FERAL HOGS, THE RAINFALL INDEX ANNUAL FORAGE PROGRAM, AND PECAN IRRIGATION

By

ABBY MYKAILA BIEDENBACH

Bachelor of Science in Agricultural Economics, Animal

and Veterinary Science, and Mathematics

University of Idaho

Moscow, Idaho

2016

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2018

FERAL HOGS, THE RAINFALL INDEX ANNUAL

FORAGE PROGRAM, AND PECAN IRRIGATION

Thesis Approved:

B. Wade Brorsen, Ph.D.

Thesis Adviser

F. Bailey Norwood, Ph.D.

Jon T. Biermacher, Ph.D.

ACKNOWLEDGEMENTS

I would first like to thank Jon Biermacher and all of the consultants at the Noble Research Institute for countless hours of conversations and guidance. Thanks for taking an Idaho girl under your wings and teaching me about pecans, feral hogs, Bermudagrass, and many other wonderful things. Furthermore, none of these projects would have been possible without the data and knowledge of the Noble Research Institute. Secondly, I would like to thank my advisor, Dr. Brorsen. I learned a lot about being resilient and how to just hit "submit" from you. Thirdly, I would like to thank Will Maples, Devon Meadowcroft, and Brian Mills. The past two years have barely felt like school because we have been having so much fun! Lastly, I would like to thank my husband, Jay ShalekBriski, for never letting me give up on my education. Thanks for letting me go to school 7,207 miles away from you. While it has not been easy, it most certainly has been worthwhile.

Name: ABBY BIEDENBACH

Date of Degree: JULY, 2018

Title of Study: FERAL HOGS, THE RAINFALL INDEX ANNUAL FORAGE PROGRAM, AND PECAN IRRIGATION

Major Field: AGRICULTURAL ECONOMICS

Abstract: The first essay examines feral hog control as an economic issue. Feral hogs are an invasive species and their presence can lead to spread of disease to livestock, crop damage, loss of wildlife, intrusion in green spaces, and many other detrimental consequences. The key to widespread control and eradication of feral hogs lies not only with innovative technology but with institutions and incentives. A change in laws that prevents incentives for individuals to continue to transport and release wild hogs as well as help reallocating abatement resources to work towards a socially optimal level of feral hog control. The second essay assesses the relationship of the RMA index and forage yields for the Rainfall Index Annual Forage Program and proposes additional indices composed of precipitation frequency events and minimum temperature events. The precipitation frequency index sums the number of days precipitation events occurred over a two month time period while the minimum temperature index sums the number of days where the minimum temperature was below 32 degrees Fahrenheit over a two month time period. The RMA index intervals were positively related to yields and significant for wheat. For triticale, oats, rye, and ryegrass, none of the indices were consistently significant indicating that a variable that better explains forage yields is necessary to assist producers in protecting against forage yield loss. The third essay determines the effects of irrigation system upon young pecan growth, nut quality, and nutrient uptake. The five irrigation systems were Nelson R-5 rotator (35 ft diameter) sprinkler, Nelson R-10 rotator (70 ft diameter) sprinkler, two subsurface driplines irrigating for two days a week alternating between water for two hours and no water for two hours, two subsurface driplines irrigating one day a week for twenty hours continuously, four subsurface driplines irrigating for ten hours continuously for one day a week, and a control with no irrigation. Irrigation systems affected foliar levels of potassium, boron, and manganese levels. No significant difference was found in expected change in trunk diameter or kernel percentage by irrigation system. Using a spatial Durbin error model, trunk diameters of non-irrigated and the four subsurface dripline irrigation system trees were significantly less than those trees that were irrigated by the two subsurface irrigation driplines for twenty hours continuously system.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

CHAPTER I

FERAL HOGS

Abstract

Feral hog populations in the United States have grown over the past several decades. Feral hogs' highly adaptable nature, ability to rapidly reproduce, and omnivorous diet make them a formidable pest capable of causing crop damage, spread of livestock diseases, destruction of green spaces, and pose a threat to native species. Trapping, hunting, aerial shooting, poisoning and other control techniques have been developed. Despite advances in control and eradication techniques, feral hog populations continue to grow. Economics suggest that collective action will be necessary to control feral swine populations. Laws have been passed in several states to promote public education about feral swine and eradication efforts as well as help control the population. Prior research by Elinor Ostrom and others suggests that government control is not the only solution in

scenarios that require cooperation among a variety of interests. Informal institutions that are local and assist affected parties in aligning their own interests for the broader social goal of feral hog control may be the "missing piece" in finding a viable solution to the feral hog problem. This study explains the attributes of feral swine, presents current techniques for control and eradication efforts, comments on legislation surrounding feral swine, examines the shortcomings of current institutions concerning feral swine, and suggests a framework of cooperation that may

make eradication of feral swine more feasible. While local, informal institutions and markets may be the preferred mechanism to coordinate collective action to eradicate feral hogs, predator contracts previously suggested by Yoder (2000) may be more appropriate.

Introduction

In recent years, the United States feral hog population has grown tremendously. Over 38 of 50 states (Mclure et al. 2015) report feral hogs with over 4 million feral hogs estimated to be in the United States (Hutton et al. 2006). Feral hogs carry diseases that can infect livestock (Hernández et al. 2018; Cummings et al. 2018; Bevins et al. 2014), cause crop damage (Bevins et al. 2014), encroach on common use recreation areas such as parks (Engeman et al. 2003), and can even be aggressive towards humans (Keiter et al. 2017). Feral hogs are nonnative to North America and are considered an invasive species (Doherty et al. 2016). Their presence can significantly impact an ecosystem. Documented cases of depredation of ground nesting birds such as quail (Rollins and Carroll 2001), disturbance of plant ecosystems, (Siemann et al. 2009) and even discouragement of other hunting game species such as deer (Mapston 2007) have occurred due to competition for resources. The ability of feral hogs to dramatically change the landscape in their environment has a diverse group of individuals and institutions interested in eradication and control of feral hogs.

Over the past several years, a plethora of population management tools have been suggested and invented. Live trapping, poisoning, and aerial hunting (Keiter el al. 2017) are possible options for feral hog control. Eradication of feral hogs seems unlikely in most areas where they have been introduced. For instance, it has been documented that in areas of California over 40% of feral pigs would need to be removed (Waithman et al. 1999), and a study in Australia reports removal of approximately 55% of feral pigs (Caley 1993) a year to prevent population growth. In several areas, there are stories of eradication but with a hefty price tag (McCann and Garcelon 2008; Parkes et al. 2010). As the feral hog population continues to grow so do the laws concerning feral hogs. A majority of the southern states have created new legislation regarding the hunting, trapping, and transportation of feral hogs (Byrd et al. 2015). However, these laws seem to do very little to assist in finding viable ways to control feral hogs.

What may be the missing piece to the management of the feral hog population is the proper institutions and incentives. Property rights of feral hogs are ill defined. Feral hogs can range over a wide territory (Barrett 1978) and thus they move across properties of multiple landowners. None of these landowners explicitly claim ownership of the feral hogs. No interest group, entity, or agency is forthcoming in stating that their intended purpose is widespread feral swine management and mitigation. When an invasive species moves in, who takes action? Previous research by Epanchin-Niell et al. (2010) shows in areas where land has been subdivided and many landowners exist, there is a reduced likelihood that invasive species will be controlled. Epanchin-Niell et al. (2010) define these individually managed properties with varied land uses as management mosaics.

Management mosaics prove to be challenging because each owner's decision to control or not to control feral hogs affects the surrounding properties' users. However, most property owners make decisions on whether or not to control an invasive species based on the damages incurred on their own property and thus usually leads to a lack of coordinated control across landowners (Epanchin-Niell et al. 2010). These management mosaics create a collective action problem (Epanchin-Niell et al. 2010; Olson 1965). In our discussion of the economic issues surrounding feral hogs, we examine the implications of management mosaics for control and eradication of feral swine.

This paper will review the characteristics of feral swine and more specifically the public good aspects. In this paper, we assume current control and eradication technologies are capable of at least reducing the growth of the feral hog population in the United States if implemented in coordinated and consistent fashion. We will outline the current control mechanisms, regulations, and describe the collective action problem that producers, landowners, and other interest groups face. We discuss existing institutions that assist in facilitating control and eradication of feral swine. The paper will conclude with a discussion about the appropriateness of current institutions and possible institutional arrangements that would better facilitate the eradication of feral swine.

Issues with Feral Hogs

Feral hogs can damage crops and livestock, transmit disease, and reduce native wildlife through competition for resources, depredation, and destruction of habitat (Tolleson et al. 1995). Feral hogs are known to uproot crops (Bevins et al. 2014), spread diseases such as pseudorabies virus (Hernández et al. 2018), campylobacteriosis (Cummings et al. 2018), brucellosis (Bevins et al. 2014), and trichinosis (Bevins et al. 2014), and even discourage the presence of deer in habitats that are suitable for feral hogs and deer (Tolleson et al. 1995). Feral hogs may also cause algae blooms, oxygen depletion, and bank erosion in rivers and ponds in which they wallow (Mapston 2007).

Besides reducing revenues of landowners through spread of disease to livestock and crop damage, feral hogs can be detrimental to landowners who depend on game hunting as part of their income. Often feral hogs will eat at supplemental feeders and food plots discouraging other wildlife from using them (Mapston 2007). Feeders and food plots are often used by game ranches for supplemental feeding to ensure trophy bucks for hunts. In addition to ensuring their game reach optimal size through additional nutrition, many game ranches have expensive high fences that keep game in and unwanted hunters out. Many anecdotal stories and documented research shows that feral swine are adept at digging under, going over, and destroying fences (Mapston 2007). Game ranches may not only lose valuable trophies to damaged fences but will be burdened with the maintenance and repair of these fences if feral swine are present.

In addition to be ingenious, feral hogs are also highly adaptable. Feral hogs lack natural predators (Tolleson et. al 1995) and consequently can multiply rapidly. Sows can give birth to two litters a year with an average litter size between 4.2 and 7.5 piglets (Taylor et al. 1998). Females can reproduce at six to ten months of age (Barrett 1978). Feral hogs also have a global presence. They have been successfully introduced to every continent except Antarctica (Barrios-Garcia et al. 2012).

Feral hogs universal presence can also be attributed to their utilitarian nature. Feral hogs are omnivores and can utilize a large variety of foodstuffs (Seward et al., 2004).). They will root in fields, uproot seedlings, and cause damage by wallowing in stock ponds (Bevins et al. 2014). Current projections suggest feral hogs will occupy 35% of watersheds in the contiguous U.S. by 2025 (McClure et al. 2018). While in recent years, reports of feral hog damage have peppered the news, it has been posited that feral hogs do not consume large amounts of crops when there are plentiful natural resources available (Barrios-Garcia et al. 2012). However, the rapid explosion in the feral hog population has created high density populations (Bevins et al. 2014) thus making competition for natural resources greater and crops a viable food source. Feral hogs activities in crop fields increase during crepuscular and night time periods (Franckowiak et al., 2018). In addition to impacting a producer's revenue by destroying crops, feral swine may eat foodstuffs such as acorns (Taylor and Hellgren 1997) that trophy game animals such as deer consume. Landowners who depend on revenue from game birds such as bob white quail may also experiences losses as feral hogs are known their nest predation (Rollins and Carroll 2001). While considered omnivores, unclear the extent of their carnivorous behaviors is unclear. There are documented cases of feral hogs consuming small vertebrae such as voles, mice, and birds as well as carrion of large mammals (Wilcox and Van Vuren 2009). In diet studies, feral hogs did consume small amphibians and reptiles such as toads, lizards, and snakes when given the opportunity (Jolley et al. 2010). Preying on small mammals and amphibians is of concern as many of these species may be considered endangered (Jolley et al. 2010). In addition to small vertebrae and carrion, there are reports of feral hogs preying on livestock. Feral hogs in Australia and the southwestern United States have been reported to prey upon newborn lambs (Seward et al. 2004; Choquenot et al. 1997).

Feral hogs are considered nomadic animals and may have large home ranges (Podgórski et al. 2013). The actual size of their home range depends on a variety of factors such as population density, availability of food, sounder dynamics, and quality of habitat (Gabor et al. 1999; Hayes et al. 2009; Podgórski et al. 2013). Natural habitats such as floodplain systems, cross timber oak forest, and woodland habitats were preferred by feral hogs in studies performed in Texas (Franckowiak et al. 2018). Feral hogs often prefer habitat that is moist such as river bottoms, marshes, lakes, and ponds (Mapston 2007).

Feral Hog Control Options

Feral hog hunting has gained some traction in the Southern United States. Hogs are usually taken in addition to other trophies such as white tailed deer (Tolleson et al. 1995). While used by some landowners as a way to control the feral hog population, hunting creates an interesting paradigm. Individuals can generate revenue from hunting leases or hunts for feral hogs, which creates an incentive for some to release feral hogs (Seward et al. 2004). When landowners attempt to grow prize boars, additional feed may be provided to the local feral swine population. Supplementary feeding on an operation may also occur in order to bait the hogs to a trap. Regardless of the reason, supplemental feeding of hogs to support hunting or control efforts may actually increase local feral swine populations (Ditchkoff et al. 2017; Bevins et al. 2014). Supplemental food sources such as corn become an easily accessible, high energy foodstuff that allows the local swine population to flourish. Supplementary feeding has other unintended consequences as well such as encouraging depredation of birds that have ground nests located near feeding sites (Oja et al. 2015).

