Distribution, Characteristics and Management of Tamarisk at Pómac Forest Historic Sanctuary

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I. INTRODUCTION

I.1. Problem Definition

In recent decades, stands of non-native tamarisk have established along a 10 kilometer stretch of the La Leche River passing through Pómac Forest Historic Sanctuary. A natural protected area of Peru, administered by the National Service for Natural Protected Areas, or SERNANP, Pómac Forest encompasses more than 5800 hectares of fragile equatorial dry forest in the northern coastal department of Lambayeque and is home to an abundance of endemic flora and fauna to complement more than thirty adobe pyramids from the pre-Columbian Sicán culture.

Tamarisk, also known as salt cedar, is a genus of halophytic shrubs and trees originating across North Africa and the Middle East. During the 19th century, tamarisk was spread extensively outside its native ranges, planted as an ornamental for its aesthetically pleasing form, for shade in arid zones with sparse tree cover and as natural windbreaks in areas like the Southwest United States; around the 1930s, authorities in the U.S. observed that the species had escaped cultivation and was spreading rapidly along rivers, replacing native vegetation (Robinson, 1965). Since that time, the spread of tamarisk has become an issue of concern for natural resource managers in many countries, including Peru. The problem has spread to encompass river valleys in the low-altitude, coastal desert regions of the country, where *Tamarix aphylla* (athel pine) is found ranging from the southern department of Ica to Lambayeque, more than 1000 kilometers to the north.

As an invasive, tamarisk occupies riparian zones and wetlands, often replacing native woody species at these sites and leading to concerns by natural resource managers about site conversion to tamarisk dominance (Longland, 2014). The competitive advantage of tamarisk compared to native species at many sites can be attributed to the specie's stress tolerance to drought and salinity, its aggressive rate at reproducing itself and its ability to form deep root networks (Wei & Ramanitharan, 2010). Stands of the this invasive can significantly alter the ecology and water patterns of affected sites, including increased water consumption and loss, increased occurrence of wildfires, a higher concentration of salt in soil, increased occurrence and severity of flooding events, a reduced quality of habitat for native wildlife, and a potentially reduced recreational utility of the site (Barz, Watson, Kanney, Roberts, & Groeneveld, 2009).

Unfortunately, the complete eradication of tamarisk is viewed by many researchers as an unattainable goal due to tamarisk's production of large quantities of water- and wind-dispersed seeds that make reestablishment likely; managers instead need to adopt strategies to mitigate any further spread and impact of tamarisk on native ecosystems (DiTomaso, 1998). Natural protected areas like Pómac Forest would be prudent to investigate and adopt appropriate strategies to contain tamarisk and ensure the integrity of riparian sites in the long term.

I.2. Capstone Goal

SERNANP's awareness but lack of monitoring for tamarisk at Pómac Forest has left an information gap regarding the current distribution and population characteristics of the tree within the limits of the protected area. As an environmental volunteer serving with Peace Corps and assigned to Pómac Forest for three years (September 2014 - December 2017), the author has had access to the protected area along with human and material resource support of its park guards and forestry engineers in conducting a comprehensive field inventory of tamarisk within the vicinity of the La Leche River. The desired results of the study is to close the information gap on tamarisk and provide management with necessary knowledge about its distribution and characteristics for an informed management decision to control the spread of tamarisk and to protect the natural identity of the riparian zone for one of the few remaining equatorial dry forests of its size in Peru.

To accomplish this, the author based the study on three goals:

I.3. Objectives

Objective 1: Enhance knowledge of tamarisk's spatial distribution and abundance.

The primary focus of the investigation is to establish a base line population count with accompaniment of geographic coordinates for tamarisk at Pómac Forest. After a thorough review of academic literature and consideration of available time to conduct the study, the author determined the following objectives:

- Conduct field transects of the protected area's riparian zone (1.5-kilometer search buffer on either side of La Leche River).
- Map the point data of tamarisk distribution using QGIS software.

Objective 2: Gain an understanding of the present tamarisk population through field measurements.

With the completion of field transects, the author separated the observed tamarisk population into two zones – *East* and *West* – using a diversion dam on the La Leche River as a dividing line. Of the two zones, *East* was chosen for measurement based on its smaller, more sparsely distributed tamarisk population. Of the 35 identified occurrences in this zone, the author collaborated with park guards on the following objectives:

- Biometric measurements (diameter at breast height, lateral spread and tree height)
- Photographic records
- Catalogue spreadsheet of existing trees.

Objective 3: Compare existing tamarisk control methods.

With a review of tamarisk management strategies from academic studies and natural resource agencies in the United States and elsewhere, the author identified and compared existing methods for tamarisk control to provide a recommendation for SERNANP. From prior coursework, the author integrated a problem-solving tool for a method-based approach to the recommendation.

- Apply the "Decision Making Framework" from *Rural Resource Management: Problem Solving for the Long Term* (Miller et al., 1995).

I.4. Important Terms

Halophyte: a plant adapted to growing in saline conditions, as in a salt marsh.

Invasive species: non-native (or alien) to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm.

NDVI: (normalized difference vegetation index) a standardized way to measure healthy vegetation through remotely sensed imagery, measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs).

Remote Sensing: the collection and interpretation of information about the environment and the surface of the earth from a distance, such as aerial photography, radar, and satellite imaging.

Restoration: the action of returning something to a former owner, place, or condition.

Riparian: relating to wetlands adjacent to rivers and streams.

Shade tolerance: the ability of a plant to become established, grow and persist under shade or low light intensity, quality and duration.

II. LITERATURE REVIEW

The literature review is divided into three sections, each corresponding with the three goal areas of the report. Note: most academic literature cited in the study pertains to research from the southwestern United States. No published studies could be found on the spread of tamarisk in Peru, in neither English nor Spanish, at the time of writing.

II.1. Remote Sensing of Tamarisk

In recent years, studies have employed remotely sensed data (i.e. satellite imagery from Landsat, Quickbird and IKONOS sensors and/or aerial photographs) using spectral reflectance analysis in GIS software to examine the spread and physiological changes to tamarisk populations across distance and time. Based on a closer reading of these studies, there is promise for its application to tamarisk management in Peru, though there remains uncertainty over whether the accuracy of the results obtained via these methods can provide monitoring that is accurate enough for the needs of sensitive ecosystems like Pómac Forest.

A study from Colorado (Carter et al., 2009) showed the limitations of the coarser spatial resolution inherent to Landsat sensor data available through the United States Geological Survey. With 30 square meters of ground per pixel, researchers found it difficult locating ground plots that contained at least 80 percent tamarisk coverage to be used as training pixels for classification purposes. Their success with higher 2.5-meter resolution imagery from the Quickbird sensor showed some promise, although the study admitted these results contained higher errors of commission, or inclusion of non-tamarisk pixels to tamarisk classification. Furthermore, the success of the Quickbird sensor images were highly dependent on the winter leaf loss of the tamarisk species at this site to distinguish it from surrounding riparian vegetation, a characteristic not present in the evergreen *Tamarix aphylla* species encountered at Pómac Forest.

High resolution imagery, although more detailed, is no guarantee for successful tamarisk detection. One study in northern California showed that tamarisk's reflectance couldn't be well enough distinguished from associated vegetation to allow for classification even with aerial images of a relatively high resolution of 1 square meter per pixel (Evangelista, Stohlgren, Morisette, & Kumar, 2009). The study highlighted the need for ground truthing of data (i.e. direct field observation) to provide greater certainty when examining satellite imagery of a site. As with any study utilizing remotely sensed imagery, researchers studying tamarisk still need to visit study sites and verify their data.

Estimating the abundance at the species level with Landsat sensor data can be a challenge in diversified landscapes, like the riparian zones where tamarisk establishes. At a site near the Rio Grande in Texas (Diao & Wang, 2016), researchers attempted to identify the spectral signatures of tamarisk with Landsat imagery taken for every month of the year. With the data, the researchers created models in GIS to unmix tamarisk from other species in the images and estimate its abundance per pixel based on seasonal changes to leaf color; in sites where tamarisk is present on the Rio Grande river border between Texas and Mexico, the senescence stage of tamarisk sees its leaves turn an orangish-yellow which can help to distinguish it from darker native species at those sites, although this lasts only several weeks and is difficult to predict without previous knowledge of phenological patterns at the study site. And although researchers initially used normalized difference vegetation index (NDVI) comparisons to identify the leaf senescence, they ultimately found identifying the spectral signatures of tamarisk and comparing across time yielded more accurate and promising results for future studies (Ji, Wang, & Knutson, 2017). This methodology could be useful in monitoring the river valleys of coastal Peru, although the difference in hemispheres would likely change the months of observations for seasonally-dependent phenological patterns of tamarisk. Although the study achieved success with its unmixing model, any future study would need to consider that predictor models would be different for every unique forest type. The unmixing model for tamarisk at an equatorial dry forest in Peru, for example, would be different from a model for tamarisk at riparian sites in Texas or China with the change in associated vegetation. Furthermore, the study unfortunately fails to mention the specific species of tamarisk at the Rio Grande site which is also important to consider as *Tamarix* is a broad genus including both deciduous and evergreen species.

Another study from Colorado (Evangelista et al., 2009) combined inventory data collected by the Tamarisk Coalition (www.tamariskcoalition.org) as ground control points to compare with Landsat imagery. The study had success distinguishing three different times during the growing season at the Colorado site when phenological attributes of tamarisk could help distinguish it from native vegetation using time-series analysis. However, the study emphasizes that spectral data from these months may not perform as well in other ecosystems, geographic regions or scales compared to the study area in Colorado. And although the study referenced field observations points, they failed to verify geographical coordinates for the chosen study site. The researchers point this out, recommending future studies record presence and absence points from field data to help increase data quality and minimize sampling error with image analysis. One important takeaway from the study was that smaller study areas may be better suited for high-resolution imagery, which would enhance the detection of individual plants and low-density infestations. As data from Pómac Forest show, Zone East of infestation is characterized by a sparse distribution that would be nearly impossible to detect through coarse resolution images like Landsat.

Kite aerial photography, an accessible form of high spatial-resolution remote sensing, has allowed researchers to gain a bird's eye-view of a study site with the benefit of large-scale imagery at frequent time intervals. A cost-benefit analysis of kite-aerial surveys versus traditional ground surveys across multiple study sites over many years show that the low-height photography is both less expensive and provided more objective results. Consequently, the practice has been adopted by the U.S. Bureau of Reclamation to document its biocontrol studies at sites in the western United States at a study site near Pueblo, Colorado (Aber, Eberts, & Aber, 2005). In recent years, drones have also entered the picture, providing researchers across many fields to conduct relatively inexpensive, on-demand surveys of site conditions. Both kite and drone platforms could be a very useful remote sensing resources for future monitoring of tamarisk at Pómac Forest.

One potential option for remote sensing of tamarisk in Peru in the years ahead could be the high-resolution images provided by Peru's domestic satellite, PeruSat-1. This Earth observation satellite system was launched in 2016 an in cooperation with the French government and is operated by the Peruvian Air Force. The sensor features the NAOMI instrument with 70 cm resolution and is being used to collect images for use by the Peruvian government for applications in agriculture, urban planning, border control and drug trafficking, the management of humanitarian aid and the evaluation of natural disasters; to date, PeruSAT-1 has acquired more than 102,200 images that have been used by more than 70 public entities registered at the CNOIS (National Satellite Image Operation Center) (Kramer, 2016). As a natural protected area administered by the State, SERNANP management at Pómac Forest could foreseeably request this high-resolution imagery, free of cost, to help with the monitoring and protection of a national asset from invasive species like tamarisk.

