes agricultural project (-16.3°, -72.2°); river channelization of the Rio Majes (-16.3° , -72.45°); and snowpack and glaciers on the peak of the Coropuna Volcano (-15.55°, -72.6°).

Urban Expansion and Development

Arequipa is the capital of the Arequipa Region in Peru. Back in 1966 the human-modified landscape was ~73% agricultural fields (85 km²) and ~27% urban (32 km²). By 1978 the humanmodified landscape was ~68% agricultural fields (100 km²) and \sim 32% urban (46 km²). Finally, by 2019, the landscape had become ~63% urban (172 km²) and only ~37% agricultural fields (103 km²). The marginal increase in agricultural area between 1978 and 2019 is due to much of the new agricultural development to the west of the city in Cerro Colorado (Figure 2) being largely offset by the development of $\sim 14 \text{ km}^2$ of agricultural fields into urban areas. Approximately 65% of the developed urban area in the landscape around Arequipa was developed in the last 42 years from barren land totaling ~113 km² (Table 1). Only $\sim 18\%$ (~ 32 km²) of the 2019 urban area across the landscape dates back to 1966 or earlier, with $\sim 10.5\%$ of the urban area ($\sim 18 \text{ km}^2$) having been developed on previously agricultural lands.

Most of the agricultural area ($\sim 66\%$ or ~ 68 km²) across the landscape has been cultivated since at least 1966 (Table 2). The proportions of 2019 agricultural land linked to agricultural expansion, i.e., the conversion of barren land to agriculture, between 1966 and 1978 ($\sim 18\%$ or ~ 18 km²) and 1978 to 2019 ($\sim 16\%$ or ~ 16.5 km²) are nearly identical despite a 3.4 times longer time interval (41 years vs. 12 years) in the second case, reflecting relatively little recent net agricultural expansion.



Figure 1. Urban expansion - Arequipa city located in the eastern part of the Arequipa Region in June 1966 (top, KH-40), May 1978 (center, KH9-14), and December 2019 (bottom, PlanetScope). Agricultural areas are outlined in blue and urban areas in red in each panel. Provinces are labeled by name in the top panel and outlined in black in all panels. The 1978 Keyhole panel is missing a small portion of landscape analyzed. For this area we used a Keyhole image from 1980 to complete the delineation of those agricultural and urban polygons. Urban expansion is particularly prominent in the Districts of Cayma, Cerro Colorado, and Alto Selva Alegre in the north abutting large lava flows from the Volcanoes El Misti and Chachani.

Table 1. Land cover change analyses of urban developed areas in and around the city of Arequipa. Land cover transitions are read from left to right via three letters corresponding to the cover in 1966, 1978, and 2019. "B" is barren, "U" is urban, and "A" is agricultural fields.

Land Cover Transition	Total Area (km²)	Percent of Total 2019 Urban Landscape
BBU	112.9	65.1%
BUU	10.3	5.9%
UUU	31.9	18.4%
AUU	4.3	2.5%
BAU	1.4	0.8%
AAU	12.6	7.3%

Table 2. Land cover change analyses of agricultural developed areas in and around the city of Arequipa. Land cover transitions are read from left to right via three letters corresponding to the cover in 1966, 1978, and 2019. "B" is barren and "A" is agricultural fields.

Land Cover Transition	Total Area (km²)	Percent of Total 2019 Agricultural Landscape
BBA	16.5	16.1%
BAA	18.1	17.6%
AAA	68.2	66.3%

In total, agricultural land under cultivation has increased by about a third over the last 53 years with an average rate of increase of +0.6% or 0.65 km² per year. This was matched by an average increase in urbanization from 1966 to 1978 of ~0.7% or 1.2 km² per year; however, between 1978 and 2019 the rate of urban expansion more than doubled averaging ~1.8% or ~3 km² per year. Over two thirds of the agricultural fields date back to at least 1966, and 84% date back to at least 1978. Most of the urban developed areas are far newer, with 82% of the area more recent than 1966 and 73% more recent than 1978, reflecting a large influx of people in the last forty years.

