Geophysical Studies Of The Characteristics Of Fluvial And Desert Soils In Rio Grande Valley Of West Texas And Southern New Mexico

Aimee V. Garcia
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GEOPHYSICAL STUDIES OF THE CHARACTERISTICS OF FLUVIAL AND DESERT SOILS IN RIO GRANDE VALLEY OF WEST TEXAS AND SOUTHERN NEW MEXICO

AIMEE VIVIANA GARCIA

Master’s Program in Geophysics

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GEOPHYSICAL STUDIES OF THE CHARACTERISTICS OF FLUVIAL AND DESERT
SOILS IN RIO GRANDE VALLEY OF WEST TEXAS AND
SOUTHERN NEW MEXICO

by

AIMEE VIVIANA GARCIA, B.S.

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Earth, Environmental and Resource Sciences
THE UNIVERSITY OF TEXAS AT EL PASO
December 2021
Acknowledgements

The research conducted in this thesis could not have been put together without the support and guidance from multiple people. I would like to express my sincere gratitude to my advisor, Prof. Diane Doser, for her continuous support, guidance, motivation, and immense knowledge. I would also like to thank Galen Kaip for his guidance, training for using various geophysical techniques and sharing his vast expertise. Thanks to the Ivey Family for permission to use their pecan orchard. I would also like to thank Nohemi Valenzuela for assisting me in data collection and sharing her Ground Penetrating Radar data at the Jornada Experimental Range. I owe deep sense of gratitude to Gerardo Vela, Andres Garcia, David Mendoza, Angelica Valdez, Joel Mejia, and Prof. Lin Ma for assistance with the data collected at all field sites during the COVID-19 pandemic. Furthermore, I would like to thank my committee members, Prof. Lixin Jin, and Prof. Anthony Darrouzet-Nardi, for the constant feedback, encouragement, and support during this project. I am profusely grateful to my fiancé Gerardo Vela, for his endless moral support, motivation, and reassurance during my research period. Last but certainly not least, I would like to thank my parents, Adriana, and Jose Luis Garcia, for providing a window of opportunity and endlessly supporting my education.
Abstract

Agriculture in arid lands, such as in the Rio Grande Valley in west Texas, relies on flood irrigation. However, flood irrigation can cause salt buildup and greenhouse gas emissions associated with pedogenic carbonate precipitation. The ability of irrigation to promote crop growth is influenced by geochemical and hydrological processes controlled, in part, by soil grain size, larger-scale soil structure, and mineralogy. This study investigated soils from 3 regions 1) A pecan orchard in the river valley of Tornillo, TX, with soil derived from fluvial deposits, undergoing flood irrigation every 2 to 3 weeks in spring through fall, 2) The El Paso Water Utilities Well-field in Canutillo, TX, also in the river valley but not farmed in over 70 years and 3) A piedmont – slope site at the Jornada Experimental Range northeast of Las Cruces, NM with upland soil that has been grazed but never farmed. This study utilized shallow geophysical methods (e.g., ground conductivity, magnetics, and resistivity) for 1) measuring various soil properties (soil texture, salt buildup, water table depth, and water flow patterns), 2) determining how texture and structure influence soil changes (e.g., salt buildup, pedogenic carbonate buildup, moisture retention) during irrigation cycles at the pecan grove, and 3) comparing the variability of these properties to understand the impact of agricultural practices on soils and crop growth. Soil texture firmly controls the physical, hydrological, and chemical properties of soils. At the pecan orchard, previous geological, geochemical, and geophysical data indicated finer soils and salt buildup contribute to the pecan trees' unequal growth. However, we note a “Goldilocks effect” because, at the well-field, the fine soil holds the water necessary to support the vegetation at the site that is not already undergoing irrigation or agricultural practices. Finally, at the Jornada experimental range, specifically the Piedmont site, a relationship between the
topography, depth to caliche, and vegetation is influenced by hydrological processes where caliche acts as a barrier to water movement.
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Chapter 1: Introduction

Globally over the last decade, the demand to support population growth has turned marginal arid lands including deserts into large-scale agricultural fields, with agricultural lands occupying 37% of the Earth’s land surface (The World Bank, 2021). Deserts cover about 35% of the land surface area of the world (Tchakerian, 2015). However, agricultural practices are unsustainable in such regions due to freshwater limitations (Ortiz, 2018). With limited rainfall, these arid agricultural lands rely on intensive irrigation for crop growth leading to high evapotranspiration causing salt buildup (halite NaCl, gypsum CaSO₄•2H₂O, calcite CaCO₃). Soil development in natural and irrigated drylands derives from the accumulation of pedogenic carbonate (PC) and the production of CO₂ (Jin et al., 2019). PCs develop from the dissolution of soil inorganic carbon (SIC) pools – mostly CaCO₃ – through recrystallization and redistribution in soil, affecting the physical, chemical, and biological soil properties, and thus, influencing the ability of plant roots to obtain water that affects the plant’s growth and productivity (Zamanian et al., 2016).

There is a growing demand for near-surface tools to study soils in arid regions (Allred et al., 2008), such as the Rio Grande Basin. Geophysics provides a set of tools capable of rapidly estimating the thickness and composition of shallow layers of soil (Bitella et al., 2015). This study uses geophysical techniques (e.g., ground conductivity, magnetics, resistivity, and ground-penetrating radar) to investigate how flood irrigation influences CO₂ emission and salt buildup in the Rio Grande Valley, West Texas, and southern New Mexico by comparing these techniques at the irrigated pecan grove to sites where irrigation does not occur. The study sites (Figure 1.1) included three locations within the Rio Grande region (Table 1.1) 1) a pecan orchard in Tornillo, TX, with soil derived from fluvial deposits, that undergoes flood irrigation every 2 to 3 weeks in
spring through fall (Figure 1.2), 2) the El Paso Water Utility (EPWU) well-field in Canutillo, TX, derived from young fluvial deposits but not irrigated, and (Figure 1.3) and 3) the Jornada Experimental Range (JER) northeast of Las Cruces, NM, with upland desert soil derived from alluvial fan deposits (Figure 1.4).

My research utilized shallow geophysical methods for 1) measuring various soil properties (soil texture, salt buildup, water table depth, and water flow patterns), (Doser et al., 2019), 2) determining how soil texture and structure influence soil changes (e.g., salt buildup, pedogenic carbonate buildup, moisture retention) during irrigation cycles at the pecan orchard, and 3) comparing the variability of these properties to understand the impact of agricultural practices on soils and crop growth.

The main driving question involved the usage of geophysical techniques (Table 1.2) to determine how grain size is associated with soil changes (e.g., salt buildup, carbonate buildup, moisture retention) during the irrigation cycle. This interdisciplinary research project also made use of data from separate geological and geochemical studies by other researchers that were collected from several small boreholes. The goal of my study involved using geophysics to determine the homogeneity of the sites and conclude how far the results could be extrapolated from boreholes both laterally and vertically.

