12-2021

ASSESSING FREEZING EFFECT ON KIWIFRUIT CULTIVARS AND MAPPING SUITABLE AREAS FOR GROWING THE CROP IN EASTERN TEXAS

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By

LAIS DE OLIVEIRA MACHADO, Bachelor of Science in Environmental Science

Presented to the Faculty of the Graduate School of

Stephen F. Austin State University

In Partial Fulfillment

of the Requirements

For the Degree of

Master of Science

STEPHEN F. AUSTIN STATE UNIVERSITY

December 2021

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ABSTRACT

Kiwifruit is a perennial vine originating from China where it has been grown for centuries. In the United States, green kiwifruit (*Actinidia deliciosa*) is primarily produced commercially in California. They are fuzzy, green fleshed and well known in the marketplace. Kiwifruit plants require low to moderate soil pH, adequate winter chilling and adequate precipitation to guarantee plant development and good fructification. *Actinidia chinesis* or golden kiwifruit are smooth skinned, feature golden flesh and are a more recent introduction into the global market. Kiwifruit crops have attributes that favor production in east Texas, including low pest problems, current long market window for the fruit, strong consumer acceptance and a growing marketplace. There are few kiwifruit study plots in Texas that will determine its adaptation in the region for commercial potential. In February 2021, Texas experienced a historic freezing event. Vines at evaluation plots were exposed to very low freezing temperatures, which could permanently damage the plants. This study covered the assessment of kiwifruit at five locations after freeze events from November 2020 to March 2021. The study indicated that the kiwifruit varieties experienced different responses to the freeze effect on plants. Green kiwifruit cultivars were more susceptible to the February freeze, thereby presenting more damage on plants than gold cultivars. Also, the use of trunk protection in Hayward cultivar did not reduce/prevent plant damage. Another study, ‘Bruno’ rootstock had a different proportion of plant injury among study sites: Crockett, Nacogdoches, and

Simonton (TX). A chilling hours map for east Texas counties was created using weather data from the past ten years. The map can be used as an auxiliary tool when deciding on cultivars according to their chill hour requirements. The suitability map to grow kiwifruit in the east exhibited a great portion of eastern Texas being optimal areas to grow kiwifruit. The suitability map is an additional resource to use in decision-making to grow the crop when in conjunction with other agricultural management.

DEDICATION

This thesis is dedicated to my father, Jose Antonio Machado, who taught me to respect and take good care of the plants and nature. He installed in me the passion for agriculture and environment. I would also like to dedicate this work to my mother, Marlene de Oliveira Machado, who always encouraged me to pursue my dreams even when they sounded impossible at first. I want also to dedicate this work to my brother, Israel de Oliveira Machado, who encouraged me to finish it and took the responsibility of taking care of our family during difficult moments when I was in the United States working on this project. I could not have done this without my family’s support.

ACKNOWLEDGEMENTS

Many people helped me during this journey but, before I start thanking people, I want to thank God for great care and protection. I would like to thank Stephen F. Austin State University and the Texas Department of Agriculture Specialty Crops Block Grant for providing resources for this project. I would like to extend my gratitude to my advisor, Dr. David Kulhavy, for guidance, work review, for the opportunity of an assistantship during my study and introducing me to Dr. David Creech who is passionate about Kiwifruit production. Many thanks to Dr. David Creech for the opportunity to work together and to learn a little more about this amazing and complex plant, called kiwifruit. I am very thankful to Dr. I-Kuai Hung guidance, valuable review of my work, and input. Thanks to Dr. Yuihui Weng for great talks and guidance on statistics. I cannot thank enough Mr. Malcolm Turner of SFASU for helping me in the field with kiwifruit plants. Thanks to Dr. Timothy P. Hartmann for sharing knowledge about kiwifruit production and for helping me in College Station with the weather data loggers and in the kiwifruit orchard. I cannot forget to thank Dr. Sheryll Jerez for being a humble and excellent instructor during the period I was under her supervisor as a Teaching Assistant. Thanks to Dr. Kenneth Farrish for accepting me in the Master of Environmental Science Program. Many thanks to all the collaborators that reserved a time to receive me on their farms during the project period. Finally, thanks to Arthur Perlman, my first English teacher in the United States, who voluntarily checked my written work.

"A vida sem luta é um mar morto no centro do organismo universal"

"A life without fighting is a dead sea in the universal organisms"

-Machado de Assis, Brazilian Writer.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ANOVA: Analysis of variance

CU: Chill Unit

FAO: Food and Agriculture Organization

GIS: Geographic Information System

IDW: Inverse Distance Weighting

NOAA: National Oceanic and Atmospheric Administration

NRCS: Natural Resources Conservation Service

PCU: Positive Chill Unit

TAMU: Texas A&M University

TDA SPCB Grant: Texas Department of Agriculture Specialty Crops Block Grant

SFASU: Stephen F. Austin State University

SSURGO: Soil Survey Geographic Database

USDA: United States Department of Agriculture

X^2: Critical Chi-Square Value

INTRODUCTION

Kiwifruit is a semi-tropical, perennial vine originating from China where it has been grown for centuries. The crop migrated into other regions of Asia and is currently intensively cultivated in Italy, New Zealand, Iran, Chile, and Greece (FAO, 2019). In the United States, green kiwifruits (*Actinidia deliciosa*) are primarily produced commercially in California, attained a ranking of 10th globally in production (Hartmann, 2020). They are fuzzy, oval-shaped fruit, green fleshed and well known in the marketplace. Over 20 years, researchers from Auburn University, Alabama, USA, tested new kiwifruit cultivars suitable to Alabama, and they were provided to Dr. David Creech from Stephen F. Austin State University (SFASU) to evaluate in east Texas. These cultivars were AU Golden Dragon, AU Golden Sunshine, AU Fitzgerald and AU Authur (Basset et al., 2013). *Actinidia chinensis* or golden kiwifruits are smooth skinned, feature golden flesh, sweet flavor, and a more recent introduction into the global market. The cultivars AU Golden Sunshine, AU Golden Dragon and Gulf Coast Gold are patented introductions from the Horticulture Program at Auburn University, Alabama and originated from the Hubei Fruit and Tea Institute in China. While more recent introduced cultivars are now available, at this time these three varieties are the sole and most promising candidates for commercial production in the Gulf South. Collaborating with Auburn University, SFASU initiated a planting in 2011 and now has a history of six successful crops out of eight, 2014-2021.

Kiwifruit crops have attributes that favor production in the Gulf South, including low pest problems, a long market window for the fruit (can be in storage for up to six months), strong consumer acceptance and a growing marketplace. Kiwifruit are high in nutrition with beta carotene, polyphenols and vitamins C and E (Paliyath, 2015). These characteristics are appealing not only to growers as a promising high-value specialty crop but to the homeowners wishing to add a new fruit to the garden.

Kiwifruit plants require low to moderate soil pH, adequate winter chilling and adequate precipitation to guarantee plant development and good fructification. An important factor to starting a new crop of kiwi includes economic viability for crop production. The highest cost for the establishment of kiwifruit is the infrastructure of the trellis and irrigation system. On average the trellis strategies should be designed to support up to 15,000 Kg per hectare of fruit, plus vines, and foliage. It is important to have a robust, stable, and durable infrastructure that supports the plants throughout the growing phases, especially during the fructification. Kiwifruit can produce fruit for over one hundred years; thus, it is necessary to build a solid trellis infrastructure to support a heavy load and avoid frequent repairs. Worldwide, wood, concrete, and tubular steel are the materials commonly used to support kiwifruit. The material selection is done according to product availability and price.

The aims of this project are to identify suitable growing zones for Kiwifruit in east Texas using Geographic Information System, to present climate analysis of five study sites in Texas and evaluate freeze injuries on plants caused by events during Winter

2020 to Spring 2021. Therefore, the project will present a better understanding of a few cultivars tolerance response to freeze in different locations in Texas.

OBJECTIVES

The main goal of this project is to provide reliable resources for future kiwifruit growers and the scientific community through a study of the freeze effect on selected kiwifruit cultivars at different locations in Texas and present a land suitability map showing potential areas to grow this exotic fruit in Texas. This project will present knowledge of the suitable species for Texas and their peculiarities. Also, this study will provide needed information for cultivating kiwifruit for commercial purposes and provide a land suitability map showing potential areas to grow kiwifruit in Texas.

LITERATURE REVIEW

Kiwifruit Origin

The kiwifruit is a subtropical fruit in the family Actinidiaceae which includes two economic species: *Actinidia chinensis* and *Actinidia deliciosa.* The genus *Actinidia* includes over 75 species and cultivars. *Actinidia* is native to the northern region and on the coast of eastern region of China, where it was cultivated at least 300 years ago on a small scale (Auburn Agriculture, 2013). *Mihou Tao* is the Chinese name of the current kiwifruit, meaning "strawberry peach" that was changed by Europeans to "Chinese gooseberry" and later to "kiwifruit" by New Zealand growers in the 1950s (Stein, 2014). The most famous and commercial Actinidia species are *Actinidia chinensis* "golden kiwifruit" and *Actinidia deliciosa* "green kiwifruit" (Morton,1987). There are differences between these two species. Studies in Alabama indicated that golden kiwifruit is more precocious and productive. Also, the flesh is yellowish, sweeter, and the fruit is more attractive for being less fuzzy and having a thin skin in comparison to green kiwifruit. The green kiwifruit has oblong-ovoid shape, dark green flesh fruit, more tartly flavor and has a dark brown pubescence (Auburn Agriculture, 2013). *Actinidia chinensis* and *Actinidia deliciosa* cultivars are adapted to grow in USDA cold hardiness zones 7 to 9, which opens the possibility to potential commercial growth of kiwifruit in Texas (Arnold, 2018).

Botanic Description

The kiwifruit has vines that are dioecious, therefore, it is generally necessary to have male and female plants for growing fruits. Although the male and female flowers are produced on separate plants, they are morphologically perfect in both plants (Morton,1987). It is possible to distinguish the plants by identifying the male by the bright yellow pollen on the anthers in the center of the flower and its fibers are more visible. The flower on a female vine has few anthers, but only the stigma is functional, whereas the flower on male vines has a small vestigial stigma and considerable anthers that surround the stigma (Thorp, 1994). For an effective pollination, the female plant has to be planted closely to a male plant (Gold and Green Kiwifruit, n.d.). Therefore, for commercial growth, it is recommended to plant one male plant to pollinate every eight female plants (Paliyath, 2015). The vine's bloom must have similar period for better pollination and consequently fruit production. In general, kiwifruit flower two months or more after bud break and the harvest occurs five to six months after flowering.

The pollination can occur naturally by insects or artificially by blowing pollen on flowers. In commercial crops, kiwifruit normally flower within three to four years of planting and the trees produce oblong fruits, up to 6.26 cm long and average weight of 75 g for each, depending on the cultivars. Fruits ripen in September throughout early November, depending on the cultivar. If freezes occur by then in the area, the harvest must be anticipated, so the fruit will finish ripening under refrigeration (Carberry, 2020). Kiwifruit vines can grow up to nine meters and they need to be grown on trellises to support the branches when they start bearing fruits in three or four years leading to better yield (Morton,1987).

Worldwide Producers

In the past, the Chinese did not have much interest in the fruit due to high dense population, consequently little space for expansion of the kiwifruit industry. In 1900, scientists gathered seeds in Hupeh, China and sent them to England – the vines bore the first fruits in 1909. In New Zealand, the seeds from China were introduced in 1906 and the vines bore fruits in 1910. Several growers demonstrated interest in the kiwifruit, so they selected seedlings from the best fruit types in 1930. The fruits were being marketed by 1940 and commercial exporting was first launched in 1953 to several continents. At that time, New Zealand was the biggest fruit producer, supplying 99% of the world production of kiwifruit (Morton,1987). In the period of 2007 to 2018 New Zealand produced 437 thousand tonnes of kiwifruit, less than China, which produced 1.2 million tonnes of fruit leading the world production by country. The increasing demand for the fruit worldwide over the years led to market projection of 5.9 million tonnes for the period from 2019 to 2025 (IndexBox, n.d.). United States in 2013 was in seventh place in the top ten exporters of fresh kiwifruit with over 14,947 metric tons (World Kiwifruit Review, 2016). Today, many countries produce kiwifruit, and it is an important crop for China, Italy, New Zealand, Chile, Greece, and others (FAO, 2019).

Kiwifruit Industry in the United States of America

The first state to produce kiwifruit commercially was California in the middle of the 1960s. That time, farmers knew very little about growing, processing, or marketing this unfamiliar fruit. However, by the 1980s, kiwifruit production increased tremendously to meet the high demand of the market. In 2014, California produced 98% of the kiwifruit industry in the United States (Stein, 2014). The fruit production is still strong in California especially for green kiwifruit; however, growers face many agricultural challenges including pests, drought, heat, high taxes, and costly water. Also, the introduction of new golden cultivars, trending on the global market, is a new competition for green kiwifruit cultivars.

In Alabama, kiwifruit research began in the 1990s at Auburn University, Alabama. Cultivars as AU Golden Sunshine, AU Golden Dragon, and AU Gulf Coast Gold, have been intensively studied and have produced crops in central Alabama for over 15 years (Spiers et al., 2018). The kiwifruit cultivars from Auburn University were provided by Dr. Jay Spiers who was interested in their performance further west. Therefore, they were planted in February 2011 as a trial on the campus of Stephen F. Austin State University in Nacogdoches, Texas. The first harvest of golden kiwifruit in Texas was in the fall of 2014 with production of 65.32 kg (144 lbs) of fruit. It was a light crop, but the fruit had good appearance and acceptance (Hartmann, 2020). In 2015, the fruit production was higher with 397 kg (875 lbs) of golden fruit from eight plants of ‘AU Golden Dragon’ (Creech, 2018). Depending on the in-row spacing kiwifruit (*Actinidia deliciosa*) can produce between 7 to 24 tons per hectare (Testolin, 1990).