II.2. Botanical and Ecological Characteristics of Tamarisk

The Tamaricaceae genus contains 54 species globally, with ranges native to northern Africa and the Middle East. Within this genus of shrubs and trees, the larger *Tamarisk aphylla* found at Pómac Forest is a perennial tree with shallow lateral rhizomes and deep roots dominated by a root crown 12 to 18 inches below the soil surface that can reach below 30 feet. Buds on the root crown quickly sprout new stems when above portions of the plant are cut (U.S Forest Service - Southwestern Region, 2010)

Tamarisk have high rates of growth, adaptability to a wide range and survivability in a range of harsh climates is regarded as a suitable species to mitigate land degradation (Dawalibi, Monteverdi, Moscatello, Battistelli, & Valentini, 2015). The portions of coastal Peru where tamarisk has been observed in recent years, including the Lambayeque region containing Pómac Forest, are classified as *Hot desert climate* (BWh) under the Köppen-Geiger system. This category is shared by most of the native tamarisk ranges in North Africa and the Middle East and help to explain tamarisk's ease of adaptation:

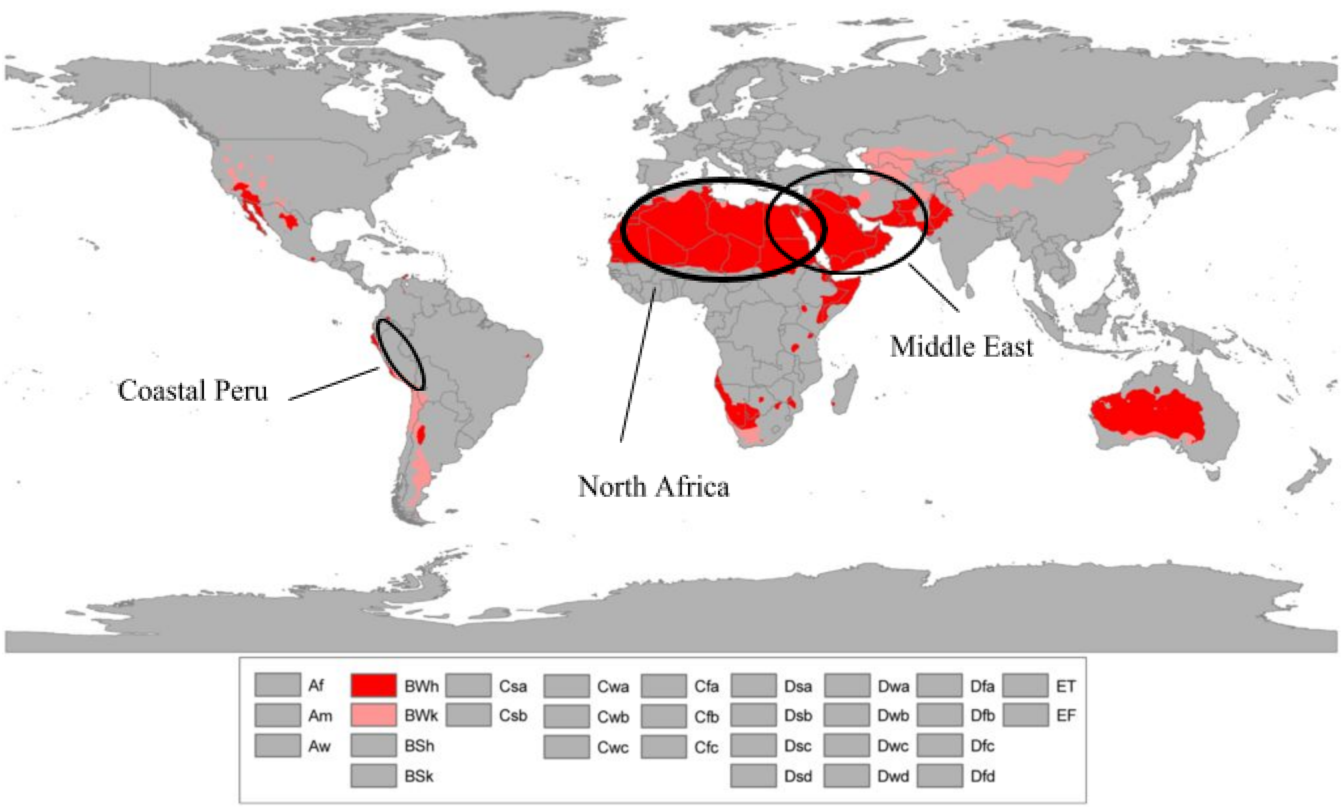


Figure 1: World map of the Köppen-Geiger climate classification, Hot desert climate (BWH) (Peel et al. 2007)

Tamarisk has spread extensively outside these native ranges and currently occupy riparian zones and wetlands in the Americas and Australia, often replacing native woody species at these sites and leading to concerns about site conversion to tamarisk dominance (Longland, 2014). The higher level of tamarisk compared to many of the native vegetation it has replaced at sites in the Western United States, for example, is believed to be caused by higher rates of evapotranspiration (Barz et al., 2009), which provide more hydrogen ions for photosynthesis and, consequently, higher rates of growth for site competition and domination

The spread of tamarisk to Peru is not well documented, although one plant guide mentions the introduction of tamarisk to the Ica region beginning in the 1940s (Whaley et al., 2010). According to the guide, tamarisk currently covers extensive areas of the lower Ica Valley and is found growing in groves or as individual trees throughout the region. Although some birds nest in forests of tamarisk, there is no species associated with this non-native vegetation. However, tamarisk does provide nectar for bees and is said to be appreciated by some beekeepers.

Figure 2: Local beekeeper Nesthor Velasquez Acosta removing a honey bee hive from a tamarisk branch at Pómac Forest. Quadrant L-11

Propagation

Tamarisk has scaly, filament-like leaves that resemble evergreen needles and 5-petal pink-to-white flowers. From these flowers are produced thousands of fine seeds (1000 per gram) that can be dispersed by wind or water. *Tamarisk aphylla* produces a large quantity of seeds, approximately 500,000 seeds per year from a single tree. The spread of tamarisk commonly occurs with flooding events in riparian zones; seeds drop and float on water and are carried along waterways and establish where there is damp soil moisture for germination and survival (U.S Forest Service, 2010).

At Pómac Forest, the La Leche River serves as an important vector of dispersal for tamarisk. The river's passage through private, non-protected agricultural land upstream of the protected area where tamarisk has been observed at several sites by the author.

A calendar for *Tamarisk aphylla* in Table 1 shows month-by-month estimations for the reproductive cycle of the species. Peru, like Australia, is located in the Southern Hemisphere; although the study did not directly observe seed or flower production during the months of field work, the tamarisk at Pómac Forest likely reflect the following yearly pattern.

	MONTH											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Flowering	X	X									X	X
Seed Formation	X	X	X									X
Seed Drop			X	X	X					X	X	X
Germination			X	X	X						X	X

Table 1: Tamarisk reproductive calendar for Australia (Cooperative Research Centre for Australian Weed Management, 2003)

Establishment

To survive arid landscapes, tamarisk forms thick groves along riparian zones, close to water sources (Ceurvorst & Allred, 2013). As shown in the following study data, tamarisk establishment within the dry forest landscape of Pómac Forest is dependent on proximity to the La Leche River, with the farthest tamarisk observation at 1.2 kilometers from river's edge. In terms of soil preference, tamarisk is dependent on the availability of bare unshaded mineral sediment typically found on river banks (DeWine & Cooper, 2010). In the riparian zone of Pómac Forest, the soil is characterized by sand deposits along the bed of the Leche River and alluvial clay forming the raised riverbanks (SERNANP, 2011).

Figure 3: Tamarisk seedlings along a stretch of unshaded sandy bank of the La Leche River. Quadrant I-10

Tamarisk is classified as a halophyte, able to endure salinity levels equal to seawater (around 35g/l) with only a 50% reduction in growth (Glenn & Nagler, 2005). Habitat suitability models from the United States have shown that distance to water is the most important predictor variable for tamarisk. Another critical limiting factor to tamarisk's establishment is the occurrence of frost events Furthermore, flow regulation of rivers and streams has been shown to place an important role in tamarisk's replacement of native species in arid regions; lack of overbank flooding means that regulated rivers are unable to flush salts that accumulate at the base of tamarisk stands, making it extremely difficult for native non-halophyte species to establish themselves (Nagler, Glenn, Jarnevich, & Shafroth, 2011). The La Leche River at Pómac Forest does contain a diversion dam linking two canals that redirect some of the water to irrigation canals used in regional agriculture. The final 2 kilometers of the La Leche River beyond this man-made structure contain both the densest concentration and the great majority (87.8%) of the 287 observed tamarisk along the 10 kilometers of river that traverse the protected area.

In one study comparing the effects of drought conditions on tamarisk, it was found that limited water only had a slight effect on tamarisk's height and biomass for the period observed, likely due to the species ability to adapt quickly in the efficient use of water towards the production of dry material (Dawalibi et al., 2015). The drought resistance of tamarisk has been shown in numerous studies, with the tree capable of tapping underground aquifers as deep as ten meters. (Nagler et al., 2011). It is currently unknown whether the tamarisk at Pómac Forest can access the subterranean water supply, with the water table level resting between 18 and 20 meters ground depth (SERNANP, 2011) Research also has shown that tamarisk displays a highly variable water use, with stand-level estimates for evapotranspiration in a range between 0.75 and 1.45 meters per year; consumption is dependent on stand density, local climate and yearly weather (Sueki et al., 2015). This range tolerance is crucial for tamarisk survival at Pómac Forest. The La Leche River carries water sporadically between the months November and April with an average flow of 60 cubic meters per second while drying up the rest of the year (SERNANP, 2011). Rain is very limited outside of years when the El Niño Phenomenon occurs, with the last two events occurring in 1998 and 2017. Between those two events, between 2000 and 2014 the average rainfall per year was just 30.0 mm, dropping to as low as 2.3 mm during the drought year of 2005 (SENAMHI, n.d.).

Another study from the Western United States used a Hyper-Envelope Modeling Interface (HEMI) tool within GIS software to produce a habitat suitability map for tamarisk based on temperature and precipitation based on the ecological niche theory to predict species distribution based on optimal climate conditions. However, the model was limited due to its limitation to only continuous geographic data and could not include discontinuous variables like soil type (Graham et al., 2013). A similar study could be conducted for Peru, with the only limiting factor being availability of appropriate geospatial data. Data on precipitation, for example, is freely provided by SENAMHI, Peru's National Meteorological and Hydrological Service.

In the western United States, it is believed tamarisk likely already occupies most of the sites for which it is suited, although climate change may extend its reach further north from evolutionary adaptation to frost, climate change or further construction of reservoirs (Nagler et al., 2011). The extent of the spread of tamarisk in Peru is currently unknown and requires further study.

Site Competition

It has been argued that the presence of invasive tamarisk may not threaten ecosystems in certain cases and that one must examine their abundance relative to other species in site and the interaction between the two groups (Nagler et al., 2011). According to the most recent Master Plan for Pómac Forest, the predominant native plant species encountered along the La Leche River in association with tamarisk are shown in Table 2 (trees are preceded by an asterisk):

Common Name	**Scientific Name**
*Algarrobo	*Prosopis pallida*
Caña brava	*Gynerium sagittatum*
Cerecillo	*Muntingia calabura*
Chilca	*Baccharis lanceolada*
*Faique	*Acacia macracantha*
*Guásimo	*Guazuma ulmifolia*
Junco	*Phragmites australis*
*Pájaro bobo	*Tessaria integrifolia*
Sacuara	*Cortaderia cubata*
*Sauce	*Salix chilensis*

Table 2: Riparian trees and shrubs at Pómac Forest (SERNANP, 2011)

A better understanding of competition and succession along the La Leche River at Pómac Forest can be formed with knowledge about the growth rates and shade tolerances of each individual species. For example, pájaro bobo (*Tessaria intergrifolia*) is a fast-growing species of tree that already occupies the sandy, exposed margins of the La Leche River in clusters, similar like tamarisk. The species in Pómac Forest's riparian zone and is commonly harvested by local farmers for wooden fence posts because due to the straight, columnar form of its trunks (Carolina Guevara, personal communication, 23 August 2017). Managers should be aware that without planning, treated areas can be quickly reinvaded by tamarisk or other invasive species and that to achieve sustainable control, they should look to plant competitive native plants that can exclude tamarisk (U.S Forest Service, 2010) In the future, a comparative study of pájaro bobo against tamarisk could help determine the utility of that species as part of an overall management strategy to mitigate reestablishment of tamarisk in areas of eradication attempts.

One study on the successional replacement of tamarisk in the United States with native box elder, *Acer negundo*, along a tributary of the upper Colorado River, show evidence that adult stage tamarisk trees may be outcompeted by shade-tolerant native species that establish during the later stages of ecological succession. By outgrowing and overhanging tamarisk within a stand, the native box elders reduce light levels that prove insufficient for the tamarisk in the understory that eventually lead to mortality. (DeWine & Cooper, 2010). The researchers argue the results contradicts previous theories that tamarisk maintains site dominance via exclusion, but rather because of its physiology that has adapted to stress tolerance, dispersal characteristics and lack of natural herbivores outside their native range. Whether this applies to the dry forest species at Pómac Forest is unknown but would make for a beneficial study by the protected area's forestry engineers.