**STUDY SITES**

The study sites (Figure 1.1; Table 1.1) are located near two agricultural settings in Las Cruces, New Mexico, and El Paso, Texas. In 2012, El Paso County, Texas was ranked first in Pima cotton production and second in pecan production for the State of Texas (Agricultural Statistics, 2013). The first field site (Figure 1.2), a managed pecan orchard in Tornillo, TX, is located 81 km southeast of the University of Texas at El Paso (UTEP) campus along the river
valley. This site has been heavily farmed for 90 years, relying on flood irrigation to grow crops. The current orchard dates from 30 years ago and is only 600 m from the Rio Grande. The orchard obtains water for irrigation mainly from the Elephant Butte Dam-Rio Grande Project and, in years of drought, relies on some local groundwater from nearby water wells. Pecan crops rely heavily on water requiring 10 to 12 irrigations (every 2 to 3 weeks) per season from April to October, in which fields are flooded with about 10 cm of irrigation water during each irrigation, for a total of approximately 1.5 m of water per growing season (Cox et al., 2017; Ortiz, 2018). The high concentration of irrigation water contributes to the transformation of sodic soils, increasing permeability in clayey soils and accelerating salt accumulation (Table 1.3) (Jin et al., 2019). The pecan orchard agricultural site is flushed in the spring to dissolve salts, allowing the saltier water to exit. Thus, the ability of the crop to grow relies on the soil’s capacity to hold water between irrigation cycles (Doser et al., 2019), but allow some drainage otherwise the roots become waterlogged.

The second field site (Figure 1.3), the EPWU well-field in Canutillo, TX, serves as the natural fluvial derived soil site. The Canutillo well-field is located 21 km northwest of the UTEP campus, bounded on the east by the Rio Grande. The EPWU well-field is one of the two primary water sources in the city of El Paso, located in the southeastern portion of the Mesilla basin bounded to the east by the Franklin Mountains and the west by La Mesa surface (Hiebing et. al., 2018). In the 1950s, the city began to develop the Mesilla bolson/aquifer in the Canutillo well-field. Before development, the EPWU well-field had been used as an agricultural field; it is mowed occasionally but not plowed or used for farming. The soil in the Rio Grande Valley is formed by various river processes, leading to variability in grain size, porosity, and mineral content of the local soils (Table 1.3) (Doser and Baker, 2020). The well-field is ideal for
studying fluvial deposited soils that have not undergone heavy farming or irrigation that better represent natural desert soils in the Rio Grande Valley.

The Jornada Experimental Range (JER) northeast of Las Cruces, NM, the third field site (Figure 1.4), comprises 193,000 acres of the USDA’s Agricultural Research Service. The Jornada del Muerto is a north-south trending basin lying to the east of the Rio Grande surrounded by the San Andres Mountains to the east, the Doña Ana Mountains to the south, and the lava fields beside the Fra Cristobal Mountain range to the north (Perez, 2020; Land, 2016). The water table at the JER is 76 m or deeper in some places in the basin (Havstad et al., 2006). The JER lies in a broad valley filled with alluvial materials (Greb, 2004). The Jornada has never been used for growing crops, although the land was used for livestock grazing starting between 1888 and in 1912 (Perez, 2020), and is currently still used for grazing in some areas today. Vegetation at the JER consists of desert grasslands (McClaran, 1995) and is dominated by C3 shrubs, honey mesquite, and creosote bush (Gibbens et al., 2005, Serna-Perez et al., 2006, Bergametti and Gillette, 2010). The major physiographical parts of JER include mountains, piedmont slopes, basin floors, and the Rio Grande Valley (Havstad et al., 2006). The surveyed area for my study is a piedmont slope site bounded by the San Andres Mountains on the east.

Climate, Geology, and Soils

West Texas and southern New Mexico have arid climates, with annual precipitation around 16 cm (Cox et al., 2017). Annual precipitation in Las Cruces averages 20 to 23 cm, falling from July through September (Leroy et al., 2017). West Texas is the most arid region of the state, due to its low rainfall and high evaporation. The Rio Grande supplies the Rio Grande Valley in west Texas and southern New Mexico with water for agricultural use and domestic consumption. The river originates in the Colorado Rocky Mountains. It drains southward,
controlled with dams at various points along its main tributary, and terminates in the Gulf of Mexico. About 169 km north of the Texas border (Brown, 2014), the Elephant Butte and Caballo dams in New Mexico disperse water mainly for New Mexico, west Texas, and northern Chihuahua, MX for use from April to October except during extreme droughts. The soils found in the river valley (Table 1.3) are formed by river channels, natural levees, crevasse splay, and flood plain deposits (Doser et al., 2019).

The natural desert soil at the JER contrasts with the other two field sites since it is formed by an alluvial fan system rather than a river valley system. Parent materials at the Jornada Basin range from Precambrian granite to historical alluvium with textures ranging from sand to clay (Havstad et al., 2006). There are roughly twenty-two known different soil types at the Jornada basin, composed of almost no organic matter, with slight changes in texture between soil and subsoil. The high lime content of the soil is responsible for forming thick caliche layers that are often so dense they affect water or root penetration through the soil (Jornada Geology and Soils n.d.). Caliche is characterized as soil-carbonate accumulation (pedogenic-calcrete) that build up as subsurface soil horizon typically found at 0.5-3 m depth. Caliches are common in semiarid landscapes like at the Jornada Basin (Kambhammettu et al., 2010; Newton et al., 2015). Gypsum layers, deposited onto the piedmont – slope as older alluvial materials, sourced from the adjacent San-Andres Range (Kambhammettu et al., 2010), are also common.

**Soil Texture Data**

Soil and grain size information at the pecan orchard and well-field is based on the National Resources Conservation Survey (NRCS, 2020) for the pecan field and the well-field sites (Table 1.1). Previous researchers analyzed soil samples from boreholes (Figure 1.5) at the pecan orchard for grain size (Figure1.5) and salinity (Figure 1.6) distribution using a wet sieving...
method (Sosa, 2019) at 10 cm intervals, as well as at the well-field (Figure 1.7; Figure 1.8) (Jin and Hartman, personal communication, 2021). Borehole measurements typically extend 1 to 3 meters but do not provide information on changes in soil conditions laterally or at deeper depths (> 1 to 3 m). We know that plant roots extend deeper than 1 to 3 m at all sites. Thus, geophysical surveys were conducted to image the deeper soil zone and the lateral changes in soil layering between boreholes. Figure 1.5 illustrates the location of the two sampled boreholes at the pecan orchard. Note that each sample was taken from different identified soil variations from Sosa (2019), where Borehole 1 was in the pecan coarse, and Borehole 2 was located at the pecan fine site. The depth of the boreholes extends from the surface to 250 cm (2.5 m).