The kiwifruit industry in Texas is still represented by two plots in Nacogdoches and six kiwifruit plots spread out north to south in eastern Texas. A range of cultivars available commercially and selections from other provinces are being tested for climate adaptability, flavor for public acceptance and good production. This exotic plant has attracted the attention of growers by appearing to be a potential and profitable crop that should be future evaluated in Texas.

Climate Requirements and Cultural Techniques

The natural sources available in an area are very important to grow kiwifruit without environmental disturbances. Temperature, precipitation, sun hours, wind, soil pH, and water quality are some of the natural factors that impact the cultivation of successful crops. Climate has a fundamental role in woody plants development. The intensity, oscillation, or even the lack of these climatic characteristics can speed up or delay the development of crops. Consequently, it can cause death in plants depending on the growing stage. In short, the climatic exigence varies from one agriculture culture to another agriculture culture, requiring special attention for its peculiarities, which is true with kiwifruit crops. Kiwifruit demand good water quality, good soil drainage, acidic to moderate soil pH, adequate chilling hour, and many other factors presented hereafter.

Soil And Fertilization

Soils generally range from an extremely acidic pH of 3.5 to strongly alkaline pH of 9. This range is a result of many factors, such as soil's parent material, organic matter, soil microorganisms, annual rainfall, and factors that affect soil pH (USDA Natural Resources Conservation Service, 1998). In plants, soil pH is very important for plant adaptation and growth because it affects the availability of nutrients in the soil.

Like many plants, kiwifruit has its own demands such as soil with excellent drainage and good permeability. Kiwifruit prefer acidic to moderate soils within pH range of 5.5 - 6.5 (Strik and Davis, 2021). Every plant type has a preferred range of soil acidity. If the pH level is out of the range, it can interfere with the nutrient uptake by plants. Plant nutrients become unavailable or available according to the soil's pH level. Therefore, it is important to know the pH of the soil solution for nutrient availability (Ritchie, 1945). Before changing the soil pH of a soil, it is necessary to know the current pH status by a soil analysis. The test result will determine how much it should be raised or lowered, if at all. There are many pH correctives available in the market, generally limestone is used to raise a pH level and Sulfur is used to lower it. If some magnesium deficiency is present in the soil, dolomitic limestone ($CaMg(CO_3)_2$) is an effective way to raise soil pH because it neutralizes acidity and adds magnesium to the soil (White and Greenwood, 2013). The soil analysis determines the best pH corrective and fertilizer. Although kiwifruit are robust plants, fertilization is important especially during the establishment phase when nitrogen is usually the most limiting factor. Also, the plants need high water quality and low salinity during the growing season.

Chilling Requirements

Actinidia species vary in their climatic requirements. For instance, *A. deliciosa* is less susceptible to winter cold and spring freeze than *A. chinensis*. The plants are cold tolerant and for both kiwifruit species; *A. deliciosa* and *A. chinensis,* they are reportedly hardy to about -12.2°C or lower (Norton, 1994). For maximum production and quality of the fruit, full sun is preferred.

One of the biggest challenges for kiwifruit production is winter chilling requirement. The winter chilling requirement for kiwifruit vary between species and cultivars. In general, kiwifruit needs to be exposed to temperatures below 7 degrees Celsius for a specific number of hours each year, ranging between 700-900 hours average for maximum fruit production depending on the cultivar. Golden kiwifruit requires 750-850 chilling hours, whereas green kiwifruit requires 900 to over 1000 chilling hours (Jackson, 2020). According to Wall et al. (2008), the chilling requirement estimated for maximum budbreak was for golden and green cultivars: AU Golden Sunshine (700 h), AU Golden Dragon (800 h), Bruno (700 h), AU Fitzgerald (800 h), AU Authur (900 h) and Hayward (900 h).

Protection of kiwifruit plants from hard freezes is recommended to avoid trunk damage and death of young plants. It is essential to protect them during winter because they are usually very sensitive to winter chills and spring freeze, therefore, growers should keep young plants protected for one to two years (Hartmann, 2020). Extra protection from spring freezes is very important to minimize plant stress, trunk damage, bud delay and deformity (Zhao et al. 2017). In addition, kiwifruit is susceptible to damage from wind especially in combination with freeze. Thus, sheltered sites are preferred in areas where strong winds can be a problem. A simple, less expensive solution is to provide screening from wind using evergreen shrubs or trees (Dozier et al., 1992).

Pest and Diseases

Kiwifruit vines have relatively few pest and disease issues that pose a serious threat in Texas. In other regions, kiwi vines can be affected by different pest and diseases. For instance, *Pseudomonas viridiflava* cause phytophatological problems such as blossom blight in ‘Hayward’ orchards that flowers rot obtaining brown coloration. This disease is more prevalent in years of abundant rainfall during flowering season and can cause severe reduction in kiwifruit production (Mansilla et al., 1999). The vines are also susceptive to attack by root-knot nematodes, *Melodeogyne hapla* and *Heterodera marioni* (Morton, 1987). Roots are more susceptible to root knot nematodes in coarse sandy soils, exhausting plant vigor and yield. Plants are also vulnerable to the fungal pathogen *Phytophthora* causing decay of the roots and crown (Hartmann, 2019).

Ceratocutis wilt is a plant disease caused by *Ceratocystis fimbriata,* another fungal pathogen that attacks several plants of economic importance to Brazil including kiwifruit crop. Symptoms caused by *Ceratocystis fimbriata* in kiwifruit are wilted, curled leaves, deformed fruits, and dead and defoliated plants. The disease is responsible for killing 10% to 30% of kiwifruit. The pathogen is soil-borne and spreads through neighboring plants by root grafting, infected material, or occasionally insect vectors

(Piveta et al., 2016). The aggressiveness of this pathogen vary to cultivars; however, it is an important disease that needs to be prevented and controlled, especially in countries where the pathogen is present while farmers are trying to expand the crop production.

Diseases on fruit is less likely to happen because of the surface hairs, but pathogens can entry on injured fruits and permanently damaging it. Post-harvest fruit decay can be caused by *Altenaria* spp., *Botrytis* spp., and blue mold from infection by *Penicillium expansum* (Morton, 1987). Another disease of importance is a bacterial canker disease called *Pseudomonas syringae pv. actinidiae* (PSA). PSA can result in leaf spotting, cane dieback and in severe cases, and vine death. This disease has devastated many commercial plantings in New Zealand, Italy, Korea, Chile where it is of high virulence. Fortunately, it has been kept out of the United States through quarantine (Hartmann, 2020).

The brown marmorated stink bug (BMSB), *Halyomorpha halys*, is an important pest that results in significant production impacts to the kiwifruit industry. The BMSB is an invasive species first identified in the United States near Allentown, Pennsylvania in 2001, but is now present in many states. The insect feeds on tree fruit that leads to corky spots in the flesh; feeding injury causes discoloration, necrosis, and malformed fruit (Penca and Hodges, 2019). The brown marmorated stink bug is present in Alabama causing economic loss from direct crop damage and increased control costs. There is no report of the brown marmorated stink bug on kiwifruit vines in Texas.

Vine Conduction and Pruning

There are two ways to establish a kiwifruit orchard; with potted material or with a bare-root plant. The most common is bare-rooted kiwifruit rootstock, which must be grafted after establishment- normally one year. Rootstocks provide resistance to diseases. Kiwifruit does not have deep roots, therefore, to establish these plants on the field, a wide, shallow hole is preferred ("Associação dos Jovens Agricultores de Portugal", 2017). In general, 15-20 centimeters (6-8 inches) deep and 0.6 meters (2 feet) in diameter. The root system should be spread out in the hole, then fill it back with soil (T. Hartmann, personal communication, April 8, 2021). In the most systems, the objective is to develop a straight leader and then allow the arms to develop into two cordons,

The structure of the kiwifruit vine is a single trunk, 2 meters (6 feet) tall that ends with arms stretched laterally. In a high – density orchard the spacing can be 5.5 meters (18 feet) in the row, which is equivalent to 201 plants per acre. The female and male plants must be planted closely for better pollination efficacy. Male plants must be planted closely to females, and they must have bloom times that coincide with the female plants. The number of male plants must be sufficient to reach all females; ideally one male for every eight females to ensure pollination and fructification (Creech, 2018). For commercial purposes, growers use six-foot-high wire trellises with T-bar spaced 15 – 20 feet apart. Plants need to be pruned once a year by cutting the lateral shoots that go off to the sides of the vine. Once the plant reaches the top of the trellis using the T-support system, the vines can grow more horizontally on the wires. Male plants are pruned earlier than female plants, after flowering, whereas female plants are pruned while plants are dormant in the late winter (Carberry, 2020).

Cultural care must be taken for female and male vines; the treatments are different according to the plant season. During the initial stage, female vines are commonly cut back close to the ground after the first growing season to encourage a vigorous root system. In the second year, an individual shoot should be elected and trained to the top of the trellis system, where it is cut back to strengthen it to fork. The two remaining shoots are then developed in opposite directions down the length of the trellis system to model the cordons of horizontal trunks. From these cordons, lateral shoots will break and will be used as the fruiting canes for the next year. By the third year, vines can produce a small crop. However, significant production can be observed by the fourth year. Male vines are cut back severely after bloom to encourage new growth and make more room for female plants (Hartmann, 2019). Pruning is important during the dormant and the growing season. It is necessary to prune two or three times during the summer by cutting nonflowering lateral shoots and trimming flowering shoots. In the dormant season (especially in mature plants), canes that fruited previously should be removed as well as deadwood, diseased, or tangled canes (Sheavly et al., 2003).

Propagation and Pollination

Like most fruiting plants, kiwifruit propagation is through vegetative or clonal methods, such as micropropagation using tissue culture, by rooted cutting of the preferred cultivar or grafting cultivars onto seedling rootstock (Paliyath, 2015). The kiwifruit flowers are mostly insect pollinated by bees; however, it is now common to use hand pollination or using equipment to blow pollen direct on the flowers to improve yield and fruit size. The time of flowering is crucial for plants to bear fruits so that the male and female flowers events need to coincide. Flowers appear generally 5 – 6 weeks after bud break in Spring--the period is variable between cultivars. The flowers of both green and golden kiwifruit have the same color, light-yellowish petals, and the female kiwifruit plant bears fruit (Zehra et al., 2020). The amount of chilling received during winter impacts optimal floral density and uniformity in spring (Snelgar et al., 1997). Yet, to avoid freeze plant damage special attention should be given to early fall freezes in the middle of November, the beginning of December, and in the middle of February (early Spring) in Texas.

Harvesting

Kiwifruit is a climacteric fruit; therefore, fruits can be picked when they are still immature and capable of ripening off the vine. The fruits are generally harvested when the total soluble solids content (SSC) is 6.5 °brix or higher depending on the cultivar. Early harvesting between 5 – 6 °brix is not recommend as it will result in poor fruit quality (Guroo et al., 2017). In California, kiwifruits are harvested when the fruit soluble solids range between 6.5 – 8 °brix (Morton, 1987). In Texas the harvest season begin in September and goes throughout November, respectably, for golden and green kiwifruit. In general, kiwifruits are harvested when they attain 8 °brix (Creech, 2018). More studies should be done to determine best brix point for picking in Texas. The harvest should be done before early-mid November to avoid a damage from early winter freezes in Texas.

Kiwifruit Cultivars Used in the Studies

Several kiwifruit cultivars have been selected and developed by researchers with different features such as bloom period, maturation rate, fruit shape and fruit flavor. Therefore, some kiwifruit cultivars are now tested in Texas in different environments for plant adaptation and fruit production.

‘The Golden Kiwifruit’ *(Actinidia chinensis)*

Starting with the ‘Golden’ cultivars, *Actinidia chinensis*, AU Golden Dragon, AU Golden Sunshine, and AU Gulf Coast Gold are the first golden cultivars tested in the Gulf South. The cultivars AU Golden Sunshine (‘Jinyang’) and AU Golden Dragon (‘Jinlong’) were selected from seedlings of wild *Actinidia chinensis* in the 1980’s in China (Ferguson, 2008).

The cultivar AU Golden Dragon came from seeds from open pollinated native kiwifruit of *Actinidia chinensis* in Fang County, China. However, ‘AU Golden Sunshine’ was chosen and refined from native kiwifruit plants in Chonyang County, China. These two cultivars were registered in 2004 by the Hubei Province Crops Variety Approval Committee in 2004. Later, in 2008, The Institute of Fruit and Tea, Hubei Academy of Agricultural Science of PR, China and Auburn University, Auburn, AL, USA signed an agreement for joint release and US patent application (Spiers et al., 2018).

Some features differ among the Auburn golden cultivars. For instance, 'AU Golden Dragon' has cordiform fruit shape. Its full bloom is achieved in early to mid-April and the fruit harvest follows in late August into the Fall (Table 1). Production can be severely affected by spring freezes. 'AU Golden Sunshine' has cylindrical fruit shape with rounded shoulder on the stalk. Plants achieve full bloom in mid-late April and fruits are harvested in early September. 'AU Gulf Coast Gold' cultivar comes from a bud mutation that occurred in an 'AU Golden Sunshine' vine research plot in south Alabama, USA. These two cultivars have been studied as potential kiwifruit to grow commercially in the southeastern United States (Hartmann, 2020). In addition, 'AU Gulf Coast Gold' has shown low chilling hour requirement; therefore, it perhaps is an option to cultivate in warmer environments such as southeast Texas. The different bloom periods that these cultivars have are favorable for growing in regions where spring freeze damage in kiwifruit plants is a concern. Early bloom is a huge issue with peaches, plums, blueberries, and other east Texas crops. Blooming in late in March is a positive attribute.

Table 1.Most common *Actinidia chinensis* cultivars cultivated in the southern of the United States (Spiers, 2018).