Urban expansion is a concern because it draws upon surface or subsurface water sources and potential for water pollution downstream from cities (Carpio and Fath 2011). Latin America experienced large increases in urbanization from the 1930s to the 1970s, with over 45% of urban growth attributed to internal migration from rural to urban areas (Rodriguez-Vignoli and Rowe 2018). Most of this migration was focused to a few, large urban areas (Zlotnik 1994), spurred by the lack of educational and employment options in rural areas (ECLAC 2012). This can be seen in Peru, where economic troubles and political violence in the 1980s led to increased internal rural to urban migration largely focused in the cities of Lima, Callao, Chiclayo, Trujillo, Chimbote, and Arequipa (Durand 2010). Urban centers in Peru continue to have large rates of urbanization, with the province of Arequipa experiencing a population growth from approximately 677,000 in 1993 to 1,081,000 inhabitants in 2007 (INEI 2017). These migrants tend to concentrate on the peripherals of the city, forming informal communities. Figure 1 clearly shows increased agricultural and urban areas from 1966 to 2019, with particular increases in peri-urban sprawl from 1978 to 2019.

The Region of Arequipa is made up of 29 districts, of which five contain 54% of the provincial population (MPA 2016). Four of these, Alto Selva Alegre, Cayma, Cerro Colorado, and Socabaya, were either predominantly agricultural or undeveloped land, as seen in the Corona imagery in 1966 (Figure 1). Cayma, in the northeastern portion of Figure 1, serves as an interesting case study on urbanization in Arequipa. The central part of Cayma is inhabited by traditional farmers, and their ancestral fields are being encroached on from the south by the urban expansion of Arequipa's city center, and from the north, where informal migrant communities are forming in previously unoccupied areas. This expansion has led to differential socioeconomic levels in the district. According to a governmental study, the southern portion of the district, near the city center, has the highest socioeconomic status, the middle of the district occupied by traditional farmers has a medium-low socioeconomic status, and the northern portion of Cayma, settled by migrant communities, represents the lowest socioeconomic classes (MPA 2016). Since the migrant communities are not legally established and are not recognized by the government, they do not have formal water or sewage services.

Historic imagery can aid in determining how these informal settlements have formed over time, particularly when there are no historic governmental records, and can also help in governmental planning and resource allocation. Imagery can also help in establishing more precise dates, locations, and extents of city land cover to evaluate anecdotal information provided by residents. For instance, when talking to farmers in Alto Cural (part of the district of Cerro Colorado) about when farming began on their plots, dates provided spanned many decades and were almost unanimously before 1978 when Keyhole imagery clearly shows that irrigation had not yet expanded to this area (Figure 1). Farming in Arequipa was developed over centuries, and the information provided by historic imagery can provide valuable information on how these lands have developed over the last 60 years, assisting in evaluation of spatial variation in soil properties and crop yield. Since Arequipa is a water scarce region, the historic imagery can also provide information to various stakeholders on water needs, allocation, and future projections.

Rural Agricultural Development

In addition to tracking urban development, high-resolution satellite imagery can provide information about less populous rural areas experiencing agricultural expansion and changing water use (Nellis, Lulla, and Jensen 1990; Naylor 2011). Moving west across the Arequipa Region towards Santa Rita de Siguas, we are confronted by an example of agricultural development in arid sub-optimal soils, the Majes-Siguas project. In 1966, only Santa Rita de Siguas, to the east of what would become the Majes, was under cultivation of ~11.8 km² (Figure 2, top). By 2018 the cultivated area of Santa Rita de Siguas would more than double to $\sim 30 \text{ km}^2$, but this agricultural expansion seems minimal in comparison to the Majes agricultural development (Maos 1985). Totaling ~166 km² in 2018, Majes, along with the expansion of Santa Rita de Siguas, increased agricultural land cover by more than 16 times relative to 1966 (Figure 2, bottom).

Majes-Siguas is located in the hyper-arid rain shadow of the Andes Mountains (Alva et al. 1976; Stark, Guillén, and Brady 2012), receiving only 6 mm of annual precipitation and 519 cal-1 cm-1 min-1 of solar radiation (Gobierno Regional Arequipa 2016; Moraes et al. In preparation for submission). Although the total Peruvian area in this rain shadow contains the two largest cities in the country and over one third of Peru's population, agriculture has been limited, as the area contains only 1.8% of Peru's water (Alva et al. 1976; Hendriks 2009). The Peruvian government has worked to enhance and regulate the distribution of water spatially and temporally through dams and other hydraulic infrastructure to irrigate arid uplands (Maos 1985; Hendriks 2009). This expansion and its impact can be mapped and tracked through historic, remotely sensed images. Figure 2 shows the result of irrigation expansion in the Majes-Siguas agricultural fields after the massive hydrologic engineering completion of tunnels and canals for water transport between 1971 and 1982. The



Figure 2. Rural agricultural development - Majes-Siguas agricultural development project area in May 1978 (top, KH9-14) and 2018 (bottom, Sentinel 2018 mosaic).