At the two EPWU Well-field sites (WF-1 and WF-2), soil samples (Figure 1.6) were collected at two boreholes to determine particle grain size and conductivity (Jin and Hartman, personal communication, 2021). For the most part, the grain size plots indicated that the shallow subsurface <160 cm (1.6 m) had slight vertical variations in grain size, with a predominantly clayey silty soil at WF-1 and a sandier soil at WF-2. To examine soil properties at the JER site Engle, Ma, and Valenzuela (personal communication, 2021) augered shallow holes along a transect line (Figure 1.9) to determine soil texture and estimate the depth to the caliche layer. Borehole data at the three locations do not go deep enough to capture the entire root zone and fail to provide more information on the lateral changes; thus, geophysical techniques best serve to provide information on these lateral and depth changes.

**Geochemical and Biological Data**

This multidisciplinary research project's overarching goal was to quantify the CO₂ effluxes due to pedogenic carbonates by separating them from soil respired CO₂ flux and studying the physical, chemical, and biological controls on these fluxes (Jin et al., 2019). The
amount of CO₂ emitted was quantified by conducting a spatial survey using a portable infrared gas analysis system (model EGM-4 Environmental Gas Monitor for CO₂ by PP Systems U.S.A) at the pecan orchard (Figure 1.2) (Orona, 2020). The spatial CO₂ survey contributes by adding supporting material to the soil properties that control crop growth and promote calcite accumulation at the pecan orchard.

**Geophysical Data**

The study incorporated a variety of geophysical techniques (Table 1.2): ground penetrating radar (GPR), DC (Direct Current) resistivity (both vertical soundings and capacitively coupled measurements), ground conductivity meters (EM38-MK2 and EM31-MK2), and magnetics. Geophysical methods are often combined because the ambiguity from one survey result may often be resolved using another method (Bitella et al., 2015). Table 1.2 summarizes how each geophysical technique serves the purpose of this study.

Ohm mapper resistivity determines the correlation between tree size and soil texture by averaging resistivities over 2.5-3.25 m in depth. DC resistivity is directly affected by the difference in soil porosity, permeability, ionic content, and grain size and can be used to identify underlying soil textures and water flow. Conductivity meters (EM31-MK2 and EM38-MK2) serve to map variations in features such as soil particle size, salinity, and moisture content (Jin et al., 2019). The EM31-MK2 averages conductivity over 3- and 6-meters depth. The EM38-MK2 averages conductivity over 0.5 and 1-meters depth, complementing the identification of the topsoil layers from GPR studies. Various soil properties influence electrical conductivity, including clay content and mineralogy, organic matter, bulk density, and temperature (Allred et al., 2008).
Magnetics records the magnitude of Earth's local magnetic field at a sensor location. This geophysical tool best captures near-surface soil grain size variability since coarse river sands of the Rio Grande contain a high percentage of magnetite (up to 10% by weight, Sellepack, 2003). It helps distinguish between soil types (Doser et al., 2019). GPR surveys contribute to understanding soil layering in the fields and might image the depth and lateral extent of the plants' roots.