Female	**Pollinators**	**Bud swell**	**Full Bloom**	**Harvest**	**Soluble Solids (%)**
AU Golden Dragon	CK03 (Meteor)	Late March to Early April	Middle April	Late August to Early September	7.17 ± 1.3
AU Golden Sunshine	AU Golden Tiger	Middle to Late April	Late April	Early September	9.27 ± 1.97

Table 1. (continued).

AU Golf Coast Gold	AU Golden Tiger	Middle April	Late April	Late September to Early October	10.1 ± 1.07

‘The Fuzzy Green Kiwifruit *(Actinidia deliciosa)*

Green cultivars of *Actinidia deliciosa* have been cultivated for crop production for a longer period than golden kiwifruits. Hayward cultivar is a good example. Hayward is the most popular cultivar in New Zealand and is a cultivar of *A. deliciosa* made by Hayward Wright. He used seedlings derived from a single seed that was introduced into New Zealand early in the twentieth century. Attributes of Hayward are green flesh, satisfactory flavor, large fruit, and long shelf life for up to six months under refrigeration. This cultivar needs a growing season of approximately 225 to 240 frost-free days (Paliyath, 2015).

Another known green cultivar is Bruno. The seedling of the cultivar Bruno was discovered in the 1920s, but it was introduced as leading cultivar in New Zealand in the 1930s. ‘Bruno’ plant vines are robust and prolific, and the female plants bare large, elongated cylindrical fruit with dark brown skin and light-green fresh. It has great acceptance by the public for good flavor (Morton,1987). Because of its attributes Bruno cultivars has been used in rootstock studies.

The AU Authur cultivar is a suitable male plant used in the pollination of AU-Fitzgerald, which is a female kiwifruit plant selected from Auburn University, AL

(Arnold, 2018). In addition, ‘AU-Fitzgerald’ is the result of an open-pollinated seedling of Hayward, which has shown good performance on the Gulf Coast of the United States (Wall et al., 2008).

Suitability Analysis

Geographic Information System (GIS) is a tool that can be used in different professional fields including medical, civil engineering, business intelligence, social demography, environmental science, agriculture, and many others (Conrad et al., 2017). In kiwifruit production, GIS analyses play an important role in generating information to optimize physical and financial aspects of a crop production system (Panagopoulos et al., 2007). The overlay function is an important tool used for land suitability. Thus, overlay analysis can be performed in GIS to generate a map showing the potential growing areas for a specific crop. This method has been used for analysis and defining potential new areas for viticulture in Portugal based on climate, soils, and slope (Madruga et al., 2015). This reinforces the importance of having a map depicting potential growing areas for kiwifruit crop in east Texas. The map should serve as a decision support tool in the site selection process for the establishment of new kiwifruit vines, in conjunction with agricultural analysis of the terrain and climate. This analysis would help in decision making regarding whether to take the risk to commercially grow kiwifruit crop in Texas or not. For this study, GIS was used to find suitable growing areas for kiwifruit in east Texas based on climate and soil data available in public domains.

JUSTIFICATION

Kiwifruit has been cultivated in several countries, being the major crop for New Zealand and China. The crop has shown agricultural characteristics for production in several continents including Asia, Oceania, Europe, and Americas. Although establishing a kiwifruit orchard is expensive, requiring a substantial investment, it can be very profitable if managed well. Also, the long shelf life gives more opportunity to sell fruits for a longer period, expanding the marketing and selling window. Another important fact about this crop is the nutrition value. People today have healthier habits and look for nutrients where kiwifruit has shown a great source of beneficial nutrients. Kiwifruit has been produced in some parts of the United States of America, starting in California with green fuzzy cultivars. However, in the 1990s, researchers and farmers from Alabama saw potential for kiwifruit production in southern states. So, Auburn University initiated several studies to grow and to evaluate the crop. They tested new cultivars, especially goldens that offer favorable characteristics for cultivation and public consumption. The exotic plant grabbed the attention of scholars in Texas who wanted to understand better this new crop and introduce it to farmers interested in commercial production.

In Texas, kiwifruit studies started at Stephen F. Austin State University in 2010 in Nacogdoches and later at Texas A&M University in College Station. In Nacogdoches, the kiwifruit plants have already produced six successful crops out of eight years and have demonstrated good potential to be cultivated in Texas. Therefore, more studies are needed to determine the best cultivars and growing strategies for Texas. To minimize different types of loss in agriculture, the use of technology is important for better understanding of the land, the climate, and the new business. Using a Geographic Information System allows for integrating different sources of data and creating interactive maps, which best depicts the information allotted. For instance, a GIS map showing suitable areas to grow kiwifruit in Texas can be accomplished by using climate and soil data, thus contributing to farmers investing in this new crop in Texas. This can be used as a guide to choose a potential growing area and to minimize investment loss.

This study aims to better understand the adaptation of different kiwifruit cultivars in several locations and to identify potential growing sites in Texas using GIS. The results will provide future growers additional information on where to produce kiwifruits without the extra expense for wind damage protection and major soil pH adjustment. These interventions not only increase farming expenses but also negatively impact the environment due to land disturbance. With information compiled from growers' evaluations, kiwifruit can be another source of income for Texas farmers. In turn, consumers would benefit from a more competitive market where kiwifruit would be lower cost because of less cost with transportation and importation dependency.

METHODS OF STUDY

The project includes four studies that complement each other as the common objective is to identify the most adaptable, productive kiwifruit cultivars in Texas. The four scenarios investigated the adaptation of kiwifruit to local climate and other variables present in each study location. The study areas were selected by the cooperator's consent and land availability. These cooperators are from private and public sectors interested producing kiwifruit as a new crop in Texas. The four studies are: (I) analysis of four different kiwifruit cultivars to freeze events in Nacogdoches, (II) analysis of two different kiwifruit cultivars to freeze events in College Station, (III) freeze influence in 'Bruno' rootstocks at different locations in Texas, and (IV) suitable growing areas for kiwifruit in east Texas.

Visual analyses on plant damages that commonly occur in wood plants after hard freezes were evaluated in studies I-IV. Each location has its own particularities that could not be controlled due to ongoing kiwifruit production. The experiments were in the field, with no control of the climate. Therefore, irrigation systems, fertilizer applications, and other agricultural procedures were not evaluated. The plant assessment started five weeks after the historical freeze event on February 16, 2021. The analytical results of the associations are presented and discussed in the Results section as well as in the Discussion and Conclusion section.

Weather Data Collection

Two weather data loggers were installed to record temperature of each location: Dangerfield, Nacogdoches, Crockett, College Station, and Simonton. The purpose of it is to evaluate the climate interference, especially freeze, on different kiwifruit cultivars planted in these study sites. The temperature recording period started on November 1, 2020 and ended on March 1, 2021. The data was collected using the Elitech RC-51 weather data logger recorder (Elitech Technology, Inc., n.d.). The recording length covers the critical period for kiwifruit performance when the plants are at dormancy and susceptible to freeze events. Plants were evaluated from March to April of 2021 within locations for any injury or death caused by freeze events during the studied period, using the Mengmeng scale on plant assessment (Table 2).

Mengmeng Scale to Estimate Freeze Damage on Perennials

Freezing injury in wood plants occurs when temperatures drop below the freezing point of water (0^{o}C). Freezing is a major environmental stress that limits the geographical distribution of kiwifruit. It can affect growth, and productivity of temperate fruit trees. Freezing injury in the trees includes winter sunscald, freeze splitting of trunks, blackheart of stems, freezing of roots, kill dormant flower buds (end of winter), death of cambium in trunks, branches, and freeze damage to flowers and fruit during spring (Yu et al., 2020). In addition, kiwifruit plants are very sensitive to freezing temperatures during Spring as bud begin to swell. In case of bud damage, lateral fruitless buds will grow with a reduction of yield (Nanos et al.,1997).

The Mengmeng scale was created by Mengmeng Gu, Associate Professor and Extension Ornamental Horticulturist at Texas A&M University (D. Creech, personal communication, March 8, 2021). The scale measures plant stress effect caused by freeze on perennials, annuals, succulent, and ferns. In the study, the scale was used for woody tree vines where kiwifruit is classified. On kiwifruit, the freeze effect would be mostly observed on stem, tip, trunk, and roots because the plants are dormant during the winter.

Table 2.Mengmeng's scale for freeze injuries in perennials (Mengmeng, nd).

Perennials	**Scale**
No damage	**1**
Minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable	**2**
Major foliar, stem damage, base and main stem acceptable, and deemed recoverable	**3**
Death to ground, however, it appears to resprout from the base or roots	**4**
Total death	**5**

Statistical Analyses

The tests were chosen based on the data measurement scale, which was ordinal for this study. Therefore, two non-parametric tests were used: Chi-square (X^2) and Kruskal-Wallis. These tests do not assume that the data fits a specific distribution type, nor require assumption of normality. Both tests provide methods for testing the hypothesis of equal means or medians through groups. In the project, the observations were assigned to predetermined categories. The values obtained from visual observations, using Mengmeng's scale as a parameter, is a Likert scale that uses an ordinal interval ratio to represent plant injury from one to five.

A Chi-square test is a hypothesis testing method commonly used when working with two categorical variables. There are two well-known Chi-squared tests: Chi-square Goodness of Fit test and Chi-square Test of Independence; both check if the observed frequencies in one or more categories match expected frequencies (Donnelly, 2007). In this study, the Chi-square Test of Independence was used to consider if two variables might be related or not; therefore, to check if cultivars tolerance is related to freeze damages.

Kruskal-Wallis (Rank Sums) and Wilcoxon (Rank Sums) are nonparametric tests, which do not require normal distribution, and work well with categorical data. The main difference between them is the quantity of levels (groups); specifically, Wilcoxon (Rank Sums) is recommended for two groups or less and Kruskal-Wallis (Rank Sums) is for more than two groups. These tests are commonly called the one-way ANOVA on ranks, as the ranks of the data values are used in the test preferably more than the actual data points (JMP®, 2019). Basically, the two tests determine whether the medians of two or more groups are different. Similarly, most statistical tests first calculate a test statistic and then compare it to a distribution cut-off point. Wilcoxon/ Kruskal-Wallis tests (Rank Sums) tell if there is a significant difference between groups analyzed. However, they do not tell which groups are different. Therefore, it is necessary to run a Post Hoc test.

Chi-square and Wilcoxon / Kruskal-Wallis Tests (Rank Sums) were utilized to identify cultivars tolerant to freeze events, with a significance level of .05 ($\alpha = .05$). JMP Statistical Software from SAS was the program used for the statistical analyses.

Richardson Model and the Conversion of Temperatures to Chill Units

Chilling assigns to the physiological requirement of low temperature to concede regular spring growth by plants, and failure to gain sufficient winter chilling results in poor quality fruit and declination of yield (Chhetri et al., 2018). Winter chill is a necessary factor for deciduous fruit trees in temperate climates because they can be affected by temperature on the breaking of bud dormancy in wood plants (Dennis, 2003). The chilling hour is accumulated throughout the dormancy period, also called the rest period. Therefore, many models exist to predict the response of the buds of woody plants to chilling.

The most common model used in the United States is the Utah Model by Richardson (also called Richardson Model), which is an ideal for temperate zones. The model contains a weight function assigning different chill units to different temperature ranges, including negative chill increments by high temperatures (Richardson et al., 1974). The Positive Utah Model is a modification of the previous model; however, it does not consider negation by warm temperature (Linsley-Noakes and Allan, 1974). The model calculates partial accumulation at 0.5 units increments by mean average temperature in each one hour within the temperature ranges. The range considered optimum to accumulate chill is 2.4 - 12.4 °C (Table 3).

Chilling negation is a big concern in regions such as Texas where the winters are dynamic, with high variance of temperatures throughout winter and early spring. Therefore, it is necessary to know the chilling hours of a region and the effects of freezing on kiwifruit especially during an early freeze in the Spring, so the accumulation of chilling hours is guaranteed for adequate vegetative growth, bud break, and yield production on a commercial scale.

Table 3. Chill unit contributions for temperature ranges based on Richardson chilling model used in the assessment of kiwifruit cultivars' response to chilling during Winter 2020 – Spring 2021 (Richardson et al., 1974).

Temperature Range		**Chill units contributed**
Celsius (°C)	**Fahrenheit (°F)**	
< 1.4	< 34	0
1.5 - 2.4	35 - 26	0.5
2.5 - 9.1	37 - 48	1
9.2 – 12.4	49 - 54	0.5
12.5 – 15.9	55 - 60	0
16 - 18	61 - 65	-0.5
> 18	> 65	-1

Chilling Hours Acquired by Location

The data used to calculate the effective chill units came from the data loggers that were installed previously (October 2020) in each study location. The period used to calculate the total chilling hours was from November 1, 2010, to March 1, 2021.

Table 4. Estimated chilling hours from November 1, 2010 to March 1, 2021 by location.

	Location				
Chilling Hours	Dangerfield	Nacogdoches	College Station	Crockett	Simonton
	1144	964	872	869	784

To obtain the estimated total chilling hours, the data was manipulated using Excel and JMP statistical software to calculate the average temperature in one hour (Table 4).

Dangerfield indicated higher chilling hour (1144 h) in comparison to other locations, followed by Nacogdoches (964 h), College Station (872 h), Crockett (869 h), and Simonton (784 h).