Site Impacts

Tamarisk can significantly alter the ecology and water patterns of affected sites, including increased water consumption and loss, increased occurrence of wildfires, a higher concentration of salt in soil, increased occurrence and severity of flooding events, a reduced quality of habitat for native wildlife, and a potentially reduced recreational utility of the site (Barz et al., 2009). Each of these potential negative site impacts undermine the conservation efforts at Pómac Forest and provide sufficient justification for tamarisk management.

The effects of tamarisk on soil salinity is a cyclical process. As the trees uptake water and nutrients through its root system, it concentrates salt compounds from the surrounding soil, which are then transported to the leaves. These salts are then returned to the soil at the base of the tree either through leaf or rain fall. One study found tamarisk concentrating soil salts at levels around 18% higher than surrounding control areas (He et al., 2016). The concentrations of salts help tamarisk reduce competition in understory growth by salt-intolerant species. The impact of salt concentration on native riparian plants along the La Leche River at Pómac Forest is currently unknown and would require a future study. Tamarisk is also known to reduce soil moisture around its base through the interception of precipitation at its dense crown and root uptake. The shade provided by tamarisk also reduces air temperature and evapotranspiration in its subcanopy (DeWine & Cooper, 2010).

From a beneficial standpoint, dense stands of tamarisk have been shown to help stabilize and narrow streams and rivers by providing vegetation with roots that protect banks against erosion during high flow and have been associated with reduced sediment buildup that reduces flooding hazards. However, this positive effect is negated in some cases by the buildup of stream wood from tamarisk vegetation that can cause damming downstream, resulting in floods during high flows. It can be said that the cost of clearing a river of tamarisk may be the release of soil sediments that had been held out of the river flow by the trees (Barz et al., 2009). Pómac Forest did experience significant flooding and bank erosion of the La Leche River during the most recent El Niño Phenomenon rains in 2017. However, sites of erosion observed by the author were already densely occupied by large native tree species like algarrobo and faique; it is unlikely that a tamarisk presence at the site would have prevented erosion against the force of the current. During the flooding events of the 1998 El Niño event, the La Leche River's volume was recorded at approximately 1000 cubic meters of water per second, more than 16 times its normal rate during the wet season (SERNANP, 2011).

A study from Arizona examining the effects of exotic riparian species removal showed that the elimination of tamarisk did not affect ground water dynamics at site, likely because evapotranspiration by stands of tamarisk is considered relatively low, and that the sites were transitioning to dry grasslands (Reynolds & Cooper, 2011). Another study, based on small mammal trappings at tamarisk monoculture sites in the Great Basin of Nevada, show there to be no negative impacts on species diversity and negligible effects on the abundance of the species captured (Longland, 2014). Knowing whether the results of these two studies apply to Pómac Forest would require future investigation.

II.3. Tamarisk Management

Complete eradication of tamarisk is viewed by many researchers as an unattainable goal due to tamarisk's production of large quantities of windborne seeds that make reestablishment likely; instead, mangers are urged to focus on control and management of the trees to mitigate their impact (DiTomaso, 1996). An investigation on the cost-benefit data for tamarisk control in the western United States and northern Mexico conducted in the late 1980s had shown that, although a 100% eradication of tamarisk may be an unrealistic goal, the environmental and economic impacts of control far outweigh the costs at all levels (Barz et al., 2009). These positive impacts include improved waterflow, flood control and aesthetics for recreation at managed sites (U.S Forest Service, 2010).

Success of control strategies of tamarisk tend to combine more than one strategy to achieve long-term, sustainable results. Such strategies thus require an informed knowledge of their distribution, the site conditions that are beneficial or detrimental to their survival and propagation, and their abundance in particular ecosystems (Nagler et al., 2011). For that reason, an inventory of tamarisk at Pómac Forest is a prerequisite before any strategy should be formulated.

One weakness of many control methods, is that they fail to prevent reinvasion by not correcting the site conditions that led to the initial invasion (DeWine & Cooper, 2010). Although tamarisk control can affect microclimates and leave voids in riparian zones, restoration activities through active management can help to mitigate negative impacts such as the establishment of undesirable plant species following a reduction in tamarisk density and canopy cover (Mosher & Bateman, 2016). With these points in mind, a control method for Pómac Forest would need to not only eradicate the species from site but also change the margins of the La Leche River to prevent a reestablishment from seeds dispersed further upstream that are outside the jurisdiction of the protected area.

A wide range of methods exist for the control and removal of tamarisk, from the introduction of biocontrol agents such as leaf beetles, mechanical removal with heavy machinery, the application of chemical herbicides and the use of controlled fires (Wei & Ramanitharan, 2010). Where the protection of surrounding resources is necessary, as in Pómac Forest Historic Sanctuary, the U.S. Forest Service recommends either physical control via hand removal or selective mechanical removal, or chemical control by the cut stump method or foliage spray for individual plant treatment (U.S Forest Service, 2010).

Mechanical Removal

The regional government of Lambayeque has used bulldozers in the past to clear the La Leche River within Pómac Forest of obstacles and to reinforce embankments near the protected areas interpretation center at the eastern entrance. However, the mechanical removal of exotic species like tamarisk with heavy machinery, though effective, is costly in terms of capital and labor inputs and provides little, if any, additional benefits for reestablishment by native vegetation over the cut-stump method of tree removal (Reynolds & Cooper, 2011). SERNANP's lack of heavy machinery would require renting equipment and paying operators to perform removal would. A more feasible scenario would be for SERNANP to contact the regional government of Lambayeque to share resources, possibly coinciding with future embankment or road construction work at the protected area.

Chemical Treatment

The cut stump treatment can be use where mechanical treatment or herbicide spraying is restricted by logistics or the treatment needs to be highly selective to minimize harm to native, non-target species. Mortality rate from the method under best conditions can yield 60-80, however, follow-up treatments with leaf application can achieve the best results. Herbicides recommended for the cut-stump method incudes triclopyr ester, imazapyr, or a mixture of imazapyr with glyphosate (U.S Forest Service, 2010). As of December 2017, these herbicides are widely available from several agro-equipment vendors in the nearby regional capital of Lambayeque, Chiclayo.

In a cut stump treatment, the tree is cut down at the base and herbicide solution is applied to the outer cambium layer of the trunk. It is recommended to apply the herbicide soon after cutting to ensure the herbicide can make contact with the tree's vascular system before it seals off. In some species, cutting off the main trunk may stimulate root sprouting (Kyser, Oneto & Moore, n.d.) If possible, sites should be deep ripped with heavy machinery to bring root material to the surface and, where appropriate, a suitable native species like pájaro bobo be planted to help outcompete the regrowth of tamarisk. Otherwise, care must be taken to reduce the amount of soil covering fallen stems and exposed roots as they may re-shoot (Cooperative Research Centre for Australian Weed Management, 2003).

Aerial application of herbicides is considered effective and relatively inexpensive, although it has a higher susceptibility to cause collateral damage to surrounding native species (DeWine & Cooper, 2010). A 4-year study by the United States Bureau of Reclamation conducted on 8700 hectares at the McMillan reservoir in New Mexico showed that aerial spraying of tamarisk was the most effective method, although in the end mechanical and extraction methods were mainly used (Barz et al., 2009). Unfortunately, the riparian zone at Pómac Forest is densely vegetated and collateral damage would make this method an undesirable approach.

Biocontrol Treatment

Biocontrol treatment of tamarisk with leaf-eating beetles has been practiced at sites in the Western United States for several years now. Habitats where tamarisk dominate have been shown to change drastically after a biological control event with leaf beetles, becoming more open and less shaded to the benefit of understory plants (Longland, 2014). Although the introduction of leaf beetles at sites in the United States has met with success, there is always an uncertainty about unintended consequences when introducing a new species into an ecosystem. Before any biocontrol agent can be introduced to Pómac Forest, a thorough investigation should be conducted.

During larval and adult stages of life, leaf-eating beetles attack the leaves and outer layers of stem tissue of tamarisk. Over enough time, the beetles can defoliate enough to cause eventual plant mortality. Studies have shown that species, such as *Diorhabda elongate deserticola*, kill more foliage than they consume through feeding. This feeding patterns of the beetles affects water transport to non-consumed foliage, causing the death of leaves and a change to a reddish-brown color in tamarisk (Aber et al., 2005).

Remote sensing has proven a useful tool for tracking biocontrol methods on ecosystem functioning and processes. One study from the Lower Rio Grande in western Texas used Landsat images to show how introduced beetles of the species *Diorhabda sublineata* were able to spread at a rate of around 102 square kilometers during the first year of release along the Lower Rio Grande in western Texas and generally followed where stands of tamarisk were available (Ji et al., 2017). For comparison, the riparian zone at Pómac Forest is only around 60 square kilometers.

Effects of leaf beetles on tamarisk mortality were shown in another study that followed the release of the northern tamarisk beetle, *Diorhabda carinulata*, at ten sites with 265 tamarisk trees in western Colorado over a six-year period. Of the ten sites, mortality was observed at seven of the sites where it ranged between 15 and 56 percent. In addition, both crown cover and volume decreased by over 50 percent averaged across the ten sites, showing the beetle's ability to lower site dominance of tamarisk in riparian ecosystems by reducing their crown cover and opening the canopy to competing species. Their success as a control agent tend to be higher at sites that contain narrower streams and sandier soil types (Kennard et al., 2016).

The effects of defoliation by leaf beetles on tamarisk were studied at a site on the Virgin River in Nevada; continual defoliation by leaf beetles between 2011 and 2012 showed a reduction in annual evapotranspiration by 18% and a reduction of annual daily groundwater fluctuation by 35%. The study argues that the long-term changes in these values would depend on repeated defoliation over many years, as partial recovery was observed after just 20 days when defoliated branches begin to produce new leaves (Sueki et al., 2015).

The impact of leaf beetles or other biocontrol agents on animal habitat is an important point of consideration. At Utah and Nevada sites along the Virgin River tributary of the Colorado, a study of amphibians and reptiles showed the necessity of performing riparian restoration at sites exposed to tamarisk biocontrol. Restoration included the mechanical removal of dead tamarisk, transplanting native trees to the site and restoring hydrologic flows to accommodate the herpetofauna. Sites with active restoration showed positive effects on abundance of lizard species compared with non-restoration sites (Mosher & Bateman, 2016). This is an important consideration for Pómac Forest where riparian zone is an important habitat for 21 species of amphibians and reptiles, including the endangered macanche boa (*Boa constrictor ortoni)* (SERNANP, 2011).

The response of bird species to tamarisk biocontrol with leaf beetles can be complex, depending on their ability utilize the beetles as a food source, their sensitivity to the timing of the defoliation on their nests, and their present dependence on tamarisk stands as a habitat. A study on the effects of tamarisk defoliation using leaf beetles shows the potential for lower productivity for nesting in tamarisk stands, which would consequently mean reduced success at reproduction. Ultimately, the long-term effects of leaf beetle introduction on bird species would be measured against the habitat's rate of recovery once the tamarisk is gone.

Site Competition

Because of tamarisk's seed production and dispersal abilities, the eradication of a stand site may only reset succession and simply see new tamarisks replace those that are removed; a bottom-up control using fast growing, shade-tolerant native species in the subcanopy of tamarisk stands could naturally replace and inhibit future establishment of shade-intolerant tamarisk (DeWine & Cooper, 2010). As studies with box elder (*Acer negundo*) have shown along the upper Colorado River, native trees that provide dense shade are potential agents of control for reducing tamarisk populations in riparian zones. Focusing on successional trends instead of complete removal of target non-native species may prove more effective at controlling non-native incursions (DeWine & Cooper, 2010). As discussed earlier, a comparative study of pájaro bobo against tamarisk could help determine the utility of that species as part of an overall management strategy to mitigate reestablishment of tamarisk in areas of active management.

Figure 4: A dense stand of pájaro bobo along the river margin. Quadrant O-11.

Harvesting

One study has been suggested the removal of invasive species like tamarisk could be turned into a profitable industry, utilizing harvested biomass for energy production, for example (Wei & Ramanitharan, 2010). Surrounding Pómac Forest on its outer perimeters are several rural farming communities. SERNANP has worked closely with these communities in the past through a network of Volunteer Park Guards associations that enroll the help of locals to help with conservation effort, from mending fences, patrolling against illegal logging and reseeding the soil in degraded sectors of the protected area. In exchange, members of the associations are granted privileges for collecting firewood and fruit from the algarrobo trees in a sustainable manner, as defined under article 21b of the Law for Natural Protected Areas cited previously (National Congress of Peru, 1997). Any management plan for tamarisk would be wise to include this group as they could complement the labor force that would be required to control the spread of tamarisk as well as educate the local populace on the issue. As part of their remuneration, volunteer park guards could be permitted to collect tamarisk wood fuel for their daily cooking needs. A study on tamarisk use in charcoal, for example, could be useful for better understanding a potential economic resource for the local populace.