Table 1.1: Research Locations

<table>
<thead>
<tr>
<th>Site</th>
<th>Environment</th>
<th>Age</th>
<th>Flood Irrigated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pecan Orchard</td>
<td>Fluvial Derived Soils</td>
<td>Younger Soils</td>
<td>Yes</td>
</tr>
<tr>
<td>EPWU Well-field</td>
<td>Fluvial Derived Soils</td>
<td>Younger Soils</td>
<td>No</td>
</tr>
<tr>
<td>Jornada Experimental Range</td>
<td>Alluvial Fan Deposited</td>
<td>Older Soils</td>
<td>No</td>
</tr>
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</table>
## Table 1.2: Geophysical Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Applications</th>
<th>Sensitive to …</th>
<th>Depth</th>
<th>Surveyed Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM38 – Ground Conductivity</strong>&lt;br&gt;Units: milliSiemens/m (mS/m)</td>
<td>o Electromagnetic methods use alternating magnetic fields to induce current in ground.&lt;br&gt;o Detects depth to water table and delineates clay and sand deposits.</td>
<td>Sensitive to soil particle size, salinity, and moisture content</td>
<td>0.5 m and 1.0 m</td>
<td>1. Pecan Orchard&lt;br&gt;2. Well-field&lt;br&gt;3. Jornada</td>
</tr>
<tr>
<td><strong>EM31 – Ground Conductivity</strong>&lt;br&gt;Units: milliSiemens/m (mS/m)</td>
<td>o Electromagnetic methods use alternating magnetic fields to induce current.&lt;br&gt;o Detects depth to water table and delineates clay and sand deposits.</td>
<td>Sensitive to soil particle size, salinity, and moisture content</td>
<td>3.0 and 6.0 m.</td>
<td>1. Pecan Orchard&lt;br&gt;2. Well-field&lt;br&gt;3. Jornada</td>
</tr>
<tr>
<td><strong>Direct Current (DC) Resistivity</strong>&lt;br&gt;Units: Ohm-meters (Ω-m)</td>
<td>o Measures resistivity (inverse of conductivity) through alternating current flow through ground.&lt;br&gt;o Can identify soil texture, water flow and water table.</td>
<td>Sensitive to moisture content variations, grain size, mineral conductivity, water table, porosity</td>
<td>2.5 m, 3.0 m, and 3.25 m (ohm mapper). Variable depends on electrode spacing.</td>
<td>1. Pecan Orchard&lt;br&gt;2. Well-field</td>
</tr>
<tr>
<td><strong>Magnetics</strong>&lt;br&gt;Units: nano Teslas (nT)</td>
<td>o Captures near-surface soil grain size variability and distinguishing between soil types&lt;br&gt;o Coarse sand and gravel containing magnetite and other grains sizes.</td>
<td>Sensitive to changes in magnetic properties of materials.</td>
<td>1.0 – 100’s m depends on line length and spacings.</td>
<td>1. Pecan Orchard&lt;br&gt;2. Well-field</td>
</tr>
<tr>
<td><strong>Ground Penetrating Radar (GPR)</strong>&lt;br&gt;Units: milliSiemens/m (mS/m)</td>
<td>o Applied to mapping stratigraphic changes identify lateral extent of plant roots.</td>
<td>Sensitive to dielectric constant of material, dependent on bulk density, clay content and water content of subsurface.</td>
<td>Generally, images from 20 cm to 5 meters</td>
<td>1. Pecan Orchard&lt;br&gt;2. Well-field&lt;br&gt;3. Jornada</td>
</tr>
<tr>
<td>Soil Name</td>
<td>Depositional Setting</td>
<td>Soil Characteristics</td>
<td></td>
<td></td>
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<tr>
<td>-----------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
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<tr>
<td>Gila fine sandy loam (Ga)</td>
<td>Flood plain formed from proximal and distal crevasse splay deposits with high carbonate content</td>
<td>o  Light-brown, friable, calcareous fine sandy loam roughly 15 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Stratified alternating layers of fine sandy loam, silt loam, silty clay loam and loamy fine sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gila Loam (Gc)</td>
<td>Developed in stratified, loamy, friable sediments having a high content of lime. Recently deposited on the floodplain of the Rio Grande.</td>
<td>o  Surface layer is reddish-brown, very hard, calcareous silty clay about 18 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Overlies mainly silty clay loam but includes silt loam.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glendale silty clay (Gs)</td>
<td>Developed in stratified, loamy, friable sediments having a high content of lime. Recently deposited on the floodplain of the Rio Grande.</td>
<td>o  Surface layer is reddish-brown, very hard, calcareous silty clay about 18 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Overlies mainly silty clay loam but includes silt loam.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harkey loam (Ha)</td>
<td>Flood plain formed from proximal and distal crevasse splay deposits of the Rio Grande and has moderate permeability.</td>
<td>o  Pale-brown at the surface, friable and calcareous loam.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Layers of loamy very fine sand, fine sandy loam, loam, and vert fine sandy loam ranging from sand to clay in texture.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harkey silty clay loam (Hk)</td>
<td>Derived from the proximal part of a crevasse splay deposit.</td>
<td>o  A pink, friable, calcareous silty clay loam roughly 10 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Layer soft silt loam, loamy very fine sand, and vert fine sandy loam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saneli silty clay loam (Sa)</td>
<td>Stratified, very firm material recently deposited on the flood plain of the Rio Grande consisting of silty clay over sandy sediments.</td>
<td>o  Light-brown, friable, calcareous silty clay loam roughly 18 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Clay poorly suited for growth of plant roots and susceptible to salinity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tigua silty clay (Tg)</td>
<td>Derived from distal floodplain deposits and is at the greatest distance from the river.</td>
<td>o  Surface layer is composed of a pinkish-gray, very hard, calcareous silty clay roughly 10 inches thick.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Underlaying the clay there is a very fine sandy loam stratified with layers of finer textured or coarser texture material permeability is moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vinton Fine Sandy Loam (Vn)</td>
<td>Derived from a river channel complex.</td>
<td>o  Deep, pale-brown soils on the Rio Grande flood plain. Vn soils are usually dry between the depths of 7 and 20 inches.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o  Surface layer is pale-brown, very friable, calcareous fine sandy loams-12 inches thick. Underlain by loamy fine sand that extending 60 inches and is stratified with thin layers of very fine sandy loam and fine sand.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1.1: Three study sites located along the Rio Grande Valley of west Texas and southern New Mexico.
Figure 1.2: A map of the Pecan Orchard, Ivey Family Farm in Tornillo, TX. Yellow area shows the entire pecan orchard and smaller white area is the area of interest for this study. Rio Grande runs east to west roughly 600 m south of the pecan orchard.
Figure 1.3: Map shows the EPWU Well-field in Canutillo, TX. The Rio Grande runs north to south about 250 m east of the study area. Two sites within the orchard were surveyed, WF1 and WF2.
Figure 1.4: Jornada Experimental Range Piedmont slope site showing alluvial fan soil depositional environment from the San Andres Mtn Range to the east and White Sand National Park/White Sands Missile Range located to the northeast.
Figure 1.5: Borehole Grain Size at Pecan Orchard Borehole provided by Sosa, 2019; Ortiz et al., 2018
Figure 1.6: Soil salinity from boreholes (Figure 1.5) from Ortiz and Jin, 2021.
Figure 1.7: Borehole grain size at EPWU Well-Field Site provided by Jin and Hartman Summer 2021.
Figure 1.8: Soil salinity from boreholes (Figure 1.7) at EPWU Well-field provided by Jin, Bali, Hartman, Molina, and Quiroz, 2021.
Figure 1.9: Depth to Caliche data at the Jornada Experimental Range Piedmont site provided by Ma conducted in March 2021. The auger holes were located in the same transect as GPR by Valenzuela and conductivity.
Chapter 2: Methods

Resistivity Surveys

Data were collected for the entire pecan orchard with an Ohm-Mapper capacitively coupled resistivity system in 2013 but never analyzed (Figure 2.1). The system was towed with an ATV along northwest-southeast trending lines, where 2.5 m long dipole cables were placed on either side of the receivers (Doser et al., 2019). Using this configuration, allowed changing the cable lengths to give three different n-factors (ratio of the distance between the receivers and transmitters and the dipole length) of 0.5, 1.5 and 2.5 that roughly correspond to depths of penetration of 2.5m, 3m and 3.25 m, respectively.

Surveys at the well-field utilized the 4-electrode Price Array resistivity method, with spacings between the voltage electrodes moved from 1 to 10 m in 1 m intervals to cover a 30 by 30 square meter area (Figure 2.2). At the WF1 site, only 4 lines (N, S, E, W) were surveyed due to minimal variability in the readings and the thick, unmowed vegetation at the time of the surveys. At WF2 (Figure 2.3), 8 lines were surveyed (N, S, E, W, NE, SE, NW, SW). Resistivity data from the well-field incorporated the DCres software package (Baker, 2019) to model the 1-D vertical resistivity soundings for the 4 lines at WF1 and 8 lines at WF2 to plot the best-fit Price array resistivity models.

Ground Conductivity

Conductivity surveys or electromagnetic surveys (EM) measure the ability of soil to conduct alternating electric currents. Ground conductivity meters from Geometrics EM31-MK2 and EM38- MK2 were utilized at all three sites. Both instruments can take measurements in the horizontal loop (at 3 m average depth for EM31 and 0.5 m for EM38) and vertical loop (at 6 m average depth for the EM31 and 1 m for EM38) modes.
At the pecan orchard (Figure 2.1), EM31-MK2 data were previously collected in May 2013 for the entire pecan orchard, but not analyzed until this study. A second, more localized study area (100 x 100 m) was selected in 2020 for analysis of CO2 spatial variation, tree sizes, and other geophysical techniques. The EM38-MK2 survey was conducted within this smaller area along 10 lines running from north to south, each 100 m long, with a reading spacing of 2 m.

At the well-field, two sites were surveyed, WF1 (Figure 2.2) and WF2 (Figure 2.3), from fall 2020 to spring 2021 using both the EM31 and EM38 meters. At WF1, fifteen east to west lines were surveyed; each line was 20 m long with a 1 m spacing. At WF2, a 30 by 30 square area was surveyed using the EM31 with lines running east to west with a 1 m spacing. An EM38 survey was also conducted that covered a 60 by 60 square meter area with 30 lines running from east to west with a 1 m spacing.

Lastly, at the Jornada (Figure 2.4), a 550 m long transect running north to south was measured using both instruments with a 1 m spacing. The surveys were conducted by running one instrument one way and the other instrument back so that the readings from both instruments were not at coincident points.

