Climate Impacts on 21st Century Conservation in Texas: A Resilience Strategy for Thornforest Restoration in the Lower Rio Grande Valley

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Technical Report

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Abstract

Texas' Lower Rio Grande Valley (LRGV) has been a center of ecological restoration work for the past 60 years due largely to objectives in wildlife conservation. While the region's base of protected lands [e.g., National Wildlife Refuge System, U.S. Fish & Wildlife Service (USFWS)] is consisted in part by preserved patches of the native Tamaulipan thornscrub or thornforest ecosystem, a large portion of these lands have been acquired while in active production for field crops (e.g., cotton, sorghum, etc.) where little to no natural vegetation exists. The intent is to then periodically plant these fields into native woody cover that will complement and eventually approximate the wildlife habitat value of preserved thornforest fragments. These are vital actions in a region where less than 10% of this ecosystem's historical (pre-1900) cover still exists and where a plethora of conservation threats (rapid urbanization, disturbance, invasive species, etc.) are now endemic. Planning is a significant component of this restoration process and while the aforementioned threats intuitively factor into individual project designs, forecasted climate change impacts for south Texas (e.g., increasingly infrequent rainfall, increased average high temperatures by mid-late century) are set to pose even greater overarching challenges to this effort. Herein, we provide a retrospective on thornforest restoration efforts in the LRGV and detail a working baseline strategy for climate-informed thornforest restoration on USFWS lands. We also discuss both the expected outcomes and challenges represented by this strategy at increasing levels of adoption by other regional land managers.

Resumen

El Valle Inferior del Río Grande de Texas (LRGV, por sus siglas en inglés) ha sido un centro de trabajo de restauración ecológica durante los últimos 60 años en gran medida a los objetivos de conservación de la vida silvestre. Si bien la base de tierras protegidas de la región [por ejemplo, refugios nacionales de vida silvestre, Servicio de Pesca y Vida Silvestre de EE. UU. (USFWS)] está formada en parte por parches preservadas del ecosistema nativo del matorral espinoso o bosque espinoso Tamaulipeco, una gran parte de estas tierras se adquirieron mientras estaban en producción activa para cultivos extensivos (por ejemplo, algodón, sorgo, etc.) donde existe poca o ninguna vegetación natural. La intención es plantar periódicamente estos campos con una cubierta boscosa nativa que complemente y eventualmente se aproxime a los hábitats silvestres de los fragmentos de bosque espinoso preservados. Estas son acciones vitales en una región donde existe menos del 10% de esta cobertura histórica (anterior a 1900) y donde una plétora de amenazas para la conservación (urbanización rápida, perturbación, especies invasoras, etc.) son ahora endémicas. La planificación es un componente importante de este proceso de restauración y, si bien las amenazas mencionadas anteriormente se tienen en cuenta de manera intuitiva en los diseños de proyectos individuales, los impactos del cambio climático pronosticados para el sur de Texas (por ejemplo, más seco, más caluroso para mediados de finales del siglo) plantean desafíos globales aún mayores a este esfuerzo. En este trabajo, proporcionamos una retrospectiva sobre los esfuerzos de restauración del bosque espinoso en el LRGV y detallamos una estrategia de trabajo para la restauración de las tierras de USFWS con base en el clima. También discutimos los resultados esperados y los posibles desafíos de los administradores regionales de las tierras para expandir esta estrategia.

About the Authors

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At approximately 200,000 acres, STRC provides important habitat for the many species that rest, nest, feed and live in south Texas. Many of these species can only be found in deep South Texas, including the highly endangered ocelot and several types of birds that draw wildlife watchers from around the world.

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Jon Dale is American Forests' senior manager for forest restoration in Texas' Lower Rio Grande Valley and is the chair of the Thornforest Conservation Partnership, a coalition of agency, non-profit, research and industry stakeholders working toward a unified goal of biodiversity conservation in the LRGV's 4-county area. Jon has 20 years of experience in planning and implementing ecological restoration and natural resource monitoring projects throughout Texas, the US and the neotropics, while working with a wide range of conservation-based and agricultural non-profits, agencies, universities and environmental consulting firms.

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Introduction

South Texas' subtropical climate exists on the periphery of seasonal, temperate zones to the north and winterless, tropical areas to the south (Figure 1). Similarly, the region also occupies a semi-arid interface between higher precipitation areas to the east and drier regions farther west in both the US and Mexico (Rappole et al. 1986, Le Houerou and Norwine 1988, Yu et al. 2006, Murgulet et al. 2017). These circumstances have shaped survival strategies within native plant communities and dependent wildlife associations over millennia (Newton et al. 1991, Chavez-Ramirez et al. 1997, Cameron and Scheel 2001). As the 21st century progresses, however, a changing climate is projected to amplify these climatological patterns in ways that will have far-reaching effects on this geography (Biswas and John 2007, Hassanzadeh et al. 2020, Thayer et al. 2020). Specifically, projected trends in extreme weather due to increasing average daily temperatures, higher evapotranspiration and decreasing rates of annual precipitation are of universal implication for the area's inhabitants, including plants and wildlife (Wehner et al. 2011, Hernandez and Uddameri 2014, Piao et al. 2019, Nielson-Gammon et al. 2020). From a conservation land management perspective, the challenge of mitigating these effects will require that regional stakeholders work together to design, implement and adapt existing and new programs for the continuing benefit of native species (Tribbia and Moser 2008, Heller and Zavaleta 2009, Joyce et al. 2013).

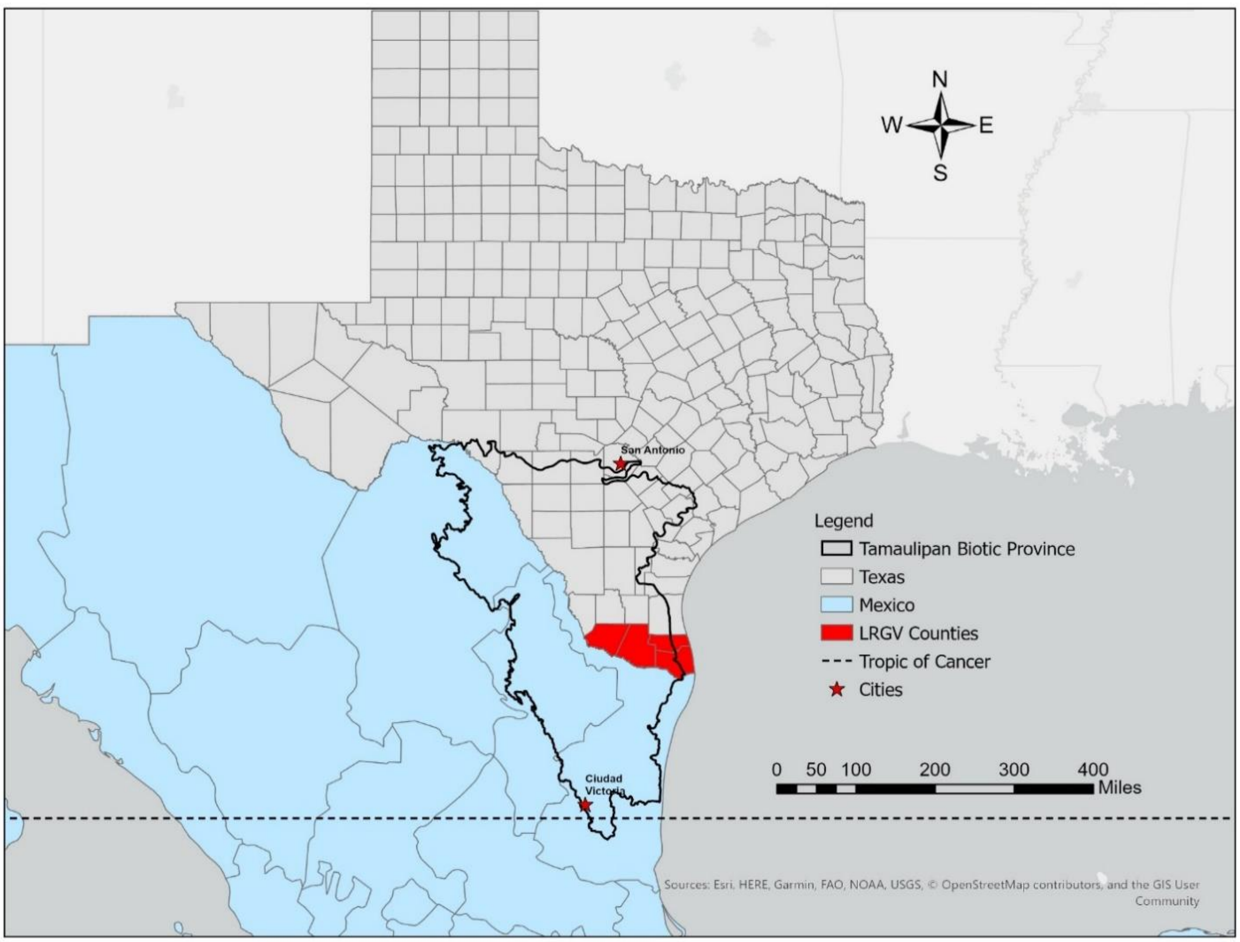

Figure 1. Lower Rio Grande Valley (LRGV) of Texas.

Conservation measures within the southernmost portion of Texas, the Lower Rio Grande Valley (LRGV: Cameron, Hidalgo, Starr and Willacy Counties, Figure 1), are central to maintaining this area's endemic biodiversity, which includes neotropical species associations not found elsewhere in the US (Gehlbach 1987, Opler 1995, Jenny et al. 2004, Arvin 2007, TPWD 2012; Figure 2). These measures are unique as they incorporate one of the largest regional bases of protected public land in a state that is 97% privately owned (Haines et al. 2006). However, what makes this region's conservation effort stand out further is the convergence of factors relating to its geography, economy and existing level of anthropogenic disturbance (Ricketts and Imhoff 2003, Brannstrom and Neuman 2009). With less than 10% of its native Tamaulipan thornforest cover remaining intact, conservation planning in the LRGV faces numerous challenges beyond those attributed to a changing climate (Parvin 1988, Terry et al. 2012, Parcher et al. 2013). A similar trajectory for this same forest type in adjacent parts of northeastern Mexico has also unfolded in the past 60 years (de Jesus Návar-Chaidez 2008, Jiménez Pérez et al. 2013).