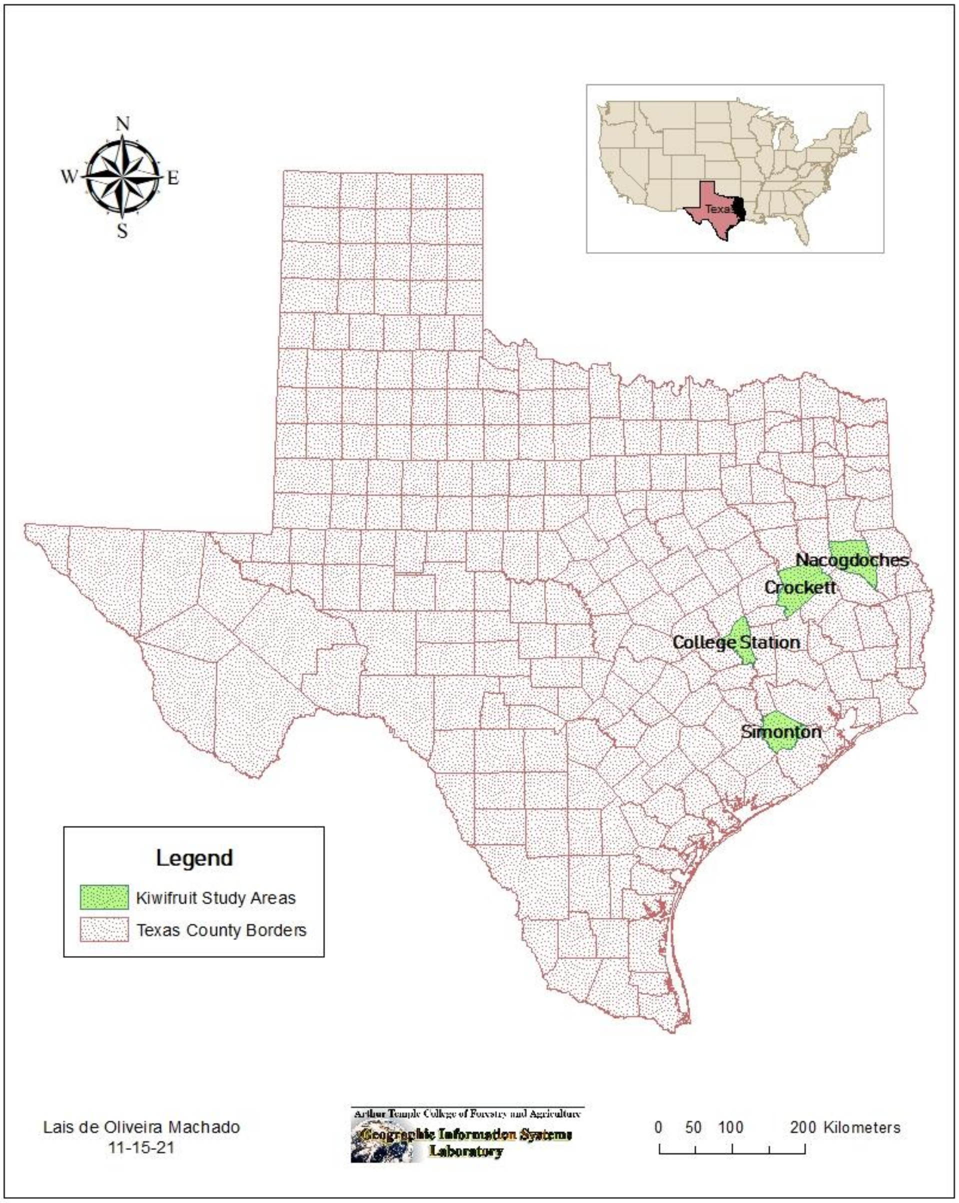

Figure 1. Map showing four locations used in the studies I to III.

Timeseries of Temperatures

In the past, two mega freeze events stand out in Texas: December 1983 and December 1989. The lowest temperature registered was -14 °C for the freeze in December 1983, which impacted the entire state and lasted over two weeks. The December 1989 freeze event lasted two weeks with low temperatures; the lowest temperature registered was -16 °C. The Winter of 2020 was marked by epic freezes in Texas history. The Winter storm Uri heat in Texas in mid-February 2021 and every county in Texas fell under a freeze alert. The winter storm emergency impacted business, infrastructure, landscape, crops, and of course humans' life. Thus, Texas has a brand-new benchmark for cold; the coldest day was registered on February 16, 2021, and the freeze lasted a week (Figure 2).

The Winter of 2020 embraced dips of freeze events followed by below zero temperatures in Texas. The low temperatures broke records across the state. Two weather data loggers, Elitech RC-51, were installed in October 2020 at each of the following locations: Dangerfield, Nacogdoches, Crockett, College Station and Simonton, Texas. Temperatures were recorded every fifteen minutes.

The following graphs exhibit minimum and maximum temperatures in Celsius for each site. The time-series of temperatures uses weather data from November 2020 to March 2021.

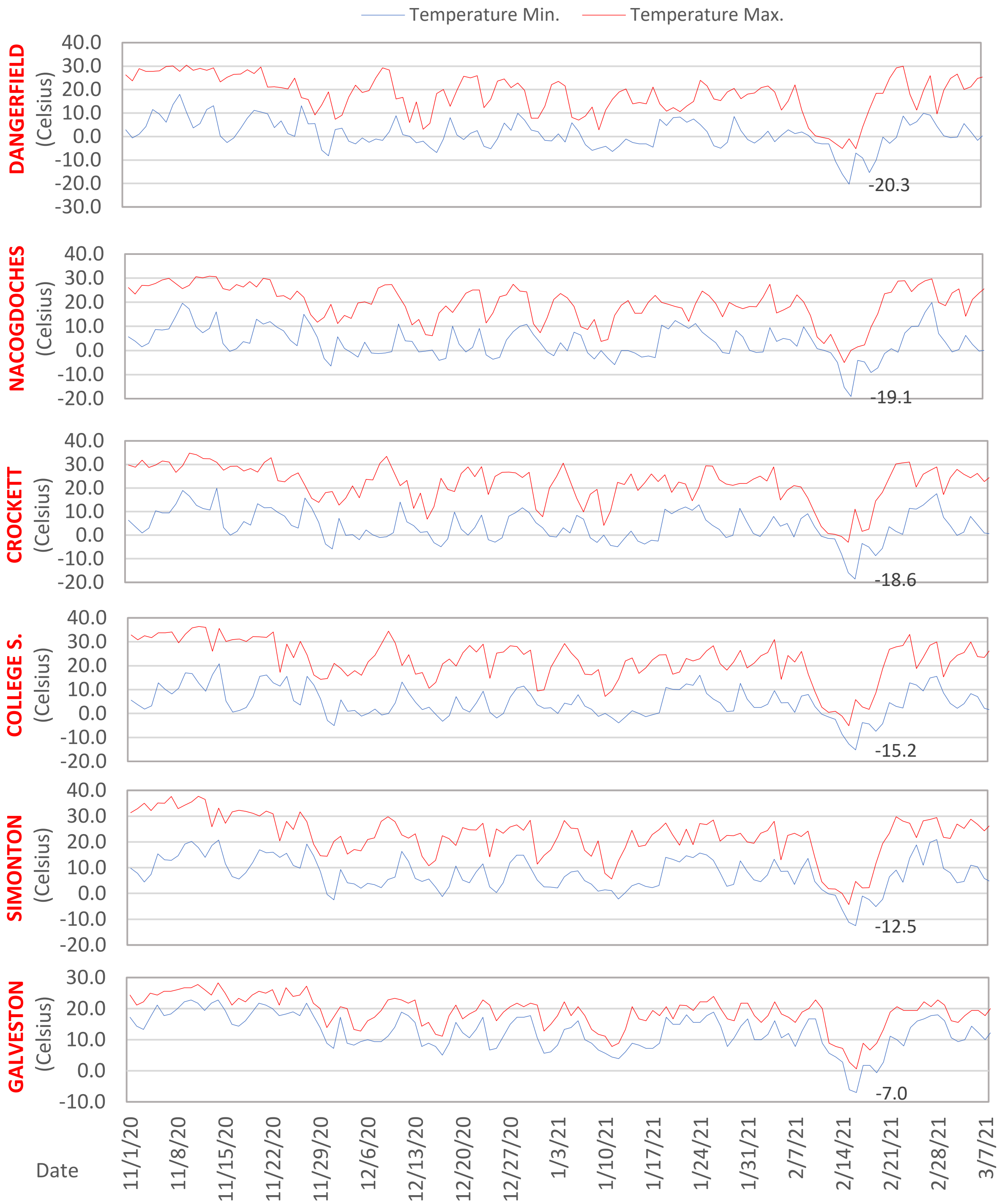

Figure 2. Timeseries of maximum-minimum temperatures, prospecting locations in Texas: Winter 2020 to Spring 2021.

Two weather data loggers were installed to record temperature in Daingerfield, where there was one kiwifruit plot with 96 ‘Bruno’ rootstocks of two years old. A visual evaluation was completed on April 28, 2021. All plants died to the ground. However, 66 plants did survive, and 30 plants were lost completely. The kiwifruit in Daingerfield suffered from constant low temperatures below 10 °C from November 28, 2020, to March 9, 2021. The first dip and the lowest temperature was -8 °C in 12/1/2020, followed by the second dip, marking -20.3 °C in 2/16/2021, and -15.4 °C in 2/19/2021 (Figure 2). Daingerfield is the coldest site studied; ‘Bruno’ seedlings suffered with consecutive freeze events, as a result 31.25% of the plants died. However, the plants will be continually evaluated to verify their performance and recovery in 2022 and following years.

Nacogdoches had the first lowest temperature of -6.4 °C occurred in 12/1/2020, followed by the second dip, marking -5.9 °C in 1/12/2021, then the historical coldest event within a century registered -19.1 °C in 2/16/2021 (Figure 2). The first dip and the lowest temperature in December for Crockett location was -5.8 °C in 12/1/2020, followed by the second dip, marking -4.9 °C in 1/12/2021, lastly the historical coldest event within a century registering -18.6 °C in 2/16/2021 (Figure 2).

In College Station the lowest temperature was -5 °C in 12/1/2020, followed by -3.9 °C in 1/12/2021, then the historical coldest event within a century registered -15.2 °C in 2/16/2021 (Figure 2). NOAA (2021) recorded coldest temperature of -14.4 °C, and coldest wind chill of -22.22 °C for the same day in College Station. The combination of wind and very low temperatures further decreases the temperature readings. Compared to the observations of previous locations, Simonton recorded mild-cold temperatures. The first dip and the lowest temperature was -2.5 °C occurred in 12/1/2020, followed by the second dip, marking -2.2 °C in 1/12/2021, and -12.5 °C in 2/16/2021 (Figure 2). The Simonton location was marked with the presence of winds, so the cold sensation during the freeze events was intensified by the wind.

Galveston was not in the kiwifruit study but was added in the discussion to provide a southern coastal location. Galveston temperature data was collected from the NOAA database on October 26, 2021. While not part of kiwifruit studies, it is presented to represent a southernmost location. By looking at Figure 2, the maximum and minimum temperatures have less variation compared to the other locations. The lowest temperature marked was -7 °C for the timeseries and 597 chilling hours for the period of November 1, 2020 to March 1, 2021. Low chilling hour accumulation is critical for the commercial cultivation of kiwifruit, especially because most commercial cultivars require a minimum of 700 - 800 chilling hours during dormant period.

Kiwifruit is a woody plant; therefore, the damage caused by freezing temperature can be seen up to four weeks after freeze event (T. Hartmann, personal communication, February 21, 2021). Figures 3, 4 and 5 depicts plant aspect two days after the first freeze event on December 1, 2020. For all three cultivars of kiwifruit, the plants showed brown and curved leaves on the tops but there was no noticed splitting or cracking signs at the base of the vines. Although these mentioned signs can be seen only after few weeks, they are good indicators that plants were resistant to freezing temperatures at that time.

There are no pictures taken in Nacogdoches for the second freeze event on January 12, 2021, with minimum temperature of -5.9 °C; temperatures maintained below 0 °C for three days. Also, there is no pictures recorded for plants after the historical freeze event that occurred on February 16, 2021, showing minimum temperature of -19.1 °C. The site was covered by 15 cm (6 inches) of snow for a few days after the event. Plants evaluation was completed five weeks after the last freeze event happened.

Figure 3. Hayward cultivar assessed after first freeze event on December 1, 2020.

Figure 4. AU Authur cultivar assessed after first freeze event on December 1, 2020.

Figure 5. Bruno cultivar assessed after first freeze event on December 1, 2020.

Images of Plant Injury to Freezing Events: Winter 2020 to Spring 2021

Figure 6. Burst bark/stem (left); dead meristem (right).

Figure 7. Vertical bark fissures (left); total death (right).

Figure 8. Longitudinal cracks (left); dead stem, sprouting from the root (right).

DATA ACQUISITION AND PREPARATION

Study I. Analysis of Four different Kiwifruit Cultivars to Freeze Events in Nacogdoches.

This study area is located at the north end of the Pineywoods Native Plant Center at Jimmy Hinds Park and on the premises of the SFASU, Nacogdoches, Texas. The site includes muscadine grapes and kiwifruit rootstocks planted in rows. The last five rows contain for kiwifruit of 27 to 30 plants per row for this project. The four cultivars available for the study were AU Authur, Hayward, Bruno and AU Golden Dragon. The experiment was done in the field, with no control of climate, and the plants were randomly selected.

The green kiwifruit plants in Nacogdoches were planted in 2019. Each row was planted with one cultivar, so for this study, the plants were randomly flagged. The first row had twenty-eight 'Bruno', the third row had twenty-seven 'Hayward', and the fifth row had twenty-eight 'AU Authur' plants. Plants were flagged on November 3, 2020 (Figure 9, 10 and 11). In addition, at SFASU, 1 km from Jimmy Hinds Park, thirty 'AU Golden Dragon' seedlings were randomly selected for the study from the first row. These plants were one year younger than the other cultivars mentioned above. The cultivars were flagged with different colors in November 2020 and evaluated until the next early Spring. The weather data collection and plant evaluation were completed on the same date at each location.