I used Golden Software’s Surfer package to generate maps of resistivity and conductivity data. I used the minimum curvature technique for gridding the data because resistivity and conductivity are smoothly varying potential fields. To compliment soil texture variability and correlate with vegetation growth and disparity, Michelle Quiroz (personal communication, 2021) measured tree size circumference in meters. The tree size data set aided in understanding how soil distribution in the irrigated field affected the vegetation growth.
Magnetics Surveys

Magnetics serves to identify the magnetic content of the soil and differentiate between coarser river channel sands (with magnetite contents of ~10 %) and finer grained material that affect plant growth and health. Magnetics data were collected using a Geometrics proton precession magnetometer on a 2.4 m high pole. Pecan orchard (Figure 2.1) data involved surveying ten lines that extended 100 m with 2 m spacing. At the well-field data (Figure 2.2; Figure 2.3) were collected in a 30 by 30-meter survey region along 8 lines (N, S, E, W, NE, SE, NW, SW) with a 1 m sample interval. To correct for drift in the field, duplicate measurements were taken at a base station after each surveyed line to record the temporal changes in magnetic strength (Doser and Baker, 2020).

Magnetic data require little processing besides drift correction. Drift is caused by the earth's magnetic field constantly changing due to circulation in the earth’s outer core as well as interaction between Earth’s magnetic field and the sun. During the day magnetic field readings tend to be low at dawn and increase until the sun reaches its zenith, followed by a decrease from zenith to sunset. Very large and rapid changes in magnetic field can occur if their solar storms or thunderstorms occur and data cannot be collected under these conditions. Golden Software’s Surfer package was used to plot the drift corrected magnetics data. Again, I used the minimum curvature technique for gridding the data because the magnetic field is normally a smoothly varying potential field.

Ground Penetrating Radar Surveys

GPR data were collected in tandem with the Real-Time Kinematic (RTK) system for maximum accuracy of up to a millimeter for survey points and positions. Real-time kinematics is a method that returns analytical results obtained in real-time, where a station and rover are linked
using radio telemetry. Before initializing the survey, a base station needed to be established at each site to determine its exact location by running a static survey. Once the base stations were established, the RTK GPS positions could be linked into the Noggin Plus 250MHz Smart Cart or GPR instrument using the Topcon GB-100 GPS receivers (Galen Kaip, 2021-Personal Communication). At the pecan orchard one line survey was taken with zigzag lines running north to south between 10 rows of pecan trees for 100 meters along each line. At the well-field, two locations were surveyed, WF1 and WF2. Each site utilized a line survey that zigzagged lines from east to west and then from north to south for a width of about 30 m by 30 m. At JER, a survey line ran for about 550 m covering an area that previous tests (using a stake pounded into the ground until refusal) suggested having caliche layers 1 – 2 m deep (Figure 2.4). GPR data were analyzed using Ekko Project, a GPR processing software.
Table 2.1: Geophysics Survey Parameters at Pecan Orchard.

<table>
<thead>
<tr>
<th>Survey Method</th>
<th>Lines</th>
<th>Spacing between lines (m)</th>
<th>Sampling interval (m)</th>
<th>Date sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (Ohm-mapper)</td>
<td>10</td>
<td>30 m</td>
<td>N/A</td>
<td>May 2013</td>
</tr>
<tr>
<td>Conductivity (EM31)</td>
<td>4</td>
<td>30 m</td>
<td>1 m</td>
<td>Summer 2013</td>
</tr>
<tr>
<td>Conductivity (EM38)</td>
<td>10</td>
<td>15 m</td>
<td>2 m</td>
<td>April 2021</td>
</tr>
<tr>
<td>Magnetics</td>
<td>10</td>
<td>15 m</td>
<td>2 m</td>
<td>Feb. 2021</td>
</tr>
</tbody>
</table>

Table 2.2: Geophysics Survey Parameters at Well-Field

<table>
<thead>
<tr>
<th>Survey Method</th>
<th>Lines</th>
<th>Spacing between lines (m)</th>
<th>Sampling interval (m)</th>
<th>Date sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (EM38)</td>
<td>16</td>
<td>1 m</td>
<td>1 m</td>
<td>Oct. 2020 (WF2) May 2021 (WF1)</td>
</tr>
<tr>
<td>Conductivity (EM31)</td>
<td>16</td>
<td>1 m</td>
<td>1 m</td>
<td>Oct. 2020 (WF2) Jan. 2021 (WF1)</td>
</tr>
<tr>
<td>Resistivity</td>
<td>8 (WF2) 4 (WF1)</td>
<td>N/A</td>
<td>1,2,3,4,5,6,7,8,9,10</td>
<td>June 2020 (both)</td>
</tr>
<tr>
<td>Magnetics</td>
<td>8</td>
<td>N/A</td>
<td>1 m</td>
<td>June 2020 (both)</td>
</tr>
</tbody>
</table>

Table 2.3: Geophysics Survey Parameters at Jornada Experimental Range.

<table>
<thead>
<tr>
<th>Survey Method</th>
<th>Lines</th>
<th>Sampling interval (m)</th>
<th>Date sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (EM38)</td>
<td>1</td>
<td>1 m</td>
<td>August 2021</td>
</tr>
<tr>
<td>Conductivity (EM31)</td>
<td>1</td>
<td>1 m</td>
<td>August 2021</td>
</tr>
</tbody>
</table>
Figure 2.1: Pecan Orchard Surveys, left-map shows data collected for the entire pecan orchard and right-map shows data focusing only on smaller region where CO$_2$ data were also collected.
Figure 2.2: Well-field 1 site map of geophysical surveys and boreholes for grain size and salinity studies. Note that region has considerable vegetation.
Figure 2.3: Well-field 2 site map of geophysical surveys and borehole grain size and salinity. Map shows region has less vegetation compared to Well-field 1 site.
Figure 2.4: Ground conductivity surveys conducted at the Jornada Experimental Range using EM38- and EM31 conductivity meters in summer 2021 to compare with GPR survey by Valenzuela July 2021 and Ma’s March 2021 auguring data to determine the depth to the top of the caliche. All transects followed the same path extending roughly 600 m with a 1 m spacing to detect any slight changes in soil texture.
Chapter 3: Results

Geophysics at Pecan Orchard

EM conductivity at the pecan orchard varied with penetration depths between 0.5, 1.0, 3.0, and 6.0 meters (Figure 3.1). At 0.5 m, the topsoil conductivities corresponding to sandier soil texture ranged from 40 to 80 mS/m (blue) in the south-southeast to higher conductivities associated with finer textured soils ranging from 120 to 180 mS/m (green and yellow) in the north-northeast). Conductivity values increased profoundly at 1.0 m depth. The higher conductivities vary from 235 to 325 mS/m (red) in the north-northeast, corresponding with high clay content and salt buildup, and the lower conductivities range from 120 to 180 mS/m in the southwest (green) and southeast (yellow) associated with very fine clay and silt textured soil. At 3.0 m depth, the distribution of soil texture was more spatially dispersed, having coarser textured soils from 40 to 85 mS/m in the southcentral and northeast (sky blue to cyan) and finer textured soils from 130 to 200 mS/m in the northwest (lime green to red). Lastly, at 6.0 m depth, the soils become less diverse with values ranging from 130 to 175 mS/m for finer soil textures in the northwest to north (lime green to orange) and 40 to 85 mS/m in the slightly coarser soils of the southcentral and northeast regions (sky blue to cyan). Tree size measurements appear correlated to soil texture values (Figure 3.1), where finer soils (130 to 175 mS/m) are associated with smaller (0.81 to 1.3 m) tree sizes and coarser soils (40 to 85 mS/m) correspond to larger tree sizes (1.3 to 1.8 m).