Different styles of feral hog hunting exist. Hunting in the United States often includes a form of ground hunting. Ground hunting may be done during daylight hours, over bait, or even at night (depending on state laws). Feral hogs may be hunted with dogs (Stevens 2006). While hunting may physically remove feral hogs, hunting may cause the feral hogs to shift their home range from one landowner's property to another that does not participate in hunting (Stevens 2006). While a popular pastime, public hunting programs have not removed enough hogs to control population numbers (Massei et al. 2011). Many states have started aerial hunting. Aerial hunting involves flying small helicopters with trained hunters equipped with shotguns. It has been shown to be effective if done with an experienced pilot and hunter (Mapston 2007). Aerial hunting is often used in open areas with high density populations of feral hogs as it effectively eliminates a large number of hogs. In most areas, continued flyovers are necessary even once a large number of feral swine in an area are eliminated. Other hunting or trapping methods may be used in conjunction with aerial hunting to try to completely eradicate a swine population in an area. Bounty programs that pay hunters on a per pig basis have been tried on several occasions.

Anecdotes of individuals submitting tails from meat processors (Bevins et al. 2014) suggest that these programs have had mixed results. These programs also create a perverse incentive for individuals. If feral hogs are eradicated, such bounty programs will no longer exist and revenue opportunities from hunting will disappear (Bevins et al. 2014). Individuals may release more hogs in order to ensure the continuation of a bounty program in an area.

Over the past several years, use of oral toxicants to control feral hogs has been debated. Sodium-nitrate in bait delivery has been tested as an oral toxicant (Snow et al. 2016). Oral bait delivery has faced pushback in recent years due to concern about the safety of non-target species. Studies have shown that current delivery systems for sodium-nitrate do not adequately discourage non-target species (Snow et al. 2016). Species specific bait stations that deliver toxic bait to large portions of the feral swine population and reduce the hazard to non-target species have been extensively studied. For example, Snow et al. (2016) tested the strength of raccoons and wild pigs to determine if there was a difference in physical abilities. A difference of 13.6 kg of resistance between raccoons and feral hogs provides an opportunity for innovative bait delivery designs that protect raccoons from accidentally consuming oral toxicants intended for feral swine. Other bait delivery systems that are currently commercially available use cameras to recognize target species. When the target species is present, the feeder opens. If a non-target species appears at the feeder, it closes. These innovations ensure targeted bait delivery without endangering humans, pets, livestock, or wildlife and show great promise for future implementation as part of control programs.

Another popular form of feral hog mitigation is live trapping. Live traps come in many forms such as cage and corral traps (Stevens 2006). Traps are typically baited with corn or another feedstuff to attract feral hogs. Traps are baited for several days to attract feral hogs prior to setting the traps (Stevens 2006). In the instance of live trapping, technology integration has assisted in increased efficacy. Suspended traps such as the BoarBuster® combine advantages of a corral trap and drop net in addition to using a motion detector and camera system so the trap can be dropped remotely. As trap designs become more effective at catching feral swine, more affordable, and less time consuming, it would seem that live trapping will continue to grow in popularity as a feral swine mitigation technique.

Exclusion is another form of feral hog mitigation. While exclusion does not remove feral hogs from the population, it may protect private property. A combination of mesh wire fencing and electric fence can be used effectively to keep feral hogs out of areas (Mapston 2007). When exclusion fencing is done properly, it can be one of the most effective ways of keeping feral swine out of an area. Actual application of exclusion fencing is limited as the cost of such fencing is very high. In practice, the cost of exclusion fencing may only be beneficial for high value land usage like golf courses or high priced specialty crops such as strawberries.

If a form of hunting, live trapping, or toxicants have reduced the population of feral hogs to a low density, Judas pigs may help remove the remaining hogs that have become trap or bait shy. A hog is captured and fitted with a radio collar then released to be tracked back to the location of other feral hogs (Campbell and Long 2009). While not suitable for areas where feral swine might be difficult to track (i.e. dense brush) or a large population of feral swine still exist, it is a tool that can be employed to reach full eradication in an area.

A plethora of options are available to landowners, government officials, and interested parties to control feral hogs. It would seem that the technology to reduce or eradicate feral swine already exists. Widespread adoption of control methods and cooperation between interested parties to enable eradication seem to be lacking. For the purpose of this paper, we assume current methods are indeed capable of controlling or eradicating hogs where institutions and incentives that induce coordination for affected parties exist. This paper aims to explore the current institutions associated with feral swine control, examine their structures, and discuss possible alternatives.

Current Legislation

Legislation on the trapping, hunting, and control of feral hogs varies by state and sometimes even by county. While laws made at a local or state level may allow flexibility to account for local institutions and customs, the incohesive laws can be confusing. For example, feral swine may have different classifications in different states. Feral swine may be classified as exotic livestock, wildlife, or any number of other categories. These are determined by who actually regulates feral swine at the state level. Byrd et al. (2015) details that at the state level either the feral swine are usually under the jurisdiction of the state department of agriculture or wildlife services. For instance, in the state of Texas feral swine are considered exotic livestock while in the state of Louisiana they are considered outlaw quadrupeds. The difference in the categorization or agency control results in a hodgepodge of state laws and agencies that differ in laws on hunting, trapping, transportation, etc. The difference in these laws may make interstate agency coordination difficult as well as be confusing to private citizens.

Feral Hog Control as an Economic Problem

Control of feral hogs or any resource comes down to a simple problem. When ownership of a resource is not well defined, a tragedy of the commons type problem can occur. Currently, there is no clear party responsible for instigating coordinated control plans for feral hogs. Most frequently, land owners are left to their own actions to decide on how to best manage the feral hog population. Land owners may only choose to engage in control actions until their control efforts result in reducing the marginal cost of feral hog damage to the marginal benefit of engaging in control efforts. In this spirit, if their neighbor(s) does not control for feral hogs, they may find their actions all for naught and not engage in feral hog mitigation tactics.

This lack of coordination among land owners creates a conundrum. Feral hogs may have large ranges that span properties of multiple landowners. Feral hogs are also prolific. Without persistent efforts across a multitude of interest groups, combating the growing population of feral hogs in the contiguous United States may prove futile. It may seem that large scale, top down coordination should produce a universal optimal outcome that would minimize the costs of mitigation and damage caused by feral swine. However, top down coordination often fails when turned to for solutions.

Top down efforts to create regulation and coordination often do not present successful solutions because designers and administrators are unaware of local institutions and cultural norms. Informal institutions arise in local settings and may not be recognized within the ongoings of the formal law (Leonard and Libecap 2015). While not within the "traditional" realm of law, informal institutions may play an important role in coordinating parties and defining property rights.

Analysis of property rights have been performed within the realm of natural resource economics. Both a mixture of private and public institutions exist to govern wildlife populations (Lueck 1995). As illustrated above, laws and regulations regarding the trapping, transportation, hunting, and sometimes the ownership of feral hogs do exist. However, the existence of these laws is not proving to be effective in the control and eradication of feral swine in the United States as demonstrated by the increasing population density and encroachment of feral hogs.

Returning to the scenario mentioned above, suppose a landowner owns property where feral hogs are known to exist. Suppose this landowner owns a piece of property that is large enough to encompass the entire range of a sounder of feral hogs. Since the landowner does not have to contract with neighbors to control feral hogs, they may be more likely to engage in feral hog control. Previous literature by Lueck and Yoder (1997) tend to agree with this pattern of behavior. They argue that large landowners are more likely to internalize the effects of their abatement and wildlife management issues. It should be noted that an assumption is made that the value of the land, crop, or activity is high enough that it is economically efficient for a large land owner to control feral hogs. If the land, crop, or activity is of low value, a land owner may have little incentive to perform eradication or control. While this decision does not lead to an optimal socially efficient outcome, it does maximize the individual landowner's utility.

In an ideal world with perfect information (knowing where feral pigs are, how your neighbor is reacting, etc.) and zero transaction costs, landowners could coordinate control efforts across a patchwork landscape of ownership. Efficient outcomes could occur even if feral hogs spread across multiple properties. However, transaction costs are indeed ever present and therefore must be considered when talking about an institutional structure to control feral hog populations.

While there could be benefits from cooperative private actions among landowners, an asymmetric information problem currently exists in many places. One party may be well informed about the number of feral swine on their property and control methods appropriate for the land type, a neighbor may be unaware of the scope of the feral hog problem on their own land, making it difficult to create a plan that benefits both parties. With no asymmetric information problem, coordination could lead to sustainable control of feral hogs in a cost effective manner. The cost of creating and enforcing an agreement to control feral hogs could be prohibitive to private landowners. The anecdotal necessity of having all landowners in an area participate in control efforts for successful population control or eradication provides a strong disincentive for producers to engage in such an arrangement. Proven effective strategies such as aerial hunting, large corral traps, and potentially poison are costly in terms of dollars and time spent by a landowner. In addition, experience or specialized knowledge is often necessary for successful use of feral hog control tools. In areas where small parcels of land are held, there may be many landowners involved in such an agreement to take coordinated efforts. Without such an agreement that calls for joint action, each individual would most likely underinvest in feral swine control.

When costs of contracting are high between parties, no action will be taken, and it may be best to vest the power to act in a third party such as a government agency. Some of these programs already exist in relationship to feral hogs. For example, USDA APHIS was awarded $20 million in 2014 for the creation of a national feral swine damage management program. The goal of this program is to "protect agricultural and natural resources, property, animal health, and human health and safety by managing damage caused by feral swine in the United States." Transferring control and coordination decisions to a public agency such as USDA APHIS has potential benefits. In giving control to a public agency the number of decision makers is reduced, which simplifies the coordination process (Lueck and Yoder 2015). However, assignment of responsibilities to a third party such as a public agency may create incentives that detract from its potential gains.

Trappers hired by federal or state agency do not have incentives to aim for complete eradication of feral swine. In fact, eradication of feral hogs would leave trappers in search of other employment opportunities. In addition, public programs for control or eradication of wildlife lessen the incentive for private landowners to control or eradicate feral swine as the landowners no longer bear the full brunt of cost.

Implications for Control and Eradication

Government control of feral hogs has been successful in some contexts. For example, using an integrated wildlife damage management approach with monitoring at the local, state, and federal level, the APHIS Wildlife Management Program has eliminated feral swine in seven states over the past three years. It should be noted that the states where eradication occurred are "fringe states." These are states that have typically been at the edges of feral swine's creep upwards such as Michigan that had low population levels of feral swine. While these states may be considered victories in slowing the spread of feral swine in North America, these are not traditional high density populations of feral swine where eradication has been achieved. As demonstrated above, current government intervention fails in other contexts. The legislation passed by states such as Texas, Oklahoma, etc. has not been enough to stop population growth. These laws have very few incentives and even fewer enforcement mechanisms for parties affected by feral swine.

Elinor Ostrom (2015) suggests that total privatization and government control are not the only possibilities in cases such as these. The problem with feral hogs is similar to that of the tragedy of the commons. Imagine a landowner with feral swine present on their property. Depending on distance from neighboring properties and established communications with neighboring parties, they may or may not know whether or not neighbors are experiencing damage from feral swine. If swine damage is being experienced, without monitoring, a landowner does not know if a neighbor is participating in abatement techniques. Why would a landowner incur the cost of trapping, shooting, poisoning, etc. of feral hogs if other affected parties do not do the same? Inevitably, there will be free riders who depend on other people to take action. Little to no recourse exists if a neighbor does not participate in control or eradication of feral swine. Ultimately, in this scenario with no mechanism for parties affected to coordinate, Hardin's tragedy of the commons will occur. While no over depletion of resources occurs in this scenario such as the classic examples of overgrazing and overfishing, there is no question that logic that leads to the tragedy of the commons is involved.

The dilemma created by the tragedy of the commons-esque logic in the case of feral hogs leaves us asking what type of institutions could arise or be erected that might lead to successful cooperation of affected parties. Tarko (2017) states that sometimes such a social dilemma can be solved when people discover rules that align their personal interests with broader social goals. In this case, creating incentives and institutions that encourage eliminating feral hogs on personal property in order to achieve a larger goal of feral hog population control. Feral hog infestation occurs over a widespread area geographically. It follows that there is no "one size fits all" solution or plan that will achieve success in every situation. Consequently, while some overarching order to feral hog control programs may be necessary from a state, federal, or even international level, local institutions that reflect a set of incentives that encourages affected parties to participate will be crucial in the success of feral swine control.

Looking across the landscape of invasive species, there have been incentives proposed for the control of similarly destructive species. For example, in the country of Australia, kangaroos are considered pests that compete with sheep or crop production (Grigg 1996). Since they are indigenous to Australia, management of kangaroos differs from feral swine as complete eradication is not wanted. In order to encourage keeping kangaroo populations at a manageable level as well as ensure conservation of the species, it has been proposed that landowners become producers of kangaroo products to receive an economic return from their presence and management (Ampt and Baumber 2006). The majority of kangaroos harvested end up as pet food however a market does exist for consumption of kangaroo meat by humans (Ampt and Baumber

2006).

This proposal reflects sentiments that many echo in the control of feral hogs. In fact, buying stations for feral hogs do exist in the state of Texas reports the *Lubbock Avalanche Journal*. In 2016, it was reported that over 100 buying stations existed for feral hogs in the state of Texas. All feral swine purchased by buying stations must undergo a USDA inspection prior to being slaughtered. In addition, feral hogs must be brought to buying stations live as the inspection is required to be pre-mortem in order to meet the Federal Meat Inspection Act (Byrd et al. 2018). Therefore, feral swine must be trapped live and transported to the processing facility. While someone who traps feral hogs does not incur the costs of raising and feeding the pigs, the costs of baiting, trapping, and transporting coupled with the fact that hogs might not be saleable (due to disease, size, etc.) may not provide much economic incentive for people to sell feral hogs they trap. In addition, the raising of domestic swine in the United States has become quite efficient due to genetic selection, superior nutrition, and husbandry techniques. Pork consumers are accustomed to a uniform, affordable product. It is unlikely that many consumers are going to change their preferences to a more inconsistent, unfamiliar product and thus the market for feral swine meat is likely to provide insufficient incentive to control feral swine.