Urbanization, for example, is continuously expanding to accommodate a population expected to double in the next 30 years to near 3 million inhabitants (Lombardi et al. 2020). The added infrastructure needed to service this population and increasing levels of traffic associated with the region's border economy (e.g., strong service and government sectors, trade, energy development) contribute to this trend (McCray 1998, Tewes and Blanton 1998, Lopez 2006, Kuvlesky et al. 2007, Ramirez and Mosley 2015). Additionally, federal immigration policies centered on surveillance and deterrence activities have had a multi-level impact on conservation efforts in this international border environment (Abhat 2011, Lasky et al. 2011). These realities emphasize the importance of continuing efforts to provide stability for the LRGV's native biodiversity by establishing connectivity amongst the region's extant thornforest fragments (Rappole et al. 2007, Marzluff and Ewing 2008).

Ecological restoration of thornforest has been a regional focus for achieving this connectivity for the past 40 years. In terms of methodology, unassisted succession is not considered an effective means of re-establishing habitat functions within this ecosystem due to depleted native seed banks, invasive species persistence and other factors associated with past land uses (Wuerthner 1994, Middleton 2003). The U.S. Fish & Wildlife Service and Texas Parks & Wildlife Department have taken the lead in purchasing lands and developing management programs to realize mission goals involving these activities (USFWS 1997, Land 2020). As a result, Tamaulipan thornforest has been restored on over 16,000 acres of former range since 1982 and at an average annual rate of 300 acres over the past 10 years ((USFWS 2020, pers. comm). Over time, restored lands provide new habitat, dispersal and recruitment routes for species populations that inhabit existing thornforest fragments or that originate in adjacent regions (e.g., Tamaulipas, Mexico) (Wright 1996, Sternberg and Judd 2006, King 2015). These areas also provide valuable stopover habitat for migratory bird and insect species that traverse the region's numerous flyways (e.g., neotropical migrants, monarch butterflies en-route to/from wintering grounds in central Mexico) (Borland et al. 2004, Twedt and Best 2004). Restored areas also facilitate ecosystem services that are becoming increasingly critical as the LRGV's development boundaries expand into periurban zones. Here, forest value can be measured in terms of carbon

Figure 2. LRGV biodiversity sample. Credits: Mayra Oyervides, Tony Henehan and Eric Sprague.

sequestration, erosion control, economic gains in ecotourism, recreational opportunities, pollinator services and others (Akland 1997, Mathis and Matisoff 2004, Woosnam et al. 2011, Kurpis 2019).

A key objective for conservation in the LRGV, then, is to adapt this flourishing ecological restoration effort and its partner network to a design informed by expected impacts from a changing climate (Brennan 2007, Povilitis and Suckling 2010, Gillson et al. 2013). Here, a strategy that includes ways of transitioning the existing program's capabilities to reflect success in increasingly arid conditions is needed. This same approach will be critical to incorporating measures of resilience into the program, whereby the effort has an identifiable and accessible toolkit with sufficient variation to account for detailed aspects of restoration (e.g., parcel-level considerations). An important part of this strategy is that it must be cognizant of the complex challenges that face the LRGV geography, including lessons previously learned. This is a key consideration in ecosystem management since gaps regularly occur between conservation theory and real-world application (Cross et al. 2012). By addressing these needs, this strategy will provide a starting point for an evolving paradigm into climate-adapted forest restoration in this unique region.

Thornforest Restoration: Retrospective

From their inception in the 1950's, thornforest restoration efforts in the LRGV have been dedicated to preserving native wildlife populations. Early focus by the Texas Parks & Wildlife Department (TPWD) was on providing additional habitat for White-winged doves (*Zenaida asiatica*; Riskind et al. 1987; Figure 3). These actions were a direct response to population declines in this regional game species that first manifested in the 1920's and which became protracted as a result of freezes in 1951 and 1962, which destroyed mature citrus groves important for nesting (Cottam and Trefethen 1968, Hayslette et al. 1996). These groves had supplanted original thornforest cover earlier in the century and doves were able to successfully adapt to structural similarities (e.g., spiny branches and perennial foliage) that the predominant citrus varieties provided (Oberholser 1974). Whitewings were also adapting to limited urban forests (e.g., backyard trees) in many 40 to 50-year-old LRGV towns at this time but these canopies were still young and confined within a relatively solid matrix of working croplands. State wildlife experts realized that one way to help correct this deficit was to purchase portions of decimated groves and work to establish new forest cover on them. This enhanced the value of existing thornforest and helped dove populations recover in the following decades (Small et al. 2006). As in other U.S. geographies, funding enabled by the Pittman-Robertson Act (1937) provided the genesis for most of this early restoration work (Lewis et al. 1942).


Figure 3. White-winged Dove (*Zenaida asiatica*). Credit: Mayra Oyervides.

While these efforts continued, a more comprehensive approach to conserving lands for wildlife in the LRGV was initiated at the federal level and spearheaded by the U.S. Fish & Wildlife Service (USFWS) in the late 1970's (Jahrsdoerfer and Leslie 1988, USFWS 1997). The impetus for this new initiative included conservation planning for declining, non-game species (e.g., ocelot, federally listed in 1982) from its early stages but now with a focus on providing geographic connectivity between protected lands in the LRGV (Perez et al. 1996, USFWS 2016). As an objective, restoration on these parcels and surrounding lands would provide additional habitats for wildlife species with a thornforest habitat requirement. Subsequently, in the early 1980's, the Department of the Interior began purchasing properties along the length of the Rio Grande in Cameron, Hidalgo and Starr Counties to establish connectivity for these purposes. Additional non-riverine parcels in these counties and in Willacy County have also been added over time. With the exception of Santa Ana National Wildlife Refuge (SANWR), which dates back to 1943, the "river corridor" parcels purchased since 1980 now constitute a major portion of Lower Rio Grande Valley National Wildlife Refuge's (LRGV NWR) 105,000 acres of protected lands (Figure 4).

Although TPWD continues sporadic restoration efforts to complement regional patronage in ecotourism (e.g., state parks, World Birding Center sites) and hunting (Las Palomas Wildlife Management Area), much of their local restoration focus has transitioned into providing technical assistance to private landowners interested in pursuing their own restoration-related activities (Perez 2020). This is a critical role to fill as all paths to successful conservation planning in Texas ultimately run through private lands and, by extension, strong relationships between landowners and stakeholders (Sorice et al. 2011, Kreuter et al. 2017). In contrast, USFWS' restoration program (hereafter program) has expanded over the past 40 years to include annual planting targets of several hundred acres on protected lands throughout the entire region. The program has improved upon the original framework developed by TPWD and, in conjunction with a variety of private nurseries, has pioneered most aspects of a cost effective, thornforest restoration methodology for the LRGV (Fulbright et al. 1986, Young 1992). This includes developments in container-grown nursery production (e.g., seed harvest, seed banking, propagation techniques, cultural practices) and restoration planning/implementation (e.g., supply chain development, planting design, labor/supplies procurement and outplanting success).

A learning approach has governed the program's efforts from the start as, for example, a focus on direct seeding from 1982 to 1995 led to mixed results in stand establishment and was replaced by nursery seedling production (Vora 1989, Sternberg 2003). Similarly, variation in seedling planting design was limited early on as the capacity necessary to produce many individual species in larger quantities had yet to be developed. Planting densities have also evolved since 1995, especially as program objectives shifted to accommodate newer goals in habitat development along the way. For example, low seedling densities (<400/acre) were commonplace before 2006 but have been replaced in most cases by medium (400-750/acre) and high (>750/acre) densities in the intervening years (USFWS 2020, pers. comm).

Restoration planning historically set a premium on selecting species that were documented as pre-existing in the immediate vicinity of where the effort would take place (Waggerman 1978). If sufficient thornforest cover already existed on other parts of the site or on adjacent parcels, the restoration design often attempted to account for the local dominance of certain species by designating a higher percentage of them in the planting 'mix'. Many of the sites that historically contained riparian vegetation, such as floodplain forests of black willow (*Salix nigra),* cedar elm (*Ulmus crassifolia*), hackberry (*Celtis laevigata*) and Montezuma bald cypress (*Taxodium mucronatum*), have transitioned into shrublands since the 1950's as a result of altered hydrology along the Rio Grande (e.g., Falcon Dam, Anzalduas Dam) and associated flood-control systems (Brush and Cantu 1998, Lonard and Judd 2002, Werner et al. 2007, Small et al. 2009). The situation surrounding freshwater allocation in the region is complex, with agricultural and municipal supply priorities currently precluding usage of any significant portion of this resource for restorative practices (Levine 2007). As such, the program treats the majority of these former riparian sites as uplands and works to establish the shrubland component that has supplanted historic vegetation in the general area.