The purpose of this study was to analyze four different kiwifruit cultivars to freeze events in Nacogdoches, Texas. Therefore, statistical analyses were conducted. The plant evaluation date for Nacogdoches was March 31, 2021.

Figure 9. Hayward cultivar, marked with purple flag.

Figure 10. AU Authur cultivar, marked with orange flag.

Figure 11. Bruno cultivar, marked with pink flag.

‘AU Golden Dragon’ plants were assigned later because they needed to be transplanted to the field, therefore, there is no picture available. ‘AU Golden Dragon’ seedlings were randomly selected for the study with thirty plants selected on the first row at kiwifruit plot adjacent to Stare Avenue: on the premises of SFASU but south from Jimmy Hinds Park. These plants were one year younger than Bruno, Hayward and AU Authur cultivars.

Study II. Analysis of Two Different Kiwifruit Cultivars to Freeze Events in College Station

This study revealed the relationship between two cultivars of kiwifruit; Hayward and SunGold seedlings (also called ‘G3’) to freeze events, in College Station. SunGold cultivar is a commercialized gold-fleshed kiwifruit by Zespri® (Eady et al., 2019). The green cultivar, Hayward, includes a sample of plants that were protected, and another that was not protected. Plants that received protection had a 60 cm tall poultry wire cage surrounding them, which was filled with pine bark mulch. These were installed in mid-November 2020, and the plants were approximately four years old. The total sample was 60 plants: unprotected ‘Hayward’ (15), protected ‘Hayward’ (15) and ‘SunGold’ seedling (30).

Study III. Freeze Influence in Bruno Rootstocks at Different Locations in Texas.

A. deliciosa ‘Bruno’ is a male, green kiwifruit cultivar commonly used as a rootstock. One important characteristic of Bruno is rustic and has a lower chilling requirement of 700 h compared to most green cultivars. Therefore, this cultivar was planted in different locations in Texas, in order to evaluate the growth and tolerance to freeze events. The growth of ‘Bruno’ plants is different among locations with plants ranging in age from six months to two years, and the study sites are Nacogdoches (two years old), Crockett (one year old), and Simonton (six months old). ‘Bruno’ rootstocks in Crockett were protected during the winter with fresh mulch and freeze cloth.

For this study, local temperatures from November 1, 2019, to March 1, 2021, were collected using the Elitech RC-51 weather data logger recorder at these locations: Nacogdoches, Crockett, and Simonton. From March to April of 2021, evaluation surveys were completed to identify freeze influence on ‘Bruno’ rootstocks at locations mentioned.

The method used to identify the damages on plants was the Mengmeng scale (Table 2). The plant assessment started five weeks after the historical freeze event in February 2021. The total sample was 93 plants: Crockett (30), Simonton (35) and Nacogdoches (28). This study focuses on the evaluation of freeze injury on ‘Bruno’ rootstocks in three different locations in eastern Texas.

Study IV. Suitable Growing Areas for Kiwifruit in East Texas.

In total, east Texas has 38 counties, with both rural areas and urban settings with enterprises led by lumber, cotton, cattle, and oil (Johnson, 1995). Although it is common to see farms in east Texas, the majority are forested from the post oak plains in the western portion, and mixed pine and hardwood, loblolly pine plantations in the eastern portion. The east Texas was chosen due to successful kiwifruit plots located at SFASU in Nacogdoches where kiwifruit has been cultivated for the past ten years. The study area for this study covers 38 counties of east Texas (Figure 12).

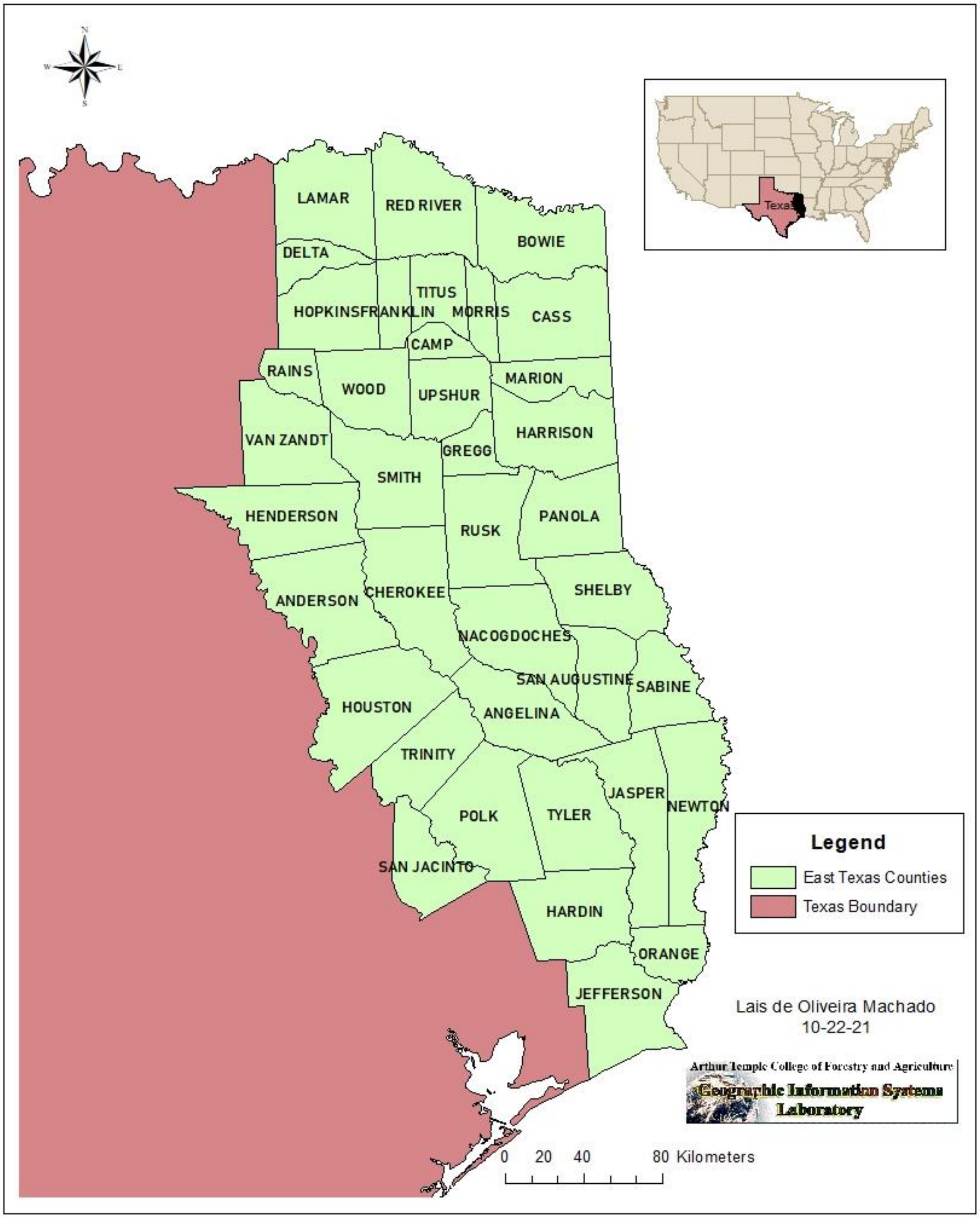

Figure 12. Map of the study area for study IV, east Texas.

The National Oceanic and Atmospheric Administration (NOAA) and the USDA Natural Resources Conservation Service, Soil Survey (SSURGO), were the two public data sources used in the project. Datasets acquired for this study were soil pH for east Texas and temperature data of the past ten years (2011 - 2021) for the 38 counties in east Texas. Calculations of cumulative chilling hours employed the average of temperature in one hour, and attributed a chill unit based on Richardson Model (Table 3). Later, estimation of average chilling hours for the past ten years was summed up for each location using the period from November 1 to March 1 of each year.

In general, the suitable range from 800 – 1000 h is ideal for chilling hours, with variability depending on kiwifruit cultivar, and for soil pH the suitable range is from 5.5 to 6.5 pH. These variables represent the optimal growing conditions for kiwifruit crop production, and they were correlated to the chilling requirements of three potential cultivars grown in Alabama and tested in Texas (Table 5). The cultivars are AU Golden Dragon, AU Golden Sunshine, and AU Fitzgerald. The cultivars were chosen because they have expressed good adaptation, fruit yield and fruit quality (Hartmann, 2020).

Table 5. Chilling requirement for female plants, maximum budbreak and maximum flowers in chill hours (Wall et al., 2008).

Female	**Males (Pollinators)**	**Maximum Bud Break**	**Maximum Flowers**
‘AU Golden Dragon’	‘CK3 -Meteor’	800 h	800 h
‘AU Golden Sunshine’	‘AU Golden Tiger’	700 h	850 h
‘AU Fitzgerald’	‘AU Authur’	800 h	1100 h

As mentioned, two types of datasets were used in this study: temperature and soil pH. The data preparation for chilling hours initially started using Excel files of temperature for each county. Unfortunately, NOAA did not have weather station in all counties in east Texas, therefore, only datasets that were available were downloaded, totalizing nineteen counties (Appendix B). Each county dataset was manipulated in JMP for average temperature calculation and chill unit estimation using Richardson model for the Positive Utah Model. In Excel, the datasets were organized by the rest period stablished in this study (November 1 to March 1) for each year, then average over the ten years. The final Excel file for chilling hours was used in ArcMap 10.6 by using Join and Relates tool to join data to east Texas vector layer using a common attribute.

The data preparation for pH was completed by obtaining a vector dataset of Texas from USDA Natura Resources Conservation Service, Soil Survey Geographic (SSURGO II). The dataset provided information about soil features such as soil pH. In ArcMap 10.6, GIS tools used to manipulate the dataset include the Clip tool to obtain a shapefile for the east Texas study area. Vector datasets for chilling hour and pH were later converted to raster datasets through the Environment Settings on ArcMap 10.6 and by using Spatial Analyst tool. In regards to the raster resolution, the cell sizes attributed for both datasets were 100 (meters). In addition to that, obtained dataset was projected to NAD 1983 Texas Statewide Mapping System (Meters) using the Project tool in ArcToolbox. In general, data preparation was realized in ArcCatalog and ArcMap 10.6 using several tools including Spatial Analyst, which enabled to apply IDW (Inverse Distance Weighted) and Overlay Analysis.

Inverse Distance Weighted

An interpolation method was used to predict values for cells in the raster datasets: chilling hour, and soil pH from a limited number of sample data points. In this case Inverse Distance Weighted was the interpolation method applied to predict unknown values for chilling hours and soil pH for east Texas. There are several interpolation methods available in ArcMap 10.6, such as Kriging, Natural neighbor, IDW and others. However, IDW tool was preferred because this interpolation method estimates cell values by averaging the values of the sample data points in the neighborhood of individual processing cells. Therefore, the nearer the point is to the center of the cell being estimated, the more weight it has in the averaging operation (Esri,1995). This method does not stipulate assumptions about statistical properties of the input data. However, the drawback of IDW is that this method can produce a bull's-eye effect around data locations. An input dataset with counties and coordinates was used for the interpolation method.

The parameters applied in this study for IDW function were power, search radius and number of points. The power function relies on the weight given to the point and it is proportional to the inverse of the distance between data point and the prediction location raised to the power of value *p*. Therefore, as the distance increases, the influence decreases briskly. The weight is dependent on value of *p;* for instance, if the p value is high, only the points that are very close will influence the prediction (the output point). Thus, high power influences a nearby points more than points further away, and the surface will be more detailed. The opposite is also true: lower power results in a smoother surface (Esri,1995). Limiting the input points used for interpolation is important in the calculation of each output cell value. The process of limiting the number of input points helps to eliminate far away points that do not contribute much for the calculation and may have poor correlation. The power value for this study is 2 and a fixed radius within points were included in the interpolation, which was the variable search radius. The radius distance varies for each interpolated cell, varying by how far it has to search around each interpolated cell to reach the specified number of input points. With the variable search radius selected, the number 19 was used in calculating the value of the interpolated cell specified. IDW parameters for chilling hours and soil pH for east Texas can be seen, respectively, in Figure 13 and Figure 14.