While attempting to generate consumer interest into feral swine meat may not be the "end all be all" solution to feral swine control and eradication, it may be a piece to the puzzle. Scriven (2018) describes another possible solution that has been implemented in Australia with some success. Thousands of miles of predator fences have been erected in Australia. Predator fences are high fences with buried skirts to prevent animals from slipping under. Once erected, animals can be kept out (or in to be eradicated) of an area. Federal, state, and local governments in Australia have been working with landowners to create islands of predator fences. Landowners form “body corporates” to decide how to proceed with cooperative eradication methods across these islands utilizing trapping, hunting, and poisoning.

Reports of other types of arrangements have been reported in the United States in regards to the control of feral swine. Stories of landowners near Electra, TX coordinating efforts to participate in aerial shooting across their private properties have been reported along with a reduction of feral swine in their area. A church group in Texas called “Hogs for a Cause” coordinates trapping, hunting, and processing on private properties to provide meat for their local food bank. While certainly this is not the traditional market coordination where prices dictate actions of participants, it is reflective of public planning from “the bottom up.”

The types of arrangements described above may actually allow eradication of feral swine in certain areas of the country. Feral swine in the United States can be considered a mobile public bad. Costello et al. (2017) categorizes fire, infectious diseases, and invasive species as mobile public bads. Mobile public bads are categorized by their mobility and renewability such as the feral hogs ability to travel and reproduce quickly. Costello et al. (2017) illustrates that the socially optimal level of control will be less than that taken by decentralized owners. Their paper creates scenarios in which decentralized owners may be willing to participate in total eradication of a mobile public bad. They find that eradication of a public bad can occur without coordination if damages are sufficiently large to all property owners. If damages are sufficiently small, decisions made by decentralized owners will lead to a level of control that would be similar to that of a single landowner. If cost of damage is moderate, decisions made by central landowners will lead to outcomes far below the socially optimal outcome.

The public bad of feral swine fall under this last category. The decisions made by many landowners suggest that while the cost of feral swine on their property may be substantial, the damages are not so great that a majority of landowners are participating in control or eradication efforts. Costello et al. (2017) suggests in these scenarios that side payments from one landowner to another that are Pareto improving may induce coordination among landowners and allow for successful control or coordination.

While one might be able to imagine such a payment system, the problem of feral swine provides an additional layer of complexity. For some landowners, feral swine are a mobile public bad. For other landowners that receive sufficiently large profits from hunting operations, meat products, etc. feral swine are actually a mobile public good. Consequently, relabeling feral swine as a mobile public bad for all landowners may be necessary to engage landowners in coordinated effort in control or eradication. Some states have already began this process. For example, the state of Nebraska has a “no-hunt” law for wild pigs. No hunt laws prevent landowners from profiting from the hunting of wild pigs and discourages them from being a public good. While seemingly counter intuitive, changing the legal status of feral swine as the federal level to “invasive species” and implementing no hunt laws may actually increase control efforts at the local, state, and federal level of feral swine.

Changing legal statutes recognizes the challenge feral hogs present to landowners, communities, and other stake holders and may assist in creating an environment that is conducive to control and eradication efforts. Relabeling feral swine as an “invasive species” does not guarantee coordination from individuals to participate in abatement programs. Abatement programs for predator control in North America date back to the Massachusetts Bay Colony in 1630 (Yoder 2000). Research by Yoder (2000) focuses on livestock producer incentives for cooperative abatement of predator-inflicted livestock loss. While feral hogs are responsible for predation loss, their damage extends to loss of wildlife, destruction of neighborhoods, spread of disease, and crop loss. However, Yoder's research (2000) on attributes that increase the value of predator control contracts gives insights into scenarios what coordinated efforts that lead to successful feral swine abatement techniques might be.

Yoder (2000) considers an assessment contract where producers pay a fee for a unit of monitorable input such as per livestock head or acre. This fee is redistributed for abatement purposes and when assessment is costless, in a joint maximization problem, an efficient allocation of abatement levels and inputs can be found. Yoder finds that voluntary predator abatement occurs mostly in situations with a small set of cooperators that have a strong desire for long term relationships. Anecdotal evidence from feral hogs seems to support this. Situations like the Hogs for a Cause or landowners gathering to put up large sections of predator fencing where a small group of people with a homogenous intent can keep contracting costs low are examples of voluntary informal institutions that arise.

For the control of feral swine, a mandatory contribution to an abatement program might be more useful due to the diverse nature of affected parties. Feral hogs' ability to easily move to a property where control techniques are not practiced causes potential for positive benefits if abatement techniques were practiced on all properties. However, the adaptability of feral hogs to a variety of living conditions makes this much more difficult than previous mandatory assessments for predators. While affected parties such as ranchers or farmers who own large tracts of land could be assessed for abatement by acre owned, what about suburban neighborhoods, recreational businesses such as golf courses, and other more urban areas that feral hogs have begun to encroach upon? Another point of debate is whether the assessment should be public or private. Public assessments done by a government agency have access to information like tax records and land holdings which may be useful in determining the amount of input (acreage or other unit used) to assess (Yoder 2000). Land property values may also prove to be a more fair way to assign payments for an assessment. Since feral swine encroachment is spread over a variety of different ecosystems, land usage types, densities of human populations, and habitats, damages will be unequal across the landscape (Kaiser and Burnett 2010). This type of spatial variation in damage and density of the feral hog population makes a uniform blanket policy concerning feral swine problematic. The variation in appropriate removal techniques of feral hogs also prohibits a uniform policy from being very effective. While ranchers with significant property holdings that is composed of open range might be able to effectively utilize aerial gunning, a golf course located in a suburban neighborhood will most likely need to use live traps for feral hog removal purposes.

The ambiguity surrounding the precise population of feral swine in any given area also makes designing a policy difficult. For individuals who have large, undeveloped landholdings, monitoring costs may be very high resulting in imperfect information concerning the level of infestation. Landowners may notice signs of rooting or down fences as evidence of the presence of feral hogs. Determining the actual amount of feral hogs can be done by placing game cameras. However, monitoring and identifying sounders on camera may take several weeks as well as be high cost due to the need to buy multiple cameras.

Conclusions

High costs of monitoring, spatial variation in feral swine density, and diverse land uses make it challenging to determine an appropriate policy or institution for feral swine eradication or control. In a perfect world, landowners would coordinate to privately eradicate feral swine. However, several characteristics of feral hogs make the scenario where private contracting would be feasible and the formation of local institutions (across the United States as a whole, we have seen instances where sets of incentives and enforcement have been created by individuals to control feral swine in certain areas) would have a crucial roles in eradication efforts not possible. First, the adaptable and mobile nature of feral swine allow them to inflict damage in an inconsistent manner across a variety of land types. Secondly, the high costs of trapping, monitoring, and knowledge necessary to be successful at control efforts often outweigh the costs of damages from feral swine for an individual landowner. In these instances, feral swine may use these properties where control techniques are not being utilized as havens. These havens may become sources of re-infestation despite neighbors' efforts for eradication. Thirdly, as long as individuals continue to profit from the hunting of feral swine, populations of feral swine will continue to crop up. With the high reproductive and survival rates of feral swine, escapees from fenced ranches and instances where people transport and release hogs can cause feral hogs to appear where they previously have not been or have already been eradicated.

Ultimately, a public assessment similar to the cost share contracts described by Yoder (2000) that reallocates abatement resources may be the best fit for the feral swine problem. One could also imagine that through a public agency or entity that would enforce this assessment, resources for baiting techniques, trap sharing, and other specialized knowledge that makes the likelihood of successful feral swine control could be shared as well.

Continued work in areas where the presence of feral hogs is new or limited such as in fringe states should be continued. Potential exists for improved incentives for people to not raise or release feral swine. Labeling feral hogs as invasive species and instating no hunt laws universally would assist in discouraging perverse incentives and promote control.

CHAPTER II

THE RAINFALL INDEX ANNUAL FORAGE PROGRAM

Abstract

The Rainfall Index Annual Forage Program (RIAFP) is designed to compensate forage producers when they have yield losses. Prior research found a weak correlation between the rainfall index and actual forage yields. Our research utilizes long-term variety trials of rye, ryegrass, wheat, triticale and oats with rainfall recorded on site to test whether the current structure of the RIAFP is effective in providing adequate coverage for annual forage growers. In addition, an alternative index based on frequency of precipitation events and an index consisting of number of days where temperature falls below 32 degrees Fahrenheit are tested to examine their ability to predict forage yields. The correlation between actual rainfall and the current RMA index was positive and significant. Most of the coefficients for the intervals created by using the current RMA index were highly significant and positive for the wheat forage regressions. Signs and significance of coefficients associated with the RMA intervals were mixed for rye, ryegrass, oats, and triticale. Little significance was found for early season intervals constructed from rainfall frequency events. However, a precipitation event in the November-December interval was found to have a positive impact upon forage yields while a precipitation event in the January-February interval was found to have a negative impact upon forage yields for observations from locations

in southern Oklahoma. Intervals constructed from days where the temperature fell below 32 degrees Fahrenheit were negative and significant for November-December, December-January, January-February, and February-March intervals for oats, rye, triticale, and wheat. Overall, the lack of significance of intervals across all indexes suggest there is still a need for a variable that can more accurately predict forage yield losses in order to assist producers in protecting against forage yield losses.

Problem Statement

Increasing pressure from multiple agencies, programs, and other interests create competition for federal and state funding. In times of budget cuts, the survival of a program may be based upon its ability to meet its stated objective. Analysis of the effectiveness of funded programs can be a useful decision factor. In particular, some have questioned the efficiency of agricultural programs designated to assist producers in managing risk.

Some recent research has called one such program, the Rainfall Index Annual Forage Program (RIAFP), into question. The RIAFP is currently available in the states of Texas, Oklahoma, Kansas, Nebraska, South Dakota, North Dakota, and Wyoming. The program aims to provide insurance for forage producers. The RIAFP offers catastrophic risk (CAT) protection and buy-up coverage to a group of previously underserved producers. The program covers annually planted crops that are used for livestock feed including grasses, mixed forages, and small grains (Campiche and Jones, 2014). The RIAFP utilizes rainfall indices from weather data by the NOAA. Maples, Brorsen and Biermacher (2016) found that RIAFP was successful in transferring income to participating forage producers, but they did not find a correlation between rainfall and forage yield, so RIAFP was risk increasing rather than risk reducing. Is the premise that forage yield is correlated with monthly precipitation a false assumption? Before reaching such a conclusion, however, it is important to note that the study conducted by Maples, Brorsen and Biermacher (2016) only studied one site on sandy soil. Inclusion of multiple sites with different soil types could provide information on the robustness and generality of their findings. In addition, a different index such as one reflective of the frequency of rain or temperature might be a stronger predictor of yield. Schlenker and Roberts (2009) find yields decline above threshold temperatures for corn, soybeans, and cotton. These findings provide a premise for further exploration into factors that may influence forage yields.

The first purpose of this research is to determine if the RIAFP provides production coverage risk for producers. By adding additional years of observations and multiple crop types across several locations, the relationship between forage yields and rainfall may be better understood. Measuring rainfall as frequency of rainfall and including days with freezing temperatures are possible ways to better predict yields. Implications of this research may be useful to policy makers to assess the effectiveness of RIAFP.

Index Based Insurance

Index insurance differs from the traditional structure of contract insurance by paying indemnities not on actual verified losses but on a variable that is correlated with actual losses (Barnett and Mahul 2007). In agriculture, the correlated variable is often a specific weather outcome such as temperature or rainfall. Weather index insurance would specify intervals of the index over which indemnities would be paid. No indemnities would be paid for the actual loss of an insured producer.

Motivation for Index Based Insurance

In agriculture, weather events such as rain, drought, floods, and freezing often cause yield losses that lead to the desire for insurance. Conventional insurance contracts consist of the insured party paying a premium and receiving an indemnity based on losses. However, this traditional structure often suffers from moral hazard and adverse selection. Moral hazard arises when after purchasing insurance, a producer may behave in a manner consistent with increasing their chances of receiving an indemnity (Smith and Goodwin 1996). In addition, producers have greater knowledge of their production practices than an insurer therefore giving producers a better idea of the actuarial fairness (Makki and Somwaru 2001) which leads to adverse selection. Index insurance prevents policyholders from having advantageous knowledge over insurers which eliminates adverse selection (Miranda and Farrin 2012). Index based insurance reduces administrative costs since policyholders do not have to be classified by risk exposure and no assessment or adjustments need to be made (Barnett and Mahul 2007).

Applications of Index Insurance

Index based insurance holds a wide appeal as a combative poverty measure in developing countries where insurance markets may be absent (Chantarat et al. 2012, Hazell and Hess 2010). Indexes linked to weather patterns for both livestock and crop producers in developing countries have been adopted in an attempt to break cyclical poverty. As well as being utilized in developing countries, weather based indices for indemnity payments have been growing in popularity in the United States and other developed nations. China has tested a number of index based agricultural insurance programs. In the United States, the Pasture, Rangeland, and Forage (PRF) Insurance has been implemented to protect livestock and hay producers (Vandeever, Berger, and Stockton 2013). The PRF is similar to the RIAFP except that it is restricted to perennial forage (Carlson 2016). Index insurance for apiculture exists in the United States as well.