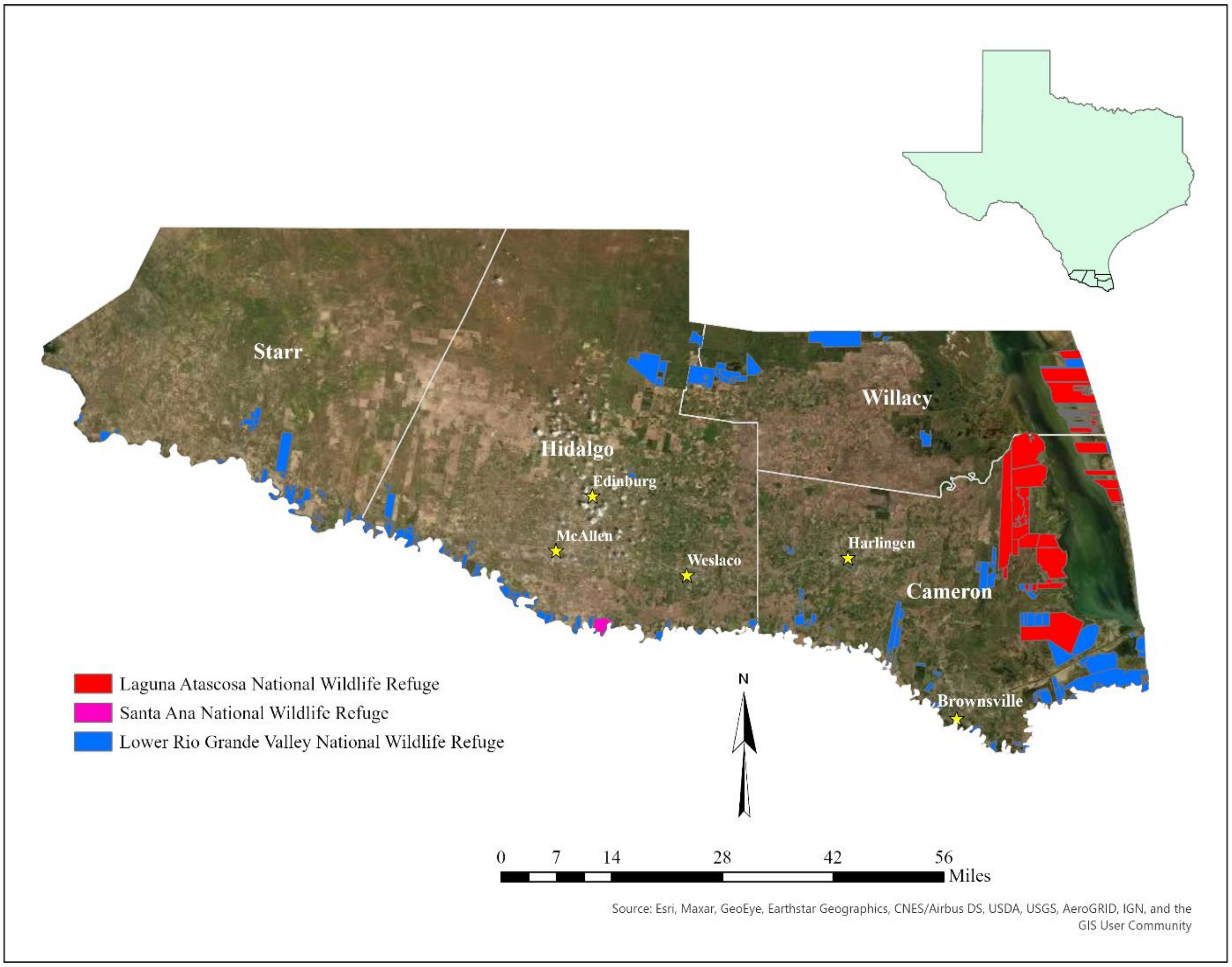

Figure 4. USFWS-managed lands of the LRGV.

Natural variation in aridity and precipitation on an east-west gradient has also influenced restoration planning. For example, woody species with distributions limited to the drier western reaches of the LRGV (e.g., upland Hidalgo and Starr Counties) intuitively figure into planting designs there but may be absent for projects based in the 3 eastern counties (Cameron, Hidalgo and Willacy). Previously, planting mixes also included a percentage of early successional trees (e.g., *Leucaena pulverulenta*) with comparatively rapid vertical growth rate characteristics. These trees were expected to facilitate multi-species recruitment over time by enabling seed dispersal among frugivores (Archer et al. 1988, Belsky and Canham 1994, Padilla and Pugnaire 2006). Seed collection has and continues to follow goals for promoting as much genetic variability as possible within individual species set for outplanting. In practice, this requires collection from a variety of constituent populations scattered throughout the LRGV (USFWS 2014).

Logistically, this effort takes the form of identifying individual trees on different land parcels, harvesting seed, processing and then carefully storing within a controlled environment for up to several years, depending on species. Wild collection is supplemented by harvest from a 2-acre plantation located at the program's nursery. Outplanting methodology involves preparing sites through a ground-up approach that removes all existing non-native vegetation and/or monotypic stands of invasive native species. In some instances (e.g., remote burn scars), more labor-intensive efforts, such as herbicide spot-spraying for invasive species, are required to prepare areas not accessible to large machinery. In either event, seedlings are planted by hand at regular intervals within a matrix that already includes a significant invasive grass component temporarily weakened through a pre-plant herbicide application or likely will within 1-5 calendar years post-plant due to emergence from the soil seed bank or dispersal (Wied et al. 2020).

Expected Climate Impacts

Projections for climate change paint an increasingly extreme weather trajectory for south Texas as the remainder of the 21st century unfolds. Research using variations in modeling over the past decade indicates that the region will be experiencing greater variability in precipitation and warmer average temperatures by mid-to-late century (Jiang and Yang 2012, Cook et al. 2015, Venkataraman et al. 2016; Figure 5). These advertised conditions could manifest in drought conditions of previously unseen severity and would inevitably impact every facet of the area's ecology and economy (Ziolkowska 2016, Schwantes et al. 2017). Drought is generally defined as a period of time in which an area receives below-normal precipitation and leads to reductions in soil moisture, stream flows and/or other associated water shortages. The duration and magnitude of the event are especially key to considerations in forest survival since most plants native to south Texas have some degree of morphological and physiological adaptation to drought stress already in place (Rodríguez et al. 2000, Quiring and Ganesh 2010, Wonkka et al. 2016). In the LRGV, Tamaulipan thornforest associations that depend on soil moisture derived from 20-30 inches of annual precipitation may be predisposed to suffering increased rates of mortality in these scenarios (González-Rodríguez et al. 2011, Adhikari and White 2014, Yang et al. 2020). This could then lead not only to negative impacts on listed species dependent on these associations for critical habitat but also to reductions in productivity related to biomass, thereby reducing the carbon sequestration potential of these forests (Adhikari and White 2016).

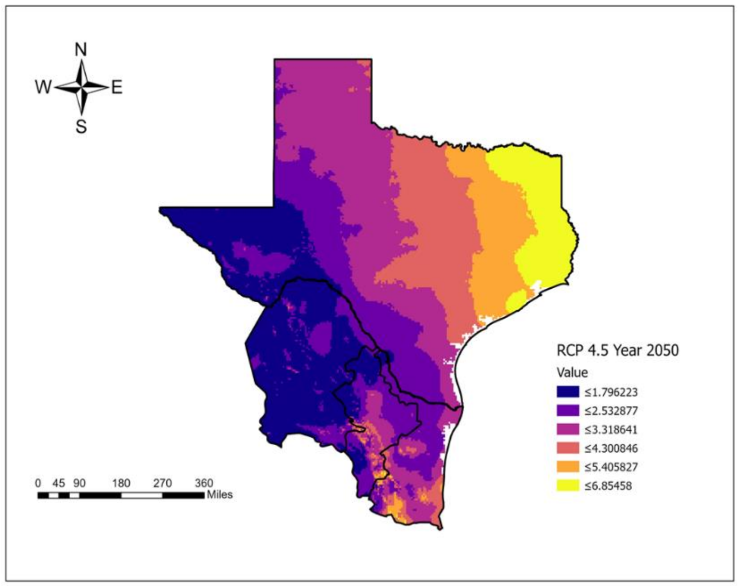

Figure 5. Climate model simulation projecting future aridity index values for Texas and Northeastern Mexico in 2050. Courtesy of Natalie Salinas.

The story of periodic drought in the LRGV is a familiar one to residents and conservation land managers. The region's drought of record (1949-1957) is becoming a more distant living memory as the years pass but episodes of shorter duration in the late 1990's and early 2010's have not failed to generate serious concern among the region's populace (Fipps 2001, Evan Garrick et al. 2016, Heim 2017). The chief threat to local communities in these circumstances has typically been water rationing among both agricultural and domestic users once sequential thresholds in diminished storage capacity along the Rio Grande are surpassed (Nava et al. 2016). However, a detrimental byproduct of these events is the additional groundwater pumping that communities farthest inland on the LRGV's irrigation distribution network have employed to help compensate for these situations. These networks double as conveyances for municipal water and in drought circumstances their role as a lifeline becomes magnified (Knight 2009). City officials are then forced to buy or lease acre-feet allotments on the open market and employ irrigation districts to move that allotment off the Rio Grande, up the network and into a town's distant storage facilities (Characklis et al. 1999, Stubbs et al. 2004). Costs can be prohibitive and many of these municipalities return to groundwater wells to help offset these operating costs.

These unsustainable methods can lower water tables for surrounding areas. Projected trends in urbanization place the LRGV's populace near 3 million by 2050, essentially doubling the region's existing needs with respect to infrastructure and resources (TWDB 2016). In conjunction with intensified drought, these conditions could lead to additional groundwater pumping that would further impact water tables, including those extending into nearby protected areas. Further, drought exacerbates erosion as related to the intensity of rainfall events and resulting sediment runoff (Allen et al. 2011). The implications for this and other forms of land degradation associated with drought include more basic soil substrates with reduced fertility and which may not be sufficient to support higher levels of regional thornforest species diversity in the future (Ruthven et al. 1993, Navar et al. 2014).

Drought will also work to expand urbanization in the LRGV by driving the region's rural economies into further decline, as evidenced in previous episodes. The 1950's drought is estimated to have eliminated approximately 100,000 farms and ranches throughout Texas and much of the populace displaced by that event permanently relocated to growing urban areas in the state (Burnet 2012). The LRGV's rural economy is emblematic of these concerns as farming and ranching enterprises dominate activities outside of urban zones (Norwine and Bingham 1985; Figure 6). While many proprietors of these operations already live within the region's expanding frontier of development, their support staff typically remain on-site in rural enclaves. It is these individuals who will be most at risk for relocating to the urban environment out of necessity. Climate-change induced drought will also have severe impacts in adjacent parts of northern Mexico (Nawrotzki et al. 2013). Rural families displaced from these areas will likely turn in part to employment opportunities in the expanding trade culture of the LRGV to hedge their bets on a stronger personal economic foundation (Orrenius et al. 2008). In the process these future immigrants will also expand the growing urban footprint of the region, compounding many of the dynamic conservation challenges that the region currently faces.

On the surface, intensified drought's effects on the program will be most evident in the expected survivorship of new plantings. Thornforest seedlings are most susceptible to environmental stressors (e.g., lack of soil moisture, desiccating winds, exposure to high heat) in their first few months post-plant (Fulbright et al. 1992, García 2011). Plantings conducted amid past multi-year droughts have suffered poor establishment and there is every reason to believe that these results would be repeated without pathways to mitigation (Dick et al. 2016). These failed efforts would

Figure 6. LRGV grapefruit harvest. The region has approximately 26,000 acres of citrus. Credit: Texas Farm Bureau.

translate into losses of time, funding and resources for the program. Further, intensified drought will likely alter the existing composition of thornforests as variations exist in individual species' capacities to resist these environmental stressors for prolonged periods (Stienen et al. 1989). The aforementioned loss of many riparian forests provides an instructive example of the deeper ecological consequences of not anticipating these types of challenges. In this case, historic assemblages of dependent avian species have become rare or been lost altogether at many relict sites (Sennett 1879, Rupert and Brush 2006).