The Choice of Strategy

The alteration of riparian ecosystems from tamarisk removal could significantly alter riverbank scenery and impact the enjoyment of scenic views by visitors to Pómac Forest. In a survey of visitors to Canyonlands National Park in Utah, most respondents were in favor of the removal of tamarisk. Of those in favor, the majority thought the use of a biocontrol like the tamarisk beetle, and the cut-stump herbicide application, while less favorable methods were controlled burns and mechanical removal (Ceurvorst & Allred, 2013). Based on informal conversations with local residents, the author found that knowledge of tamarisk is minimal; an education campaign by SERNANP at schools and cultural activities could disseminate information on the species and allow a public opinion on tamarisk removal to form.

Public opinion is a critical factor for the management of tamarisk on public lands like Pómac Forest. In the United States, agencies, like the Bureau of Land Management, are mandated by executive order to help educate the public in acting to prevent the introduction of invasive species, and to detecting and responding to their spread of these populations in cost-effective, environmentally sound manners (Exec. Order No. 13112, 1999). Under Peruvian law, Article 102 of Law Nº 28611 – General Environment - deals with conservation of native species in the country, defining the state's responsibility to evaluate and control the entrance and dispersion of exotic species (National Congress of Peru, 2005). Article 29 of Law 26834 – Natural Protected Areas – states the recognized importance of protected areas like Pómac Forest in developing activities of scientific investigation for educational purposes to the public (National Congress of Peru, 1997). Combined, these two laws justify educating visitors to Pómac Forest on the threat of tamarisk to the riparian zones of coastal Peru, most of which lies outside the small footprint of state-administered natural protected areas. Through this education outreach, SERNANP can help improve public understanding on the urgency of tamarisk management and to sway public opinion in favor of any future management actions.

III. METHODS

Field observation of tamarisk began during the author's second year serving as an environmental volunteer at Pómac Forest through Peace Corps. Coordinate data for tamarisk was collected over nine months, with field transects of the riparian zone beginning in May 2016 and ending by late December of that year. In August and September of the following year, biometric measurements (diameter at breast height, lateral spread and tree height) were taken of 35 tamarisk occurrences located upstream of a diversion dam as part of an initial inventory project for the protected area. Finally, the author integrated the "Decision Making Framework" described in *Rural Resource Management: Problem Solving for the Long Term* (Miller et al., 1995) to help determine the best control strategy for SERNANP to implement managing the tamarisk problem at Pómac Forest.

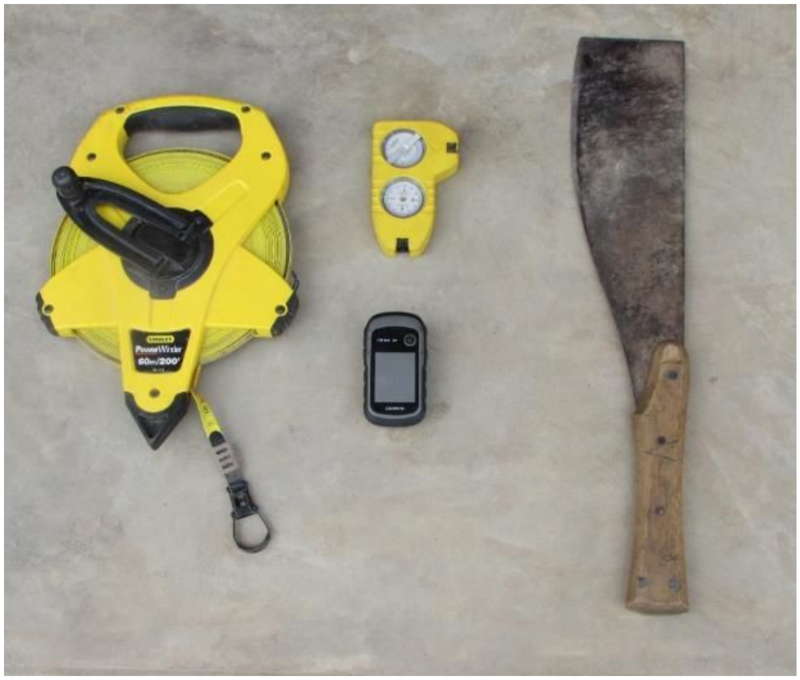


Figure 5: Field equipment used for tamarisk mapping and measurement. 60-meter tape, clinometer, GPS receiver and machete.

III.1. Tamarisk Observation and Mapping

Based on conversations with park guards William Zeña and Carlos Llauce from SERNANP, along with personal observations of tamarisk during hikes of Pómac Forest during 2015, it was decided to limit the scope of the study to a 1.5km buffer zone surrounding the La Leche River within the protected area. SERNANP provided georeferenced layer files for the La Leche River, the border limits of the protected area, and an alpha-numerical patrol grid used by park guards for incident and observation reports. The layers were imported into QGIS where a buffer of 1.5 km was performed on the river layer. With this buffer, the patrol grid layer was cut based on their intersection within the buffer area to determine which quadrants of the patrol grid to be included in the study.

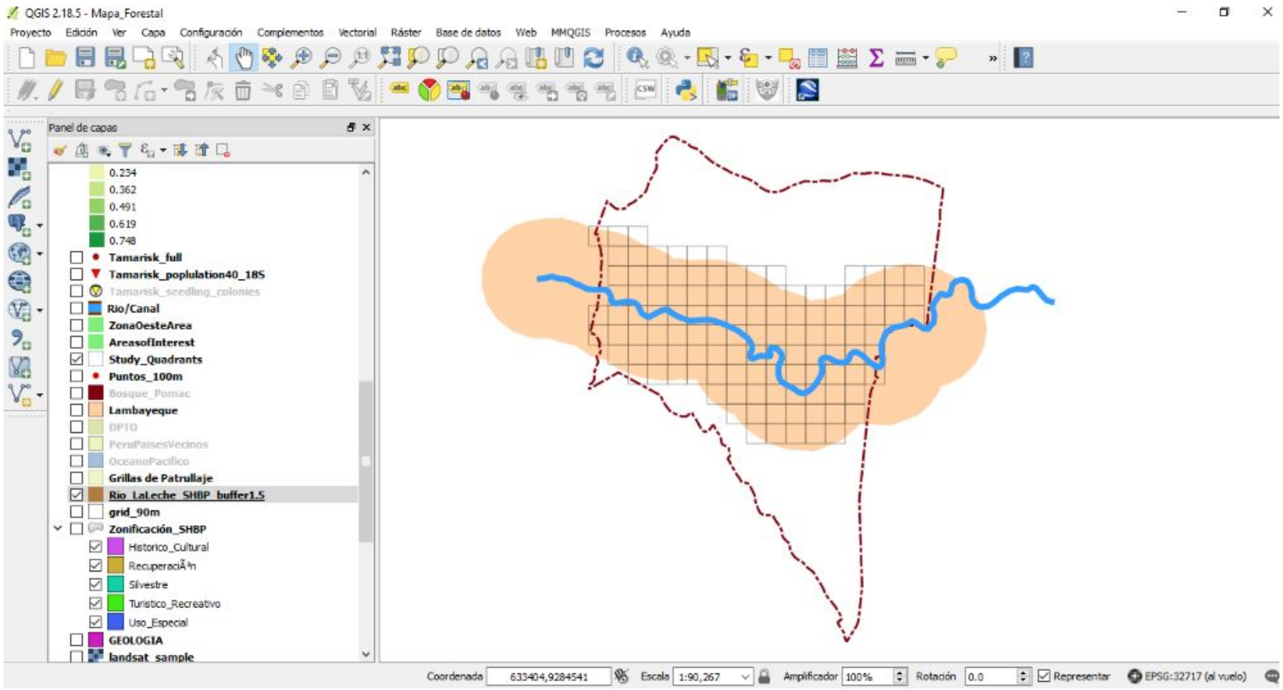


Figure 6: Extraction of study quadrants in QGIS, using a 1.5km buffer of the La Leche River.

The resulting 117 quadrants, measuring 500m x 500m each, were then divided into 25 sub-quadrants of 100m x 100m, or 1 hectare. The center point for each sub-quadrant was extracted and its associated coordinate in the *Universal Transverse Mercator - Zone 17S* projection for each of the 2925 points was created as a field in the attribute table of the layer file.

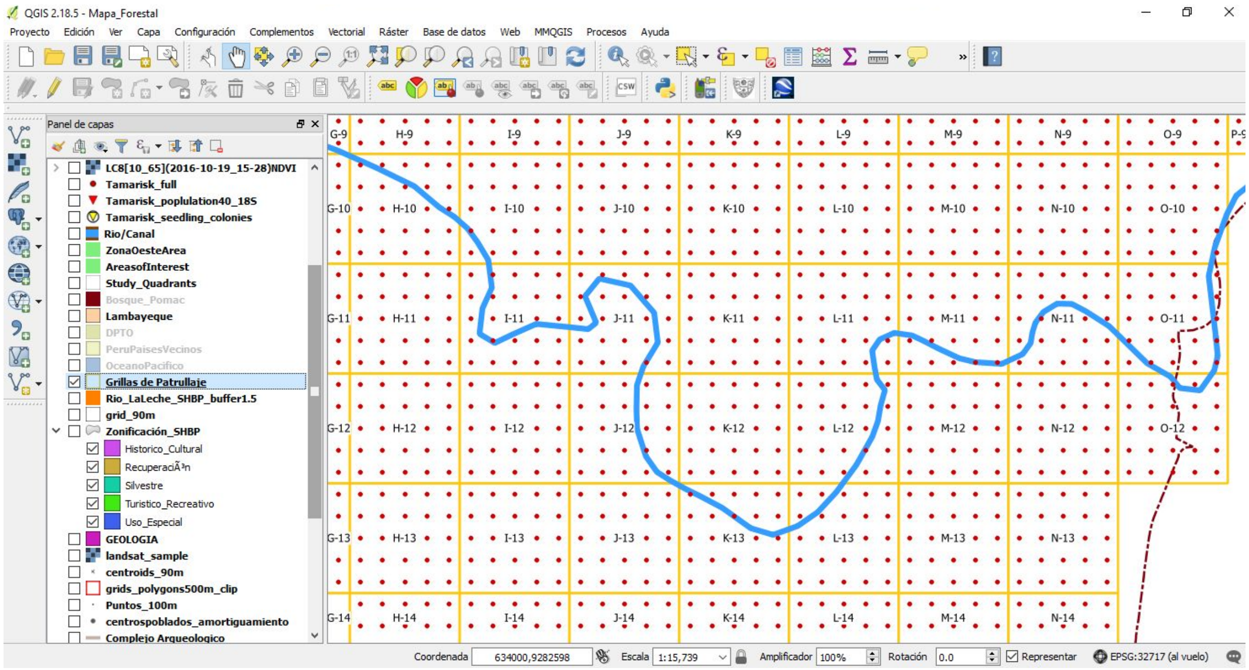


Figure 7: Creation of center points for study sub-quadrants.

