MANAGEMENT TOOLS FOR PRESCRIBED BURNING FOR TALLGRASS PRAIRIE RESTORATION AT THE LEWISVILLE LAKE ENVIRONMENTAL LEARNING AREA

Maria C. Moreno, B.S.

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APPROVED:

William T. Waller, Major Professor
Kenneth Dickson, Committee Member
Dwight Barry, Committee Member
Thomas LaPoint, Coordinator of the Program in Environmental Science
Arthur J. Goven, Chair of the Department of Biological Sciences
Sandra L. Terrell, Interim Dean of the Robert B. Toulouse School of Graduate Studies

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The Lewisville Lake Environmental Learning Area (LLELA) is a wildlife management area with tallgrass prairie, an endangered ecosystem. Essential ecosystem processes, especially fire, are part of restoration. To support fire management efforts at LLELA and surrounding areas, this project evaluated and developed tools for fire restoration. The four primary prairie grasses respond favorably to burning. Fuel loads and fuel models vary by scale and survey method. One- and 10-hour fuel moisture can be predicted using a statistical model; 100- and 1,000-hour fuel moisture cannot. Historic weather data suggests that burning can occur when it is most effective. The production of ozone precursors produced by burning is comparable to those emitted every six minutes by regional automobiles.

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CHAPTER 1: INTRODUCTION

Fire has played an instrumental role in shaping many of the landscapes of North America (Wright and Bailey 1982; Knapp and Seastedt 1986). Prairies are just one of the many types of ecosystems that have developed under the influence of fire (Bragg and Hulbert 1976; Knapp and Seastedt 1986). The natural history of the prairie has been shaped by disturbance—primarily extended periods of drought, wildfire, and grazing (Risser *et al* 1981; Reichman 1987; Samson and Knopf 1996; Packard and Mutel 1997). In the absence of disturbance, prairies often progress through vegetative succession to either poor quality grasslands or thorn woodlands or scrublands (Risser *et al* 1981; Reichman 1987; Sampson and Knopf 1996; Packard and Mutel 1997).

The relationship between fire, humanity and ecosystem processes is ancient. Early humans used fire as a tool for over one million years, using it during hunting to drive prey, and to entice grazing species to the recovered site. Fire was also used to clear the land for agriculture (Bragg and Hulbert 1976; Scifres and Hamilton 1993). The advent of agriculture may be tied to the use of fire, as it was used to increase and maintain wild cereal grass stands in early historical times; the use of fire to increase and maintain cereal grass would have led to early agricultural activities (Blumler 1991).

In North America, native peoples used fire to shape ecosystems to promote game and to support small-scale agriculture. As a result, fire shaped nearly every ecosystem in North America until the arrival of European settlers and their philosophy of lifestyle and land use. As European settlers moved into North America, they brought new ideas about land use and management. Land use shifted to larger scale agriculture and to raising livestock. Fire became a threat to property ownership. Experiences with fire, especially wildfire, led to an ideology that fire was a destructive force in nature and must be controlled. Around the turn of the 20th century, the formation of the United States Forest Service gave the government a systematic approach to managing fire. As a result, strong fire suppression policies were developed and implemented. These suppression efforts were very successful for nearly 100 years (Wright and Bailey 1982).

Over the course of time it became apparent that removal of fire was detrimentally impacting some landscapes. The equation for creating the problem is clear, but the solution is not. Logically, the re-introduction of fire, through prescribed fire, should be the solution. Prescribed fire is, succinctly, the “systematically planned application of burning to meet specific management applications” (Scifres and Hamilton 1993:6). Prescribed burns are conducted within the limits set forth in a burn plan by a prescription for particular ranges of weather, fuel moisture, fuel loads, fire behavior, and ignition patterns to achieve particular management objectives (EPA 1996). The problem many managers now face is how they should apply burning to meet management goals in landscapes that have been altered by fire exclusion.

Wildlands have experienced substantial changes in species composition, species diversity, and ecological succession patterns, particularly since fire suppression policies have been in effect. Land managers are faced with re-introducing fire into landscapes that are very different than they were before fire exclusion (Christensen 2003).

Some landscape types have clear fire records, such as wooded areas, so fire regimes are known with more certainty. Woody species carry fire scars that indicate how often fires occurred and to some extent how intense the fires were. In prairie systems there is no fire record, because there are no woody species to carry fire scars.

However, historic records and studies of grasses in other landscapes allow researchers to theorize that grassland fires occurred every one to three years (Pyne 1982).