Beyond drought, climate change impacts for south Texas are also expected to take the form of intensified precipitation events as the century progresses (Trenberth et al. 2018). This would further exacerbate a recent trend in increased downpour frequency that saw parts of the LRGV reach increases of 700% over mid-20th century levels from 2005-2014 (Thompson 2015). Tropical storms or hurricanes originating in the Atlantic basin have historically impacted the region on a seasonal basis and continue to do so, as witnessed in 2020's Hurricane Hanna (Davila et al. 2020, Shultz et al. 2020). However, the rapid intensification and frequency of some of these tropical systems and other more stochastic supercells over the past decade have become troubling (NWS 2019). Research indicates that Hurricane Harvey's 2017 intensity (e.g., highest storm precipitation total in U.S. history) over the mid and upper Texas/Louisiana coasts may only be a preview of what's to come for the western Gulf region over the next several decades (Wang et al. 2018). The response to that event has led to the creation of Houston's own Climate Change Action Plan, where restoration of forested natural areas within urban zones will figure prominently into mitigating future flood events (Bower et al. 2020).

In 2010, copious precipitation in the Rio Grande watershed associated with Hurricane Alex and consecutive tropical depressions produced a scenario which required maximum coordination in bi-national water management to avert catastrophic flooding in the LRGV (Pena 2010). However, the real impact to the region's conservation landscape came with the inundation of protected lands behind the river's primary flood control levee for over 2 months afterward in both Hidalgo and Starr Counties (Wogan 2010, Moore et al. 2016). In addition to reshaping land managers' concepts of what climax thornforest composition might have originally consisted of along those portions of the river in the region's pre-dam era, the flooding introduced invasive saltcedar (*Tamarix* sp.) for the first time into numerous protected areas. Dedicated efforts by USFWS were able to minimize this threat over the next several years but the prospect of high-intensity storms in similar scenarios or on a more frequent basis due to climatic change makes this combined threat very relevant to conservation planning in the LRGV (Scifres and Mutz 1975, Shafroth et al. 2005).

Strategy Articulation: Climate-Adapted Thornforest Restoration

The success of the restoration program has solicited a strong response among both locally based and national conservation stakeholders. Over the past 20 years, this has led to increasing levels of engagement and expanded roles in LRGV public lands restoration for non-profits, industry, universities and other agencies (Leslie 2016). While the program will indefinitely chart a direction that is consistent with the regional objectives developed by USFWS, it remains mindful of incorporating partner-sponsored advances (e.g., research, technical advisory, resources) to meet these goals. The products of this shared progress have also found ready adoption among practitioners in private lands restoration and will lead to greater impacts for the region in years to come. Forest restoration is by definition a long-term investment and one that should be regularly advanced through experience and insight (Stanturf et al. 2014). Further, both local (individual stand densities, e.g., *loma* thornforest, Ewing 2000) and landscape level attributes (e.g., species movement) influence conservation planning in this region (Opdam and Wascher 2004, Fuentes-Montemayor et al. 2017). Along these lines and given our current vantage into climate change impacts, including their capacity to shape ecosystems well into the future, we feel that the time has come to articulate a strategy into climate-adapted forest restoration within the LRGV (West et al. 2009, Mawdsley et al. 2009, Vose et al. 2019). Our objective here is to help guide these developing regional synergies among partners toward greater long-term impacts in biodiversity conservation and community resilience.

The U.S. Forest Service's Northern Institute for Applied Climate Sciences (NIACS) provides a nationally recognized framework that enables climate-adapted forest management in the US (Brandt et al. 2017, Ontl et al. 2018). This Climate Change Response Framework (CCRF) incorporates an 'Adaptation Workbook' platform designed to bridge existing gaps between climate change research findings and the application of sustainable management practices by land managers (Swanston et al. 2016). This process includes:

- Defining management objectives
- Assessing climate impacts (i.e., scientific literature, vulnerability assessments)
- Evaluating management objectives
- Identifying adaptation tactics
- Monitoring and evaluating effectiveness

Inherent to the fourth stage of this process are "menus" which include general climate adaptation strategies and corresponding step-down approaches that land managers can choose from to fit their objectives in a given geography. In central Texas, for example, management of ashe juniper-oak forest at the City of Austin's Balcones Canyonlands Preserve is inclusive of menu strategies focused on preserving refugia for listed species, among other objectives[1]. As a supplement to the original workbook's guidance, Ontl et al. (2020) recently published a carbon-centric menu of adaptation strategies/approaches (Table 1). While previous sections of this narrative have touched on the basis for the first three parts of the CCRF framework process as it relates to the USFWS restoration program (e.g., defining management objectives, assessing [expected] climate impacts and evaluating management objectives), we have chosen Ontl's carbon menu as the primary medium for identifying the climate-informed restoration tactics and approaches relevant to our geography. This representation stresses the inter-related nature (e.g., co-benefits) of our climate-informed thornforest restoration strategy (Table 2). The tactics we identified are inclusive of effective restoration methods traditionally employed by the program and newer (2014 – present) methods that we consider promising and/or that have met with recurrent success in promoting thornforest establishment. This synthesis is a living document and will provide a baseline for continuing advances in climate-resilient forest restoration in the LRGV.

Figure 7. National Fish, Wildlife, and Plants Climate Adaptation Strategy. Credit: U.S. Climate Resilience Toolkit.

To further elaborate on our strategy's consistency with national goals in climate adaptation, we also cross-reference our tactics with those specific to trust species conservation as presented by the National Fish, Wildlife, and Plants Climate Adaptation Partnership (NFWPCAP 2012, NFWPCAN 2021). Led by USFWS and the National Oceanic and Atmospheric Association (NOAA), this intergovernmental working group of federal, state and tribal agencies produced the National Fish, Wildlife, and Plants Climate Adaptation Strategy (NFWPCAS) in 2012 after 3 years in development (Figure 7). This comprehensive document identifies seven broad adaptation goals for species preservation in the US and a corresponding number of step-down strategies for managers (Appendix A). Here, strategies are meant to integrate with and expand existing management programs for the benefit of species conservation in the face of expected climate impacts. Of further relevance to the LRGV is that this treatment places a premium on trans-boundary cooperation where species conservation objectives necessarily intersect along

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[1] https://forestadaptation.org/adapt/demonstration-projects/city-austin-balcones-canyonlands-preserve-vireo-preserve-restoration

international lines. These goals complement our tactics, especially where restoration tenets meet conservation and climate adaptation co-benefits for the region's wealth of thornforest biodiversity.

Forest Carbon Management Menu
Strategy 1: Maintain or increase extent of forest ecosystems
1.1 Avoid forest conversion to nonforest land uses
1.2 Reforest lands that have been deforested and afforest suitable lands
1.3 Increase the extent of forest cover within urban areas
1.4 Increase or implement agroforestry practices
Strategy 2: Sustain fundamental ecological functions
2.1 Reduce impacts on soils and nutrient cycling
2.2 Maintain or restore hydrology
2.3 Prevent the introduction and establishment of invasive plant species and remove existing invasives
2.4 Maintain or improve the ability of forests to resist pests and pathogens
2.5 Reduce competition for moisture, nutrients, and light
Strategy 3: Reduce carbon losses from natural disturbance, including wildfire
3.1 Restore or maintain fire in fire-adapted ecosystems
3.2 Establish natural or artificial fuelbreaks to slow the spread of catastrophic fire
3.3 Alter forest structure or composition to reduce the risk, severity, or extent of wildfire
3.4 Reduce the risk of tree mortality from biological or climatic stressors in fire-prone systems
3.5 Alter forest structure to reduce the risk, severity, or extent of wind and ice damage (…of extreme weather events)
Strategy 4: Enhance forest recovery following disturbance
4.1 Promptly revegetate sites after disturbance
4.2 Restore disturbed sites with a diversity of species that are adapted to future conditions
4.3 Protect future-adapted seedlings and saplings
4.4 Guide species composition at early stages of development to meet expected future conditions
Strategy 5: Prioritize management of locations that provide high carbon value across the landscape
5.1 Prioritize low-vulnerability sites for maintaining or enhancing carbon stocks
5.2 Establish reserves on sites with high carbon density
Strategy 6: Maintain or enhance existing carbon stocks while retaining forest character
6.1 Increase structural complexity through retention of biological legacies in living and dead wood
6.2 Increase stocking on well-stocked or understocked forest lands
6.3 Increase harvest frequency or intensity because of greater risk of tree mortality
6.4 Disfavor species that are distinctly maladapted
6.5 Manage for existing species and genotypes with wide moisture and temperature tolerances
6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency
6.7 Use seeds, germplasm, and other genetic material from across a greater geographic range
Strategy 7: Enhance or maintain sequestration capacity through significant forest alterations
7.1 Favor existing species or genotypes that are better adapted to future conditions
7.2 Alter forest composition or structure to maximize carbon stocks
7.3 Promote species with enhanced carbon density in woody biomass
7.4 Introduce species or genotypes that are expected to be adapted to future conditions

Table 1. Forest Carbon Management Menu: Strategies and Approaches (Ontl et al. 2020).

Tactic	Approach(es)	Anticipated co-benefits
1. Select restoration sites by soil type and through systematic conservation planning efforts	1.2 Reforest lands that have been deforested and afforest suitable lands 1.3 Increase the extent of forest cover within urban areas 2.1 Reduce impacts on soils and nutrient cycling 2.2 Maintain or restore hydrology 4.1 Promptly revegetate sites after disturbance 5.2 Establish reserves on sites with high carbon density	*Biodiversity conservation*: augment existing capacity of wildlife corridors in an urbanizing geography *Climate adaptation*: reduce sediment runoff & promote subsoil water infiltration *Carbon mitigation*: protect soil carbon stocks
2. Select restoration species based on mature seral stage representation and drought tolerance	3.5 Alter forest structure to reduce the risk, severity, or extent of extreme weather events 4.2 Restore disturbed sites with a diversity of species that are adapted to future conditions 6.4 Disfavor species that are distinctly maladapted 6.5 Manage for existing species and genotypes with wide moisture and temperature tolerances 6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency 7.1 Favor existing species or genotypes that are better adapted to future conditions	*Biodiversity conservation*: maintain listed species populations, ecosystem specialists *Climate adaptation*: increase forest resilience in the face of intensified drought *Carbon mitigation*: maintain carbon capture in xeric transition zones
3. Restore with high stand densities and utilize supplemental planting techniques where appropriate	2.4 Maintain or improve the ability of forests to resist pests and pathogens 6.1 Increase structural complexity through retention of biological legacies in living and dead wood 6.2 Increase stocking on well-stocked or understocked forest lands	*Biodiversity conservation*: increase habitat quality & structural diversity *Climate adaptation*: relieve environmental stress in young forests through facilitative interactions *Carbon mitigation*: increase carbon stores on abandoned/degraded lands

Tactic	Approach(es)	Anticipated co-benefits
4. Treatments: utilize tree shelter tubes for 1-3 years post plant and perform stem manipulations at 3 or more years post-plant	3.4 Reduce the risk of tree mortality from biological or climatic stressors in fire-prone systems 4.3 Protect future-adapted seedlings and saplings 4.4 Guide species composition at early stages of development to meet expected future conditions	*Biodiversity conservation*: mitigate ecosystem damage from exotic ungulate species *Climate adaptation*: expedite forest canopy closure to promote microclimate creation/retention *Carbon mitigation*: maintain/enhance sequestration rates over existing, disturbed land covers
5. Mitigation of invasive, exotic grass species (pre and post-plant)	2.3 Prevent the introduction and establishment of invasive plant species/remove existing invasives 2.5 Reduce competition for moisture, nutrients, and light 3.3 Alter forest structure or composition to reduce the risk, severity, or extent of wildfire	*Biodiversity conservation*: restore/maintain understory microclimate for leaf litter dependencies among species *Climate adaptation*: improve seedling establishment in semi-arid conditions *Carbon mitigation*: increase carbon stores by facilitating persistence of non-woody biomass
6. Identify and secure sources of genetically diverse, drought-resilient species through seed collection activities	6.7 Use seeds, germplasm, and other genetic material from across a greater geographic range 7.4 Introduce species or genotypes that are expected to be adapted to future conditions	*Biodiversity conservation*: assure persistence of genotypic variation in forest tree/shrub species *Climate adaptation*: augment forest cover survival in predicted climate change scenario extremes *Carbon mitigation*: reduce risk of long-term carbon losses by favoring lower risk species

Table 2. Selected adaptation tactics and associated approaches for LRGV thornforest restoration identified using the Forest Carbon Management Menu, with associated co-benefits for biodiversity conservation, climate adaptation, and carbon mitigation.