Weather Index Insurance Variables

While index insurance may cut insurance costs and prevent moral hazard and adverse selection, the effectiveness of index insurance depends upon a strong correlation between the index and losses experienced by the policy holder. With index based insurance, producers are exposed to two sources of basis risk. First, the weather variable used as an index might not be highly correlated with local weather. Second, the weather variable used might not be correlated with yields such as when losses are caused by something other than the weather variable used i.e. insect infestation (Barnett and Mahul 2007).

The last source of basis risk is the largest concern for the effectiveness of the RIAFP. Maples, Brorsen, and Biermacher (2016) find that the rainfall index used is not a good predictor of annual forage yields; but, the rainfall index is highly correlated with local rainfall. Their data, however, was limited to only one location in southern Oklahoma and a specific mix of species that changed over time. Examining the correlation between the rainfall index and annual forage yields across multiple sites would allow stronger conclusions to be drawn. In other instances, rainfall indices may not reflect all weather events influencing crop yields. Nadolnyak and Vedenov (2013) make the case for accounting for interannual climate variations in the PRF insurance premium calculations. Their models accounted for the El Nino-Southern Oscillation (ESNO) for the southeastern United States. They tested to see whether seasonal rainfall index or ENSO index is a better predictor of forage yields. Their findings show that ENSO indices lead to higher correlation in the long run forecast, supporting the idea that more weather variables beside rainfall may need to be considered.

A Better Alternative?

While rainfall is a popular index to correlate crop yields with for index based insurance, other findings suggest alternative weather variables may be more appropriate than including only rainfall. Schlenkler and Roberts (2009) estimated nonlinear yield functions for corn, soybeans, and cotton in relation to weather. Their research found a threshold temperature to where yields increase and then sharply decline. Another notable factor possibly influencing yields may be soil type. Mäkinen et. al. (2017) observed a variation in forage yield in response to weather depending on the soil type. Their research found differences in preferential growing conditions for the coarse mineral and clay soils. Yields in clay soils were greater with milder winter weather, however, a warmer winter negatively impacted yields from coarse mineral soils. These pieces of literature serve as the premise for inclusion of temperature and observations representing multiple locations with different soil types when estimating a regression for forage yields for the RIAFP.

Conceptual Framework

Following Maples, Brorsen, and Biermacher (2016), a producer's choice of participating in RIAFP is the conceptualized result of expected utility maximization:

$$\max_{A \, \epsilon \{0,1\}} EU\,(\pi) = \iint U\,(\pi)\, f\,(\theta)\, dIdY,$$

where the arguments are defined with the following equality constraints:

$$\pi = PY + Ak - \boldsymbol{r}'z$$

$$\theta = (I, Y)$$

$$U'(\pi) > 0,\ U''(\pi) < 0,$$

where E$U(\pi)$ is expected utility of profit; *I* is the rainfall index value; *Y* represents the forage yields; $f(\theta)$ represents the joint density of the rainfall index variable and forage yields; *P* is the price of forage; *A* represents the discrete choice of a producer choosing to participate in the program; *k* is the indemnity payout per acre; ***r*** denotes a vector of other input costs; ***z*** is a vector of quantities of other inputs. From the above utility function, an indemnity will be triggered when the rainfall index falls below the producer's chosen level of coverage. The indemnity payoff will vary by payoff coverage level chosen by the producer and allow the above model to be estimated based on the producer's choice of intervals as well as coverage level.

The relationships between the rainfall index, forage yields, and actual rainfall are represented in the joint distribution of θ. Weak correlations between forage yields and the rainfall index or local rainfall and the rainfall index expose insured producers to basis risk. Without correlation between forage yields and the rainfall index, no incentive would exist for a producer to choose RIAFP coverage if the program was unsubsidized. However, if the insurance program is subsidized, the program may still be beneficial to producers as it could transfer income.

Methods

<u>Data</u>

Some of the data are from ryegrass, wheat, triticale, oats, and rye variety trials at the Noble Research Institute's Red River Farm, Dupy Research Farm, and Headquarters Farm. Trials at the

Red River Farm located near the community of Burneyville were started in 1994. Trials at the Dupy Research Farm located near the community of Gene Autry were started in 2007. Trials at the Headquarters Farm located near Ardmore began in 1966. All Noble Research Institute trials were continued through 2016. Maples, Brorsen, and Biermacher (2016) used data from the same Burneyville location, but their data was from a nitrogen-trial experiment whereas we are using variety-trial data. The rest of the data set is compiled from Oklahoma State University forage variety testing. Trials for wheat varieties were conducted at the South Central Research Station in Chickasha, Oklahoma and at the Cimarron Valley Research Station in Perkins, Oklahoma. Data from the South Central Research Station was recorded from 1990 to 2003. Data from the Cimarron Valley Research Station was recorded from 1989 to 2003.

Soil type varies by location. The Ardmore location has Wilson silt loam soil, the Burneyville location has Minco fine sandy loam soil, and the Gene Autry location has silty clay loam soil. The Chickasha location soil consists of the Dale and Mclain series with a silty clay loam soil. The Perkins location soil is Teller loam. The data set includes nitrogen application, planting dates, clipping weights, and harvest dates for over 50 years, 4,834 plots, and over 1,406 different varieties of forage (Table II-1 and II-2). For the plots, nitrogen was applied as a granular top-dress. The amount of nitrogen is the same for all plots at a single location in a given year. Amount of nitrogen applied varied by location and year. Seeding rate varied by species by year.

To mimic the forage seasons designated by the RIAFP, the plot forage yields were split between clipping seasons. All plots were planted in the months of August, September, or October across all years. For each plot, fall forage yields are categorized as those clippings prior to March 1. Spring forage yields are clippings that occurred after March 1 and prior to the end of May. The annual forage yield observation for a plot is created by summing fall forage yields and spring forage yields. For our purposes, the average sum of fall forage clipping creates one observation for the growing season.

The fall forage yields in the dataset match the definition of the forage grown during season one of the RIAFP. For growing season one, two month rainfall intervals are constructed using local rainfall data from September to March by summing the precipitation occurring in that time period. These intervals mirror the current RMA indices used by the RIAFP. In addition to constructing intervals of local rainfall, an alternate index composed of frequency of rainfall is constructed. The number of precipitation events are summed across the two month periods starting in September and ending in March. This alternative structure addresses the limitations of the previous research of Maples, Brorsen, and Biermacher (2016). The previous experiment location had quick draining sandy soils which may have led to low correlations between rainfall and forage yields in their research. If water does not stay within the soil structure, forage yields may be more dependent on the frequency of rainfall events instead of only the total precipitation within an interval.

To incorporate more information about climate, a measure of temperature expected to affect forage growth was created. Two month temperature intervals like the rainfall measures above for the months of September through March were created by summing the amount of days that had a minimum temperature below 32 degrees in a two month time period. It is a wide held assumption by many plant physiologists that forage growth is possible at temperatures near but above freezing. If temperature impacts forage yields, an index based upon temperature may better protect forage producers from basis risk.

Empirical Model

Effectiveness of the RIAFP in reducing risk requires positive correlation between forage production and the rainfall index. Since five different types of forages are included in the dataset, separate regressions are used for oats, triticale, rye, ryegrass, and wheat. The current RMA indices can only be considered feasible if they reflect the rainfall experienced at the actual site. Determining the correlation between RMA indices and the actual rainfall can be done using Pearson product-moment correlation as specified by

$$r = \frac{n(\sum R_t Y_t) - (\sum R_t)(\sum Y_t)}{\sqrt{[n \sum R_t^2 - (\sum R_t)^2][n \sum Y_t^2 - (\sum Y_t)^2]}} \qquad (1)$$

with *r* being the Pearson product-moment correlation, and n is the necessary number of observations. The Pearson product-moment correlation will be used to estimate the relationship between the rainfall index and actual rainfall.

To determine if the current RMA index structure predicts forage yields well, the following nonlinear model will be estimated. This model will mimic a producer's participation in the program by regressing forage yields on three chosen RMA intervals. In addition to accounting for rainfall, adjustments to the model must be made for planting date, time trend, amount of nitrogen applied, seeding rate, and location. The basic model estimated is:

$$Y_t = \beta_0 + \beta_1 t + \beta_2 D_t + \boldsymbol{\beta_3' R_t} + \beta_4 N_t + \beta_5 S_t + d_1 D_{1t} + d_2 D_{2t} + \nu_t, \qquad (2)$$

$Y_t = \beta_0 + \beta_1 t + \beta_2 D_t + \boldsymbol{\beta_3' R_t} + \beta_4 N_t + \beta_5 S_t + d_1 D_{1t} + d_2 D_{2t} + \nu_t$,where *t* denotes time; Y_t is the average forage yields; D_t is the number of days between the planting date and August 29 of each year; N_t is the amount of nitrogen applied (kg ha^{-1}); S_t is the seeding rate; D_{1t} and D_{2t} are dummy variables that account for the different locations; and ν_t is the error, where $\nu_t \sim N(0, \sigma_t^2)$ and $\sigma_t^2 = \alpha + \kappa(\frac{1}{N_t})$ (Richter and Brorsen 2006) where α and κ are parameters to be estimated and N_t represents the number of plots used to compute Y_t. Since our data does not have a consistent number of observations (i.e. some years may have multiple plots of certain varieties while only one of others) estimation will be done using NLMIXED Procedure in SAS. In doing so, the heteroskedasticity caused by the different number of plots each year will be accounted for in the analysis.

Requirements of the RIAFP for growing season one stipulate that three intervals must be chosen from the September to March period, therefore, two scenarios must be estimated. One scenario will leave out the month of September and the other will leave out the month of March. The above models will be estimated with the RMA index intervals, the rainfall frequency index interval, and the temperature index intervals to determine the signs of the coefficients and their ability to predict forage yields.

Results and Discussion

Table II-3 reports the estimated Pearson correlation between the rainfall index and actual rainfall for the RIAFP intervals that producers may select at each location across all years. Burneyville, Ardmore, Gene Autry, and Perkins locations have high positive correlations between the rainfall index and actual rainfall across all intervals. The November-December and February-March intervals for the Chickasha location show less positive correlations, indicating that the rainfall index is not as good of an indicator for local rainfall as it may be at the other locations or during different intervals. This lower correlation may be due to the location of the four NOAA stations used to compute the index in relationship to the actual plot site.

To examine the relationship between the RMA indices and forage yields, Table II-4 and II-5 provide the regression coefficients for the effects of the RMA index variables, planting date, seeding rate, nitrogen levels, location, and time trend. In the scenario where the intervals for September-October, November-December, and January-February (Table II-4) are selected, no significance is found for RMA index variables for oats and rye. Ryegrass presents a weakly significant, negative RMA index for the November-December interval indicating that for a one percent increase in the RMA index over this time period in the rainfall index leads to a loss of approximately six pounds of forage yield per acre. Table II-4 also shows that for Noble Research Institute plots for triticale had a positively significant September-October interval and a negatively significant January-February interval. At both Noble Research Institute and Oklahoma State University wheat plots, all RMA intervals are significant. Signs are not the same across the wheat intervals. At the Noble Research Institute, the September-October, October – November, November-December, and December-January intervals were all positive. The January-February interval for wheat plots at the Noble Research Institute locations were negative while positive at the OSU plots. December-January RMA intervals (Table II-5) are positive and highly significant across all wheat plots, oats, rye, and triticale. The February-March RMA interval is negative and significant for the Noble Research Institute wheat, oats, triticale, and rye. The February-March RMA interval is positive and significant for the OSU wheat plots. Significant positive intervals soon after planting could be because the rainfall occurred in a timely manner to allow for the grains to germinate. Negative significant coefficients in later months could be associated with a precipitation event such as snowfall or light freezing rain. The conditions related to these precipitation events could be detrimental to forage growth. While the

RMA intervals are not consistently significant across oats, rye, ryegrass, and triticale, the highly significant intervals for wheat could be promising for wheat specific RMA index.

Coefficients for rainfall frequency intervals for September-October, November-December, and January-February have more significance than their RMA interval counterparts (Table II-6). The September-October rainfall frequency interval for ryegrass and wheat is both highly significant and positive. This implies that for each additional precipitation event that occurs, pounds of forage produced increases. The November-December interval for oats, rye, triticale, and wheat (Noble Research Institute) are significant and positive. The November-December interval for the OSU wheat plots is significant and negative. The January-February rainfall frequency interval is negative and significant for all Noble Research Institute crops, except for ryegrass, and negative and significant for the OSU plots. Coefficients for rainfall frequency intervals for the October-November, December-January, and February-March have little significance (Table II-7). The October-November and December-January rainfall frequency interval coefficients are negative and significant for ryegrass. These findings coupled with the results from Table II-4 and Table II-5 seem to stress the timing of rainfall events may be more important than the amount of rainfall.

Table II-8 and Table II-9 provide the coefficient estimates for the temperature index. The November-December and January-February intervals for oats and ryegrass are significant and negative meaning that for each day where the minimum temperature reaches below 32 degrees Fahrenheit, the forage yields decline. The September-October interval for both the Noble Research Institute and OSU wheat plots are weakly significant and positive. The November-December and January-February intervals for wheat plots are strongly significant and positive. The December-January and February-March intervals for oats and ryegrass are significant and negative. Noble Research Institute and OSU wheat plots for December-January and February-March intervals are negative and highly significant. The October-November interval for the Noble Research Institute wheat plots is significant and positive. Oats, ryegrass, and wheat seem to more susceptible to cold days affecting forage growth. The temperature index does little to predict forage yields for triticale and rye.