Majes-Siguas irrigation project now provides water to farms managed by nearly 2,700 farmers (Maos 1985; EcoUrbe Consultores 2013).

Such agricultural development necessitates massive water movement and distribution infrastructure with the possible downstream transportation of leached salts, fertilizers, and pesticides into streams and rivers (Russo 1983; Russo 1985; Arnon et al. 2006; Hu et al. 2008, 2010; Aranibar et al. 2011; Andraski et al. 2014; Jin et al. 2015; Shareef et al. 2019; van Es et al. 2020). Access to inexpensive, remotely sensed imagery can provide critical baseline data to assess agricultural development project impacts, especially for hydrologic engineering (Roy et al. 2016). Land managers and policy makers can use such imagery to observe historic and modern programs, quantify both formal and informal farmland expansion, estimate annual crop productivity levels, and plan and evaluate development programs (Osman-Elasha et al. 2006; Roy et al. 2016; Chang 2019). With the pressures of increasing global food demand (Grau and Aide 2008), climate change-induced desertification (Sivakumar 2007), and limited water availability (Stark, Guillén, and Brady 2012), agricultural production often must expand into marginal lands like those found in the Majes-Siguas project (Olesen and Bindi 2002; Smith and Olesen 2010).

Such drastic increases of water input to naturally dry soils can have detrimental environmental impacts, observed via satellite imagery. Agricultural irrigation flushes salts naturally found in these soils and transports them downstream. This can be seen visually in the area of San Camilo, ~30 km southeast from Santa Rita de Siguas (Figure 3). In 1980, salts flushed from agricultural fields then totaling ~16 km² had begun to leach and accumulate on soil surfaces as bright white streaks. Water chemistry analyses indicate that the lagoon, formed due to agricultural runoff and leaching over the last several decades, has over twice the dissolved salt concentration of average seawater, leaching from what is now ~22 km² of cultivated area. The movement of water through soils is not only a concern through the appearance of brilliant salts or lagoons in Arequipa but also as water enters into major rivers, some of which have been highly engineered to maximize cultivable floodplains.



Figure 3. Rural agricultural development - Agricultural development around San Camilo prior to development in 1966 (top, KH-40) with subtle solar illumination of future lagoon topography. Mid-agricultural development in 1980 (middle, KH9-16) with white salts visible derived from agricultural soil leaching and runoff tracing flow path and future lagoon areas. The concentric patterns visible here are Newton's rings and are a result of the film scanning process. Modern 2018 satellite view (bottom, Sentinel mosaic) of agricultural fields, moist saline soils, and saline lagoon.

River Channelization

Aside from the potential leaching of salts, fertilizers, or extracted minerals into rivers and streams, river channelization of braided streams is another major global human hydrological impact (Tockner and Stanford 2002; Kennedy and Turner 2011). West of the Majes-Siguas project flows the Majes River from which the project gets its name. The Majes River lies in a valley which is, in places, up to a kilometer lower in elevation compared to the dissected sloping plateau through which it cuts. Analyses of river bed area change were conducted along ~90 km of the river between the town of Chuquibamba, where a tributary joins the Majes River, and the city of Camaná, where the river reaches the Pacific Ocean. Between 1966 and 2018 the initial meandering braided river bed became extremely channelized and reduced in area by ~62% from ~59 km² to just ~22 km² in area (Figure 4).

River channelization for floodplain conversion to fields and landscape drainage has had a dramatic impact on stream paths in the valleys of the Region. Valley bottom agriculture has existed in Arequipa since pre-Columbian times (Sandor and Homburg 2017). Fertile alluvial soils and relatively abundant access to water are ideal for crop production. As modern demand for food has increased with the rise of urbanization and population growth in the region, the need for more agricultural land has led land managers to channelize the braided stream beds at the bottom of these valleys. The channelization process has accelerated over the past 60 years in the Rio Majes Valley, shown clearly when comparing 1966 Corona imagery with modern Sentinel imagery. Figure 4 provides a clear example of this in Río Camaná, located directly west of Majes. As discussed by Rosenberg et al. (2005), linear stream channelization has a dramatic impact on channel morphology, sediment transport, and flow characteristics. Changes to flow dynamics and sediment deposition or transport, along with a simple reduction in flood plain area, have almost certainly impacted river shrimp harvests (Alvarez Ocola 2015; Campos León et al. 2017; Medina Rivera 2019; IMARPE 2020) and rice cultivation management (Amesquita et al. 2017; Salazar Ticona 2018), which are principal agricultural products in the District of Camaná. River channelization