Tactic 1. Select restoration sites by soil type and through systematic conservation planning efforts. Certain soil types in the LRGV are more conducive to restoration in that they possess properties (e.g., fertility, texture, slope aspect, etc.) which better support long-term development of thornforest associations (Harveson et al. 2004). This includes a broad range of mollisols, alfisols and others under a variety of series names (e.g., Hidalgo, Racombes, Willacy, Olmito, Laredo, Lozano, etc.) (Vora and Jacobs 1990, USDA-NRCS 2020). Through biomass production (e.g., maturing thornforest), restoration on target soils can be expected to augment existing carbon stocks and reduce impacts (e.g., intensified erosion) to established nutrient cycling pathways (Northup et al. 2005, Canadell and Raupach 2008). Subsoil hydrology in these areas will also be positively impacted by processes that seek to improve moisture infiltration, including forest restoration (Návar 2011). Beyond soil type, site selection advances on parcels that have been identified through systematic conservation planning efforts recently completed by the Thornforest Conservation Partnership (Thompson 2011, Reside et al. 2018). This collaboration currently includes many of the region's prominent conservation stakeholders and aims to restore portions of the LRGV's Tamaulipan thornforest ecosystem that have been deforested through agricultural conversion and other disturbances.

The group's Thornforest Conservation Plan identifies over 70,000 acres within the LRGV that, if restored, would have the highest potential for providing essential connectivity to dependent wildlife moving between existing forest fragments (TCP 2020). While ongoing urbanization could make some of these projections obsolete over time, core restoration opportunities remain on approximately 18,000 acres of public protected lands (Figure 12). Here, site selection aims to support the long-term trajectory of listed species recovery efforts (e.g., ocelot) by creating additional thornforest patches that will help to alleviate habitat loss conditions over time (Connolly 2009, Stilley 2019).

Additionally, the co-benefits described herein also support the following goals and strategies within the National Fish, Wildlife, and Plants Climate Adaptation Strategy (NFWPCAS):

Goal 1	**Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.**
Strategy 1.1	Identify areas for an ecologically-connected network of terrestrial, freshwater, coastal, and marine conservation areas that are likely to be resilient to climate change and to support a broad range of fish, wildlife, and plants under changed conditions.

Goal 3	**Enhance capacity for effective management in a changing climate.**
Strategy 3.2	Facilitate a coordinated response to climate change at landscape, regional, national, and international scales across state, federal, and tribal natural resource agencies and private conservation organizations.
Strategy 3.4	Optimize use of existing fish, wildlife, and plant conservation funding sources to design, deliver, and evaluate climate adaptation programs.

Goal 4	**Support adaptive management in a changing climate through integrated observation and monitoring and use of decision support tools.**
Strategy 4.1	Support, coordinate, and where necessary develop distributed but integrated inventory, monitoring, observation, and information systems at multiple scales to detect and describe climate impacts on fish, wildlife, plants, and ecosystems.

Goal 5	**Increase knowledge and information on impacts and responses of fish, wildlife, and plants to a changing climate.**
Strategy 5.1	Identify knowledge gaps and define research priorities via a collaborative process among federal, state, tribal, private conservation organization, and academic resource managers and research scientists.

Goal 6	**Increase awareness and motivate action to safeguard fish, wildlife, and plants in a changing climate.**
Strategy 6.1	Increase public awareness and understanding of climate impacts to natural resources and ecosystem services and the principles of climate adaptation at regionally- and culturally appropriate scales.

Tactic 2. Select restoration species based on mature seral stage representation and drought tolerance. With over 1,200 native species, the LRGV's flora presents a wide variety of options for achieving restoration goals (Best 2006, Heep and Lester 2011). However, observations collected by USFWS staff and research conducted by Mohsin et al. (2021) indicate that survivorship is not equal among species, especially under the prevailing treatment of restoration outplantings (e.g., no supplemental watering). Rather than wait for compositional shifts in forest associations to manifest during extended droughts of the future, we emphasize that contemporary restoration projects begin utilizing an assemblage of species which appear to have greater predisposition towards tolerance of drier extremes (Timpane-Padgham et al. 2017). This includes modifying the planting percentage mixes of individual species to reflect what we perceive to be increased chances for attaining long-term canopy coverage in outplantings. These actions are key to spreading the inherent risks to forest restoration success in the LRGV's existing semi-arid climate while promoting resilience toward advertised future conditions in increased aridity.

While a restoration species palette will not initially replicate the species diversity observed in many mature stands of thornforest (e.g., >50 years old), it does provide a favorable starting point for a developmental trajectory that may ultimately approach similar functionality for a wide range of wildlife, including thornforest specialists and listed species (Judd et al. 2002). In addition to drought tolerance, mid-late successional species are also chosen to promote quicker establishment of structural diversity within restored parcels, provide benefits such as increasing bird and pollinator food sources, develop a denser canopy to exclude invasive grasses, and provide improved environmental conditions (e.g., canopy shade, moisture retention) for the germination of successive rounds of dispersed seed within a stand. Species selection is also critical in locations where forests that were historically riparian in composition have been lost to altered hydrology (e.g., floodplains along immediate Rio Grande River). Despite the loss of historic conditions, these 'xeric transition' zones can continue to function towards carbon capture where restoration with drought-tolerant species is achieved.

Tactic 2 aligns with NFWPCAS in the following goals and strategies:

Goal 1	**Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.**
Strategy 1.3	Restore habitat features where necessary and practicable to maintain ecosystem function and resiliency to climate change
Strategy 1.4	Conserve, restore, and as appropriate and practicable, establish new ecological connections among conservation areas to facilitate fish, wildlife, and plant migration, range shifts, and other transitions caused by climate change.

Tactic 3. Restore with high stand densities and utilize supplemental planting techniques where appropriate. In addition to assisting in the formation of dense stands characteristic of extant mature thornforest patches, this methodology promotes facilitative interactions between species. As in other semi-arid regions, these mutualisms likely mitigate stress in early forest establishment where interspecific disparities in growth rate can create beneficial conditions (e.g., moist microclimates, shade, mycorrhizal soil fungi associations) for one or more nearby species (Vela 2015). This approach is vital to naturally mitigating the existing weather extremes of the LRGV (e.g., desiccating winds, high heat) and will only meet with increasing value as projected aridity increases unfold in the future. This front-end investment in stand density will also pay dividends toward generating the high-quality habitat necessary for territorial expansion of imperiled species residing in adjacent, mature thornforest patches (e.g., ocelot).

Supplemental planting has been employed within the restoration program for a number of years. This effort emphasizes remedial seedling establishment on parcels where prior direct seeding from 1982-1995 failed to achieve acceptable levels of thornforest cover. While costs are generally higher to perform these actions than at ground-up restorations, they represent a critical step in salvaging both the conservation and carbon mitigation potential of protected lands that have received minimal attention.

Tactic 3 aligns with NFWPCAS in the following goals and strategies:

Goal 1	**Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.**
Strategy 1.3	Restore habitat features where necessary and practicable to maintain ecosystem function and resiliency to climate change
Strategy 1.4	Conserve, restore, and as appropriate and practicable, establish new ecological connections among conservation areas to facilitate fish, wildlife, and plant migration, range shifts, and other transitions caused by climate change.

Tactic 4. Treatments: utilize tree shelter tubes for 1-3 years post plant and perform stem manipulations at 3 or more years post-plant. We place a necessary premium on providing a

stable environment to facilitate forest development. By installing reusable tree shelter tubes on plantings for 12-36 months post plant, seedling survivorship has improved dramatically over standard 'open' planting methods, in some cases by more than 80% ((USFWS 2020, pers. comm). Specifically, tree shelters create an individual microclimate for each seedling that preserves soil moisture in the immediate root zone, prevent excess herbivory in the early establishment window and mitigate invasive grass encroachment (Brown and Archer 1988, Reid et al. 1990, Alexander et al. 2016). They perform the latter by encouraging more vertical growth from the plant in its early stages, which allows it to rapidly establish a height advantage over invasive grasses (Dick et al. 2016). At shelter removal, most species have typically achieved a height that facilitates canopy development ((USFWS 2020, pers. comm). Manipulating the resulting single stems of certain species to promote a denser, multi-branch growth habit is another element we advocate for in this strategy. Completed at 1-2 intervals after tree shelter removal but while the tree is still young (3-8 years post-plant), this effort promotes denser structure throughout the stand and approximates conditions observed in many mature thornforest patches (Rideout-Hanzak, S. 2020, pers. comm).

As in tactics 2-3, alignment with the NFWPCAS can be found in:

Goal 1	**Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.**
Strategy 1.3	Restore habitat features where necessary and practicable to maintain ecosystem function and resiliency to climate change
Strategy 1.4	Conserve, restore, and as appropriate and practicable, establish new ecological connections among conservation areas to facilitate fish, wildlife, and plant migration, range shifts, and other transitions caused by climate change.