Across all indices, variables such as time trend, planting date, seeding rate, and location dummy variables are highly significant. The time trend coefficient is often negative across the Noble Research Institute plots. This suggests, on average, lower forage yields were experienced each consecutive year. One possible explanation for the lower yields could be due to the soil becoming more acid as time went on due to a lack of lime application. Consistent lime application data and soil pH data is not available for most plots so this cannot be confirmed. Another possible explanation comes from the nature of the small grains variety trials. Each year the varieties planted were subject to change. Some varieties may have been planted to look at attributes other than maximum forage yields. Most varieties were not planted every year and the number of plots planted of any one species varied greatly from year to year. The negative time trend could be attributed to either of these explanations.

Across all regressions for the OSU plots, the planting date coefficient was significant and positive. Planting date coefficients were also significant and positive for the Noble Research Institute wheat plots for the models using RMA intervals (Table II-4 and II-5) and when the September-October, November-December, and January-February (Table II-6) intervals were selected. This suggests that wheat was often planted too early. The significant and negative planting date coefficient for ryegrass indicates that it was often planted too late. Seeding rate was also often significant and positive, save for ryegrass observations, which implies the plots were seeded at a less than optimal rate. For the Noble Research Institute species, the dummy variable coefficient associated with the Gene Autry location was always significant and positive indicating that on average forage yields were greater there in comparison to the Burneyville location. The dummy variable coefficient estimated for the Burneyville location for the triticale and wheat regressions were almost always negative and significant indicating on average forage yields were lower there than at the Red River Farm. The dummy variable coefficient estimated for the OSU plots for Perkins is consistently significant and negative indicating on average forage yields were lower there then the Chickasha location. The differences in location may be in part due to the varieties selected to be planted at each location and difference in soil types.

Conclusions

As found by Maples et al. (2016), the rainfall index is well designed because it has a high positive correlation with actual rainfall. The lack of significance of RMA intervals, except for wheat, and some instances of negative correlation indicates that the current program is not well designed to assist producers in mitigating risk. Precipitation frequency and temperature intervals do not predict forage yields much better than the current RMA index. Without variables that have a strong ability to predict forage yields, a program intended to assist cool-season annual forage producers in protecting against yield loss will not meet its intended goals.

Table II-1. Descriptive Statistics for Oats, Rye, and Triticale

Variable	Mean	Standard Deviation	Minimum	Maximum
Oats				
Average forage yield (pounds/acre)	4186.39	1474.76	0	9354
Average actual rainfall (inches per two month period)	5.33	1.95	1.61	10.3
Average rainfall index	102.98	38.74	31.02	193.98
Average rainfall frequency index (rainfall events per two month period)	11.21	3.28	5.00	18.50
Average temperature index (number of days below 32 degrees Fahrenheit in a two month period)	16.37	4.61	9.17	26.83
Rye				
Average forage yield (pounds/acre)	5257.61	2485.06	819	16614.56
Average actual rainfall (inches per two month period)	5.45	1.94	1.61	10.3
Average rainfall index	105.36	38.99	31.02	193.98
Average rainfall frequency index (rainfall events per two month period)	10.97	3.19	5	18.5
Average temperature index (number of days below 32 degrees Fahrenheit in a two month period)	16.79	4.89	7.33	27.0
Triticale				
Average forage yield (pounds/acre)	4823.07	1869.74	137	12012.06
Average actual rainfall (inches per two month period)	5.42	1.91	1.86	10.3
Average rainfall index	106.12	37.90	38.37	193.98
Average rainfall frequency index (rainfall events per two month period)	11.04	3.31	5.00	20.67
Average temperature index (number of days below 32 degrees Fahrenheit in a two month period)	17.04	4.98	9.17	33.83

Table II-2. Descriptive Statistics for Wheat and Ryegrass

Wheat				
Average forage yield (pounds/acre)	4502.79	1891.39	610.00	13946.64
Average actual rainfall (inches per two month period)	4.94	1.74	1.16	10.30
Average rainfall index	100.06	34.39	31.02	193.98
Average rainfall frequency index (rainfall events per two month period)	11.64	3.78	5.00	20.67
Average temperature index (number of days below 32 degrees Fahrenheit in a two month period)	19.20	6.15	7.33	33.83
Ryegrass				
Average forage yield (pounds/acre)	6102.25	1685.43	2619.00	11805.00
Average actual rainfall (inches per two month period)	5.33	1.94	1.61	10.3
Average rainfall index	101.31	36.93	31.02	193.98
Average rainfall frequency index (rainfall events per two month period)	9.56	3.39	5.00	18.50
Average temperature index (number of days below 32 degrees Fahrenheit in a two month period)	17.04	4.98	9.17	33.83

Table II-3. Pearson Correlations between Rainfall Index Intervals and Actual Rainfall Intervals

Months (Cumulative Rainfall)	Burneyville (RMA)	Ardmore (RMA)	Gene Autry (RMA)	Chickasha (RMA)	Perkins (RMA)
September-October	0.94***	0.96***	0.81***	0.96***	0.87***
October-November	0.99***	0.96***	0.85***	0.80***	0.96***
November-December	0.99***	0.95***	0.83***	0.51***	0.87***
December-January	0.97***	0.97***	0.92***	0.95***	0.95***
January-February	0.96***	0.97***	0.89***	0.90***	0.87***
February-March	0.85***	0.94***	0.99***	0.48***	0.96***

Asterisks (∗∗∗, ∗∗, and ∗) denote significance at the 1%, 5%, and 10% levels, respectively.

Table II-4. Coefficients for RMA Intervals 1, 3, and 5 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute Plots					OSU Plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-30177***	-31546***	31597***	-33465***	-6744.22***	-3848.97***
	(8162.38)	(4110.18)	(3363.39)	(2031.04)	(381.86)	(240.74)
September-October interval	-0.44	-1.56	3.83	2.53**	4.26***	-18.11***
	(2.76)	(1.87)	(2.30)	(1.03)	(0.57)	(0.6)
November-December interval	4.41	1.34	-6.07*	1.92	4.74***	-9.07***
	(3.18)	(2.17)	(3.04)	(1.19)	(0.66)	(0.72)
January-February interval	-0.32	-3.09	-0.12	-3.22***	-5.62***	17.19***
	(3.03)	(2.03)	(2.36)	(1.11)	(0.61)	(0.18)
Planting days from August 29	16.22	17.44	-123.06***	0.78	51.43***	79.67***
	(23.32)	(15.61)	(23.44)	(8.48)	(4.99)	(0.90)
Seeding rate	302.9***	356.44***	-613.02***	376.55***	101.94***	84.57***
	(74.87)	(42.18)	(83.78)	(21.19)	(3.69)	(3.08)
Nitrogen	0.54	2.98	4.07	1.96	4.41***	-7.54***
	(4.74)	(3.19)	(3.02)	(1.73)	(0.97)	(0.21)
Burneyville dummy variable	-374.93	329.2	-	-601.63***	-1103.66***	-
	(463.66)	(315.83)	-	(164.42)	(94.31)	-
Gene Autry dummy variable	1706.73**	2889.91***	-	2340.39***	1346.21***	-
	(791.48)	(534.77)	-	(290.26)	(162.28)	-
Perkins dummy variable	-	-	-	-	-	-236.35***
	-	-	-	-	-	(23.35)
Time trend	-63.577***	-83.78***	-184.83***	-94.75***	-74.17***	0.27***
	(22.29)	(16.07)	(27.71)	(9.51)	(4.83)	(0.06)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses.

Table II-5. Coefficients for RMA Intervals 2, 4, and 6 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute plots					OSU plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-35693***	-31832***	28708***	-30293***	-6241.05***	-6124.28***
	(7598.69)	(3571.94)	(2226.32)	(2135.81)	(511.85)	(116.78)
October-November interval	-0.75	-2.76*	7.41***	0.47	2.23***	-3.38
	(2.49)	(1.61)	(2.02)	(0.92)	(0.74)	(0.12)
December-January interval	7.71***	4.79***	-2.51	3.05***	3.58***	2.32***
	(2.58)	(1.63)	(2.07)	(0.92)	(0.74)	(0.11)
February-March interval	-6.82*	-8.27***	-2.65	-10.11***	-8.62***	12.78***
	(3.82)	(2.46)	(2.04)	(1.42)	(1.13)	(0.23)
Planting Days from August 29	18.34	23.19	-82.04***	9.50	54.27***	55.64***
	(21.86)	(14.06)	(20.19)	(7.94)	(6.78)	(0.67)
Seeding Rate	355.82***	360.34***	-572.23***	350.19***	101.27***	86.01***
	(69.93)	(36.87)	(60.56)	(22.31)	(5.00)	(1.07)
Nitrogen Application	1.59	4.18	1.21	2.84*	6.44***	-3.52***
	(4.40)	(2.84)	(2.29)	(1.60)	(1.32)	(0.12)
Burneyville dummy variable	-386.51	473.32*	-	-395.5**	-962.15***	-
	(429.18)	(280.61)	-	(154.97)	(127.65)	-
Gene Autry dummy variable	1918.4***	3167.03***	-	2476.36***	1710.71***	-
	(732.2)	(474.83)	-	(267.88)	(217.86)	-
Perkins dummy variable	-	-	-	-	-	-636.67***
	-	-	-	-	-	(16.92)
Time trend	-80.90***	-91.19***	-166.84***	-93.84***	-81.12***	0.05***
	(21.13)	(14.28)	(19.32)	(9.52)	(6.56)	(0.01)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses.

Table II-6. Coefficients for Rainfall Frequency Intervals 1, 3, and 5 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute plots					OSU plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-35693***	-31832***	28708***	-30293***	-6241.05***	-12233***
	(7598.69)	(3571.94)	(2226.32)	(2135.81)	(511.85)	(82.55)
September-October interval	-0.75	-2.76*	7.41***	0.47	2.23***	3.86
	(2.49)	(1.61)	(2.02)	(0.92)	(0.74)	(2.56)
November-December interval	7.71***	4.79***	-2.51	3.05***	3.57***	-177.14***
	(2.58)	(1.63)	(2.07)	(0.92)	(0.74)	(1.50)
January-February interval	-6.83*	-8.27***	-2.65	-10.11***	-8.62***	74.89***
	(3.82)	(2.46)	(2.04)	(1.42)	(1.13)	(1.11)
Planting Days from August 29	18.34	23.19	-82.04***	9.50	54.27***	107.8***
	(21.86)	(14.06)	(20.19)	(7.94)	(6.78)	(0.46)
Seeding Rate	355.82***	360.34***	-572.23***	350.19***	101.27***	159.94***
	(69.93)	(36.87)	(60.56)	(22.31)	(5.00)	(0.83)
Nitrogen Application	1.59	4.18	1.21	2.84*	6.44***	2.37***
	(4.39)	(2.84)	(2.29)	(1.60)	(1.32)	(0.13)
Burneyville dummy variable	-386.51	473.32*	-	-395.5**	-962.15***	-
	(429.18)	(280.61)	-	(154.97)	127.65	-
Gene Autry dummy variable	1918.4**	3167.03***	-	2476.36***	1710.71	-
	(732.2)	(474.83)	-	(267.88)	217.86	-
Perkins dummy variable	-	-	-	-	-	-1449.7***
	-	-	-	-	-	(13.35)
Time trend	-80.90***	-91.19***	-166.84***	-93.84***	-81.12	0.07***
	21.13	(14.28)	(19.32)	(9.52)	6.56	(0.002)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses below.

Table II-7. Coefficients for Rainfall Frequency Intervals 2, 4, and 6 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute plots					OSU plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-16178*	-16224***	842.52*	-35476***	-224.31	-9310.79*
	(9206.43)	(5809.3)	(491.88)	(2516.18)	(1322.53)	(4998.07)
October-November interval	-16.61	-52.21	101.71***	45.19**	14.77	-119.69**
	(44.82)	(37.42)	(5.43)	(18.00)	(35.40)	(45.58)
December-January interval	11.02	-11.93	-27.07***	6.46	-0.60	-32.07
	(42.41)	(34.57)	(4.53)	(16.66)	(32.14)	(61.59)
February-March interval	25.59	30.88	6.9	21.28	-6.28	176.9*
	(45.10)	(36.76)	(4.46)	(17.54)	(34.53)	(92.76)
Planting Days from August 29	8.89	10.18	-65.80***	-13.98	-0.44	102.25**
	(26.55)	(21.59)	(3.58)	(10.24)	(20.32)	(35.16)
Seeding Rate	174.02**	198.77***	136.23***	395.07***	52.46***	141.7**
	(84.38)	(59.43)	(12.90)	(26.01)	(14.37)	(49.65)
Nitrogen Application	3.76	5.18	2.89***	1.18	-0.11	-2.58
	(5.33)	(4.37)	(0.50)	(2.04)	(4.08)	(5.75)
Burneyville dummy variable	-91.12	978**	-	-700.62***	-492.34	-
	(529.04)	(447.54)	-	(201.13)	(406.96)	-
Gene Autry dummy variable	1742.09**	3127.4***	-	2596.5***	2044.47***	-
	(864.54)	(709.02)	-	(336.56)	(663.71)	-
Perkins dummy variable	-	-	-	-	-	-1121.04
	-	-	-	-	-	(749.57)
Time trend	-35.16	-43.98**	69.50***	-96.47***	-39.79**	-375.06***
	(23.74)	(21.05)	(4.40)	(10.91)	(19.13)	(124.1)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses below.