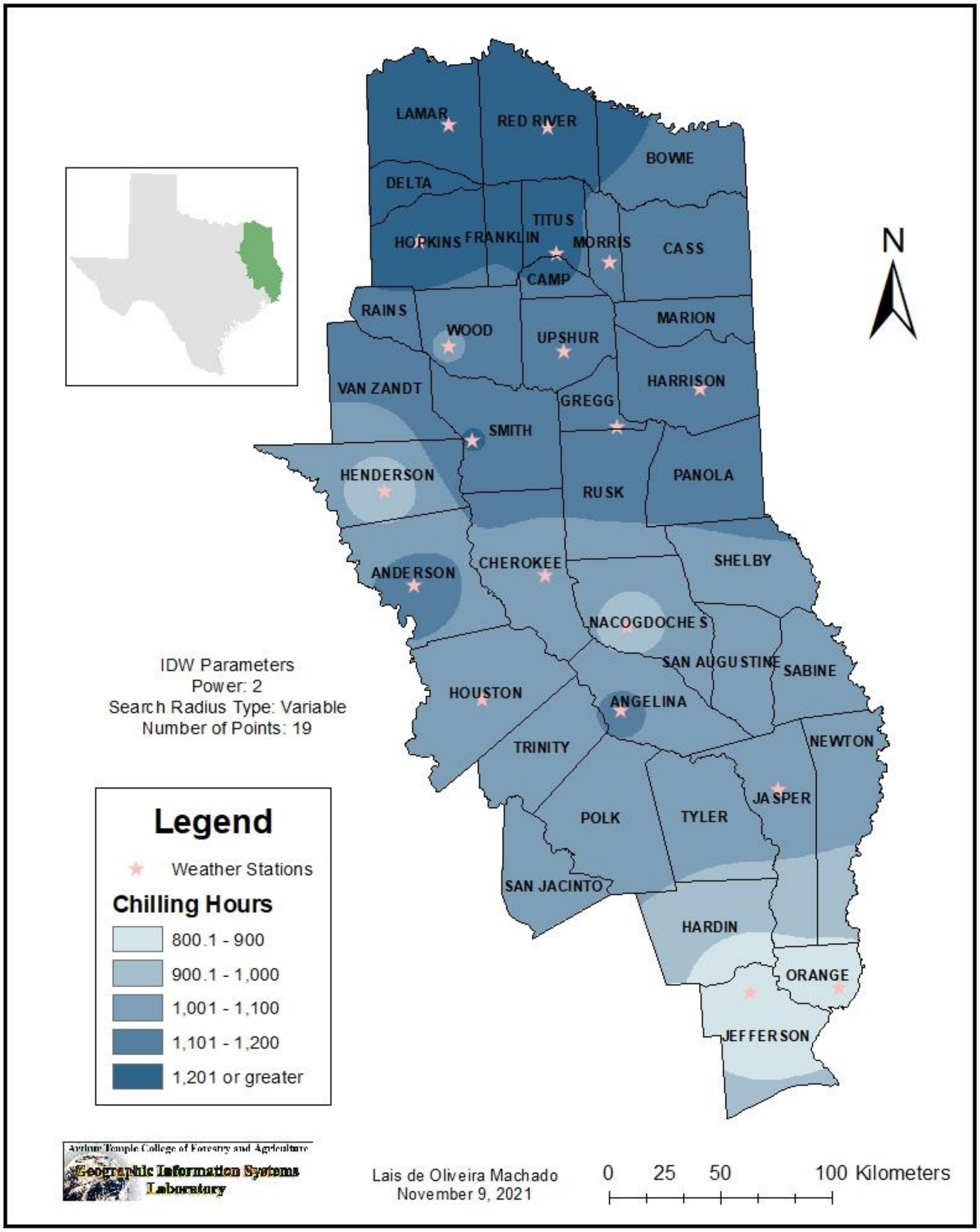

Figure 13. Map of average of chilling hours for the last ten years by county for east Texas, USA.

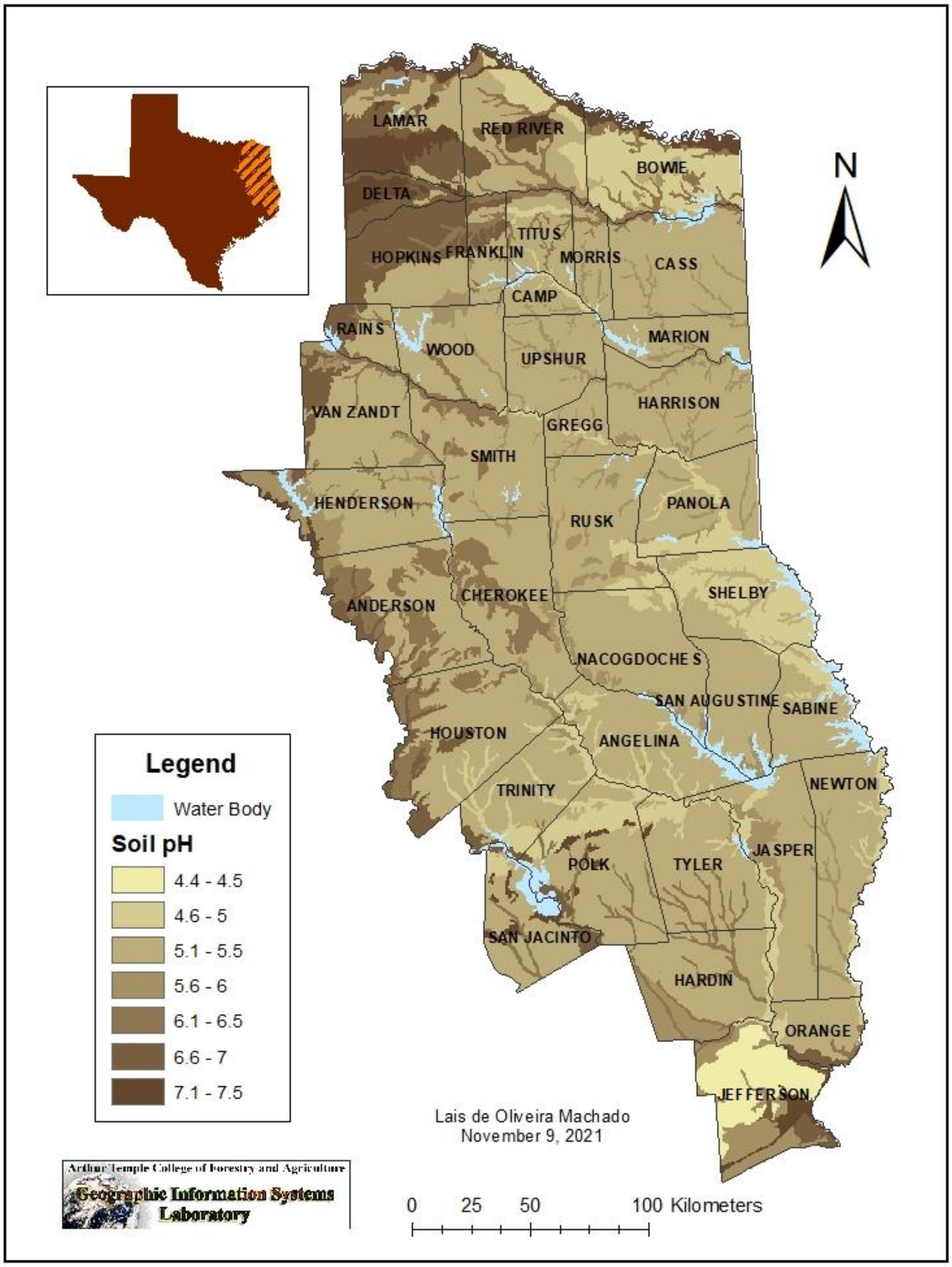

Figure 14. Map of east Texas showing soil pH levels.

Fuzzy Overlay

Fuzzy overlay was the last tool used in ArcMap 10.6 to create the final raster output that represents the map showing suitable areas to grow kiwifruit in east Texas. However, a previous tool called Fuzzy Membership was used in the data preparation. This tool reclassifies the values using a 0 to 1 scale. The conversion of the input raster into a 0 to 1 scale indicates the strength of the membership in a set (Abbaspour et al. 2011). Thus, a value 1 indicates full membership in the fuzzy set and a value 0 indicates that the member is not part of the fuzzy set. When applying fuzzy membership tool some parameters need to be selected to have desirable output raster dataset; they are membership type, midpoint and spread. There are several fuzzy membership types available in ArcMap 10.6; however, the one used for this study was fuzzy near. The fuzzy near function is defined by a midpoint defining the center of the set, assigned membership 1. As values move from the midpoint, in both sides, positive or negative directions, membership decreases until it reaches 0, defining no membership (Esri,1995). In addition, fuzzy near membership type decreases at a quick rate, with narrow spread. The spread basically determines how fast the fuzzy membership values decrease from 1 to 0. As the spread gets smaller, the fuzzy membership slowly approaches to 0 (Esri,1995). Several simulations were created, allowing the observations of different outcomes in order to make a decision. The midpoints decided for soil pH was 5.75 and chilling hours was 900. The ideal spread was 0.1 for chilling hour output raster and 0.01 for soil pH output raster.

Lastly, each output raster from the fuzzy membership process was then utilized as the input for the Fuzzy Overlay tool. This tool combines multiple fuzzy membership raster data together based on the selected overlay type. There are several fuzzy overlay types available: And, Or, Product, Sum, and Gamma. For this study, the Sum overlay type was used to combine the information from chilling hours raster and soil pH raster.

RESULTS

Study I. Analysis of Four Different Kiwifruit Cultivars to Freeze Events in Nacogdoches.

The analysis is based on golden cultivar and green cultivars in Nacogdoches. The total sample size was 113 plants: ‘AU Authur’ (28), ‘Bruno’ (28), ‘Hayward’ (27) and ‘AU Golden Dragon’ (30). The analytical results for the associations between freeze effect on AU Golden Dragon, Bruno, AU Authur, and Hayward cultivars are as it follows.

- The null hypothesis is H_0: AU Golden Dragon cultivar is similarly susceptible to freeze damage as Bruno, Hayward, and AU Authur cultivars.
- The alternative hypothesis is H_1: AU Golden Dragon cultivar is not similarly susceptible to freeze damage as Bruno, Hayward, and AU Authur cultivars.

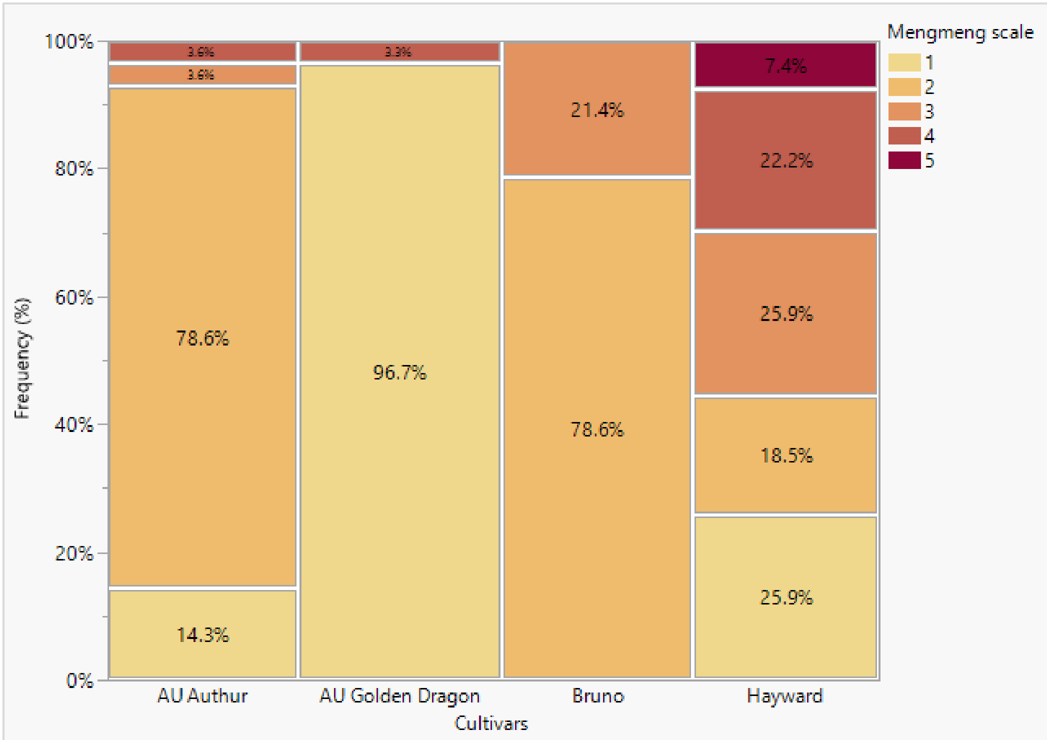

Figure 15. Frequency graph for 'Bruno', 'AU Authur, 'Hayward', and 'AU Golden Dragon' to plant damage after freeze events.

The frequency graph (Figure 15) shows frequencies for four different kiwifruit cultivars to freeze events. The colors in the graph represent the Mengmeng scale 1-5. Light yellow for scale 1, light orange for scale 2, matte orange for scale 3, dark orange for scale 4, and brown for scale 5. The width of the bars corresponds to the proportion of the total sample in each explanatory variable category. The heights of the bars represent the frequency, consequently representing the probability of plant damage occurring.

Analyzing the heights of the bars and the proportion of the colors among the green cultivars, observations include that Bruno and AU Authur had similar frequency proportion for minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable (Scale 2). Bruno cultivar did not show bars for, death to ground, it appears to resprout from the base or roots (Scale 4), nor for total death (Scale 5). However, the Hayward cultivar indicated different proportions for all five categories on Mengmeng's scale. 'Hayward' displayed a greater proportion for death to ground, it appears to resprout from the base or roots (Scale 4) compared with 'AU Authur' and it was the only cultivar to show results for total death (Scale 5). 'AU Golden Dragon' had results only for no damage (Scale 1) and death to ground, it appears to resprout from base or roots (Scale 4). But, the golden cultivar did not have results for the scales: minor foliar, tip damage, acceptable main stem and deemed quickly recoverable (Scale 2), major foliar, stem damage, base, and main stem acceptable, and deemed recoverable (Scale 3), and for total death (Scale 5).

The frequencies in percentage (Figure 15) help to understand the distribution of plant injury between the categories (Mengmeng scale). For instance, Bruno cultivar had a frequency of 21.4% for major foliar, stem damage, base and main stem acceptable, and deemed recoverable (Scale 3). Bruno and AU Authur cultivars had similar frequencies of 78.6% for minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable (Scale 2). Also, 'AU Authur' had a frequency of 3.6% for major foliar, stem damage, base and main stem acceptable, and deemed recoverable (Scale 3), and 3.6% death to the ground; however, it appears to resprout from base or roots (Scale 4). 'Hayward' had a frequency of 25.9% for no damage (Scale 1), 18.5% for minor foliar, tip damage, acceptable main stem and deemed quickly recoverable (Scale 2), 25.9% for major foliar, stem damage, base, and main stem acceptable, and deemed recoverable

(Scale 3), 22.2% for death to ground, it appears to resprout from the base or roots (Scale 4), and frequency of 7.4% for total death (Scale 5). AU Golden Dragon cultivar had a frequency of 96.7% for no damage plants (Scale 1), which was greater in comparison with all cultivars. Also, 'AU Golden Dragon' had a frequency of 3.3% for death to ground, however, it appears to resprout from the base or roots (Scale 4), which was the lowest frequency for scale 4 when compared to all green cultivars. Observing Figure 15, these are the only two categories that 'AU Golden Dragon' fits in.