can also lead to larger flood events and increased damage to crops and communities when river levels rise above their banks or constructed levees. This includes the potential for large changes in sediment delivery to river deltas depending on the nature of channel engineering (Hey and Philippi 1995; Winer 2011). Heavy precipitation or increased flow from snow and glacial meltwater on Coropuna Volcano to the northwest of this channelized streambed may lead to increased stream velocity, channel scouring, and redistribution of material further downstream (Xu 2015). Historic imagery can aid in the quantification of these changes and provide information for future management decisions.

Snowpack and Glaciers

Along with many human-mediated physical changes to the environment we are increasingly



Figure 4. River channelization - A short section of the Majes River west of the Majes agricultural development project in 1966 (left, KH-40) with the historically-braided streambed manually-delineated in yellow and modern 2018 channelized streambed filled in blue. Pronounced reduction of river meanders and channel area is visible along the full length of the river in this region.

83

seeing and experiencing the impacts of anthropogenic climate change, including loss of snowpack and glaciers (Yao et al. 2012; Laghari 2013; Miles et al. 2013; Moon 2017). Though there is a great focus on these issues in polar regions, it is a global concern in other parts of the world including high-elevation mountainous parts of South America. In the Region of Arequipa, Coropuna is a 6,377 m high dormant stratovolcano, 150 km northwest of the city of Arequipa (Venturelli et al. 1978; Bromley et al. 2011). Based on our analyses of historic Keyhole and contemporary Sentinel satellite imagery, from May 1978 to May 2019, respectively, Coropuna total ice and snow cover decreased by $\sim 12.7\%$ from ~ 88 km² to ~ 77 km². It is important to highlight that this does not factor in the depth of ice and snow cover. Coropuna has the thickest and most extensive ice cap in the Earth's tropical zone (Kochtitzky et al. 2018). It has been estimated that the ice cap has been shrinking since around 1850. Figure 5 shows Keyhole imagery of Coropuna in May of 1978 compared to May of 2019, forty-one years later. Though area analyses highlight a loss of some combination of glacial ice and snow, the boxes in Figure 5 highlight areas where visible ice-shelf retreat has taken place over this period of time. While it is expected that the ice cap will remain until 2120 (Kochtitzky et al. 2018), this shrinkage will likely have significant consequences for the local environment, local water security, and the communities which rely on the glacier meltwater downstream. Coropuna lies on the watershed divide of the Ocoña and Majes River basins which supply water for agricultural production in the regions. Tropical glaciers throughout this region also supply water to alpine wetlands, i.e., bofedales, which contain the largest amount of soil carbon in the region (Maldonado-Fonkén 2015; Pérez, Lau, and Schuler 2015; Araya-López et al. 2018). The loss of meltwater could lead to a loss of these wetlands, reduce their ability to buffer and smooth out precipitation to runoff release times, release stored organic matter as CO₂, and reduce available grazing for livestock and local herds of alpaca and vicuña (Kuentz et al. 2011; Stark, Guillén, and Brady 2012; Gałaś, Panajew, and Cuber 2014). Additionally, ~80% of Peru's hydropower capacity is buffered by glacial meltwater. Thus, glacial loss may also

impact renewable energy production in Peru (Stark, Guillén, and Brady 2012; Hanshaw and Bookhagen 2014).

Community Engagement

Historic and modern imagery can help with communication of critical findings, collection of social-environmental data, and co-production of knowledge across geographic scales with broad audiences, as implemented by the Arequipa Nexus Institute for Food, Energy, Water, and the Environment (Filley and Polanco Cornejo 2018). Farmers, students, and researchers working with the Arequipa Nexus Institute have responded positively to spatial mapping and satellite imagery in digital and printed formats. Digital imagery presentation and discussion with farmers and



Figure 5. Snowpack and glaciers - Coropuna Volcano viewed from above in May of 1978 (top, KH9-1) and in May of 2019 (bottom, Sentinel). Grey and black boxes are used to highlight several glacial ice flows and reductions in their size through time.