Table II-8. Coefficients for Temperature Frequency Intervals 1, 3, and 5 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute plots					OSU plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-20506***	-29135***	840.3	-33564***	8683.21***	5935.03
	(6621.92)	(4265.1)	(546.27)	(2330.15)	(582.73)	(3958.36)
September-October interval	260.02	156.9	25.83	25.70	182.8**	235.08*
	(183.15)	(152.1)	(57.28)	(87.21)	(80.23)	(120.53)
November-December interval	-59.03**	-30.04	-13.34***	26.68*	-42.07***	-70.04***
	(27.61)	(22.83)	(4.14)	(13.42)	(12.16)	(17.08)
January-February interval	-67.55***	-20.52	-84.09***	-16.77*	-66.17***	-257.05***
	(17.40)	(14.58)	(3.01)	(8.45)	(7.70)	(30.64)
Planting Days from August 29	24.76	14.63	-78.08***	-4.41	-38.80***	21.35*
	(19.60)	(16.53)	(3.46)	(9.53)	(8.78)	(10.27)
Seeding Rate	238.66***	339.18***	246.66***	383.62***	-2.76	82.70**
	(61.87)	(44.43)	(15.83)	(24.63)	(6.14)	(32.17)
Nitrogen Application	-1.20	2.01	2.48***	1.23	-8.56***	-4.03
	(3.92)	(3.33)	(0.50)	(1.93)	(1.75)	(2.32)
Burneyville dummy variable	69.51	591.02	-	-568.7***	616.59***	-
	(427.18)	(374.29)	-	(208.45)	(194.65)	-
Gene Autry dummy variable	1232.89*	2940.75***	-	2480.16***	2215.62***	-
	(643.61)	(549.22)	-	(316.62)	(289.51)	-
Perkins dummy variable	-	-	-	-	-	1883.68***
	-	-	-	-	-	(241.69)
Time trend	-30.8	-72.60***	83.01***	-104.28***	16.46*	122.29
	(19.34)	(17.92)	(5.08)	(11.74)	(9.38)	(80.98)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses below.

Table II-9. Coefficients for Temperature Frequency Intervals 2, 4, and 6 Effects on Growing-Season-1 Forage Yield

	Noble Research Institute Plots					OSU Plots
	Oats	Rye	Ryegrass	Triticale	Wheat	Wheat
Intercept	-20506***	-29135***	840.3	-33564***	8683.21***	2099.48
	(6621.92)	(4265.13)	(546.27)	(2330.15)	(582.73)	(1966.71)
October-November interval	260.02	156.93	25.83	25.70	182.8**	27.99
	(183.15)	(152.10)	(57.28)	(87.21)	(80.23)	(20.03)
December-January interval	-59.03**	-30.04	-13.34***	26.68*	-42.07***	-93.37***
	(27.61)	(22.83)	(4.14)	(13.42)	(12.16)	(16.35)
February-March interval	-67.55***	-20.52	-84.09***	-16.77*	-66.17***	-160.52***
	(17.40)	(14.58)	(3.01)	(8.45)	(7.70)	(17.69)
Planting Days from August 29	24.76	14.63	-78.08***	-4.41	-38.80***	70.33***
	(19.60)	(16.53)	(3.46)	(9.53)	(8.78)	(5.87)
Seeding Rate	238.66***	339.18***	246.66***	383.62***	-2.76	79.92***
	(61.87)	(44.43)	(15.83)	(24.63)	(6.14)	(17.04)
Nitrogen Application	-1.20	2.01	2.48***	1.23	-8.56***	3.56**
	(3.92)	(3.33)	(0.50)	(1.93)	(1.75)	(1.41)
Burneyville dummy variable	69.51	591.02	-	-568.7***	616.59***	-
	(427.18)	(374.29)	-	(208.45)	(194.65)	-
Gene Autry dummy variable	1232.89*	2940.75***	-	2480.16***	2215.62***	-
	(643.61)	(549.22)	-	(316.62)	(289.51)	-
Perkins dummy variable	-	-	-	-	-	-1321.03***
	-	-	-	-	-	(208.14)
Time trend	-30.8	-72.60***	83.01***	-104.28***	16.46*	104.51*
	(19.34)	(17.92)	(5.08)	(11.74)	(9.38)	(49.75)

Asterisks (***, **, and *) denote significance at the 1%, 5%, and 10% levels, respectively. Standard error are reported in parentheses below.

CHAPTER III

EFFECT OF IRRIGATION METHOD ON PERFORMANCE OF YOUNG PECAN TREES IN THE SOUTHERN GREAT PLAINS

Abstract

While irrigation is a common practice in pecan orchards, the effects of different methods of irrigation upon young tree growth, nut quality, and nutrient uptake have not been estimated. Five irrigation systems and one nonirrigated control system were established. Tree performance was characterized by change in trunk diameter, weight per nut, average kernel percentage, and total trunk diameter growth. Nutrient uptake was determined by foliar levels. The five irrigation systems were Nelson R-5 rotator (35 ft diameter) sprinkler (R5), Nelson R-10 rotator (70 ft diameter) sprinkler (R10), two subsurface driplines irrigating for two days a week alternating between water for two hours and no water for two hours (SI2), two subsurface driplines irrigating one day a week for twenty hours continuously (LI2), and four subsurface driplines irrigating for ten hours continuously for one day a week (LI4). Irrigation systems affected foliar levels of potassium, boron, and manganese levels. No significant difference was found in expected change in trunk diameter or kernel percentage by irrigation system. A spatial Durbin error model was estimated in order to use trunk diameter estimates from all trees in the

orchard. This model found the trunk diameters of non-irrigated and LI4 system trees to be significantly less than those trees that were irrigated by the LI2 system. When observations were pooled over all years, LI4 trees had individual pecan nut weights that were significantly less than all other systems.

Introduction

In the states of Texas and Oklahoma, it is estimated that pecans (Carya illinoinensis) contribute over $90 million and $14 million to each states' economies respectively (*Noble Research Institute's Pecan Research Strategy* 2010). A growing interest in pecans stems from explosive growth in the export market for pecan nuts over the past several decades (Lillywhite et al. 2014). Irrigation has been thought to be crucial in the establishment and growth of young nut bearing trees. In pecans, a recent study by Wells (2017) aimed to determine the appropriate irrigation rates and effects on growth of young pecan trees. Wells compared two microsprinkler systems with emitters of different pressures and a nonirrigated control. In years 1 and 2 of the experiment, irrigated trees had greater trunk diameter growth than the nonirrigated control trees. This work loosely agrees with previous work by Patterson et al. (1990). Patterson et al. compared a nonirrigated control with a drip irrigation system with five emitters per tree. No difference in trunk diameter was found during the first year between irrigated and nonirrigated trees. In subsequent years however, Patterson et al. (1990) did find irrigated trees had significantly larger trunk diameters.

While some research exists on irrigation effect on the growth of young pecans, little to none exists on the effects of irrigation delivery system on nutrient uptake in pecan trees.

Neilsen et al. (1995) investigated the effects of emitter (jet or microsprinkler) and frequency of irrigation and their effects upon 'Gala' apples. In this study, leaf concentrations of K, Mg, Cu, and Mn were significantly affected by irrigation type and frequency. However, fertigation of N and P occurred, potentially leaching the soil of some nutrients and consequently leading to different element leaf concentrations.

Effects of differing irrigation levels upon individual pecan nut weight has been previously investigated. Garrot et al. (1993) designed four irrigation treatments based upon a crop water stress index resulting in a "wet," "medium," and "dry" treatment as well as a grower designated irrigation treatment. 16 trees established in 1967 were included in the four year experiment that started in 1988. Data pooled over the four years showed a decrease in pecan nut weight in relation to a decrease in water. The number of saleable kernels, however, was unaffected. While the relationship between amount of water and nut quality might be documented, there is a lack of research concerning the effects of irrigation water delivery system and its effects upon the nut quality of young pecans.

Research is needed to determine the effects of irrigation water delivery method upon growth, nut quality, and nutrient absorption of young pecans. The objectives of this paper were to determine the effects of different types of drip and sprinkler irrigation systems and periodicity of irrigation as well as a non-irrigated control on change in trunk diameter, kernel percentage, and pecan nut weight.

Materials and Methods

In 2007, ‘Pawnee’ pecan trees were planted at the Noble Research Institute’s McMillan Research and Demonstration Farm near Madill, Oklahoma (34° 2' 10.4238"N 96° 56' 27.0378"W; 236 MASL). The trees on ‘Apache’ rootstock were planted at a spacing of 35 ft. x 35 ft. on Bastrop fine sandy loam soil. The soil was well drained with a depth to water table that is more than 80 inches. The infiltration rate was moderately high to high (0.60 to 2.00 in/hr). The available water storage in the profile is high (about 10 inches). ‘Kanza’ pollinator rows were located on the south, middle and north end of the study block. Trap counts were used to monitor pecan nut casebearer and pecan weevil. Visual inspection was used to determine when control for aphids was necessary. Based upon trap counts, foliar chemical sprays were applied by airblast sprayer to control for pecan nut casebearer and pecan weevil. Pecan scab was not present in this orchard. Glyphosate application was applied across the orchard floor to maintain 14 feet wide vegetation free strips down the orchard rows. Vegetation outside of the orchard was mowed twice a year with a batwing mover. Trees received fertilizer annually according to annual leaf sample recommendations based on Smith et al. (2012) to provide sufficient nutrients.

Table III-1 reports average rainfall of 966.987 mm at the Madill Mesonet station (Mesonet, 2017) which is also located on the McMillian Research and Demonstration Farm. Annual rainfall fell below the 15 year average for 2011, 2012, 2013, 2014, 2016, and 2017. In 2015, over double the amount of rainfall occurred in comparison to the 15 year average.

Treatments

Irrigation systems were installed and trees began receiving water in 2008. The study began in 2010. At the beginning of the study, the irrigation water quality was analyzed (Table III-2). The reported sodium absorption ratio, electrical conductivity, nitrate, sulfate, and chloride levels are within suitable levels as deemed by Zhang (2017). Treatments were five different irrigation systems and one nonirrigated system (Table III-3). The systems consisted of sprinkler with Nelson R-5 rotator (35 ft diameter) microsprinkler (R5), Nelson R-10 rotator (70 ft diameter) microsprinkler (R10), two subsurface driplines on a short interval watering system (two hours on, two hours off system) for two days a week (SI2), two subsurface driplines irrigating with continuous run for twenty hours, one day a week (LI2), and four subsurface driplines irrigating with continuous run for ten hours, one day a week (LI4). Sprinkler systems (R5 and R10) had one emitter per tree located 4.5 feet east in the herbicide strip. In order to ensure that sprinkler systems did not wet the leaves, the branches were pruned. However, overlap of wetting patterns did occur in the R10 system and could possibly influence the growth of neighboring trees. Subsurface drip irrigation systems with two driplines (SI2 and LI2) are located seven feet from the trunk of the tree on two opposite sides buried at 14 inches deep. The driplines for the LI4 system are also placed on two opposite sides of a tree, seven feet apart buried at 14 inches deep. All subsurface dripline systems used metifilm pressure compensating inline emitters at 0.9 gph spaced at four feet apart. All irrigated systems delivered the same amount of water per week (2.16 cm) as per the recommendations of local producers. Irrigation began at bud break in the middle of April through the summer months. Irrigation was shut off two weeks prior to harvest. Each system was replicated three times in a completely randomized design. A treatment block consisted of 12 trees where the middle two trees were sampled and the surrounding 10 trees acted as a border to negate effects for neighboring treatment blocks. A block was arranged by three rows and four columns of trees.

Data Collection

Collection of leaf samples occurred each year in July. Leaf samples were collected to ensure proper management of nutrients and elements within the orchard as well as to determine if irrigation had any effect on nutrient and element absorption. One hundred leaflets were collected per tree at random from the middle leaf. Leaves were washed in deionized water, then washed in deionized water with non-detergent soap and then rinsed again in deionized water. The leaves were dried before being analyzed by the Oklahoma State University Soil, Water and Forage Analytical Laboratory. Elemental concentrations of nitrogen, calcium, potassium, magnesium, nickel, boron, manganese, phosphorus, iron, copper, and sulfur were collected during 2013, 2014, 2015, and 2016. Change in trunk diameter (1.4 meters above the soil) was measured by caliper during dormancy annually during 2010, 2011, 2013, and 2015. Total trunk diameter was measured for all 215 trees in the orchard during January of 2018. Trees were harvested annually with a 40-nut sample after 90% split shuck. Nuts were placed on drying racks in a room with unheated air and dried to 4-5% moisture. The forty nut sample was evaluated each year for kernel percentage and weight per nut. One pecan tree in the treatment that received no irrigation died and was removed from the study in 2013.

Data Analysis

Measures of elemental concentration were subjected to analysis of variance models using a mixed effect model with repeated measures. Mathematically, the element models are represented as:

$$element_{jk} = \mu + \alpha_k + \beta_j + \epsilon_{jk} \text{ where}$$

$$\epsilon_{jk} = \rho(\epsilon_{(j-1)k}) + v_{jk}$$

where $element_{ijk}$ represents the elemental concentration of N, Ca, K, Mg, Ni, B, Mn, P, Fe, Cu, and S. μ represents the overall mean; α_k represents the fixed effects attributed to the different irrigation system; $k = 1,\ldots,5$ represents the irrigation systems; β_j represents the random year effect; $j = 1, \ldots, 4$ corresponds with the years 2013-2016; the experimental error is ϵ_{jk} where ρ is the associated correlation coefficient to account for autocorrelation and v_{jk} represents the independent random error.

The relationship between irrigation systems and the change in diameter of the tree was fitted to a log linear model with repeated measures using the MIXED procedure in SAS where irrigation system was treated as a fixed effect and year was treated as a fixed effect. This relationship is represented mathematically as:

$$\ln diameter_{it} = \sigma + \pi_i + \tau_t + \varepsilon_{it} \text{ where}$$

$$\varepsilon_{it} = \gamma(\varepsilon_{i(t-1)}) + \vartheta_{it}$$

where $diameter_{it}$ is the annual change in diameter (cm); σ represents the overall mean; π_i represents the fixed effects associated with the irrigation system where $i = 1,\ldots,5$;

fixed effects related to year is represented by τ_t where t = 1,…,4; ε_{it} where γ is the correlation coefficient and ϑ_{it} represents the portion of the error that does not contain autocorrelation. Means were separated using the LSMEANS statement in SAS ($P \leq 0.05$).