Table 6. Chi-square approximation from Kruskal - Wallis test for Bruno, AU Authur, Hayward, and AU Golden Dragon cultivars damage after freeze events.

Chi-square	**DF**	**Prob > ChiSq**
52.1702	3	<.0001*

The test was performed to tell if there was a significant difference between groups (cultivars) analyzed to freeze events (Table 6). The relation between the cultivars to freeze was significant, X^2 *(3, N = 113) = 52.1702, p = <.0001*. Therefore, there was a significant relationship between different kiwifruit cultivars' damage to freezing events. The Kruskal-Wallis test does not tell which cultivar was different, therefore, a nonparametric pair comparison was completed using Wilcoxon Method to analyze groups' performance.

Table 7. Pair comparisons for four different cultivars to freeze injury in Nacogdoches.

Groups		**Score Mean Dif.**	**Std Err Dif.**	**Z**	**p-Value**
Hayward	Golden Dragon	19.7741	3.797569	5.20704	<.0001*
Hayward	AU Authur	8.5119	4.027763	2.11331	0.0346*

Table 7. (continued).

Bruno	AU Authur	6.8929	3.121355	2.20829	0.0272*
Hayward	Bruno	5.4927	4.019811	1.36641	0.1718
Golden Dragon	AU Authur	-23.0619	3.872004	-5.95606	<.0001*
Golden Dragon	Bruno	-27.0321	4.017108	-6.72925	<.0001*

The pair comparisons in the Table 7 indicated no difference to freeze injury for Hayward versus Bruno cultivar with a p-value *0.1718*; Therefore, there was not enough evidence to reject the null hypothesis that the two medians were equal. Statistical results for other groups' comparisons indicated that there were differences in medians for plant injury for the remaining pair comparisons. The p-values can be seen in Table 7, the pair comparisons were significantly different at $\alpha = .05$. Therefore, one of the cultivars compared in a group was more susceptible to freezing events than another.

Study II. Analysis of Two Different Kiwifruit Cultivars to Freeze Events in College Station, Texas.

The following analysis examines statistical results for possible similarities between ‘SunGold’ seedlings and ‘Hayward’ to freeze effect. A statistical test was completed to identify if there was a difference between protected ‘Hayward’ (15), unprotected ‘Hayward’ (15) and ‘SunGold’ seedlings (30) to freeze events. The Kruskal Wallis test was applied to this study because it had three groups: protected ‘Hayward’, unprotected ‘Hayward’, and ‘SunGold’ seedlings.

- The null hypothesis is H_0: The medians are equal to kiwifruit cultivars to freeze injury in College Station.
- The alternative hypothesis is H_1: The medians are not equal to kiwifruit cultivars to freeze injury in College Station.

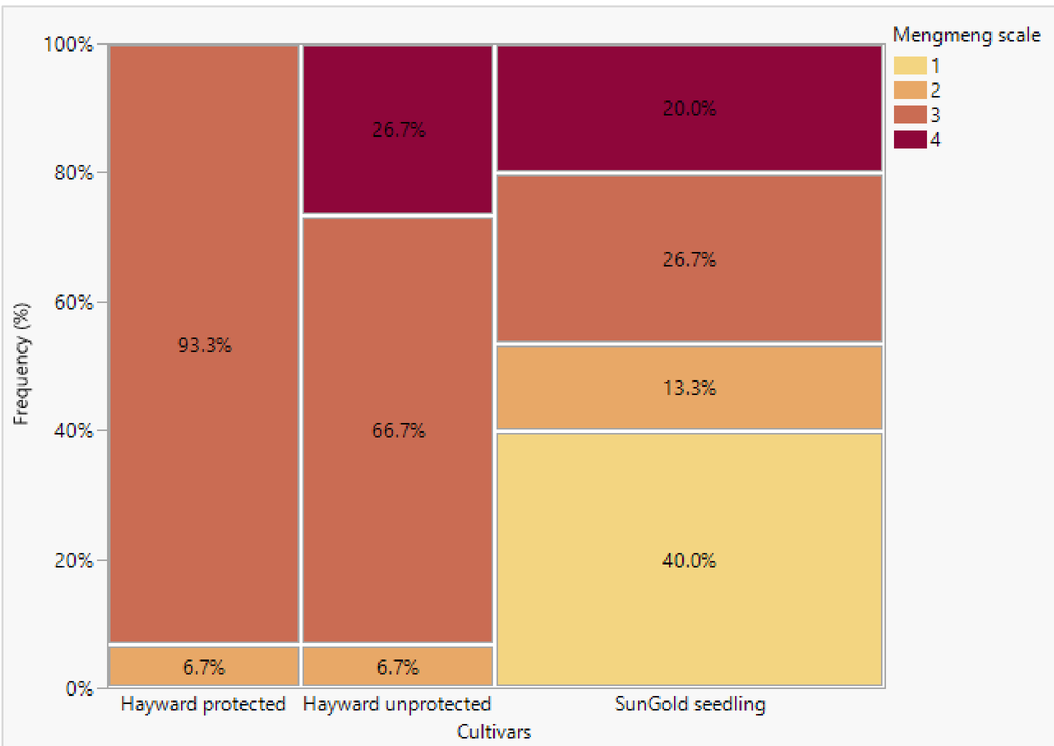

Figure 16. Frequency graph for protected and unprotected 'Hayward' and 'SunGold' seedling to freeze events.

Figure 16 shows the frequency distribution of plant injury by treatment; 'Hayward' unprotected, 'Hayward' protected, and 'SunGold' seedling. 'Hayward' protected and unprotected had the same frequency of 6.7% for minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable (Scale 2). 'Hayward' unprotected had a lower frequency of 66.7 % for major foliar, stem damage, base and main stem acceptable, and deemed recoverable (Scale 3). Also, unprotected ‘Hayward’ plants had a frequency of 26.7% for death to ground, however, it appears to resprout from the base or roots (Scale 4). ‘SunGold’ seedling had a frequency of 40% for no damage (Scale 1), 13.3% for minor foliar, tip damage, acceptable main stem and deemed quickly recoverable (Scale 2), 26.7% for major foliar, stem damage, base, and main stem acceptable, and deemed recoverable (Scale 3), and frequency of 20% for death to the ground; however, it appears to resprout from base or roots (Scale 4). The frequency distribution between cultivars was quite different, ‘SunGold’ seedling indicated to have more diverse results for plant damage. Despite that, the frequency for Scale 3 (26.7%) was lower in comparison to ‘Hayward’ protected (93.3%) and unprotected (66.7%). Also, ‘SunGold’ seedling had the lower frequency for Scale 4 (20.0%) compared to ‘Hayward’ unprotected (26.7%). There was no result for total death (Scale 5) for this study.

Table 8. Kruskal-Wallis Tests (Rank Sums) for protected and unprotected ‘Hayward’ and ‘SunGold’ seedling to freeze events.

Level	**Count**	**Score Sum**	**Expected Score**	**Score Mean**	**(Mean-Mean0)/Std0**
SunGold seedling	30	749.000	915.000	24.9667	-2.678
Hayward unprotected	15	582.500	457.500	38.8333	2.326
Hayward protected	15	498.500	457.500	33.2333	0.757

The probability of randomly selecting a score varies differently among the cultivars, therefore, the standard deviation from the medians is different than 95%. The distances from the medians were different for protected ‘Hayward’, unprotected ‘Hayward’, and ‘SunGold’ seedling for this study (Table 8).

Table 9. Chi-square approximation from Kruskal-Wallis test for 'Hayward' protected, 'Hayward' unprotected and 'SunGold' seedling to freeze events.

Chi-square	DF	Prob>ChiSq
8.1379	2	0.0171*

Table 9 shows a p-value of *.0171* smaller than the significance level *.05*. Therefore, there was enough evidence to reject the null hypothesis. The medians between plant damage to freezing events were different. Therefore, there was a different response among the kiwifruit cultivars injured to freeze events.

Table 10. Nonparametric comparisons for each pair using Wilcoxon method for protected and unprotected 'Hayward' and 'SunGold' seedling to freeze events.

Groups		Score Mean Dif.	Std Err Dif.	Z	p-Value
Hayward unprotected	SunGold seedling	9.650000	3.951409	2.442167	0.0146*
Hayward protected	SunGold seedling	6.850000	3.853570	1.777573	0.0755
Hayward unprotected	Hayward protected	3.666667	2.240690	1.636401	0.1018

Comparations between groups can be observed in Table 10, which shows the differences for each pair. The first pair 'Hayward' unprotected versus 'SunGold' seedlings indicated a p-value *.0146* lower than $\alpha=.05$. Therefore, they were statistically significantly different. The result indicates that one of the cultivars compared in the group was more susceptible to freezing events than another. 'SunGold' seedling indicated some tolerance to freeze events in College Station, Texas (Figure 16). The second pair did not show a statistically significant difference between the two groups: 'Hayward' protected versus 'SunGold' seedlings had a p-value of *.0755* greater than $\alpha = .05$. Finally, the third pair comparison resulted in a p-value of *.1018* greater than $\alpha = .05$; the last two groups were not statistically significantly different. Interesting that the statistical results for protected 'Hayward' versus 'SunGold' seedlings did not show a difference, assuming that the tolerance to freezing was similar between the green protected and the gold cultivars. The statistical analysis between 'Hayward' protected and 'Hayward' unprotected exhibited that the use of pine bark mulch on 'Hayward' plants did not enhance protection for this sample.

Study III. Freeze Influence in Bruno Rootstocks at Different Locations in Texas.

This study focuses on the evaluation of 'Bruno' rootstocks to freeze events at different sites. The total sample was 93 plants: Crockett (30), Simonton (35), and Nacogdoches (28).

- The null hypothesis is H_0: 'Bruno' rootstock injury has the same distribution in all locations.
- The alternative hypothesis is H_1: 'Bruno' rootstock injury is systematically higher in some locations than in others.

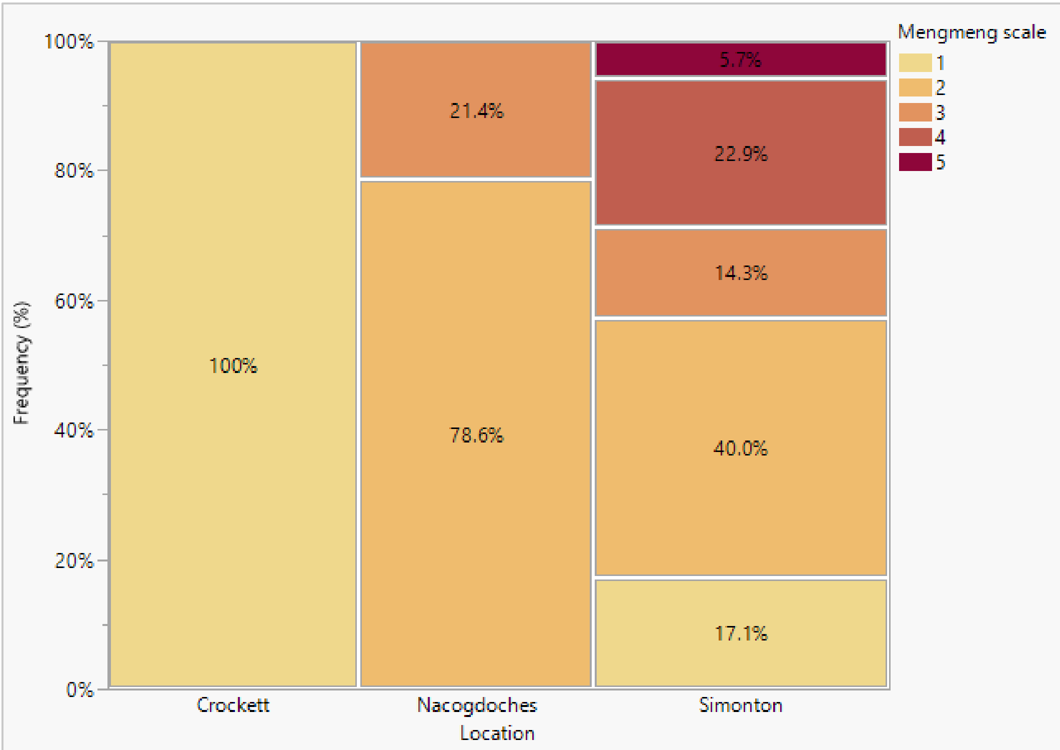

Figure 17. Frequency graph for Bruno cultivar injury at different locations in Texas.

The different heights for each Mengmeng category in Figure 17 indicate freeze impact on Bruno rootstocks. There was no plant injured recorded at the Crockett location, due to the protection made with fresh mulch and freeze cloth. The plants were healthy and vigorous when assessed. Nacogdoches showed higher proportions for minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable (Scale 2), and for major foliar, stem damage, base and main stem acceptable, and deemed recoverable (Scale 3), compared with Simonton location. Lastly, Simonton was the only location presenting plant injury for death to ground, however, it appears to resprout from the base or roots (Scale 4), and for total death (Scale 5).

Analyzing the distribution of no damage plants (Scale 1) in each location, Crockett had a greater frequency of 100% in comparison with other sites; Nacogdoches did not have a frequency for scale 1 and Simonton had a frequency of 17.1%. Nacogdoches had 78.6% minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable (Scale 2), 21.4% major foliar, stem damage, base and main stem acceptable, and deemed recoverable (Scale 3). Simonton had 17.1% no damage (Scale1), minor foliar, tip damage, acceptable main stem, and deemed quickly recoverable 40% (Scale 2), major foliar, stem damage, base, and main stem acceptable, and deemed recoverable 14.3% (Scale 3), death to ground, however, it appears to resprout from base or roots 22.9% (Scale 4), and total death 5.7% (Scale 5).