With the study quadrants and coordinates ready, the point data was uploaded to a handheld Garmin Etrex-30 GPS for navigation to each point. To avoid the high daily temperatures of northern Peru, the author would typically choose one or two quadrants to visit during the early morning hours of work days, between the hours of 7am and 10am. Upon arriving at a new quadrant, the author would follow a general pattern, making sure to visit each sub-quadrant's center point:

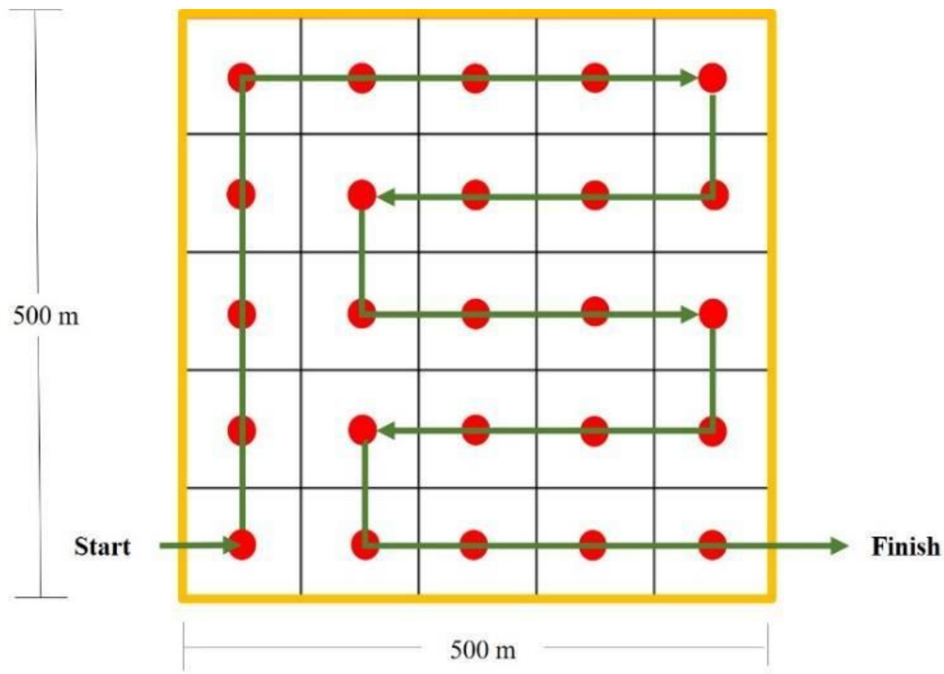


Figure 8: Walking pattern within a study quadrant

While walking between center points, the author would scan the landscape side to side in search of tamarisk. As tamarisk's verdant foliage is very distinctive in the dry forest, it was generally easy to spot. The wide spacing between trees and plants in most quadrants also provided good visibility during the survey. The only difficulty came from thicker growth of vegetation close to the river, but the 100-meter distance between navigation points helped reduce the probability of missing a tree.

When tamarisk was spotted, a coordinate point was taken at its base with the GPS receiver; five coordinate samples were taken through the waypoint averaging feature of the Garmin unit in order to improve overall accuracy. With the survey for all 117 quadrants of the study complete, the coordinate points for tamarisk were uploaded to QGIS to produce four thematic maps for SERNANP (see Results).

III.2. Biometric Recording of Tamarisk

Upon completing the mapping portion of the study, a pattern emerged that showed two distinct groupings of tamarisk at Pómac Forest. The first grouping, located west and downstream of a diversion dam where the La Leche River and a canal intersect, labeled *Zone West* in Fig. 4., show a dense clustering of tamarisk concentrated along the margins of the La Leche River, with no tree occurrences ranging further than 200 meters from the river. Although the multiple stems of tamarisk often make it difficult to differentiate between individual trees, the author counted 252 occurrences in the area. With 1.5 km^2 of affected quadrants in this area, the density of tamarisk was calculated:

$$\frac{252\ tamarisk}{1.5km^2} = [\frac{168\ tamarisk}{km^2}]$$

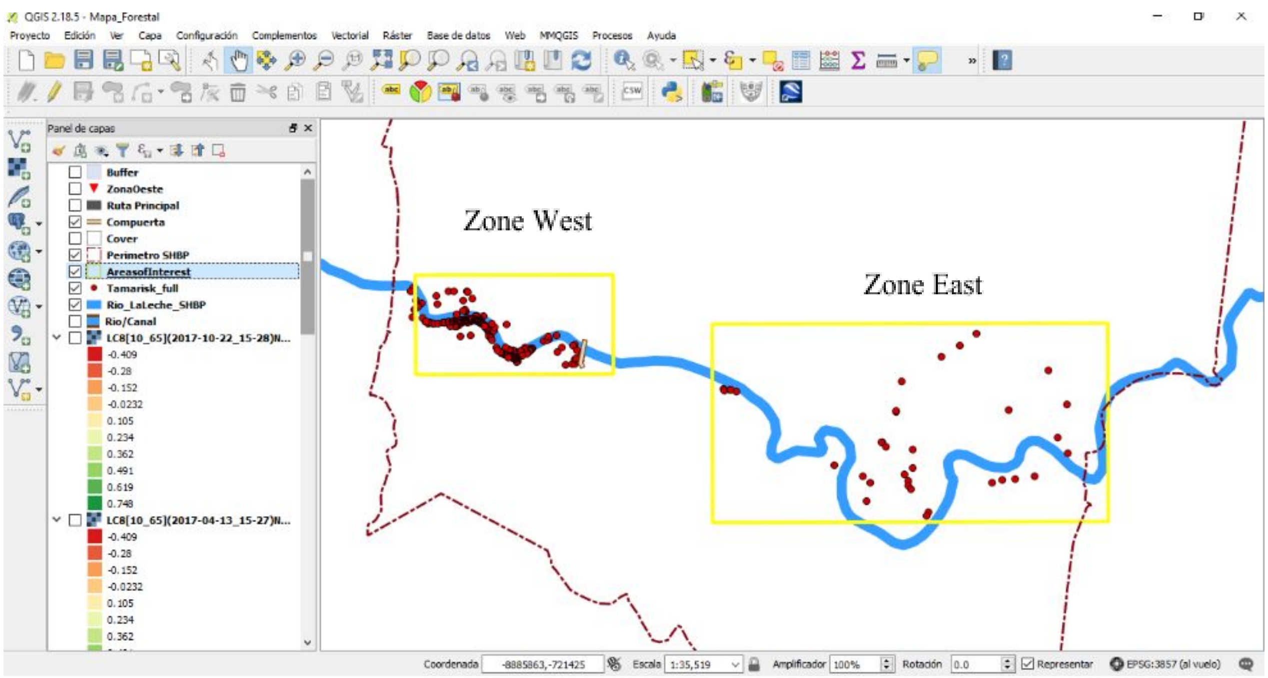


Figure 9: Tamarisk groupings revealed at Pómac Forest.

The second, smaller grouping located east and upstream of the diversion, labeled *Zone East*, shows a sparse distribution of only 35 occurrences, with some ranging more than a kilometer from the La Leche River.

$$\frac{35\ tamarisk}{4.5km^2} = \left[\frac{7.7\ tamarisk}{km^2}\right]$$

As the smaller, more manageable population of the two, Zone East was chosen to begin the inventory of tamarisk. Working with park guards when possible, the author revisited the tamarisk points from the mapping portion of the study to collect common biometric measurements (diameter at breast height, lateral spread and tree height), photographs and compile this information into a transferable resource for SERNANP. Zone West was left for future study.

Figure 10: Diversion dam at Pómac Forest, looking west. Water passes to the canal through control gates (left) while the La Leche River flows over a concrete embankment (right). Note the tamarisk grouping in the center of the photograph.

Diameter at Breast Height (DBH)

The study followed instructions for DBH measurement based on *American Forests Champion Trees Measuring Guidelines Handbook* (Leverett & Bertolette, 2015). Because calipers and diameter tape were unavailable during the study, a circumference measurement was taken with flexible meter tape to determine Circumference at Breast Height (CBH), approximately 1.5 meters from ground level. DBH was then calculated indirectly by dividing CBH by the constant π = 3.14159, written mathematically as

$$d = C/\pi.$$

There are trunk forms most commonly encountered at Pómac Forest's Zone East. The first form is a single stem trunk that divides at or above breast height:

Figure 11: Single stem trunk form of tamarisk with split at breast-height.

In this case, the tape measure is wrapped 90 degrees to the axis of the trunk. On level ground, this axis normally runs parallel to the ground.

Most tamarisk encountered, however, display a multi-stemmed trunk radiating away from a central point, making it difficult to determine whether a single tree with multiple stem is sprouting at ground level, or whether there were several trees sharing the same root system, as shown in Figure 12.

Figure 12: Multiple stem trunk form of tamarisk, radiating outward from ground level.

According to the measuring guidelines handbook, if it is concluded that the form is a single tree, but splits below 1.4 meters, the narrowest point between the split and the ground is to be measured. Because the stems for tamarisk tend to start at ground level and leave no point for measurement, it was assumed by the study that the specimen represents two or more trees that have their trunks pressing together and budding from the same root crown. In this case, the guide prescribes that the largest of the trunks be measured. The same procedure is followed as for a single stem measurement, wrapping the tape measure at 1.4 meters at a perpendicular angle to the trunk.

Lateral Spread

Due to the general tendency of tamarisk to grow in clusters of horizontally spreading stems, it became apparent that that crown spread would be an inappropriate measurement. Instead, a measurement of the lateral spread of the plant or plants at lower levels was measured to show the footprint occupied by each tamarisk point that could be used for future comparisons with high resolution, multi-band satellite imagery from the PeruSAT-1 sensor.

A simple method for calculating average spread is to take two measurements with meter tape at the widest spreads of the tamarisk at 90 degrees to one another.

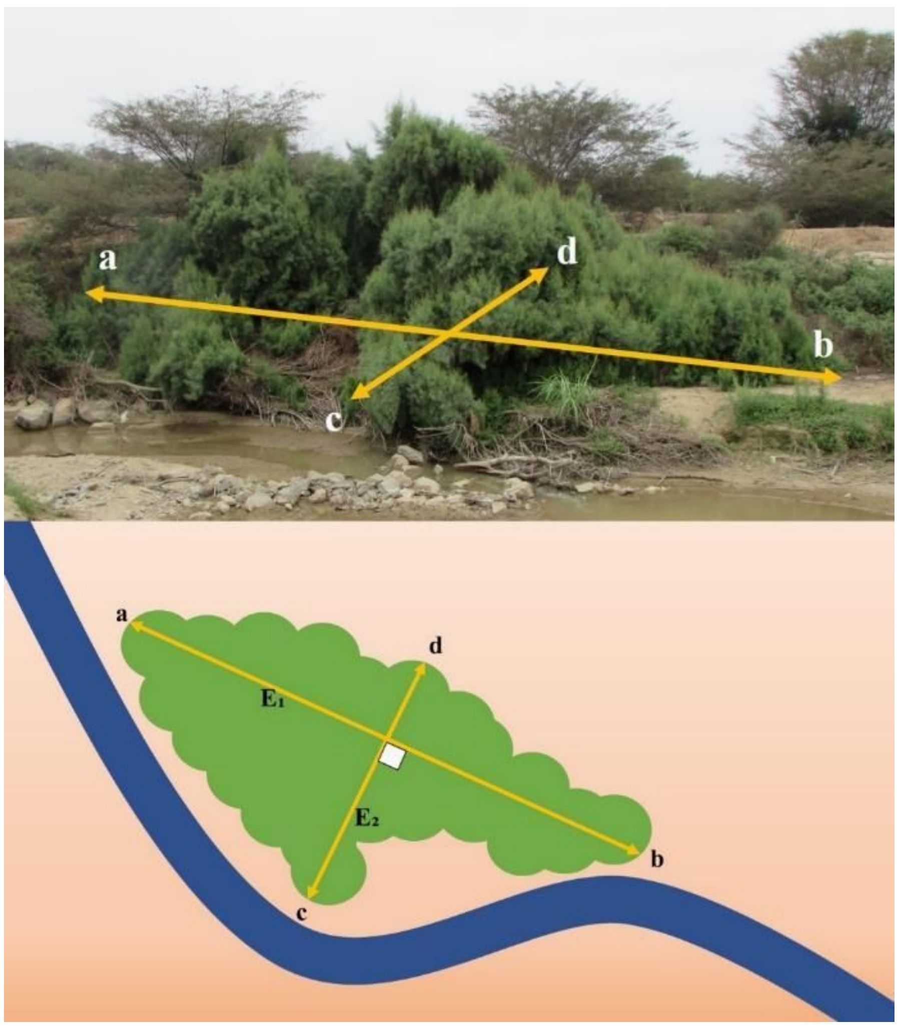


Figure 13: The longest spreads of a tamarisk as seen in the field (top) and as imagined from above for calculation (bottom).

With the two longest spreads measured (E_1 and E_2), the following formula is applied to calculate the average lateral spread (S) of the tamarisk:

$$S = \frac{E_1 + E_2}{2}$$

Height

The study utilized a 60-meter measuring tape and a Suunto-brand clinometer. Measurement with the meter tape was taken from directly beneath the highest branch of each tamarisk outwards to a standing point, typically 10 meters or more away. At this standing point, the author measured angles with the clinometer. The first angle, of inclination, was measured from the eye level to the highest point on the tree. The second angle, of declination, was from eye level down to the ground beneath that highest point, typically the trunk.