The relationship between nut kernel percentage and irrigation system as well as the relationship between nut weight and irrigation system were modeled using the NLMIXED Procedure in SAS (Wolfinger, 1999).

$$kernelpercent_{grhn} = \varphi_g + \omega_h + \theta_{grh} + \eta_{ghrn}$$

where $kernelpercent_{grhn}$ is the kernel percentage per nut; φ_g represents the fixed effect contributed by irrigation system where g = 1,..,5; ω_h is the fixed effect associated with year where h = 1,..,4; θ_{grh} is the random effect accounting for the interaction between the irrigation system, replication, and year; r = 1, 2, 3 and represents the number of replications; n = 1, 2 represents the two tree sample taken from the middle of each replication; η_{ghrn} is the error effect and based on Richter and Brorsen (2006) can be assumed to be distributed iid N$(0, \xi + \frac{1}{\sqrt{P_{grhn}}})$ where ξ is a constant to be estimated and P is the number of pecan nuts per tree to account for differing variances when less than 40 nuts are available. Means were separated using the CONTRAST statement in SAS ($P \leq 0.05$).

In January of 2018, trunk caliper measurements were taken of all 215 trees in the orchard. Previous analysis of the caliper measurements, nut weight, and kernel percentage were done for the 36 trees that were located in the center of the 12 tree treatment blocks. Little statistical significance was found, due to the small sample size. To address that issue, a larger sample size was obtained by measuring the diameter of all trees in the orchard.

When all the trees in the orchard were sampled, the border effects needed to be considered. The model used controlled for potential spillover effects from bordering trees of a different treatment, specifically the effect of a nonirrigated tree bordering a tree receiving irrigation. Utilizing exploratory spatial data analysis, which takes into account the existence of spatial autocorrelation and its effects upon the assumption of independence (Anselin 1999), a spatial weight matrix was specified that reflected if a nonirrigated tree bordered an irrigated tree. With the weight matrix specification, a spatial Durbin error model is represented as

$$TrunkDia = \phi_0 + \phi_1 tmt2 + \phi_2 tmt3 + \phi_3 tmt4 + \phi_4 tmt5 + \phi_5 tmt6 + \Gamma W IrrigationDummy + \iota$$

$$\iota = \lambda W \iota + \kappa$$

where $\phi_0, \phi_1, \phi_2, \phi_3, \phi_4$, and ϕ_5 are the coefficients estimated for the dummy variables representing the irrigation treatment, Γ is the spatial lag term associated with the weight matrix, λ is the spatial error term, and κ is the independent error term.

Results and Discussion

The leaf elemental concentrations (Table III-3) of N, S, Ca, Mg, B, Cu, Fe, Mn and Ni were all within the guidelines set by Smith et. al. (2012) for a high-input cultivar orchard (Table III-3). K, P, and Zn levels were below elemental sufficiency ranges. Leaf element concentrations for K, B, and Mn displayed statistical differences in levels by irrigation system when pooled over the years. Levels of K showed no clear pattern. The LI2 system displayed the highest levels of K while the LI4 had the lowest leaf concentrations of K. This could possibly be due to the number of emitters. Four emitters could be more detrimental to leaf concentration of K in comparison to 2 emitters. The statistical difference in Boron levels was lowest for the control system with no irrigation (none) and highest in the sprinkler systems (R5 and R10) as well as the LI2 system. Besides the nonirrigated trees, the SI2 and LI4 systems had no statistical difference in concentration of Boron and on average had some of the lowest leaf concentrations. This occurrence may be due to length of time water is applied. SI2 and LI4 systems apply water for the longest total periods of time throughout the week. This explanation however, does not give insight into why the nonirrigated systems have the lowest amount of Boron on average. Mn concentrations were lowest for the two sprinkler systems (R5 and R10) and highest for the no irrigation control (none). Since the LI4 system Mn leaf concentration is significantly higher than with both sprinkler systems, perhaps a greater number of emitters that created a highly concentrated dispersion of water, increased Mn solubility and thus availability to the trees.

During the seven years of this study, rainfall was inconsistent throughout the months of April to September. the years 2011, 2012, and 2013 were dry as the rainfall totals for the months were below the 15 year average. While no evapotranspirational or mid stem water potential data is available, it should be noted that particularly dry years could have led to water stress on the trees.

As the trees grew, the average change in diameter increased each year (Table III-4). While there was no statistically difference in change of diameter, numerically on average, both sprinkler irrigation systems (R5 and R10) as well as the LI2 system experienced a greater increase in trunk diameter in contrast to the other three irrigation systems. The lack of significant effect of irrigation on trunk diameter differs from recent findings of Wells (2017). Wells (2017) began their measurements immediately upon planting of the trees while this study had two years post planting where no records were kept, but it could also be that using only the two center trees led to our test having low statistical power.

Individual nut weights were recorded in 2012, 2014, 2015, and 2016 (Table III-5). In 2014, the non-irrigated control, R5, and SI2 systems had significantly greater individual nut weights than the R10 and LI2 systems. When observations were pooled across years, nut weights from the LI4 irrigation system were significantly lower than the other systems.

Kernel percentage (Table III-6) was significantly greater in the SI2 and non-irrigated control during 2014. When pooled across years, no significant difference in kernel percentage was found between systems.

Using data on all trees and correcting for edge effects, the effect of irrigation upon trunk diameter was significantly different for LI2 relative to the non-irrigated and LI4 system (Table III-7). The LI2 and R5 systems were the only irrigation systems to have significantly greater trunk diameters than the non-irrigated control.

These responses to irrigation method varied from year to year with weather and other variables. In some years for certain measures of growth and maturity, the nonirrigated control outperformed irrigated systems. In measures for change in trunk diameter, there was no difference between any system when using only the two center trees of each plot. When all 215 trees in the orchard were sampled and spatial effects were accounted for, the LI2 and R10 systems had significantly greater trunk diameters than the non-irrigated control. The trunk diameter of the LI2 irrigation system trees were also significantly greater than those of the LI4 trees when spatial effects were accounted for. Kernel percentage of nuts is not affected by irrigation system when pooled across all years. The individual pecan nut weight was significantly less for nuts from the LI4 irrigation system trees in comparison to the rest of the irrigation treatments. In respect to the individual nut weight and trunk diameter, the LI4 system can be generally characterized as the worst system, having significantly lower individual nut weights than even the nonirrigated control. The LI4 irrigation system also had the lowest levels of foliar K.

In this study, the nonirrigated control only significantly differed from the majority of the irrigated systems for total trunk diameter. However, the findings of this study should be extrapolated to other pecan growing regions of the country with caution. Statistical insignificance does not mean that the effect of irrigation is truly zero. Also, irrigation may more greatly affect trees in regions where little rainfall occurs or conversely have less of an effect where greater rainfall is experienced.

Table III-1. Monthly Rainfall at the Madill Mesonet Station.

	Rainfall (mm)								
Month	15 year average	2010	2011	2012	2013	2014	2015	2016	2017
January	40.39	48.51	11.18	106.68	41.15	9.91	64.77	12.95	77.98
February	44.7	71.37	34.8	26.16	62.23	22.35	26.92	37.85	37.85
March	86.11	93.98	2.03	155.45	36.58	65.28	89.92	92.2	40.89
April	107.19	107.7	73.41	92.46	49.78	46.48	117.86	195.58	130.30
May	153.42	83.82	148.84	32	212.6	40.64	553.21	174.24	50.55
June	106.93	86.11	2.79	82.3	140.97	124.21	320.55	109.98	57.40
July	70.1	82.55	8.89	4.32	93.73	153.16	216.66	11.43	74.42
August	53.59	55.12	28.19	65.53	29.72	30.48	5.33	101.09	215.90
September	75.18	239.52	63.75	48.01	29.72	61.47	36.83	80.01	4.57
October	105.92	59.18	133.86	22.61	140.46	82.3	201.17	57.15	52.83
November	61.98	31.5	75.95	12.95	70.87	114.81	195.83	54.1	4.06
December	61.47	70.87	50.04	41.4	48.01	36.32	178.31	21.59	62.99
Total	966.98	1030.22	633.73	689.86	955.8	787.4	2007.36	948.18	809.74

Table III-2. Irrigation Water Quality Measurements.

Sodium Absorption Rate	1.4
Electrical Conductivity (mmho/cm)	0.93
Nitrate (ppm)	0.1
Chloride (ppm)	26
Boron (ppm)	0.13

Table III-3. Irrigation System Abbreviation Definitions.

Abbreviation	Irrigation System
None	No irrigation
R5	Nelson R-5 rotator (35 ft diameter)
R10	Nelson R-10 rotator (70 ft diameter)
SI2	Sub-surface drip with two lines (short watering interval)
LI2	Sub-surface drip with two lines (long watering interval)
LI4	Sub-surface drip with four lines (long watering interval)

Table III-4. Mean Concentrations of Selected Elements in Pecan Leaves, 2013-2016.

Irrigation System	Elemental Concentration (%)						Elemental Concentration (ppm)					
	N	P	K	S	Ca	Mg	B	Cu	Fe	Mn	Zn	Ni
None	2.34	0.12	0.83bcd	0.2	1.58	0.4	52.6c	7.8	46.9	1324.64a	28.25	4.43
R5	2.28	0.1	0.93ab	0.2	1.73	0.42	68.32a	7.9	52.6	898.2b	26.83	2.7
R10	2.31	0.12	0.8cd	0.2	1.7	0.44	70.41a	7.8	49.1	909.54b	26.77	3.73
SI2	2.32	0.1	0.89abc	0.2	1.69	0.4	59.05bc	7.6	50.7	1091.69ab	28.78	3.65
LI2	2.29	0.1	0.93a	0.2	1.7	0.39	68.07a	8	49.5	1087.14ab	29.27	3.76
LI4	2.29	0.1	0.78d	0.2	1.62	0.43	61.19ab	7.6	47.2	1252.91a	28.08	3.7
Significance	NS	NS	*	NS	NS	NS	*	NS	NS	*	NS	NS
Sufficiency	2.3-3.0	≥ 0.14	≥ 1.0	≥ 0.20	≥ 0.70	≥ 0.30	15-300	6- 20	≥ 50	≥ 100	≥ 60	≥ 2.5

† Treatments are defined in Table 1

‡ Means in the same column followed by the same letter are not significantly different using Fisher's protected LSD at $P \leq 0.05$

Sufficiency source: Smith, Rohla, and Goff (2012)

Table III-5. Relationship of Irrigation System to Expected Change in Trunk Diameter and Weight per Nut of 'Pawnee' Pecans.

Irrigation System	2010	2011	2012	2013	2014	2015	2016	Pooled
Change in trunk diameter (cm)								
None	3.98	4.63	-	7.58	-	8.68	-	5.82
R5	4.62	5.04	-	9.33	-	9.64	-	6.75
R10	5.52	5.87	-	9.19	-	9.58	-	7.32
SI2	3.56	4.16	-	8.32	-	9.63	-	5.92
LI2	4.76	5.27	-	9.21	-	9.52	-	6.80
LI4	3.97	4.41	-	7.43	-	7.93	-	5.66
Significance	NS	NS	-	NS	-	NS	-	NS
Weight/nut (g)								
None	-	-	7.79ab	-	9.88a	9.64	9.24	9.18a
R5	-	-	9.53ab	-	10.07a	9.20	8.66	8.73a
R10	-	-	9.5ab	-	8.75b	9.83	8.83	9.86a
SI2	-	-	8.79b	-	10.13a	9.57	8.91	9.34a
LI2	-	-	10.36a	-	8.64b	9.71	8.89	8.79a
LI4	-	-	8.35b	-	9.82ab	9.63	8.22	8.05b
Significance	-	-	*	-	*	NS	NS	*

† Treatments are defined in Table 1

‡ Means in the same column followed by the same letter are not significantly different using Fisher's protected LSD at $P \leq 0.05$

Table III-6. Relationship of Irrigation System to Kernel Percentage of 'Pawnee' Pecans.

Kernel (%)								
None	-	-	52.23	-	55.64b	57.3	57.51	57.36
R5	-	-	47.22	-	51.94a	55.96	56.78	55.59
R10	-	-	50.23	-	44.34c	56.9	56.51	54.25
SI2	-	-	52.63	-	55.96b	57.71	56.93	57.17
LI2	-	-	49.39	-	45.48c	56	56.47	54.11
LI4	-	-	45.89	-	52.03abc	52.59	54.38	55.04
Significance	-	-	NS	-	*	NS	NS	NS

† Treatments are defined in Table 1

‡ Means in the same column followed by the same letter are not significantly different using Fisher's protected LSD at $P \leq 0.05$

Table III-7. SDEM Model Estimates of Pecan Trunk Diameters, January 2018.

Irrigation System	Trunk Diameter (cm)
None	134.49b
R5	155.59ac
R10	152.2abc
SI2	151.6abc
LI2	162.79a
LI4	145.71bc
Significance	*

† Treatments are defined in Table 1

‡ Means in the same column followed by the same letter are not significantly different using Fisher's protected LSD at P ≤ 0.05

REFERENCES

Ampt, P., and A. Baumber. 2006. "Building Connections Between Kangaroos, Commerce and Conservation in the Rangelands." *Australian Zoologist* 33(3):398-409.