Resistivity (Ohm-mapper) data were collected in May 2013 during the growing season within the irrigation cycle, when the field is dry enough to be accessible. Figure 3.2 shows maps of resistivities estimated at depths of 2.5, 3, and 3.25 meters. Ohm-mapper resistivities surveys were responsive to grain size changes and able to distinguish between the major soil units. Resistivities (from ohm-mapper surveys) shown in Figure 3.1 at roughly 2.5 m depth (n factor of
0.5) primarily showed a spatial pattern indicated by orange and yellow hues ranging from 40 to 100 ohm-m. Resistivity values at 3 m depth (n factor of 1) were higher, with values predominantly ranging from 140 to 210 ohm-m, with a spatial pattern indicated by cyan (140 to 150 ohm-m) and purple (220 to 230 ohm-m). Resistivity values decreased at 3.25 m depth (n factor of 1.5) to values between 30 to 50 ohm-m (orange) and 120 to 150 ohm-m (green and cyan). In Figure 3.2, the tree size circumference in meters indicated smaller trees (0.81 to 1.3 m) correspond to areas with lower resistivity (30 to 100 ohm-m) and larger trees (1.3 to 1.8 m) to areas with resistivity > 230 ohm-m.

Lower resistivity values (30 to 100 ohm-m) correspond to finer clayey soils, while high resistivity soils (140 to 230 ohm-m) correspond to coarser grain sizes associated with sands. Similarly, previous data (2D resistivity survey) (Figure 4.1) collected by Sosa (2019) revealed that in areas with high amounts of clay conductivities range from 155 – 402 mS/m (corresponding to resistivity values of 6.4 to 2.5 ohm-m). Sandier soil texture had conductivity values ranging from 60 to 130 mS/m to (corresponding to resistivity values around 17 to 8 ohm-m), revealing a correlation between trees size/growth and geophysical parameters that help to understand the soil texture’s influence.

The magnetic survey (Figure 3.3) at the pecan orchard averaged to a penetration depth > 6 m (based on the sensor height of 2.4 m). At this depth, the spatial distribution of the soil revealed low lateral variability and an eastward increasing magnetic field. Lower field intensities (<46585 nT) are associated with magnetite-poor silts and clays. Higher intensities (>46655 nT) correspond to sandier, magnetite-rich soils. Due to time constraints related to the inability to conduct field work during the COVID-19 pandemic and limitations in accessing the processing software, the
GPR survey at the pecan orchard and other field sites require further analysis before comparing to other geophysical, geological, and geochemical data sets.

**Geophysics at EPWU Well-field**

Ground conductivity at WF-1 (Figure 3.4) shows slight variations in values ranging from 70 to 90 mS/m at 0.5 meters penetration depth with the higher values at the center (cyan) and decreasing outwards (darker blue). At 1 m depth, conductivities increase dramatically to 190 to 240 mS/m, as indicated by the orange to red colors, following the same spatial trend as observed at 0.5 m, with the central values being the highest (red). At 3 m, the conductivity values decrease to 30 to 40 mS/m and slightly increase to 40 and 50 mS/m at 6 m depth (lighter blues). At WF-2 (Figure 3.6), conductivity remains consistently constant at 0.5 m, 3 m, and 6 m, with values only ranging from 32 to 38 mS/m, values generally lower than observed at WF1 at similar depths of penetration. However, at 1 m, depth values increase dramatically to 150 to 170 mS/m.

At the WF1 site (Figure 3.5), resistivity surveys were conducted along only 4 lines (N, S, E, W). WF-1 was characterized by lower resistivity values and less variability in the clay content with depth or laterally, with values ranging from 18 to 32 ohm-m. The soundings (Figure 3.5 - A) indicate that the resistivities do not change with electrode spacing or direction, suggesting exceptionally homogeneous and fine-grained soils compared to WF-2 (Figure 3.7 - A). The surveys at WF-2 (Figure 3.7 - A) displayed slightly higher apparent resistivity values, with values between 64 to 375 ohm-m and more significant variability of values between each surveyed line. The higher resistivity values at WF-2 correspond to coarser material that varies laterally and at depth. I used the software package DCres (Baker, 2019) to model the 1-D vertical apparent resistivity soundings (Price array) for the four lines at WF-1 (Figure 3.5 - B) and 8 lines at WF-2.
(Figure 3.7 - B) to determine the best fitting resistivity models. Shallower soils indicate higher near surface resistivities suggesting slightly finer soils and coarser, sandier soils below 3 m depth.

Magnetic surveys indicated almost no variation of magnetic properties at WF-1 and WF-2 (Figure 3.8) (less than 10 nT variation at each site). Results show slightly higher magnetic field readings at WF2 when compared to WF1.

**Geophysics at Jornada Experimental Range**

Ground conductivity was measured at depths of ~ 0.5, 1, 3 and 6 m at the Jornada Experimental Range piedmont site (Figure 3.9). At 0.5 m averaged depth, the ground conductivities varied from 18 to 58 mS/m. There is increasing scatter in values near the north end of the survey line. At 1 meter depth, the conductivity values increased significantly, ranging from 153 to 167 mS/m. Note that two prominent highs appear along this profile at latitudes 32.581⁰ and 32.583⁰ that also are observed on the two deeper profiles. These highs appear to occur along two changes in topographic slope as indicated by the topographic profiles beneath each conductivity plot. At 3 m depth, conductivities decrease to 5.5 to 17.5 mS/m. Lastly, at 6 m depth, the values range from 9 to 21 mS/m.
Figure 3.1: Electrical Conductivity indicating borehole locations at Pecan Orchard, compared with tree sizes (black and white dots) from Quiroz (personal communication, 2021).
Figure 3.2: Resistivity (Ohm-Mapper) results at Pecan Orchard, area located where Sosa, 2019 study was conducted. The color scheme is tied to conductivity data so reds signify high conductivity/low resistivity. Tree sizes (black and white dots) from Quiroz (personal communication, 2021).
Figure 3.3: Magnetic Anomaly with Tree Sizes at Pecan Orchard. Top left shows image of trees, top right shows magnetic field with survey points and bottom left compares magnetic field to tree size.
Figure 3.4: Electrical Conductivity at EPWU Well-Field 1.
Figure 3.5: (A) WF1 apparent resistivity showing little variation and low resistivity. (B) WF1 Resistivity shows simplest fitting model (B), spacing of survey only allowed for a depth of penetration of 3m.
Figure 3.6: Electrical Conductivity at EPWU Well-Field 2, at 0.5, 3, and 6-meters.
Figure 3.7: (A) WF2 apparent resistivity plot showing an increased variation of soil with depth.
(B) WF2 Resistivity has extremely homogeneous soils, with higher resistivity values than WF1.
Figure 3.8: Magnetic field maps at EPWU WF-1 and WF-2. Top shows sampled locations. Bottom left and right show slightly higher magnetic field readings at WF2 when compared to WF1.
Figure 3.9: Electrical Conductivity at Jornada Experimental Range piedmont site. (A) shows image of survey area (north is to right), (B) shows GPR elevation data (black) and depth to caliche (red). (C) shows conductivity data at 1m depth (blue) at higher conductivity values. (D) shows lowered conductivity values at 0.5m (orange), 3m (yellow), and 6m (green).
Chapter 4: Discussion