collaborators within the Arequipa Nexus Institute have been implemented primarily via the free Soil Explorer application on iPad. There is also webbased interface available, which allows users to interact easily with packaged map datasets and requires no previous geospatial training (Isee Network 2015-2020; Schulze 2018). Figure 6 is an example of what a user sees in Soil Explorer at the scale of the Arequipa Region, with a user's location in the city of Arequipa indicated in blue. Users can pan and zoom to explore spatial data such as those presented in the figures of this study via tile packages hosted remotely or locally saved to users' Apple iOS and iPadOS devices. The ability to easily incorporate and interact with large satellite imagery datasets has been of great benefit to the Arequipa Nexus Institute during conversations with stakeholders in the field, research planning meetings, formal training workshops, and has greatly enhanced engagement and project-based participation in knowledge co-production and capacity building (Duncan, Kyle, and Race 2010; Sletto et al. 2010; Canevari-Luzardo et al. 2015; Kar et al. 2016; Wachowiak et al. 2017; Kim 2018;

Onencan, Meesters, and Van de Walle 2018). Recent field research activities, pairing the use of historic and contemporary satellite imagery in the field with data collection applications like Epicollect (Aanensen et al. 2009) and LandPKS (Herrick et al. 2016), have been very successful. Further, it is our hope that making datasets like the Corona, Keyhole, Sentinel, Landsat, or other satellite imagery freely available in an easy to use format will increase public engagement which, with further discussion and planning, can positively affect management and policy decisions (Duncan, Kyle, and Race 2010; Koti 2010; Yates and Schoeman 2013; Kar et al. 2016).

Looking forward, accessible and affordable historic and contemporary imagery can enhance awareness and accountability for environmental impacts and disruptions which might otherwise go undiscovered. During visits to Arequipa, Peru, Soil Explorer was used to show irrigation commissions imagery regarding the history of agricultural expansion in their districts. These commissions are headed by elected volunteers, usually older members of their community, who may never have



Figure 6. Community engagement - Soil Explorer application screenshot of what a user may see with a 2018 Sentinel mosaic background, Arequipa Region outlined in yellow, and 1978 Keyhole (KH9-14) georectified image strip tile packages loaded on an iPad. The blue dot near the right edge of the 1978 image indicates the GPS location of a user in the city of Arequipa.

seen spatial imagery but have experienced the history personally. These elected stakeholders offer a unique insight for validation of environmental histories, as detailed in White, Kingston, and Barker (2010). This can highlight the utility of this type of historic spatial data, both in providing information to stakeholders and building collaborative teams in applied multidisciplinary and transcontinental partnerships (Filley and Polanco Cornejo 2018).

Conclusions

Arequipa, like much of the world, faces a diversity of new and evolving human-caused environmental challenges related to water quality and availability. Processes of urbanization, migration, irrigation, and salinization following intensive agricultural development are linked by water, as are the flows of melting glaciers and snowpack into channelized rivers more prone to flooding farms and cities. Here, we have demonstrated and discussed the utility of historic satellite imagery, paired with modern Earth observation, to document and quantify environmental change through a series of small illustrative case studies in the Arequipa Region of Peru. The incredibly low cost of historic Corona and Keyhole satellite imagery makes them an excellent initial or supporting data source for environmental research. The potential value and utility of historic imagery like Corona and Keyhole is perhaps highest in areas where records are sparse or nonexistent, due to inadequate monitoring or nonpoint sourced human impacts. The use of imagery and mapping to capture spatial environmental history is not limited to academic research. Imagery like Corona and Keyhole can be used to educate and empower citizens, managers, and researchers by providing them with tangible documentation of the history of their surrounding landscape, in formats accessible to non-specialists.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín. PlanetScope imagery was provided courtesy of Planet Labs, Inc.

Author Bio and Contact Information

ZACHARY BRECHEISEN (corresponding author) is a "critical-zonist" interested in how ecosystems respond to human disturbance, especially agriculture and oldfield succession. He pairs remote sensing with field observations to enhance soils and forestry investigations. His research includes land cover classification, geomorphic terrain analyses, gas chromatography, 3D printing, X-ray computed tomography, and data logging environmental sensors. His academic training from undergraduate (NMSU) through graduate (Duke University) education to postdoctoral research (Purdue University) has been inherently cross-disciplinary as he has worked with researchers from earth sciences, social sciences, and the humanities as part of the Critical Zone Observatory network and currently the Arequipa Nexus Institute. He may be reached at zbrechei@purdue.edu.