Anselin, L. 1999. Interactive techniques and exploratory spatial data analysis, p. 251-264. In: P.A. Longley, M.F. Goodchild, D.J. Maguire, and D.W. Rhind (eds.). Geographical Information Systems: principles, techniques, management and applications. Wiley.

Barrett, R. 1978. "The Feral Hog at Dye Creek Ranch, California." *Hilgardia* 9:283-355.

Barrios-Garcia, M. N., and S.A. Ballari. 2012. "Impact of Wild Boar (Sus scrofa) in its Introduced and Native Range: a Review." *Biological Invasions* 11:2283-2300.

Bevins, S. N., K. Pedersen, M.W. Lutman, T. Gidlewski, and T.J. Deliberto. 2014. "Consequences Associated with the Recent Range Expansion of Nonnative Feral Swine." *BioScience* 64:291-299.

Byrd, E. S., N.J.O. Widmar, and J.G. Lee. 2015. "Non-Amenable Meat Consumption, Sale, and Regulation: Bison, Beef and Bambi, Oh My! All Meats Are Not Created Equal." *Drake Journal of Agricultural Law* 20:337.

Caley, P. 1993. "Population Dynamics of Feral Pigs (Sus scrofa) in a Tropical Riverine Habitat Complex." *Wildlife Research* 20:625-636.

Campbell, T. A., and D.B. Long. 2009. "Feral Swine Damage and Damage Management in Forested Ecosystems." *Forest Ecology and Management* 257:2319-2326.

Choquenot, D., B. Lukins, and G. Curran. 1997. "Assessing Lamb Predation by Feral Pigs in Australia's Semi-Arid Rangelands." *Journal of Applied Ecology* 34:1445-145.

Costello, C., N. Querou, and A. Tomini. 2017. "Private Eradication of Mobile Public Bads." *European Economic Review* 94:23-44.

Cummings, K. J., L.D. Rodriguez-Rivera, I. McNeely, J.S. Suchodolski, B.T. Mesenbrink, B.R. Leland, and M.J. Bodenchuk. 2018. "Fecal Shedding of Campylobacter jejuni and Campylobacter coli among Feral Pigs in Texas." *Zoonoses and public health* 65:215-217.

Ditchkoff, S.S., R.W. Holtfreter, and B.L. Williams. 2017. "Effectiveness of a Bounty Program for Reducing Wild Pig Densities." *Wildlife Society Bulletin* 41:548-555.

Doherty, T. S., A.S. Glen, D.G. Nimmo, E.G. Ritchie, and C.R. Dickman. 2016. "Invasive Predators and Global Biodiversity Loss." *Proceedings of the National Academy of Sciences* 113:11261-11265.

Dutcher, J.D., R.E. Worley, J.W. Daniell, R.B. Moss, and K.F. Harrison. 1984. Impact of six insecticide-based arthropod pest management strategies on pecan yield, quality, and return bloom under four irrigation/soil-fertility regimes. Environ. Entomol. 13:1644-1653.

Engeman, R. M., H.T. Smith, S.A. Shwiff, B. Constantin, J. Woolard, M. Nelson, and D. Griffin. 2003. "Prevalence and Economic Value of Feral Swine Damage to Native Habitat in Three Florida State Parks." *Environmental Conservation* 30:319-324.

Epanchin-Niell, R. S., M.B. Hufford, C.E. Aslan, J.P. Sexton, J.D. Port, and T.M. Waring. 2010. "Controlling Invasive Species in Complex Social Landscapes." *Frontiers in Ecology and the Environment* 8:210-216.

Franckowiak, G. A., and R.M. Poché. 2018. "Short-Term Home Range and Habitat Selection by Feral Hogs in Northern Texas." *The American Midland Naturalist* 179:28-37.

Gabor, T. M., E.C. Hellgren, R.A. Van Den Bussche, and N.J. Silvy. 1999. “Demography, Sociospatial Behaviour and Genetics of Feral Pigs (Sus scrofa) in a Semi-arid Environment.” *Journal of Zoology* 247:311-322.

Garrot, D.J., M.W. Kilby, D.D. Fangmeier, S.H. Husman, and A.E. Ralowicz. 1993. Production, growth, and nut quality in pecans under water stress based on the crop water stress index. J. Amer. Soc. for Hort. Sci. 118:694-698.

Grigg, G. C. "Harvesting kangaroos in Australia." *Assessing the Sustainability of Uses of Wild Species: Case Studies and Initial Assessment Procedure. IUCN, Gland, Switzerland*(1996): 27-29.

Hayes, R., S. Riffell, R. Minnis, and B. Holder. 2009. “Survival and Habitat Use of Feral Hogs in Mississippi.” *Southeastern Naturalist* 8:411-426.

Hernández, F. A., K.A. Sayler, C. Bounds, M.P. Milleson, A.N. Carr, and S.M. Wisely. 2018. “Evidence of Pseudorabies Virus Shedding in Feral Swine (Sus scrofa) Populations of Florida, USA.” *Journal of Wildlife Diseases* 54:45-53.

Hutton, T., T. DeLiberto, S. Owen, and B. Morrison. 2006. “Disease Risks Associated with Increasing Feral Swine Numbers and Distribution in the United States.”

Jolley, D.B., S.S. Ditchkoff, D. Sparklin, L.B. Hanson, M.S. Mitchell, and J.B. Grand. 2010. “Estimate of Herpetofauna Depredation by a Population of Wild Pigs.” *Journal of Mammalogy* 91:519–524.

Kaiser, B. A. and K.M. Burnett. 2010. “Spatial Economic Analysis of Early Detection and Rapid Response Strategies for an Invasive Species.” *Resource and Energy Economics* 32:566-585.

Keiter, D.A. and J.C. Beasley. 2017. “Hog Heaven? Challenges of Managing Introduced Wild Pigs in Natural Areas.” *Natural Areas Journal* 37:6-16.

Killian, G., L. Miller, J. Rhyan, and H. Doten. 2016. “Immunocontraceptive of Florida Feral Swine with a Single-dose GnRH Vaccine.” *American Journal of Reproductive Immunology* 55:378-384.

Leonard, B. and G.D. Libecap. 2015. “Endogenous First-Possession Property Rights in Open-Access Resources.” *Iowa Law Review* 100:2457-2478.

Little, R.C., G.A. Miliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

Lueck, D. 1995. “Property Rights and the Economic Logic of Wildlife Institutions.” *Natural Resources Journal* 625-670.

Lueck, D. and J. Yoder. 2015. “The Economic Foundations of Firefighting Organizations and Institutions.” *Journal of Forestry* 113:291-297.

−. 1997. “Federalism and Wildlife Conservation in the West.” *Environmental Federalism* 89-131.

Mapston, M. 2007. “Feral Hogs in Texas.” *Texas FARMER Collection*.

Massei, G., S. Roy, and R. Bunting. 2011. “Too Many Hogs? A Review of Methods to Mitigate Impact by Wild Boar and Feral Hogs.” *Human–Wildlife Interactions* 5:10.

McCann, B.E. and D.K. Garcelon. 2008. “Eradication of Feral Pigs from Pinnacles National Monument.” *The Journal of Wildlife Management* 72:1287-1295.

McClure, M. L., C.L. Burdett, M.L. Farnsworth, S.J. Sweeney, and R.S. Miller. 2018. “A Globally-Distributed Alien Invasive Species Poses Risks to United States Imperiled Species.” *Scientific Reports* 8:5331.

McClure, M.L., C.L. Burdett, M.L. Farnsworth, M.W. Lutman, D.M. Theobald, P.D. Riggs, D.A. Grear, and R.S. Miller. 2015. "Modeling and Mapping the Probability of Occurrence of Invasive Wild Pigs Across the Contiguous United States." *PloS One* 10:e0133771.

Mesonet. 2018. Mesonet rainfall by month table, Madill, OK. 30 January 2018. <https://wwww.mesonet.org/index.php/weather/monthly_rainfall_table>

Neilsen, G.H., P. Parchomchuk, D. Neilsen, R. Berard, and E.J. Hague. 1995. Leaf nutrition and soil nutrients are affected by irrigation frequency and method for NP-fertigatedGala'Apple. J. Amer. Soc. for Hort. Sci. 120:971-976.

Noble Research Institute's Pecan Research Strategy. 2010. Noble Research Institute. 19 June 2018. <https://www.noble.org/news/publications/ag-news-and-views/2010/october/noble-foundations-pecan-research-strategy/>

Oja, R., K. Zilmer, and H. Valdmann. 2015. "Spatiotemporal Effects of Supplementary Feeding of Wild Boar (Sus scrofa) on Artificial Ground Nest Depredation." *PloS One* 10:e0135254.

Olson, M. 1965. *Logic of Collective Action Public Goods and the Theory of Groups*, 2nd ed. Harvard University Press.

Ostrom, E. 2015. *Governing the Commons*. New York Cambridge University Press.

Parkes, J.P., D.S. Ramsey, N. Macdonald, K. Walker, S. McKnight, B.S. Cohen, and S.A. Morrison. 2010. "Rapid Eradication of Feral Pigs (Sus scrofa) from Santa Cruz Island, California." *Biological Conservation* 143:634-641.

Patterson, M.G., G. Wehtje, and W.D. Goff. 1990. Effects of weed control and irrigation on the growth of young pecans. Weed Tech. 4:892-894.

Podgórski, T., G. Baś, B. Jędrzejewska, L. Sönnichsen, S. Śnieżko, W. Jędrzejewski, and H. Okarma. 2013. “Spatiotemporal Behavioral Plasticity of Wild Boar (Sus scrofa) Under Contrasting Conditions of Human Pressure: Primeval Forest and Metropolitan Area.” *Journal of Mammalogy* 94:109-119.

Richter, F.G.-C., and B.W. Brorsen. 2006. Aggregate versus disaggregate data in measuring school quality. Journal of Productivity Analysis 25:279-289.

Rollins, D. and J.P. Carroll. 2001. “Impacts of Predation on Northern Bobwhite and Scaled Quail.” *Wildlife Society Bulletin* 29:39-51.

SAS Institute. 2008. SAS/STAT. SAS system for Windows. v. 9.2. SAS Inst., Cary, NC.

Scriven, J. 2018. “Predator Fencing in Cluster Groups to Manage Pest Animals in the Australian Rangelands: Is Eradication Achievable?” Paper presented at the Wild Pig Conference, Oklahoma City OK, 15-18 April.

Seward, N. W., K.C. VerCauteren, G.W. Witmer, and R.M. Engeman. 2004. “Feral Swine Impacts on Agriculture and the Environment.” *Sheep & Goat Research Journal* 19:34-40.

Siemann, E., J.A. Carrillo, C.A. Gabler. R. Zipp, and W.E. Rogers. 2009. “Experimental Test of the Impacts of Feral Hogs on Forest Dynamics and Processes in the Southeastern US.” *Forest ecology and management* 258:546-553.

Smith, M.W., C.T. Rohla, and W.D. Goff. 2012. Pecan leaf elemental sufficiency ranges and fertilizer recommendations. HortTechnology 22:594-599.

Snow, N.P., J.M. Halseth, M.J. Lavelle, T.E. Hanson, C.R. Blass, J.A. Foster, S.T. Humphrys, L.D. Staples, D.G. Hewitt, and K.C. VerCauteren. 2016. "Bait Preference of Free-Ranging Feral Swine for Delivery of a Novel Toxicant." *PloS One* 11:e0146712.

Stevens, R. L. 2006. “Feral Hog in Oklahoma.”

Tarko, V. 2017. *Elinor Ostrom: an Intellectual Biography*. London: Rowman & Littlefield International.

Taylor, R.B. and E.C. Hellgren. 1997. "Diet of Feral Hogs in the Western South Texas Plains." *The Southwestern Naturalist* 42:33-39.

Tolleson, D. R., W.E. Pinchak, D. Rollins, and L.J. Hunt. 1995. "Feral Hogs in the Rolling Plains of Texas: Perspectives, Problems, and Potential." *Great Plains Wildlife Damage Control Workshop Proceedings* 12:124-128.

Waithman, J.D., R.A. Sweitzer, D. Van Vuren, J.D. Drew, A.J. Brinkhaus, I.A. Gardner, and W.M. Boyce. 1999. "Range Expansion, Population Sizes, and Management of Wild Pigs in California." *The Journal of Wildlife Management* 63:298-308.

Wells, L. 2017. Response of young pecan trees to irrigation in a humid climate. HortScience 53:457-462.

Wilcox, J. T. and D.H. Van Vuren. 2009. "Wild Pigs as Predators in Oak Woodlands of California." *Journal of Mammalogy* 90:114-118.

Wolfinger, R.D. 1999. Fitting nonlinear mixed models with the new NLMIXED procedure. Proc. of the 24th Ann. SAS Users Group International Conference 278-284.

Yoder, J.K. 2000. "Contracting Over Common Property: Cost-Share Contracts for Predator Control." *Journal of Agricultural and Resource Economics* 25:485-500.

Zhang, H. 2017. Classification of irrigation water quality. Oklahoma Coop. Ext. Serv. PSS-2401.

VITA

Abby Mykaila Biedenbach

Candidate for the Degree of

Master of Science

Thesis: FERAL HOGS, THE RAINFALL INDEX ANNUAL FORAGE PROGRAM, AND PECAN IRRIGATION

Major Field: Agricultural Economics

Biographical:

Education:

Completed the requirements for the Master of Science in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in July, 2018.

Completed the requirements for the Bachelor of Science in Animal and Veterinary Sciences, Agricultural Economics, and Mathematics at University of Idaho, Moscow, Idaho in 2016.

Experience:

Graduate Research Assistant
Department of Agricultural Economics, Oklahoma State University, 2016-2018