Pecan Orchard

Previous data (2D resistivity survey) collected by Sosa (2019) revealed that soils at the pecan orchard are heterogeneous laterally and also with depth, and that there is likely a shallow clay layer from about 0.5 to 4.5 m. However, Sosa’s results suggest there could also be a deeper clay layer southeast of the pecan fine borehole (starting at 5 m). Sosa’s resistivity changes are consistent with borehole information (Figure 1.5), indicating that at 100 – 150 cm (1 – 1.5 m), there are higher amounts of clayey soils, suggesting a correlation between tree size/growth and geophysical parameters related to soil texture. Sosa’s 2019 study estimates the static water table to be at 3 m depth (Sosa, 2019).

Electrical conductivity at the Pecan Orchard varied both laterally and with penetration depths between 0.5, 1, 3, and 6 meters (Figure 3.1). At 1 m depth, the higher conductivity values more likely correspond to a grain size change and salt accumulation associated with flood irrigation practices. The EM38 (1 m) (Figure 3.1) showed higher conductivity values (red) corresponding to the increase in clay at 1 m depth (to 70 %) (Figure 1.5) at the Pecan Fine borehole. The Pecan Fine borehole (red) also had higher soil salinity (Figure 1.6) than Pecan Coarse (blue). Sosa’s 2019 2D resistivity survey (Figure 4.1) also compares well with the conductivity data collected in this study (Figure 3.1). The spatial pattern found with Sosa’s 2019 survey agrees with the 0.5 m survey that shows greatest conductivities occurring near the middle of Sosa’s array. Additionally, the highest values observed on Sosa’s line occur near 1 m depth, consistent with the higher values at 1 m from the EM-38 survey. However, the EM31 values at 3m and 6m are not as consistent with Sosa’s survey, possibly due to the occurrence of the water table at ~ 3m depth. Conductivity data indicated a correlation between high conductivity areas at 0.5 m and 1 m depth.
and poor tree growth (Figure 3.1), suggesting high conductivity layers with finer particles reduce water drainage, increase soil salinity, and limit root growth in parts of the field.

Ohm-mapper resistivity surveys were responsive to grain size changes and able to distinguish between the soil units with estimated depths of 2.5, 3, and 3.25 meters (Figure 3.2). The smaller trees correspond to areas of lower resistivity, and the larger trees with areas of high resistivity. The lower resistivities correspond to finer clays and high resistivities correspond to coarser grained soils. Smaller trees growing in areas of lower resistivity seems contrary to what we were expecting based on our other geophysical results. However, one thing to note is that like the EM31 the ohm mapper is imaging deeper soils that are less likely to correlate with the tree size, since the bulk of the root mass is found above 3 m depth. Thus, the clays found at shallow depths (<3 m) appear to restrict root growth and also leave the trees’ roots waterlogged during irrigation.

The magnetics appears to be recording a deeper grain size change that does not correlate to the tree growth, unlike conductivity and resistivity results. Note that slightly more trees in the eastern half of the study area (higher magnetic values, coarser soils) are larger than trees in the western half of the study area (lower magnetic values, finer soils). This spatial distribution is very subtle since the magnetic field only varies by 5 nT across the entire site. The coarser material at depth on the eastern side of the site may promote better flushing of salts and drainage of irrigation water away from the trees.

Spatial surveys conducted by other researchers also monitored the magnitude of soil CO₂ effluxes. One survey took place in February 2021 prior to irrigation, and the other was conducted in May 2021 during the irrigation cycle but when the ground surface was dry enough to access the site (Orona 2021 – personal communication). CO₂ effluxes are higher in May than in February.
The magnitude of soil CO₂ effluxes (Figure 4.2) suggest that higher CO₂ rates correspond to larger trees and coarser soil (at depths < 3m). More statistical analysis is required to verify if there is a connection between the geophysical results and efflux studies.

**EPWU Well-field**

The well-field was ideal for studying fluvial deposited soils that have not undergone recent farming or irrigation and better represents natural fluvial soils in the Rio Grande Valley. The soils found in the river valley (Table 1.3) are formed by river channels, natural levees, crevasse splay, and flood plain deposits (Doser et al., 2019). Compared to the pecan grove, well-field soils were surprisingly homogeneous. Conductivity values at WF-1 and WF-2 (Figure 3.4 and Figure 3.6) indicated slowly varying soil properties with values attributed to mostly silty-clay (WF-1) and sandier (WF-2) soils.

WF-1 is fine-grained and extremely homogeneous, as indicated by the magnetic, resistivity, conductivity, and borehole studies. Although fine-grained soils characterized WF-1, the finer clay at WF-1 supports more vegetation by holding water for longer, when compared to WF-2. Borehole grain size results (Figure 1.7) indicate that clay content is > 20% between 1 and 1.1 m. The high conductivity observed at 1 m depth could be related to grain size. The clay content decreases at deeper depths, consistent with the EM31 (3 – 6 m) results that show decreasing conductivity with depth. The resistivity results (Figure 3.5) are also consistent with an increase in sand below 1 m depth at WF-1. Soil maps indicate Gs and Gc soils are found at WF-1 (Table 1.3) that contain significant amounts of clay and silt in the upper 0.2 m (18 inches).

WF-2 has considerably less vegetation and the conductivity results (Figure 3.6) indicate a very homogeneous soil, although there is more variation in the resistivity soundings (Figure 3.7). Conductivity at WF-2 (Figure 3.6) is generally lower and the magnetic field is higher (Figure 3.8),
consistent with the borehole results indicating sandy soils. However, the conductivity results at 1 m (Figure 3.6) are not consistent with the borehole results or the resistivity results (Figure 3.7). The best fitting resistivity models (Figure 3.7) actually show an increase in resistivity at 1 m depth. We are currently investigating why the EM-38 values at 1 m depth are consistently higher at all 3 study sites, especially at WF-2 where other geophysics and grain size analyses are not consistent with the EM-38 data. The coarser grained soil at WF-2 appears to not be able to hold moisture well enough to support much vegetation. Soil maps indicate Vn soils should be found at WF-2 (Table 1.3), soils that contain considerable amounts of sand extending to depths of 1.5m (60 inches).