Tactic 5. Mitigation of invasive, exotic grass species (pre and post-plant). this approach to climate informed restoration in south Texas would fail to achieve expected outcomes if an invasive control component was not incorporated. The LRGV's complement of exotic, invasive grasses (e.g., guinea grass [*Megathyrsus maximus*], buffelgrass [*Cenchrus ciliaris*]) has been a consistent limiting factor in achieving acceptable levels of survivorship in plantings (Ewing and Best 2004). Further, their persistence has resulted in the alteration of historic ecosystem dynamics (e.g., increased fire prevalence, severity) within some thornforest associations (Hanselka 1980, Diamond 1998, McDonald and McPherson 2011). We use a combination of mechanical cultivation (discing, ripping) and herbicide application to eliminate existing stands of these species at the site well ahead of planting to reduce resource competition. The discing portion of the process may be repeated at 1-3 pre-plant intervals to eliminate residual vegetation. However, the post-plant interval (1-5 years) will typically feature some re-establishment through either the existing seed bank or wind dispersal (USFWS 2020, pers. comm).

As mentioned, the use of tree shelter tubes helps to mitigate this inevitable return by providing a physical barrier complete with beneficial microclimate. Beyond these actions, our strategy also employs herbicide spot treatments of invasive stands where their density within the outplanting becomes problematic. This action can be repeated at recurring intervals for 1-3 years until sufficient growth in established seedlings is evident. While 1 or more of these exotic species may become reduced in frequency/distribution within outplantings due to effects from predicted climate scenarios, intraspecific variations or other introduced species with greater phenotypic plasticity may ultimately maintain the need for these proactive management measures (Clements and Ditommaso 2011).

In dense plantings with high initial survivorship, the control of invasive grass species facilitates formation of a critically important leaf litter strata beginning several years post-plant. As thornforest stands age, a comparatively moist microclimate develops within this layer and provides foraging habitat and other resources for many thornforest specialist species (e.g., White-tipped Dove [*Leptotila verreauxi*], Long-billed Thrasher [*Toxostoma longirostre*]). The persistence of this litter also works to increase soil C levels over time through decomposition (Creamer et al. 2013).

Tactic 5 aligns with the following NFWPCAS goals and strategies:

Goal 7	**Reduce non-climate stressors to help fish, wildlife, plants, and ecosystems adapt to a changing climate.**
Strategy 7.3	Use, evaluate, and as necessary, improve existing programs to prevent, control, and eradicate invasive species and manage pathogens.

Tactic 6. Identify and secure sources of genetically diverse, drought-resilient species through seed collection activities. Seeds provide the basis for climate-informed thornforest restoration and their collection is critical to this strategy. We advocate for year-round collection of drought-adapted species from a variety of source locations throughout the LRGV. These actions enhance the persistence of genotypic variation within forest species and, in turn, fitness derived from these variations may be instrumental for achieving climate-resilience in future plantings. The region's expanding rate of urbanization places a premium on collection from privately-owned sites in an effort to preserve more examples of intraspecific genetic integrity before they are permanently lost to land conversion. Collection from public lands is ongoing (Appendix C) for many species as well.

This tactic aligns with the following NFWPCAS goals and strategies:

Goal 2	**Manage species and habitats to protect ecosystem functions and provide sustainable cultural, subsistence, recreational, and commercial use in a changing climate.**
Strategy 2.3	Conserve genetic diversity by protecting diverse populations and genetic material across the full range of species occurrences.

Expected Outcomes

Beyond the direct value to forest health described in previous sections, regional adoption of the restoration strategy which encompasses these 6 tactics will result in additional overarching benefits to the LRGV. Assuming that most thornforest wildlife associations can incrementally adapt to climate-driven changes, improved forest resilience will preserve a continuing base of critical habitat for many species (Hansen et al. 2001, Kates et al. 2012). These developments would continue to promote natural processes within populations, including migration and recruitment in what is becoming an increasingly urbanized landscape (Hansen et al. 2005, Dolman 2015; Figure 8). Restoration under this scenario will also likely facilitate ongoing distributional range expansions in some species, especially under climate change scenarios (Brush and Feria 2015). Further, landscape-level restoration of conservation corridors as currently conducted by USFWS (public lands, easements) and as conceived by the Thornforest Conservation Plan (greater role for private lands) will benefit pre-existing trust species. In this context, the proposed strategy would benefit preservation efforts for regional populations of federal and state-listed species such as ocelot and Texas tortoise (*Gopherus berlandieri*) (Kazmaier et al. 2001, Jackson et al. 2005). Expanding thornforest cover through the strategy's recommendations will also facilitate the resilience necessary to maintain and enhance this ecosystem's integrity in the face of invasive species threats (Dumroese et al. 2015). While some of these impacts could be mitigated by future increases in aridity level (e.g., prolonged droughts), other invasive species will likely exploit any niches left behind, thus adaptation in resilience approaches is vital (Mainka and Howard 2010).

Figure 8. Encroachment of urban development. Credit: Mayra Oyervides.

Additional environmental benefits will also be found in a regional ecosystem services dialogue that is beginning to experience serious realignment due to recent events, changing social perceptions and impending resource scarcities (see section: Expected Climate Impacts; Durst and Ward 2016, Ward and Qualls 2020). While extreme droughts may become pervasive in the future, catastrophic flood events of high intensity and greater frequency could also punctuate these periods. This will pose continuing challenges for the LRGV's urbanization trajectory as more area is converted into hardscapes in coming decades (Dirrigl et al. 2016). Our restoration strategy will supplement intergovernmental (federal, state, local) efforts to mitigate damage from these excess waters by informing discourse on thornforest planting in zones peripheral to flood channels (Hidalgo County 2017, IBWC 2020). Here, restored areas will work to quantifiably reduce sediment loads in existing tributaries of the Rio Grande by preventing excessive runoff (Kannan 2012, Flores et al. 2017, Jones et al. 2018). This will likely provide a cost savings return on municipal filtration of the region's domestic water supply. Ecosystem service benefits also translate into recreation value for the region's growing populace as additional USFWS parcels with restoration capacity are open to the public or will be in the near future (Clark 2019).

This strategy will also work to supplement many of the ongoing positive economic impacts that thornforest conservation has on the LRGV. Expanded forests that are resistant to drought-induced mortality will provide more consistent opportunities to enhance an existing ecotourism industry which generates $135 million annually in the region (USFWS 2019a). These same habitats will provide a reliable base for the region's multitude of insect pollinators (e.g., flies, butterflies, bees) (Blair and Williamson 2008). These species figure into a lucrative regional production of agricultural commodities ($500 million annually) that occurs in areas adjacent to forest patches (Cusser et al. 2016, USFWS 2019b). Broadly-speaking, this restoration strategy will also promote a more widespread appreciation for thornforest among the public and thereby pay dividends for its continued conservation as we move forward.

Case Study: La Sal De Rey

In partnership with the Wildlife Conservation Society's Climate Adaptation Fund, we sponsored completion of a 70-acre thornforest restoration on the LRGV NWR's La Sal De Rey tract in March 2020 (Figure 10). As an expression of our mutual commitment to climate-adapted forest restoration, this effort was the product of careful planning and diligent implementation by many individuals. The project is the first restoration within the USFWS' 40-year restoration portfolio to be completely developed along the strategy tactics identified in this document and is the beginning of a larger effort by both USFWS and AF to jointly address climate change implications on thornforest management in the LRGV. The planting itself will serve as a testbed for additional study into some of the strategy's baseline precepts over the next decade, including research and observations at various successional development stages. The site will also serve as a demonstration for other regional restoration practitioners (e.g., municipal land managers, private landowners, agencies) who are interested in adopting similar design tactics for their own projects.

Figure 9. Ocelot (*Leopardus pardalis*), Cameron County, Texas, 2020. Credit: USFWS/TXDOT.

The site's selection was based on its value to ongoing efforts at preserving and enhancing habitat for the region's endangered ocelot population (Figure 9). As home to an estimated 80 known individuals, the LRGV's thornforests are currently the final U.S. refuge for this species, a neotropical cat that once ranged as far north as Arkansas (USFWS 2016). While habitat fragmentation due to agricultural development doomed the regional persistence of other neotropical species like the jaguar (*Panthera onca*) early in the 20th century, ocelots have managed to persist in scattered locations along the periphery of development

Figure 10. La Sal De Rey 70-acre Restoration Site.

(Leslie 2016). These periurban working lands, however, are quickly transitioning into a matrix of residences and roads in many areas as urbanization proceeds, with the latter posing one of the most serious threats to ocelot survival (USFWS 2010, Merem et al. 2011). Along with the reduced fitness that comes with a loss in genetic variability at isolated sites, ocelot mortality along busy roads has increased in incidence over recent years (Hoffmeister et al. 2005, Schmidt et al. 2020).

The designation of conceptual corridors to assist movements of this and other vulnerable wildlife species has been a key factor in guiding parcel acquisition by USFWS and in developing subsequent restoration priorities over time (USFWS 2020, pers. comm). As two of these parcels, the La Sal De Rey tract (5,400 acres) and adjacent Schlaben tract (1,800 acres) contain mature thornforest cover as well as a mosaic of past thornforest restorations and abandoned croplands. La Sal De Rey's location within the USFWS' 'ranchland' corridor and the documented presence of adult ocelots nearby made restoration there a high-profile opportunity for conservation of this unique species.

The ability to compare restoration trajectories over time at La Sal De Rey will also provide an efficient means for ongoing evaluations of our strategy. Specifically, metrics regarding seedling survivorship, canopy development, invasive grass persistence and community interactions (e.g., wildlife usage) will hopefully reinforce our strategy's distinguishing tenets by providing quantitative evidence of improved restoration success (Zedler 2007, Mansourian and Vallauri 2014). While comparisons at this site and others are important, restoration by its nature is a long-term process. With that reality in mind, we are seeking to mitigate the effects of projected increases in thornforest ecosystem stress by initiating this proactive strategy sooner than later across all qualified restoration activity within USFWS' LRGV jurisdiction. We also advocate for its application to restoration efforts that result from any future expansions in the recognized acquisition zone boundaries of these national wildlife refuges.

In many ways, concerns for the welfare of the Texas ocelot population are emblematic of an overarching discourse on how the region's exceptional biodiversity as a whole will be able to persist in an ecosystem that has been so heavily modified by anthropogenic disturbance (Clover 1937, Tremblay et al. 2005, Flores 2019). With climate change's impacts set to compound this predicament, we feel that the best approaches to conservation in the LRGV will be those that incorporate proactive planning and design elements that are reflective of these impending challenges. Realizing these elements in project-based restoration work will help to facilitate larger adoption of this strategy at scales beyond what is being advertised here, especially where private landowners are concerned. Here, empowerment of regional stakeholders thru technical education provided by the Thornforest Conservation Partnership and others will assist in facilitating this future expansion in scale.