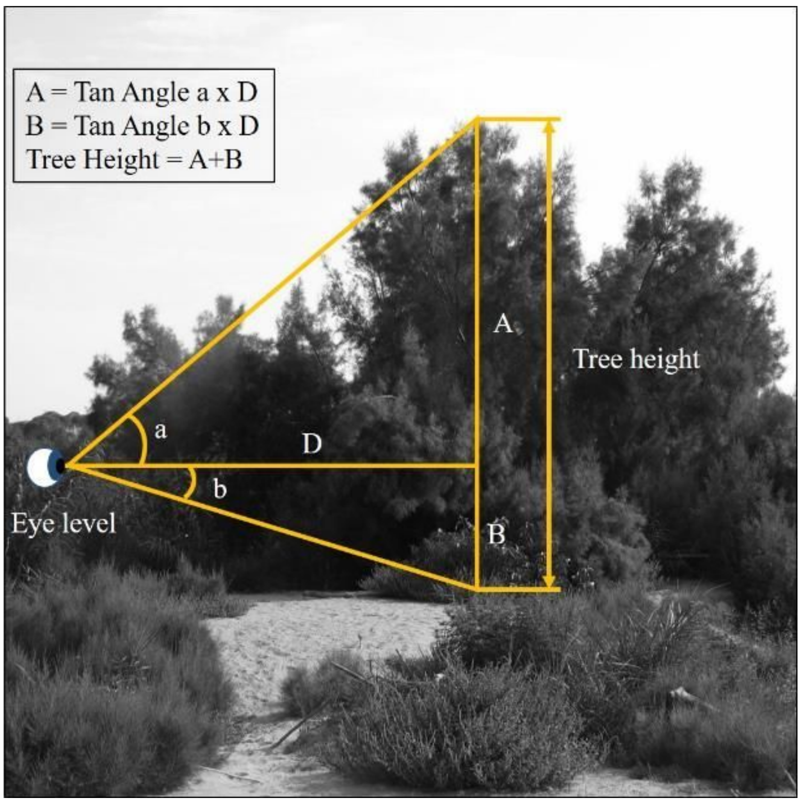


Figure 14: Tangent method for calculating tree height.

The weak apical control displayed in most tamarisk at Pómac Forest meant that the highest point of the tree was not necessarily beneath the central trunk stem. Finding the correct ground point often required several passes around the tree, observing the upper branches and estimating the point directly below.

III.3. The Decision Making Framework

The "Decision Making Framework" described in Chapter 4 of *Rural Resource Management*: *Problem Solving for the Long Term* (Miller et al., 1995) is a problem solving tool for natural resource professionals. The framework guides its user along a process, beginning with defining the management problem in its unique context.

Deciding on the issue that calls for action is the initial step. At Pómac Forest, the question being asked in the study is which control strategy SERNANP should adopt to mitigate the spread of tamarisk.

Short Term Objectives

The framework next asks to establish short-term objectives resulting from the decision. Based on field observations of tamarisk at Pómac, SERNANP should prevent any further establishment of the species beyond its current footprint at Pómac Forest. From mapping, the study has established its current distribution and abundance across *West* and *East* zones. For example, management, could begin focusing on seedling removal along the banks of the La Leche River that have established within the last year. The tamarisk at these sites measure 30-40 centimeters in height and can easily be pulled with its main root by hand.

Figure 15: Hand removal of a recently established tamarisk seedlings. Quadrant N-12.

Another short-term objective would be to begin reducing the population of mature tamarisk trees, starting with trees farther upstream whose seeds have a greater length of river along which to travel and potentially establish.

Long Term Goals

With the short-term objectives defined, the framework searches for the long-term goal behind the decision. The long-term goal at Pómac Forest would be to ensure the integrity of the dry-forest ecosystem and attempt to restore the riparian zone as close as possible to its pre-tamarisk state. However, even if SERNANP were to achieve the complete eradication of tamarisk trees in the protected area, there will still be tamarisk colonies farther upstream, outside the limits of the protected area, whose seeds will likely travel down the La Leche River and reestablish at Pómac Forest in a matter of time. Because of tamarisk's seed production and dispersal abilities, the eradication of a stand site may only reset succession and simply see new tamarisks replace those that are removed (DeWine & Cooper, 2010). Management of tamarisk, therefore, is a continuous struggle.

Decision Criteria

The framework next identifies criteria upon which to base the choice. Having worked with SERNANP over three years and understanding the organization's mission and value system, the following five criteria were selected:

1. Minimize impacts to native species: the method should not harm native plants or wildlife in its application.
2. Acceptance of control methods by the public: the method and/or aftermath should not be upsetting to locals or visitors to Pómac Forest.
3. Cost effectiveness: the method should put the least amount of strain on SERNANP's operating budget while achieving meaningful results.
4. Demand on SERNANP personnel time: the method should not require excessive input of staff time that would detract from other agency goals.
5. Inclusivity of local volunteer park guards: the method should provide an opportunity to include members who can pass knowledge and awareness of tamarisk to their respective communities.

Decision Alternatives

Finally, the framework identifies the range of feasible alternatives. No alternative is likely to fulfill all criteria perfectly, but one is likely to address the criteria better than the others.

From the literature review, the study investigated four control alternatives for tamarisk:

1. Mechanical removal with heavy machinery and hand tools.
2. Chemical treatment using the cut stump method.

3. Biocontrol treatment with leaf-eating beetles.
4. Harvesting permits for local residents

With the alternatives listed, they are placed into a ranking matrix with the decision criteria. The user keeps in mind Finally, the criteria and alternatives are place into a matrix, keeping in mind short-term objectives and long-term goals (see Results).

IV. RESULTS

Data collection for the study was completed in late October 2017 during the author's final months of service as a Peace Corps volunteer. To maximize the utility of the study, each of the three study goals resulted in a transferable resource to aid SERNANP in the future management of tamarisk at Pómac Forest.

IV.1. Objective One

In fulfilling the first study objective, "to enhance knowledge of tamarisk's spatial distribution and abundance," a set of four thematic maps were generated to provide a visual understanding of the tamarisk problem facing the protected area. The maps were drawn using QGIS version 2.18, a free GIS software, and written in Spanish for use by SERNANP personnel.

The first map, shown in Figure 16, shows which patrol quadrants contain a tamarisk presence. The map makes no distinction of the quantity of tamarisk per quadrant; a quadrant marked in red could contain 1 tamarisk or 50.

The second map in Figure 17 shows the distribution of tamarisk in *Zone West*, the stretch of study quadrants located downstream of the diversion dam represented by the yellow bar. This area contains 252, or 89%, of all tamarisk observations from the study.

The third and fourth maps in Figures 18 and 19 show the distribution of tamarisk in *Zone East,* located upstream of the diversion dam. Figure 18 includes sites of new seedling establishment represented by the yellow triangles. Figure 19 is a heat map, with the intensity of red indicating density of tamarisk distribution.

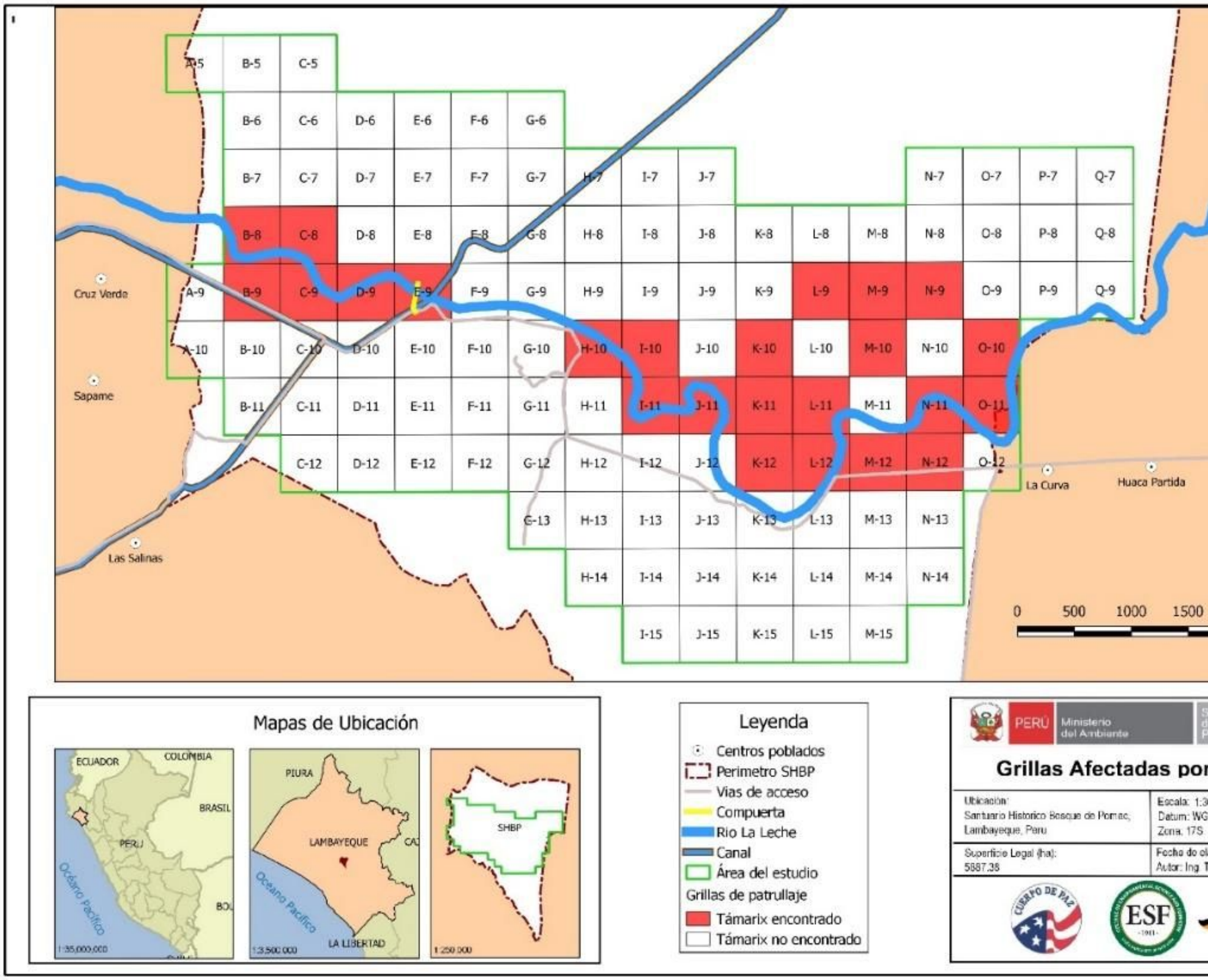


Figure 16: Map of all study quadrants with a tamarisk presence.