U.S. prairie systems are among the most degraded of all ecosystems (Morgan 2003). Like much of the tallgrass prairies of the Midwest, the Blackland prairie region of Texas has been modified to the point that it is nearly extinct. Once, the Blacklands stretched across 12 million acres, from the Red River to San Antonio; today less than one-tenth of one percent remains (Diamond and Smeins 1993; Sharpless and Yelderman 1993). Following the regional and national pattern, the most degraded environment of north Texas is its former prairie; the backgrounds of photos taken in the 1920s are often entirely devoid of trees. Today, roadsides and old grasslands support mid sized trees and large mesquites, and these former prairies—once prairie, once pasture and crops, once old-field—are turning into mesquite woodlands and poor quality shrublands.

Even with Pyne's (1982) estimation of fire frequency in prairies, using fire for prairie restoration still is not an exact science. Many species that historically did not exist in an area have been introduced over time, and although some may be controlled by application of fire, others are fire adapted. Additionally, in modern society there is some, justified, mistrust of fire. One result of urban sprawl is a fragmentation of landscapes, and privately owned property becomes interspersed with wildlands. This close interface of private property and wildland make safety and protection of property important issues. Also, in areas where wildlands are interspersed with private property, smoke production becomes not only an aesthetic issue, but legal and public health issues also. The burden has fallen on land managers to address the issues of concern as well as meet management goals that require the application of fire.

This project intends to evaluate and develop tools for the restoration of fire within prairies of the Lewisville Lake Environmental Learning Area (LLELA)—in both its ecological and managerial contexts—to further the practice of restoration ecology. LLELA, located in Lewisville, TX, is an area with approximately 800 acres of prairie and remnant prairie, but in order to begin restoration on the tallgrass prairies, several issues must be addressed.

The first issue that should be examined is prairie vegetation burn response. Part of restoring ecosystems is the re-establishment of desirable, native, functional plant species and eradication or control of undesirable, exotic, or invasive species. Historically, species composition was maintained by fire, and woody species were unable to invade fire maintained grasslands. The introduction of non-native species has complicated the solution of re-introduction of fire for restoration, because some non-natives are fire adapted or fire tolerant under certain weather conditions. When developing a fire prescription, managers must know how target species will respond to burning.

The second issue is one of fuel loads and fuel model scale. Fuel loads determine the rate of spread and intensity of a fire, within a given set of weather and topographic conditions, and the maximum temperature achieved during a burn is determined largely by fuel loading. Fuel loads are also important in their influence on post-burn effects (Scifres and Hamilton 1993). Fuel models are numeric descriptions of fire behavior and fire danger based on the type of vegetation as well as the horizontal and vertical arrangements of fuel, for example, short or tall grasses. Fuel models are defined largely based on the scale of assessment, and while issues of scale are addressed in landscape level analysis, such as with GIS, they are not addressed at other levels. This becomes an issue of concern when burn prescriptions are based on fuel models that may or may not be accurate representations of burn units.

The third issue that must be addressed is the prediction of fuel moisture. Predicting 1-hour fuel moisture is an important aspect of determining fire behavior. The 1-hour fuels carry the fire, and help determine whether or not woody fuels may be consumed (Rothermel 1983; Scifres and Hamilton 1993). The standard method for determining 1-hour fuel moisture requires fuels be dried at 80°C for 24-hours. Since 1-hour fuel moisture is so important when predicting fire behavior it would preferable to have a statistical model for predicting 1-hour fuel moisture (as well as other fuel moistures) in the field based on current weather conditions. This would give managers a useful tool for determining on-the-spot assessments of fire behavior or danger.

A fourth issue to be addressed when managing a prescribed burn is temporal planning: when will it be both appropriate and possible to burn safely and effectively? The most important issues in planning a suitable time period or window for a prescribed burn are weather, fuel, season, and time. Time and season are easily chosen and fuel management techniques exist, but weather is beyond the control of the land manager (Scifres and Hamilton 1993). Thus, managers must wait for suitable weather conditions to arrive. Conducting a prescribed burn may involve a diverse group of participants, so being able to schedule a burn with any degree of certainty would be beneficial to land managers. Poor planning can be a waste of time, money, and personnel. In light of these issues, long-range forecasting of prescribed burn weather opportunities has become an issue of interest. Knowing when weather conditions might meet those criteria necessary for burning to meet land management goals would be beneficial to the planners.

The fifth issue that requires examination is smoke impacts from a burn on the environment and the surrounding community. The issue of smoke production goes beyond obscuring smoke sensitive areas. Some communities, like the Dallas/Fort Worth Metroplex in north Texas, are non-attainment for air quality for one or more pollutants. In these areas it is important to know what air pollutants are being monitored and what some potential impacts of burning and smoke production will be. It is also important to understand that smoke emissions can be hazardous. Prescribed burn planners need to be aware of any smoke sensitive groups that may exist down-wind from a burn. Steps can be taken to minimize air pollution impacts and should be considered.