Strategy Implementation

As described, the La Sal De Rey project was developed according to the climate-informed strategy tactics outlined earlier in this narrative. Beyond verified ocelot occurrence, this site's selection (Tactic 1) was dependent on the presence of soils that support thornforest (e.g., Willacy, Delfina soil series [sandy & sandy-clay loams]) and where strategic conservation planning by the TCP had previously identified the site as ideal for restoration (Figure 12). The species allocation for the project included blackbrush (*Acacia rigidula*), which was represented in increased proportion (over previous year) due to higher confidence in establishment (1% to 4%). Another species, Texas torchwood (*Amyris texana)*, still factored into our planting design but we elected to reduce its proportional coverage (8% to 2%) as establishment has become more difficult in recent drought conditions. A full list of the 24 species utilized in the case study planting and their percent compositional adjustments from the previous year's planting cycle can be found in Appendix B.

In conjunction with the fact that all of these species are frequently represented in mature thornforest stands, these selections align with Tactic 2. While the site did not represent a supplemental planting opportunity, we restored with approximately 900-1,000 seedlings/acre, thus emphasizing high density in accordance with the strategy's third tactic. Tree shelter tubes were installed on all seedlings (63,000) at planting in March 2020 (Tactic 4; Figure 11). These tubes will begin to be removed in spring 2022 and will be completely phased out of the site by spring 2023. Our expectation is to begin incremental stem manipulations after removal to promote a denser form and closed canopy structure in the resulting thornforest stand at the site. Coverage of these manipulations will be small initially to account for research test plots designed to compare between treatments and controls.

In alignment with Tactic 5, extensive clearing of the pre-existing cover at the site was undertaken from December 2019 to February 2020. The cover consisted primarily of exotic buffelgrass (*Cenchrus ciliaris*) and extensive discing/ripping of the upper soil profile accompanied this initial work. This preparation resulted in conditions that were mostly absent of invasive grasses at outplanting in March 2020. Herbicide spot treatments are still expected in portions of the project site that exhibit recurrence of this and other invasive grass species but said conditions are not in evidence as of early 2021.

Although not in direct association with the La Sal De Rey planting, we did support extensive seed collection activities of drought-resilient thornforest species throughout 2019. These actions are essentially a down-payment on future plantings and reinforce our commitment to strategy Tactic 6. Cumulatively, 78 lbs. of seed were collected from 11 species at 13 individual sites throughout the LRGV in this window (Appendix C). The diversity of site collections for brasil (*Condalia hookeri*) exemplify the premium we place on promoting regional genetic variation in our restoration work.

Figure 11. Tree shelter tubes.

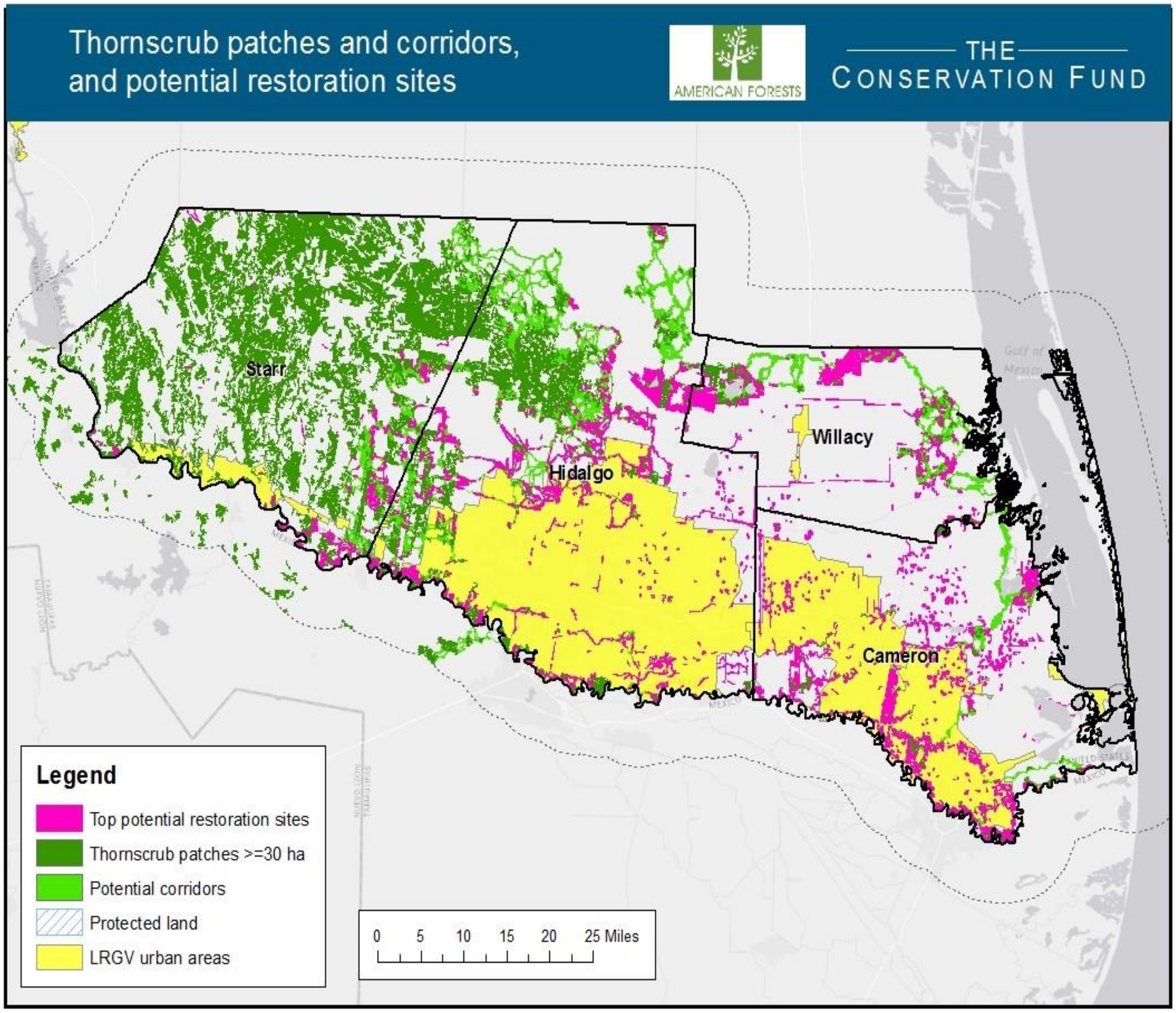

Figure 12. Systematic LRGV conservation planning efforts authored by the Thornforest Conservation Partnership.

Challenges and Next Steps

At present, our strategy's contribution to LRGV conservation is tempered by several barriers to application at greater scale. Within the restoration program, for example, seed collection continues apace for an existing demand of 300,000-400,000 seedlings per year. The cyclical nature of seed production in many of these species (e.g., on/off years) requires that a larger investment be made in any 1 year to collect as many seeds as possible. This effort supplements reduced or non-existent production in the "off" years and utilization in subsequent restorations is facilitated by cold storage to maintain seed viability. However, many of the individual nursery producers who grow seedlings under contract for the program prefer to source the majority of a given year's production from recent wild collections. Clearly, additional labor for seed collection and processing is necessary to expand the program's capacity to restore larger annual acreage targets (Broadhurst et al. 2016). By extension, additional space within the program's in-house nursery operation and/or those of contract growers will also be necessary to grow out larger numbers of seedlings for approximately 8-10 months per year (e.g., March – December; Figure

13). Additional resources are also needed to conduct comprehensive mapping of seed collection sites within the LRGV where restoration focus species are sourced. This would facilitate more efficient seed collection, especially when sufficient seed quantities of more than 1 species can be realized from the same site.

Developing a strong parallel body of research to expand our strategy's original framework through ongoing advancements will be critical. The challenge here is multi-fold, with empirical data needed to evaluate and refine methods in propagation, species selection, planting design, stand management, impact monitoring and others. These research areas can be better understood to encompass needs along a timeline to gain maximum feedback on strategy effectiveness. Capacities in seedling propagation are the basis for restoration efforts in general and this is certainly the case for continuing efforts to promote landscape connectivity within the thornforest ecosystem. While trial and error development using stand-alone techniques (e.g., acid scarification, pre-emergence, etc.) and technique combinations has led the program to its current position, additional refinements are needed to realize its full potential (Jurado et al. 2000). This work is likely to emphasize changes to the existing suite of species used within restoration efforts and hopefully lead to more efficient production methods for species already in use.

Figure 13. Contract grower demonstrating propagation techniques for thornforest seedling production.

Research into species performance over time and under differing field and greenhouse study scenarios is also needed to verify existing data and assumptions used in developing the drought-resilient species selection list (Tactic 2, Appendix B). For example, situations may arise when uncontrolled circumstances (e.g., damage to nursery, "off" year in wild seed production) may require substitution of one or more alternate species when the intended "list" species is not available in sufficient quantities. In such cases, assessments of survivorship in these alternate species could be used to justify the selection of one over another for greater long-term impact. Study into planting design is an area that would also provide a great deal of context for continuing adaptation of the strategy. Based on original planting densities, the interaction between developing thornforest canopy and either native or invasive, non-native grassland matrixes at various successional stages would be important to quantify across the region. Analysis of this data would help to codify/modify broader geographic application of target planting densities per acre and similar guidelines in the existing strategy. Likewise, an expanded and sustained effort into developing detailed metrics for impact monitoring at restoration sites is also needed. The region's research community is well-placed to provide insight into all of these areas and many others as the number of faculty appointments with an ecological study focus has increased dramatically in the past decade.

Additional funding avenues are needed to recruit these researchers from institutions that have such regional expertise (e.g., University of Texas-Rio Grande Valley, Texas A&M University-Kingsville). This relationship already exists within the restoration program but will need to be expanded in a cohesive way to develop the strategy's full long-term capacity in conservation. For example, research-based advancements in propagation can be achieved through 1-3 year grants that include budget line items for graduate student and/or post-doctoral support. However, a more sustained form of funding (e.g., targeted policy, corporate investment, etc.) will be needed to realize long-term findings from monitoring of restored forest trajectories, specifically, how they integrate with goals in conservation (e.g., expansion of endangered ocelot population toward de-listing criteria). Absent of this due diligence, it will be difficult to substantiate the presumed success that thornforest restoration is having on species recovery.