NICHOLAS G. HAMP-ADAMS is a senior in the College of Science at Purdue University. He is currently pursuing a Bachelor of Science in Environmental Geoscience expecting to graduate in December 2020. Nicholas started research with the Arequipa Nexus Institute in the summer of 2019 and has focused on mosaicking, georectifying, and analyzing Corona and Keyhole imagery. This is with the goal of understanding and quantifying how land cover has changed through time across the Region of Arequipa, Peru.

ABIGAIL TOMASEK received her Ph.D. in Civil Engineering in 2017 from the University of Minnesota. Her research has largely focused on how anthropogenic activities have affected water quality and flow. For her dissertation, she researched the driving parameters of microbial denitrification and investigated how potential management strategies could reduce nitrate loads in agricultural watersheds in Minnesota. She is currently a postdoctoral researcher in Agricultural and Biological Engineering at Purdue University and is researching the linkages between the social, environmental, and economic challenges facing urban agriculture in Arequipa, Peru.

ERIKA J. FOSTER is a Soil Agroecologist researching the response of soil biogeochemistry to management. She quantifies the accumulation and stabilization of organic matter under agricultural systems in arid environments. As an investigator within the Arequipa Nexus Institute she works within a massive irrigation project in a hyperarid region of southern Peru to develop an agricultural chronosequence of carbon development. Dr. Foster compiled and designed a soil health field test kit for small shareholder farmers of the region to combine with rapid scans of elemental content (pXRF) and organic carbon (Vis-NIR) to contribute to digital soil maps.

TIMOTHY FILLEY is a professor of stable isotope biogeochemistry in the Department of Earth, Atmospheric, and Planetary Sciences at Purdue University. He is the Director for the Purdue Center for the Environment, the U.S.-China EcoPartnership for Environmental Sustainability, and co-Director of the Arequipa Nexus Institute. Filley's research focuses on carbon and nitrogen cycling in natural and managed ecosystems and implications of emerging pollutants. His group investigates how ecosystem disturbance affects soil organic matter stability. Filley received his B.S. in chemistry from Loyola University of Chicago and his Ph.D. in isotope geochemistry from Pennsylvania State University.

MARTÍN J.C. VILLAITA SOTO received his bachelor's degree in Agricultural Sciences in 1988, title of Agricultural Engineer in 1989, Master in Agroecology in 2007 at the Peruvian National University San Agustín de Arequipa (UNSA), and Postgraduate Course in Edaphology in Spain (1996). He became Head of Edaphology Practices at UNSA in 1989 and is currently a professor of Edaphology, Soil Fertility, Soil Management and Conservation. He participates in Agricultural Research and Extension in the High Andean zones (1989); Collection of soil monoliths INIAA - ISRIC (1991); Agricultural Soil Analysis Service (1990-1995) School of Agronomy-UNSA; and Soil Health and Vulnerability Assessment UNSA-Purdue (2018-2020).

LUCIA ZUNIGA is currently a master's student in the department of Earth, Atmospheric and Planetary Science at Purdue University expecting to graduate in August 2020. Lucia did her undergraduate degree in natural resources and environmental science with concentration in resource conservation and ecological restoration at University of Illinois - Urbana-Champaign. Lucia is researching the accumulation of carbon and heavy metals in the arid environment in Majes Irrigation, Arequipa, Perú.

ANDRE GERALDO DE LIMA MORAES was born in Muzambinho, Minas Gerais, Brazil, and concluded his bachelor's degree in Agronomy (2011), Masters (2013), and Ph.D. (2018) in Agronomy-Soil Science (CPGA-CS) at the Federal Rural University of Rio de Janeiro (UFRRJ). Currently, he is a postdoc at the Agriculture and Biologic Engineering (ABE) Department at Purdue University. Research interests include soil management and conservation, genesis, morphology, survey, classification, digital soil mapping, erosion and infiltration spatial modeling, climate mapping, climate trend analysis, and general applications of remote sensing and GIS. **DARRELL SCHULZE** is a Professor of Soil Science at Purdue University. His research and teaching interests include pedology, digital soil mapping, mineralogy, soil chemistry, and international agriculture. He teaches a field-based course titled, Soils and Landscapes, for which he developed an innovative teaching-with-maps approach that is used in various courses at Purdue and elsewhere. He leads the development of Soil Explorer, a soil data visualization platform that is available as an app for iOS and Android and as a website (SoilExplorer. net). His work with the Arequipa Nexus Institute is primarily focused on visualizing soil and landscape data.

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