Table 11. Kruskal-Wallis Tests (Rank Sums) for plant injury to freeze events at Crockett, Nacogdoches and Simonton locations.

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Crockett	30	555.000	1410.00	18.5000	-7.479
Nacogdoches	28	1667.00	1316.00	59.5357	3.126
Simonton	35	2149.00	1645.00	61.4000	4.252

The probability of randomly selecting a score varies differently among the cultivars, therefore, the standard deviation from the medians was different than 95%. The distances from the medians were different at Crockett, Nacogdoches, and Simonton locations for this study (Table 11).

Table 12. Chi-square approximation from Kruskal-Wallis test for plant damage at Crockett, Nacogdoches and Simonton locations.

Chi-square	**DF**	**Prob > ChiSq.**
56.0802	2	<.0001*

A chi-square test was performed to examine the similarities between locations to 'Bruno' rootstock injury caused by freeze events. The relationship between these variables was significant, X^2 *(2, N = 93) = 56.08, p = <.0001* (Table 12). Therefore, there was a significant association between different locations to 'Bruno' rootstock injury caused by freeze events.

Table 13. Nonparametric comparisons for each pair using Wilcoxon method for 'Bruno' rootstock to freeze events in different locations in Texas.

Group		**Score Mean Dif.**	**Std Err Dif.**	**Z**	**p-Value**
Nacogdoches	Crockett	28.96548	3.984179	7.270124	<.0001*
Simonton	Crockett	26.89762	4.254681	6.321889	<.0001*
Simonton	Nacogdoches	4.40357	4.170792	1.055812	0.2911

A pair comparations analysis was completed between groups to identify the similarities of plant damage distribution in different locations (Table 13). The first two groups were statistically significantly different: Nacogdoches versus Crockett had a p-value <*.0001* and Simonton versus Crockett had a p-value <*.0001*. Therefore, they did show differences for plant damage to freeze between locations. In other words, 'Bruno' rootstock indicated more damage in one location to the other. The last pair comparison was completed for Simonton versus Nacogdoches, with a p-value of *0.291*. Therefore, they were not statistically significantly different for plant damage to freezing events.

Study IV. Suitable Growing Areas for Kiwifruit in East Texas.

Repeated simulations were completed using different functions under the fuzzy membership tool to choose the final output. Many aspects were used to obtain an ideal map depicting suitable areas to grow kiwifruit in east Texas. The final output raster shows, in general, a smooth transition between the marginally suitable, moderately suitable, and highly suitable areas to grow kiwifruit in east Texas. The dark green color in Figure 18 shows areas highly suitable to grow the cultivars: AU Golden Dragon, AU Golden Sunshine, and AU Fitzgerald. These cultivars have been studied in Texas and are potential candidates to be cultivated on a commercial scale. Light green areas are moderately suitable for the kiwifruit crops. Orange areas are marginally suitable to grow the crop, therefore, before the implementation of a kiwifruit crop, it is recommended to do an investigation of the site particularities. For instance, choose a kiwifruit cultivar with a chilling requirement of 1000 PCU or below, and be aware of possible correction of soil pH. Red color sites are not suitable for growing the kiwifruit cultivars mentioned because growers might face problems with very high chilling hours and high soil pH on the north and very low pH and chilling out of the optimal range in the south of east Texas.

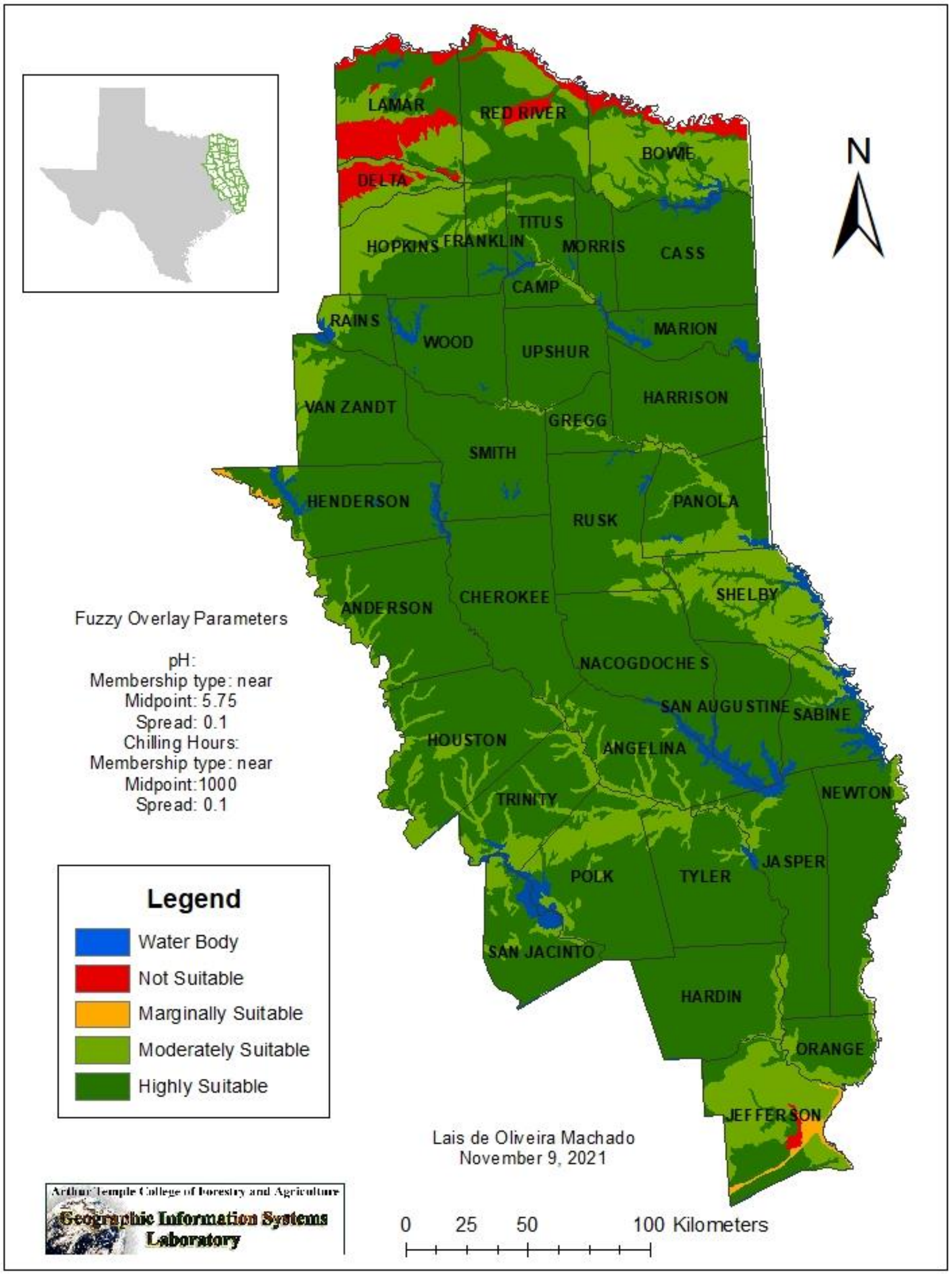

Figure 18. Map of suitable areas to grow kiwifruit in east Texas, USA.

DISCUSSION AND CONCLUSION

Study I. Analysis of Four Different Kiwifruit Cultivars to Freeze Events in Nacogdoches.

The study indicated that different kiwifruit cultivars present different responses to the freezing effects on plants. Therefore, cultivars in this study had different tolerance to freezing damage. By looking at Figure 15 and Table 7 the green cultivars seemed to be more susceptible to freeze, thereby suffering more damage than AU Golden Dragon, which contradicts Norton, 1994, in that *A. deliciosa* is less susceptible to winter cold and spring freeze than *A. chinensis*. Bruno cultivars at two years old indicated tolerance to the freeze events by showing minor damage on plants (Figure 15). Field trials with 'Bruno' rootstocks indicated that young kiwifruit plants are more susceptible to freeze injury in the first few winters in comparison to older plants (Creech, 2018). Despite the difference of age between all green cultivars and AU Golden Dragon (one year younger), the golden cultivar suffered less damage after freeze events (Figure 15). According to Wall et al (2008), the chilling requirement for 'AU Golden Dragon', 'AU Authur', 'Hayward' and, 'Bruno' range is 700 up to 900 chilling hours. Therefore, the chilling requirement for kiwifruit growth and adequate bud break was ideal for Nacogdoches (964 h) during the study period. The epic event in February 2021 (Figure 2) may have contributed to plant injury, also the oscillation of low and mild day temperatures during the winter may have had an effect, that was not investigated in the study. Therefore, overall, most kiwifruit plants survived the freeze events.

Study II. Analysis of Two Different Kiwifruit Cultivars to Freeze Events in College Station

According to Paliyath (2015), the Hayward cultivar needs a growing season of 225 to 240 freeze-free days. However, during the study (120 days) several freezing events occurred, marked with the epic freeze in February. The sample analyzed by chance indicated that there was enough evidence to suggest that the medians were not unequal. Thus, there were different responses between the kiwifruit cultivars to freeze damage.

The paired comparison for ‘Hayward’ unprotected and protected plants indicated that they were not statistically significantly different in relation to plant damage caused by freeze events. The use of pine bark mulch on ‘Hayward’ kiwifruit plants did not enhance protection. Thus, the use of trunk protection in the ‘Hayward’ cultivar is questionable; statistical results exhibited a similar injury response for ‘Hayward’ plants that were not protected. When a golden kiwifruit was analyzed with an unprotected Hayward cultivar there was a different statistical response for plant injury to freeze; one cultivar was more susceptible to freeze than the other. However, the statistical results for protected ‘Hayward’ and ‘SunGold’ seedlings indicated no difference, suggesting that the tolerance of the plants to freeze was similar between the ‘Hayward’ protected plants and the ‘SunGold’ seedlings (Table 10).

Study III. Freeze Influence in ‘Bruno’ Rootstocks at Different Locations in Texas.

‘Bruno’ rootstocks had different responses for plant injury to freeze within study locations (Figure 17 and Table 13). When locations were analyzed in pairs the groups that included protected plants indicated statistical differences; they were Nacogdoches versus Crockett and Simonton versus Crockett. Simonton versus Nacogdoches did not show a statistical difference in plant damage. The plants in Crockett received special treatment from the collaborator, they were protected against freeze by use of a frost cloth, which enhanced plant protection. Even though the kiwifruit was one year old- much younger than other locations; covering them with fresh mulch and frost cloth seemed to be very effective. It is reported that young kiwifruit plants tend to be more susceptible to freeze injury, thus, the protection boosted the tolerance of the plants in Crockett.

The plants in Simonton were approximately six months old and did not receive any protection during the freezing events. Therefore, considerable plant injuries were evaluated, and kiwifruit at the Simonton location was more affected compared to the other sites (Crockett and Nacogdoches). Simonton had mild cold temperatures compared with the other two locations, the presence of winds reduced the temperature sensation, so it was colder than registered temperatures in February (Figure 2). Kiwifruit plants suffered more in the Simonton location due to the combination of freezing temperatures, wind, and no protection. Therefore, 'Bruno' young plants were quite sensitive to freezing temperatures in Simonton, followed by Nacogdoches.

Study IV. Suitable Growing Areas for Kiwifruit in East Texas.

A great portion of east Texas indicated to have optimal areas to grow kiwifruit based on two parameters: chilling hours and soil pH analyzed in this study (Figure 18). From the results, east Texas has many suitable locations to grow kiwifruit, except a few spots in the northern region and a very small area in the southern region. This may be due to either extremely high or very low values of chilling hours for the locations, also the presence of soil pH being out of the suitable range for kiwifruit crop (5.5 – 6.5). The suitability map can be used as an additional source when selecting areas to grow kiwifruit. Also, the chilling hour map for east Texas can be used as another source when choosing cultivars for a specific region.

Although chilling hours and soil pH are important requirements to grow kiwifruit commercially, more studies in the field must be completed to evaluate the impact of these characteristics on fruit quality and yield. In addition, other agriculture characteristics must be analyzed when making a decision to grow this crop in east Texas. Climate cannot be controlled depending on the purpose of production such as ornamental or fruit crop, instead, it is a limiting factor for the plants' size and yield. Thus, more studies on freeze injury on kiwifruit in Texas should be completed to better understand how the climate can affect these plants on a commercial scale. Finding ideal areas that embrace most of the plant needs is important to avoid environmental problems by reducing land disturbances and decreasing fiscal input by growers with unnecessary implements.

PROBLEMS ENCOUNTERED

Some obstacles were encountered during this study which may have affected results. Due to a miscommunication, the kiwifruit in Crockett and College Station received trunk protection in order to reduce freezing damage on plants. Also, ‘Bruno’ plants were pruned in College Station; therefore, it was not included in the study that evaluated the freeze effect among the locations. Thus, there was a reduction in the sample size.

Another issue is the limited temperature data available in the public domains. Only a few weather stations were active in east Texas, which was half of the 38 countries. Eventually, it contributed to the loss of information for locations without a weather station. Thus, the IDW was applied to estimate the chilling hours for missing locations, however, it is not the exact information but an average. The limited sample size of chilling hours available to the interpolation may have affected the output raster. Therefore, the chilling hour map had some bull’s-eye effects around specific locations as predictable when using IDW (Figure 13).

Also, the project was composed of four field studies, where each location had its characteristics that seemed to have interfered with plant damage caused by freezing temperatures. The locations have different environment settings such as soil properties (pH), water quality, fertilization, plant spacing, trunk protection on plants, different ages of plants, and more. All these factors combined might have had an effect on the conclusion of this study. The chilling requirement remains an issue, therefore, more studies for kiwifruit crop need to continue in Texas.

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VITA

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This thesis was typed by Lais de Oliveira Machado based on the style of *American Psychological Association* (APA).