This study addresses these issues with specific application to the Lewisville Lake Environmental Learning Area (LLELA), a 2,000-acre wildlife management area located within the Dallas/Fort Worth Metroplex. Like many ecological principles, there are some broad concepts in fire ecology that may be widely applied. However, the application of fire ecology concepts to achieve particular results is site specific. The focus of this research will be to delve into these site-specific issues to produce information about LLELA that will be used in prairie restoration.

CHAPTER 2: LITERATURE REVIEW

Introduction

Prescribed burning is a technique for re-introducing fire to fire-suppressed regions for restoration and maintenance of ecosystems. Prescribed burning involves defining a burn prescription, a set of limits and ranges for weather, fuel moisture, and fuel loads, to produce a fire that will achieve land management goals. Before writing a burn prescription, clear, achievable land management goals must be stated, such as “reduce fine fuels by 90% to enhance new growth of native prairie grasses.” Based on the management goals, conditions can be set forth that will provide the type of fire needed (e.g., cool or hot fire) to produce these results. The conditions set forth in the burn prescription are designed to produce a burn of the intensity and duration required to meet the management goals. Furthermore, burn prescriptions include the expected or desired fire behavior based on the prescription, patterns for ignition of the fire, smoke management plans, and safety and contingency plans. On a small scale, under specified conditions, fire behavior is somewhat predictable. Fire behavior, as with many natural processes, does have a small percentage of uncertainty, but a burn prescription allows managers to take that into account and plan accordingly. Proper prescription development requires extensive knowledge of ecology, natural history, fire behavior, fire effects, and suppression.

Prairie Vegetation

Tallgrass Prairie, also known as true or bluestem prairie, once covered a large percent of the Great Plains, from Canada to Texas (Bragg and Hulbert 1976). These prairies were composed primarily of *Andropogon*, *Panicum*, *Schizachyrium*, and

Sorghastrum species (Bragg and Hulbert 1976). Today, the only extensive, unaltered section of Tallgrass Prairie is the Flint Hills, located in eastern Kansas (Bragg and Hulbert 1976; Knapp and Seastedt 1986). The Flint Hills region has survived extensive alteration because of its rugged topography and shallow soils (Bragg and Hulbert 1976).

Fire is an integral component of natural, healthy Tallgrass Prairie ecosystems (Bragg and Hulbert 1976; Grace *et al* 2002). Without periodic burns, woody species begin to encroach and eventually dominate prairie grasslands (Bragg and Hulbert 1976). Also as a result of fire-exclusion, a substantial number of invasive, non-native grasses, forbs, and woody species have invaded prairie grasslands. Many of the species have been introduced deliberately for any of a number of reasons, such as range management, forage development, pastures, lawns, and ornamentals (Grace *et al* 2001).

The ability of fire to maintain prairies depends on plant response to fire. The net effect of fire on plants depends on a complex interaction of several factors, including physical, morphological, and physiological adaptations of specific plants during exposure to increased temperatures. Additionally, the tolerance of plants to the modified post-burn environment will play a role. Many combinations of these factors will determine whether a plant will succumb to the heat, or flourish under the influence of fire treatments (Scifres and Hamilton 1993). This, in turn, will determine the successional pathways and future species composition of a given site.

Heat damages and kills plant tissues by coagulating proteins and rupturing cell membranes. The thermal death point for plant tissue occurs between 50°C and 55°C, whole plant death occurs at approximately 60°C. However, temperature alone is not responsible for plant death. Thermal death is a function of temperature and duration of exposure; as temperature increases, less exposure is needed to achieve mortality, but temperature and duration required for heat killing vary from species to species (Wright and Bailey 1982; Scifres and Hamilton 1993). There are several physical adaptations that may help to make plants more heat resistant. For example, succulent plants are generally less heat resistant than plants with lower moisture contents because the greater the hydration of the plant tissues, the more likely proteins are to coagulate with heat. Dry seeds are the most heat-resistant phase of a plants life cycle because of the protective seed coat and the low degree of hydration of the seed. Bark insulates woody plants against heating, but the insulating value of bark varies, based on density, thickness, chemical composition, water content, and integrity (Scifres and Hamilton 1993).