Supplemental lines of research will also be needed to support our assertions on expected outcomes in ecosystem service provisioning and social impact. As part of a multi-disciplinary initiative to impact LRGV conservation over the next decade, the TCP is currently engaging a cross-section of regional stakeholders to develop both conservation and community resilience outcomes for restoration. These outcomes and their respective attributes (e.g., plans for implementation, success metrics) will be shovel ready for investment scenarios in the near future. The strategy's value to other regions that are projected to face similar climate impacts is another consideration (Wilder et al. 2013). However, application outside of the LRGV (e.g., other parts of Texas, northeastern Mexico and/or the U.S. Southwest) would be contingent on both consistent successes in thornforest restoration (e.g., application) and credibility derived from a supporting record of research-based findings. In this scenario, the strategy would further evolve as a critical mass of best management practices and insights into local adaptation in these other geographies take shape around it.

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Appendix A. National Fish, Wildlife, and Plants Climate Adaptation Strategy (NFWPCAS): breakout of major goals and strategies.

Goal 1	**Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.**
Strategy 1.1	Identify areas for an ecologically-connected network of terrestrial, freshwater, coastal, and marine conservation areas that are likely to be resilient to climate change and to support a broad range of fish, wildlife, and plants under changed conditions.
Strategy 1.2	Secure appropriate conservation status on areas identified in action 1.1.1 to complete an ecologically-connected network of public and private conservation areas that will be resilient to climate change and support a broad range of species under changed conditions.
Strategy 1.3	Restore habitat features where necessary and practicable to maintain ecosystem function and resiliency to climate change
Strategy 1.4	Conserve, restore, and as appropriate and practicable, establish new ecological connections among conservation areas to facilitate fish, wildlife, and plant migration, range shifts, and other transitions caused by climate change.
Goal 2	**Manage species and habitats to protect ecosystem functions and provide sustainable cultural, subsistence, recreational, and commercial use in a changing climate.**
Strategy 2.1	Update current or develop new species, habitat, and land and water management plans, programs and practices to consider climate change and support adaptation.
Strategy 2.2	Develop and apply species-specific management approaches to address critical climate change impacts where necessary.
Strategy 2.3	Conserve genetic diversity by protecting diverse populations and genetic material across the full range of species occurrences.
Goal 3	**Enhance capacity for effective management in a changing climate.**
Strategy 3.1	Increase the climate change awareness and capacity of natural resource managers and other decision makers and enhance their professional abilities to design, implement, and evaluate fish, wildlife, and plant adaptation programs.
Strategy 3.2	Facilitate a coordinated response to climate change at landscape, regional, national, and international scales across state, federal, and tribal natural resource agencies and private conservation organizations.
Strategy 3.3	Review existing federal, state and tribal legal, regulatory and policy frameworks that provide the jurisdictional framework for conservation of fish, wildlife, and plants to identify opportunities to improve, where appropriate, their usefulness to address climate change impacts.
Strategy 3.4	Optimize use of existing fish, wildlife, and plant conservation funding sources to design, deliver, and evaluate climate adaptation programs.

Goal 4	**Support adaptive management in a changing climate through integrated observation and monitoring and use of decision support tools.**
Strategy 4.1	Support, coordinate, and where necessary develop distributed but integrated inventory, monitoring, observation, and information systems at multiple scales to detect and describe climate impacts on fish, wildlife, plants, and ecosystems.
Strategy 4.2	Identify, develop, and employ decision support tools for managing under uncertainty (e.g., vulnerability and risk assessments, scenario planning, strategic habitat conservation approaches, forecasting, and adaptive management evaluation systems) via dialogue with scientists, managers (of natural resources and other sectors), economists, and stakeholders.
Goal 5	**Increase knowledge and information on impacts and responses of fish, wildlife, and plants to a changing climate.**
Strategy 5.1	Identify knowledge gaps and define research priorities via a collaborative process among federal, state, tribal, private conservation organization, and academic resource managers and research scientists.
Strategy 5.2	Conduct research into ecological aspects of climate change, including likely impacts and the adaptive capacity of species, communities and ecosystems, and their associated ecosystem services, working through existing partnerships or new collaborations as needed (e.g., USGCRP, NCA, CSCs, RISAs, and others).
Strategy 5.3	Advance understanding of climate change impacts and species and ecosystem responses through modeling.
Goal 6	**Increase awareness and motivate action to safeguard fish, wildlife, and plants in a changing climate.**
Strategy 6.1	Increase public awareness and understanding of climate impacts to natural resources and ecosystem services and the principles of climate adaptation at regionally- and culturally-appropriate scales.
Strategy 6.2	Engage the public through targeted education and outreach efforts and stewardship opportunities.
Strategy 6.3	Coordinate climate change communication efforts across jurisdictions.
Goal 7	**Reduce non-climate stressors to help fish, wildlife, plants, and ecosystems adapt to a changing climate.**
Strategy 7.1	Slow and reverse habitat loss and fragmentation.
Strategy 7.2	Slow, mitigate, and reverse where feasible ecosystem degradation from anthropogenic sources through land/ocean-use planning, water resource planning, pollution abatement, and the implementation of best management practices.
Strategy 7.3	Use, evaluate, and as necessary, improve existing programs to prevent, control, and eradicate invasive species and manage pathogens.
Strategy 7.4	Reduce destructive capture practices (e.g., fisheries bycatch, destructive fishing gear), over-harvesting and illegal trade to help increase fish, wildlife, and plant adaptation.

Appendix B. Prescribed species list for restoration planting at La Sal De Rey. March 2020.

Species Name	2017-2018 % of planting mix	2018-2020 % of planting mix	Species Distribution Range
Acacia greggii var. *wrightii* , Wright's acacia	**1.0**	**2**	wide range through south and west TX, northern MX
Acacia rigidula , blackbrush	**1.0**	**4**	wide range through south and west TX, and northern MX. Dominant species in Starr county.
Adelia vaseyi , Vasey's adelia	**1.0**	**1**	
Aloysia gratissima, Whitebrush	**1.5**	**4**	wide range through south and west TX, into NM and AZ
Amyris texana , chapotillo	**8.2**	**2**	wide range on coastal TX counties
Castela erecta , amargosa	**8.2**	**8**	wide range through south and west TX
Celtis pallida , granjeno	**4.1**	**4**	wide range through south and west TX, southern NM, and southern AZ
Chromolaena odorata , crucita	**4.1**	**2**	
Condalia hookeri , brasíl	**6.1**	**6**	wide range through south and central TX and northern MX
Diospyros texana , Texas persimmon	**1.0**	**2**	wide range through south and west TX and northern MX
Ebenopsis ebano , Texas ebony	**8.2**	**12**	wide range through south TX and MX
Forestiera angustifolia , elbowbush	**16.3**	**16**	wide range through south and west TX
Guaiacum angustifolium, guayacán	**2.0**	**3**	wide range through south and west TX and northern MX
Havardia pallens , tenaza	**4.1**	**2**	
Karwinskia humboldtiana , coyotillo	**4.1**	**4**	wide range through south and west TX
Malpighia glabra , Barbados cherry	**1.0**	**1**	
Phaulothamnus spinescens , snake eyes	**6.1**	**6**	wide range through south TX
Randia rhagocarpa , crucillo	**10.2**	**2**	
Schaefferia cuneifolia , capul	**1.0**	**1**	wide range through south and west TX
Sideroxylon celastrina , coma	**0.5**	**2**	wide range through south TX and northern MX
Viguiera stenoloba , skeleton-leaf golden-eye daisy	**2.0**	**2**	
Yucca treculeana , Spanish dagger	**2.0**	**4**	wide range through south TX
Zanthoxylum fagara , colima	**2.0**	**5**	wide range through south and coastal TX
Ziziphus obtusifolia , lotebush	**4.1**	**5**	wide range through south, central and west TX, southern NM, AZ, southern NV, and southern CA
	100	**100**	

Appendix C. Drought-resilient seed collection activity. Spring - Fall, 2019.

Species	Location	Amount Collected (grams)	Estimated number of seeds	Germination Rate - % (estimate)	Plant Production Potential
Acacia berlandieri	Falcon Heights	2,819	7,919	40	3,168
Acacia rigidula	Sam Fordyce	519	24,833	50	12,417
Acacia rigidula	Unknown	97	4641	50	2,321
Acacia schaffneri	Sal del Rey	3,607	52,427	30	26,216
Acacia wrightii	La Joya	39	592	50	296
Celtis pallida	Santa Ana NWR	873	37,468	25	9,367
Celtis pallida	Fish Hatchery Rd	275	11,803	25	2,951
Celtis pallida	Ranchito, LRGVNWR	49	2,103	25	526
Celtis pallida	La Joya, LRGVNWR	165	7,082	25	1,771
Celtis pallida	Fish Hatchery Rd	275	11,803	25	2,951
Celtis pallida	Santa Ana NWR	386	16,567	25	4,142
Celtis pallida	La Joya, LRGVNWR	445	19,099	25	4,775
Cercidium macrum	Sal del Rey, LRGVNWR	82	1,092	30	328
Citharexylum berlandieri	Phillip Banco, LRGVNWR	743	31,088	5	1,554
Condalia hookeri	Marinoff, LRGVNWR	63	1,624	30	487
Condalia hookeri	Sal del Rey, LRGVNWR	36	928	30	278
Condalia hookeri	Marinoff, LRGVNWR	56	1,443	30	433
Condalia hookeri	Brushline Rd	223	5,747	30	1,724
Condalia hookeri	La Coma, LRGVNWR	69	1,778	30	533
Condalia hookeri	Brushline Rd	35	902	30	271
Condalia hookeri	Unknown	4	103	30	31
Condalia hookeri	Fish Hatchery, LRGVNWR	45	1,160	30	348
Condalia hookeri	Santa Ana NWR	5	129	30	39
Condalia hookeri	Santa Ana NWR	9	232	30	70
Condalia hookeri	Santa Ana NWR	6	155	30	47
Condalia hookeri	Ranchito, LRGVNWR	665	17,139	30	5,142
Diospyros texana	Santa Ana NWR	776	5,082	30	1,525
Diospyros texana	Santa Ana NWR	474	3,104	30	931
Diospyros texana	Santa Ana NWR	848	5,553	30	1,666
Diospyros texana	Santa Ana NWR	2,303	15,082	30	4,525
Ebenopsis ebano	Laguna Atascosa NWR	954	1,851	50	926
Ebenopsis ebano	Phillips Banco, LRGVNWR	5,180	10,048	50	5,042
Ebenopsis ebano	Sal del Rey, LRGVNWR	1,686	3,271	50	1,636
Ebenopsis ebano	Laguna Atascosa, NWR	10,949	21,240	50	10,620
Yucca treculeanana	Sal del Rey, LRGVNWR	534	16,231	20	3,246
	Total	**35,294 grams (77.8 pounds)**	**341,319**		**112,303**