**Jornada Experimental Range**

The conductivity studies at JER (Figure 3.9) suggest the soils are dominated by clays, sands, and calcium carbonate (thick caliche). Specifically, a variation between finer-grained, wind-blown silt, coarser-grained pebble surfaces, and outcrops of caliche was observed at the surface. At 0.5 m (EM38) (Figure 3.9 – B), a scattering in values occurs in areas with greater vegetation coverage, which is at the depth plants should interact with the water (Darrouzet-Nardi 2021 – personal communication). Similar to the Pecan Orchard and the well-field sites, at 1 m depth (EM38) (Figure 3.9 – C), the values were higher, except in this case, these values corresponded to Ma’s depth to caliche (Figure 3.9 – A), generally at 0.2 to 0.4 m in the uplands and > 1 m in the vegetated areas. Caliches could be the limiting factor to vegetation growth at the JER site.

The conductivity highs for all measurements (Figure 3.9) are on the hill slopes. The conductivity lows are in the areas where there are channels (either the shallow channels in the uplands or the deeper channels in the arroyo). Considering that surveys were collected during a wet period, the highs could indicate where rainwater has flowed from the side of the uplands along
the top of the shallow caliche layer (and then likely into the arroyos). The lows are in the bottoms of the channels where soils are likely more permeable and the depth to caliche is greater. GPR studies also show that areas covered by vegetation (creosote and mesquite) have higher scattering of the radar signal, indicating higher moisture content. Caliches form from the Ca in soil, CO₂, and water. The CO₂ from microbial respiration combines with water to form carbonic acid leading to the formation of calcium carbonate, driven by more hydrological processes. Eventually, as the calcium carbonate is not water-soluble, it begins to cement with the surrounding soil layers, typically around pebbles and stones, forming a thick caliche layer over time (Whitford, 2017). Although caliche was formed due to the high calcium content at JER, the higher conductivity values at depth correspond to the accumulation of gypsum and nitrate (salts) in the soils, which are highly conductive minerals. Similar to salt accumulation in clays, caliche acts as a barrier to water movement (Whitford, 2017).
Figure 4.1: Electrical Resistivity at the pecan orchard site (Sosa, 2019). Top panel shows image of survey area (northwest is to right), and bottom shows conductivity model obtained from the inversion of resistivity data along survey line.
Figure 4.2: The CO₂ efflux at the Pecan Orchard, left shows data collected in February 2021 and right image shows data collected in May 2021. Spatial CO₂ surveyed at the same smaller scale as magnetics, EM31, and GPR.
Chapter 5: Conclusion

Concluding statements on all three sites

We measured the various properties such as soil texture, salt buildup, and water table depth and determined how the soil texture and structure influence soil changes such as salt and carbonate buildup and moisture retention during irrigations. Lastly, we compared the variability of these properties vertically and laterally at each site to understand the impact of agricultural practices on soils. Specifically, at the pecan orchard, previous geological, geochemical, and geophysical data indicated finer soils and salt buildup contribute to the pecan trees' unequal growth. However, we note a “Goldilocks effect” because, at the well-field, the fine soil is “just right” and holds the water to support the vegetation at a site that is not undergoing irrigation or agricultural practices. Finally, clays at the pecan orchard and caliche at the Jornada sites act as a barrier to water movement, barriers that can be imaged using geophysical techniques.

The study contributed to filling in the knowledge gap on what controls soils' physical, hydrological, and chemical properties (Jin et al., 2019) at 3 dryland critical zone sites. Based on the shallow geophysical approach of the study, we were able to determine the effects of flood irrigation on an agricultural field compared to two other sites where irrigation is absent. At the pecan orchard, both borehole data, previously conducted resistivity soundings (Sosa, 2019) and additional geophysical studies indicated the high level of clay soil contributes to the unequal growth of the pecan trees. Similar soil processes occur in other agriculture fields located along the Rio Grande Valley (e.g., Doser et al., 2019). The two other field sites, the EPWU Well-field and the Jornada Experimental Range, served to investigate soil deposits at different scales and environments where the hydrogeological system has not changed much over the last hundred years (Newton 2015).
Soils at the EPWU Well-field site indicated very homogeneous soils. Studies at the well-field also suggested that, unlike the pecan orchard, in unirrigated soils clay aids plant growth. At the Jornada site, a region associated with alluvial fan deposits, we found caliche was the dominant control on groundwater flow and plant growth.

**Future Work**

Future research will continue at these sites to contribute to the NSF-funded study’s larger focus on dryland critical zones. For example, GPR data collected in my study will be analyzed and processed for all three sites using Ekko Project software. Additional geophysical surveys will be conducted to better document how soil properties related to seasonal variations in moisture content and plant growth. We also hope to determine why the 1 m EM-38 surveys gave such high conductivity values compared to conductivity measurements at other depths or resistivity measurements at the same depths. Although qualitatively, there appears to be some correlation between tree size, CO2, and conductivity, more detailed statistical analyses are required to quantify our confidence in these observations. In addition to continued geophysical studies, others will continue to collect, process, and analyze alkalinity, bulk density, soil gas chemistry, spatial CO2, and soil moisture data at the pecan orchard, well-field, and Jornada Experimental Range.
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Vita

Aimee Garcia completed a Bachelor of Science in Geological Sciences at the University of Texas at El Paso in fall 2019. In the spring of 2020, she enrolled to pursue a Master's of Science degree in Geophysics and a Graduate Certificate in Geospatial Information Science and Technology (GIST). Aimee has worked as a research and teaching assistant and presented at multiple conferences. In summer 2018, she took part in her first NSF REU (National Science Foundation Research Experiences for Undergraduates), focusing on the Riviera Maya's water quality and resources in Mexico. In fall 2019, she worked as an undergraduate research assistant as part of an NSF REU grant to investigate Himalayan tectonics using seismological techniques to analyze surface wave dispersion. The research focuses on the magnitude 7.8 earthquake that struck Nepal on April 25, 2015. Her experience as a student researcher in the two NSF REU's helped hone skills as a scientist and prepared her to educate others about the scientific process. Last summer (2019), she had the opportunity to serve as a student mentor as part of another (NSF REU), the UTEP- Research Opportunities for Community College Students (ROCCS) Program, where she mentored community college students on research projects in the field and laboratory. Continuing her interest in local issues and community, she uses shallow geophysics to investigate desert soil processes and their impact on local agriculture and groundwater and global CO2 flux.