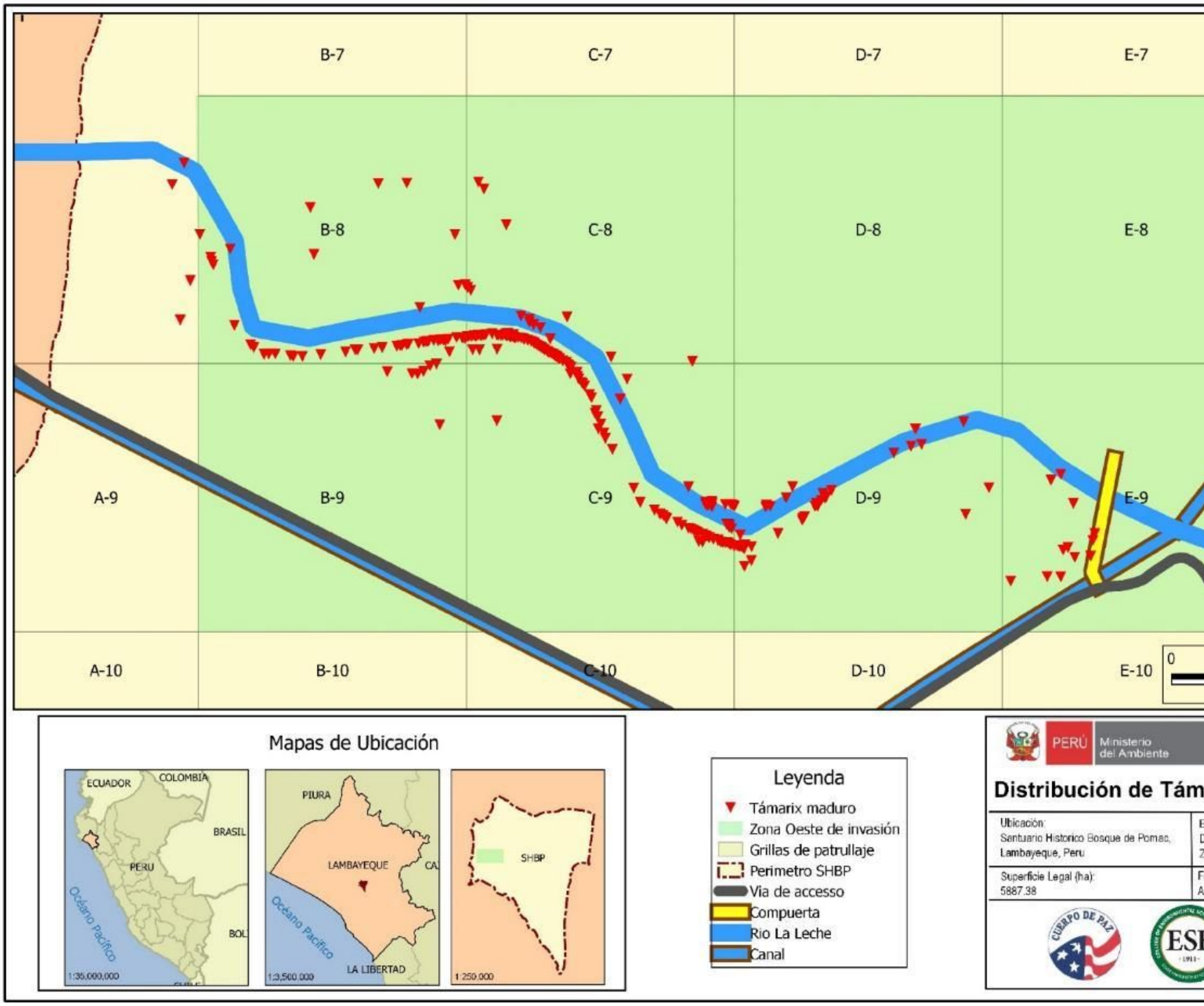


Figure 17: Map of tamarisk distribution, Zone West

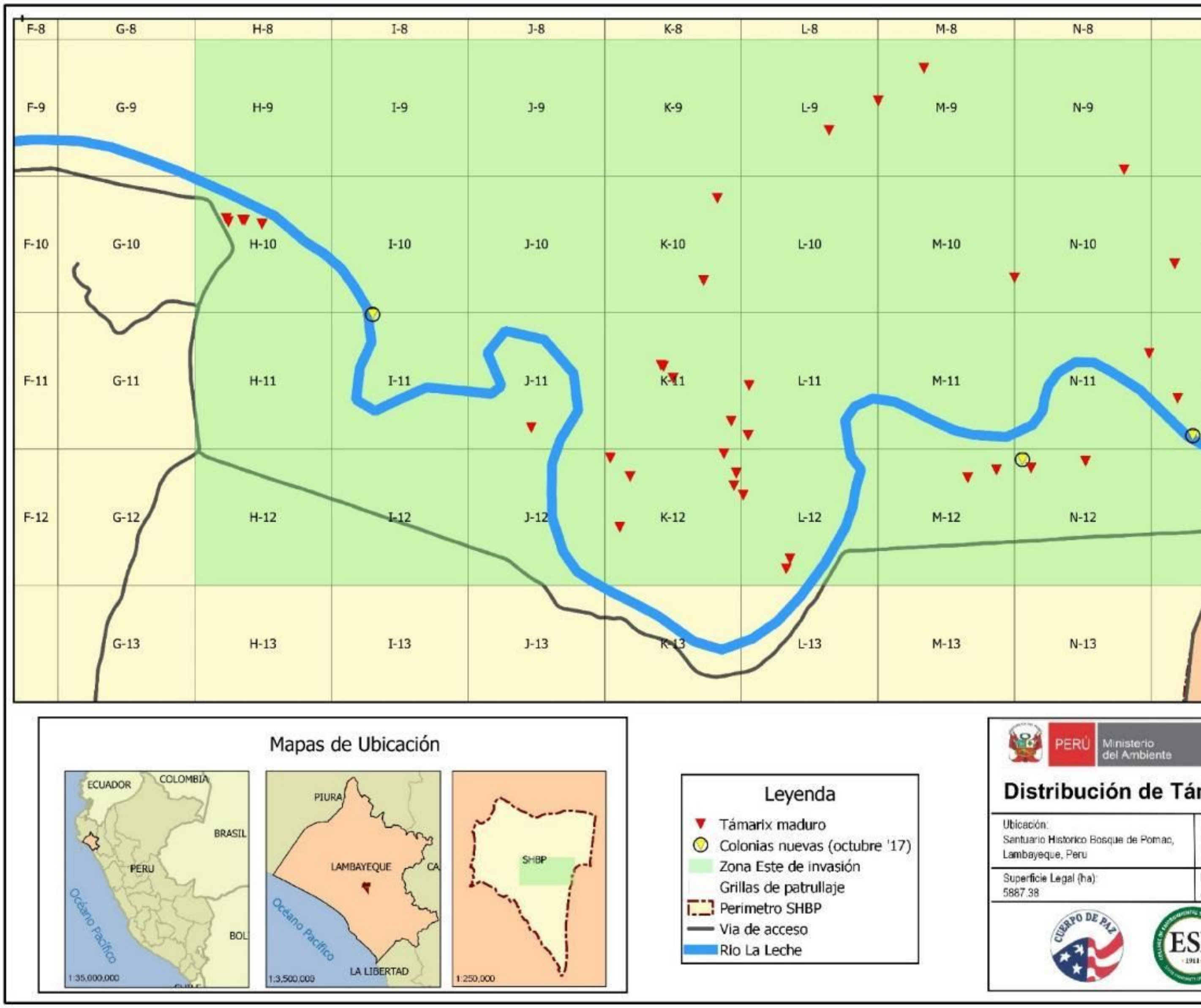


Figure 18: Map of tamarisk distribution, Zone East

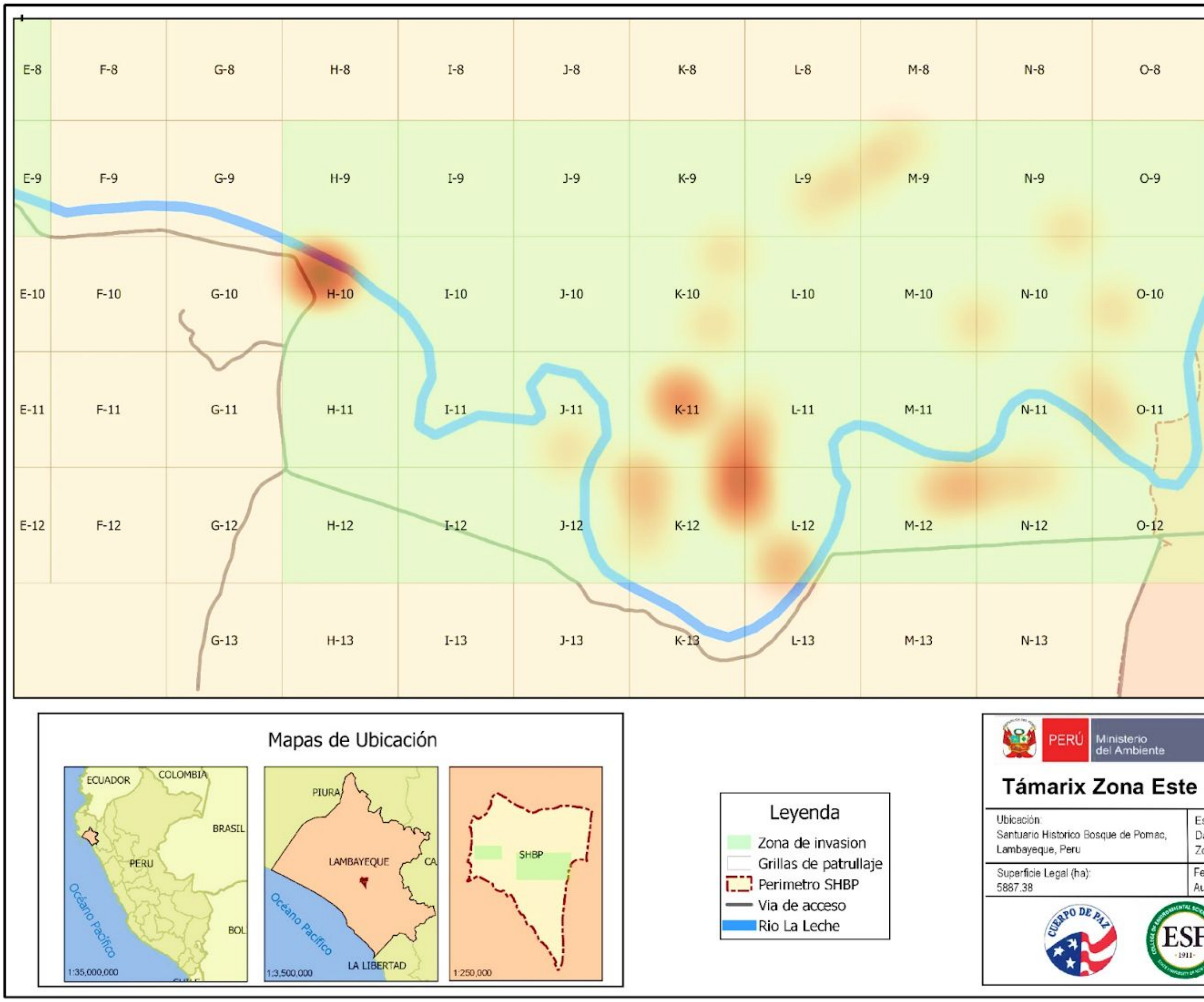


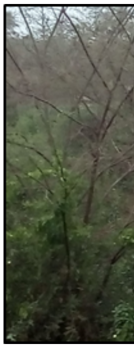
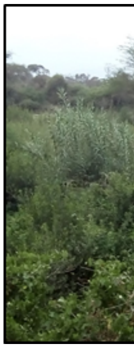
Figure 19: Heat map of tamarisk distribution, Zone East

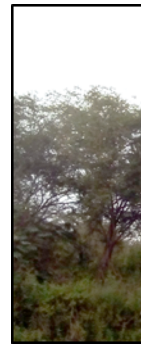
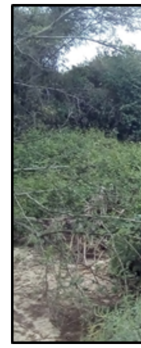
IV.2. Objective Two

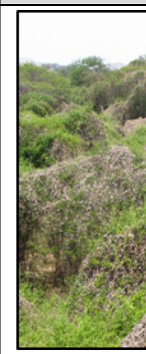
In accomplishing the second study objective, "to gain an understanding of the present tamarisk population through field measurements", a catalogue of the biometric measurements (diameter at breast height, lateral spread and tree height) and photographs of all tamarisk incidences in Zone East was compiled.

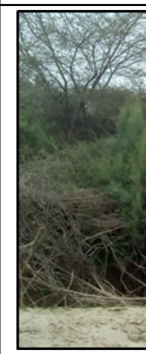
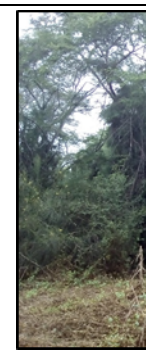
The catalogue, shown in Table 3, can be viewed as the initial entries of a more comprehensive inventory to completed at a later date. Also, if SERNANP decides to delay active management of tamarisk for a long period, the baseline measurements established in the catalogue can be used for growth comparisons for future studies.

Table 3: Catalogue of tamarisk observations in Zone East.

Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
H-10	H10.1	634215	9283943	0.24	5.4	5.1	
H-10	H10.2	634223	9283931	0.26	5.6	5.2	
H-10	H10.3	634274	9283938	0.14	4.0	3.7	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
H-10	H10.4	634282	9283936	0.12	5.2	3.9	

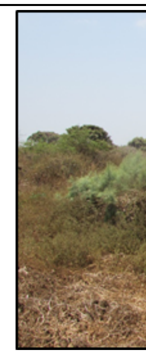
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
H-10	H10.5	634346	9283922	0.21	6.4	13.0	
J-11	J11.1	635331	9283178	0.09	3.6	3.8	
K-10	K10.1	636012	9284017	0.19	8.7	3.8	
K-10	K10.2	635961	9283716	0.34	15.5	3.7	

K-11	K11.1	635806	9283406	0.40	13.3	9.7	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
K-11	K11.2	635815	9283402	0.23	6.9	4.1	
K-11	K11.3	635850	9283358	0.41	15.3	5.7	
K-11	K11.4	636064	9283202	0.73	11.1	11.3	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog

K-12	K12.1	635620	9283067	0.59	22.7	9.4	
K-12	K12.2	634282	9283936	0.12	5.2	3.9	
K-12	K12.3	635655	9282814	0.73	15.3	9.7	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
K-12	K12.4	636036	9283082	0.45	8.6	7.5	

K-12	K12.5	636081	9283011	0.35	12.7	6.3	
K-12	K12.6	636072	9282965	0.38	9.1	9.6	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
L-9	L9.1	636421	9284266	0.23	5.9	2.7	
L-11	L11.1	636128	9283332	0.34	12.6	5.7	

L-11	L11.2	636124	9283149	0.51	11.0	8.7	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
L-12	L12.1	636106	9282931	0.31	10.3	8.8	
L-12	L12.2	636278	9282698	0.55	11.8	12.0	
L-12	L12.3	636264	9282661	0.53	12.3	9.1	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog

M-9	M9.1	636768	9284493	0.32	6.8	4.0	
M-9	M9.2	636600	9284374	0.35	10.7	4.0	
M-10	M10.1	637099	9283726	0.22	6.1	3.0	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
M-12	M12.1	636928	9282994	0.22	6.1	4.4	

M-12	M12.2	637033	9283023	0.44	18.7	10.4	
N-9	N9.1	637500	9284122	0.33	6.1	6.2	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
N-11	N11.1	637592	9283450	0.32	9.3	4.5	
N-12	N12.1	637160	9283030	0.52	7.4	5.9	

N-12	N12.2	637359	9283055	0.53	13.2	6.5	
Patrol Quadrant	Inventory Code	UTM X Coordinate	UTM Y Coordinate	DBH (m)	Lateral Spread (m)	Height (m)	Photog
O-10	O10.1	637685	9283777	0.20	5.3	3.8	
O-11	O11.1	637696	9283285	0.08	3.9	2.6	

IV.3. Objective Three

In completing the third study objecitve, to “compare available tamarisk control methods,” the lists of feasible alternatives and decision criteria were placed into a decision matrix shown in Table 4 below. With knowledge of tamarisk gained through the literature review, and keeping in mind long-term management goals, the author used best judgement to score and tally each alternative.

With the matrix complete, the selection of the best alternative could be more easily made. Based on the cumulative ranks for each alternative, the chemical treatment with the cut stump method could be the best option for SERNANP to choose in managing the tamarisk problem. It demonstrates an excellent balance among the important decision factors. It has both low impact on surrounding vegetation and has shown public acceptance in the Canyonlands study (Ceurvost & Allred, 2013). It is also relatively cost effective and provides a good opportunity to include volunteer park guards in its execution. Harvest permits for volunteer park guards also scored very well.

Table 4: Decision matrix for tamarisk management at Pómac Forest.

	Alternatives			
Decision Criteria	**Mechanical removal**	**Chemical treatment with the cut stump method**	**Biocontrol treatment with leaf-eating beetles**	**Harvest permits for locals**
Impact on native species	High, heavy machinery would likely compact surrounding soil and damage vegetation (3)	Low, isolated application of herbicide guaranteed (1)	Uncertain, unknown long-term impacts to other flora and fauna at Pómac Forest (3)	Medium, training of volunteers needed to ensure only tamarisk is harvested (2)
Acceptance by the public	Lower, as indicated by the Canyonlands study (3)	High (Canyonlands) (1)	High (Canyonlands) (1)	Likely high, as a sustainable alternative to other types of fuel wood. (2)
Cost effectiveness	Costly, need for heavy machinery and skilled operators (3)	Economical, chainsaw, hand tools and herbicide solution (1)	Cost of purchase and import of beetles uncertain (2)	Very economical, training and supervision (1)
Demand on SERNANP personnel time	High, constant supervision of work teams needed to reduce site impacts. (3)	Medium, park guards could perform cutting and herbicide application in spare time. (2)	Low, application and monitoring by one or two specialists. (1)	Low, park guards inform volunteers about tamarisk and its current locations for harvesting (1)
Inclusivity of local volunteer park guards	High, high demand for extra labor, volunteers could assist with removal and loading (1)	High, volunteers and university students could be trained to assist. (1)	Low, the application of biocontrol would be performed by forestry engineers or biologists (2)	High, local volunteers would be the driving force for control (1)

Overall Rank	**4**	**1**	**3**	**2**

V. DISCUSSION/CONCLUSION

The study was a unique opportunity to research invasive tamarisk while fulfilling the obligations of Peace Corps service in Peru. SERNANP's general awareness but lack of monitoring or plan for management of tamarisk at Pómac Forest left an obvious information gap needing to be addressed. The results of the study helped close that gap and provide management with knowledge about the distribution, characteristics and management strategies of this invasive needed for informed future decisions.

V.1. Study Limitations

A major obstacle during the completion of the study was the occurrence of the El Niño Phenomenon in February and March 2017. Due to the heavy rains and flooding that affected the northern coast of Peru, Peace Corps volunteers were evacuated back to the United States or to other departments of the country to wait while conditions improved. When the author could finally return to Pómac Forest in May, the protected area had transformed from a dry, sparsely vegetated ecosystem to a dense tangle of vines and plants whose seeds had remained dormant in the soil for years, as shown by the NDVI maps for the protected area in Figure 20.

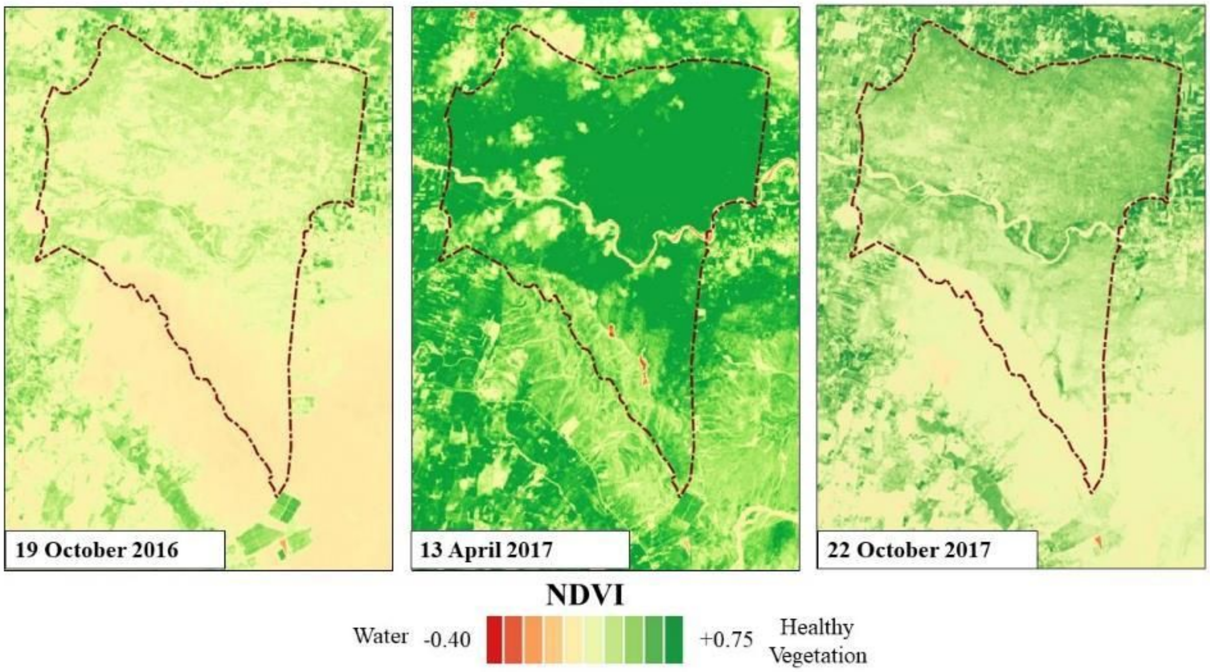


Figure 20: Normalized difference vegetation index (NDVI) imagery of Pómac Forest before, during and after the heavy rains of the El Niño Phenomenon in early 2017 (Landsat 8).

One of the principle plants contributing to the explosion in new vegetation was *Luffa operculata*, known locally as jabonillo. The thick blankets formed by jabonillo across fields and in the canopies of trees made the measuring and photographing of tamarisk specimens difficult at times. A proposal to acquire satellite imagery from PeruSAT-1 was postponed as it became clear that jabonillo, as the top forest cover in many sections of the protected area, would conceal the trees beneath. It had been the hope of the author to use the high spatial resolution imagery of the Peruvian satellite sensor to attempt a supervised classification of tamarisk pixels in QGIS. At the time of writing this report, the dried husks of jabonillo remain covering large parts of the protected area more than a year after its initial emergence. Such a study using remote sensing would have wait until the majority of jabonillo litter dissipates. According to SERNANP, that may take between three and five years (William Zeña, personal communication, 10 November 2017).

Figure 21: Emergence of jabonillo (Luffa operculata) following the heavy rains of the El Niño Phenomenon.

V.2. Future Investigations

There are several potential studies that would further enhance knowledge of tamarisk for Pómac Forest.

The first project could be to acquire multi-band, high spatial resolution satellite imagery, such as that recorded by the PeruSAT-1 sensor, to attempt supervised classification of tamarisk. With the coordinate data obtained from this study, the user could use the dense stands found in West Zone where tamarisk comprises at least 80 percent of ground cover as training areas for the unique spectral reflectance of tamarisk. Once a range of reflectance values could be determined, a supervised classification of the entire protected area could reveal if any tamarisk in the canopy had been missed.

Tamarisk located in Zone West of the study area have yet to be measured for diameter at breast height, lateral spread or height as were the tamarisk in Zone East. Completing this inventory work could be an appropriate project for university students in the region studying forest or environmental engineering.

A long-term study the propagation and production of pájaro bobo (*Tessaria integrifolia)* in a tree nursery setting could provide valuable information on a potential site competitor of tamarisk. The interpretation center of Pómac Forest already has a constructed nursery space with a permanent water supply. The seedlings produced at the nursery could be test planted along sections of unshaded river where tamarisk seedlings are also found. The two species could be planted side by side to compare their site competition, or the tamarisk seedlings could be hand pulled and the pájaro bobo planted to see if tamarisk reestablished at the site in the future.

The potential introduction of leaf-eating beetles of the *Diorhabda* genus should be investigated to determine the ecological impacts of a new species of insect on the equatorial dry forest at Pómac. One species, *Diorhabda sublineata*, showed a spread rate of 102 square kilometers during its first year of release along the Lower Rio Grande in western Texas (Ji et al., 2017); with only 29.3 square kilometers in the study area, the riparian zone of Pómac Forest would easily be treated. However, as shown in studies from other sites included in the literature review, tamarisk defoliation by the beetles needs to be followed up by stream restoration, including the mechanical removal of dead tamarisk, transplanting native trees to the site and restoring hydrologic flows to accommodate the herpetofauna (Mosher & Bateman, 2016). The largest concern would be the impact of leaf eating beetles on the native trees, mainly algarrobo (*Prosopis pallida*) and sapote (*Capparis scabrida*), the latter of which is critically endangered (SERNANP, 2011).

V.3. Recommendations for Management

The decision-making framework was an effective tool for identifying and narrowing down the potential solutions for a tamarisk management strategy. In the author's prior conversations with Antonio

Gamonal, the SERNANP manager for the protected area, the various methods of tamarisk control had been discussed but there was uncertainty on which was best for Pómac Forest. The results of the framework exercise made the advantages and drawbacks of each method clearer and will provide for a better informed final decision.

Moving forward, an initial step could be an activity coordinated park guards to bring volunteers and university studies studying environmental topics to spend a few days combing the bed of the La Leche River during the dry months to hand pull seedlings established during the last year. At the same time, SERNANP would decide on a control strategy, possibly combining two or three of the discussed alternatives. SERNANP may choose the cut stump method, which could be complemented with harvest permits to local volunteers for removing discarded wood to the volunteer park guards. The herbicide treatment would ensure tamarisk mortality and harvest permits would help to clean the sites. Although not included in the decision matrix, the subsequent planting of pájaro bobo or other similar native riparian species of tree would help to avoid resetting succession for a reinvasion of tamarisk seedlings from parent trees further upstream on the La Leche River. A bottom-up control using fast growing, shade-tolerant native species at eradication sites would help inhibit future establishment of shade-intolerant tamarisk and reduce future expenditure of time and resources in dealing with the tamarisk problem.

The question of whether it makes sense to proceed is a question of prudence. To act now is to save time and money in the future. SERNANP could ignore the problem for several years. However, the longer the delay in action, the larger the problem will become as tamarisk establishes along new sites along the La Leche River at Pómac Forest.

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