Physiological adaptations that may aid a plant in heat resistance include tissue chemical composition and the physiological status of their cells. For example, some xerophytes contain carbohydrates in the protoplasm of their cells, which increases their resistance to heat. Also, quiescent plants are more heat resistant than actively growing plants; seeds are an example of heat resistance during quiescence (Scifres and Hamilton 1993). Seeds are highly heat tolerant and are reported to be able to survive temperatures of 82°C to 116°C for five minutes. Grass fires have a minimal effect on dormant seeds, even if they are lying on the soil surface (Wright and Bailey 1982).

Plant morphology gives more information as to how a plant will respond to burning. In herbaceous plants, the above-ground portion of the plant is usually consumed, but the rate of consumption influences the survival of regenerative organs.

In addition, the orientation of regenerative organs determines their heat exposure. Since heat rises, regenerative organs located near or below the soil surface escape the worst of the heat (Wright and Bailey 1982; Scifres and Hamilton 1993). Rhizomatous grasses usually survive fire because the rhizomes are located approximately 2.5 cm below the soil surface, where heating does not penetrate. Bunchgrasses may suffer damage to their regenerative organs if the organs are located near the soil surface and there are large quantities of dead plant material. Large amounts of dead plant material will take longer to burn and burn hotter causing heat damage to regenerative organs (Wright and Bailey 1982).

The season of burning can be planned to maximize the damage to invasive or non-native grasses, based on their growth cycle. Burning while cool-season grasses are dormant may only remove the top portion of the plant and allow it to re-grow. However, burning in the spring, while plants are actively growing, may inflict enough damage to cool-season grasses and eliminate them for the entire growing season (Scifres and Hamilton 1993).

Research into mechanisms controlling energy flow and nutrient cycling in tallgrass prairies found that dead plant material, both standing and on the ground, has a profound effect on overall productivity, amounts of plants and animals present, and species composition of plants and animals. Accumulated dead material can affect almost every ecosystem process and can lower productivity (Knapp and Seastedt 1986).

Tallgrass prairies are known as tallgrass because the stands of the dominant grasses are often over 0.5 meter high and flowering stems of big bluestem may exceed

2 meters (Knapp and Seastedt 1986). When the foliage of tallgrass prairies dies in winter, it does not fall to the ground, but remains upright, until removed or compacted. Usually, snow and rain, fire, or grazers accomplish this process of removal and/or compaction. The rate of decomposition is slow in prairies because of dry microclimates and low nutrient values of plant material, but compression near the soil increases the rate of decomposition. In the absence of fire or grazers to remove dead plant material, it may accumulate substantially, resulting in unusually low primary productivity in undisturbed prairies (Knapp and Seastedt 1986). The introduction of ungulates can increase productivity up to 50%, and burning after several years of suppression and no grazing can increase productivity by over 75% (Knapp and Seastedt 1986).

Detritus accumulation has a negative impact on plants for several reasons. It limits the amount of photosynthetically active radiation (PAR) that is able to reach the soil surface (Peet *et al* 1975; Knapp and Seastedt 1986). The decrease in solar radiation can be 58% less in unburned sites compared to burned sites; the decrease in PAR leads to decreased productivity (Knapp and Seastedt 1986). A consequence of decreased solar radiation reaching the soil surface is cooler soil temperatures compared to sites without detritus accumulation. Soil temperatures measured at 3 and 5 cm below the soil surface were consistently warmer on burned plots than on unburned plots (Peet *et al* 1975). The decreased soil temperature delays the emergence of new shoots in spring, and the delay leads to a shorter growing season. The root systems of plants also display later growth and activity, until the soil warms (Knapp and Seastedt 1986). Some studies (Hulbert 1988) have tried to duplicate the effects of solar warming with artificial warming; the results suggest that physical warming does have a beneficial effect on tallgrass prairie species, but does not account for all the benefits. Lack of PAR and solar warming are both responsible for delays in vegetative reproduction below the standing dead plant material (Knapp and Seastedt 1986; Hulbert 1988).

Although the accumulation of detritus decreases productivity for tallgrass prairie species, productivity for woody species increases, encouraging woody species encroachment (Knapp and Seastedt 1986).

Nitrogen and water dynamics are also influenced by detrital accumulation. Nitrogen loss from surface run-off is usually negligible in both burned and unburned prairie plots (Knapp and Seastedt 1986). Subsurface structures, such as roots and rhizomes, are rarely adversely affected by burning, and these structures prevent soil erosion (Knapp and Seastedt 1986). Plant material intercepting rainfall affects the amount and chemical composition of rain that reaches the soil. Undisturbed prairie intercepts about 40% of rainfall and prevents it from reaching the soil surface, whereas burned prairie only intercepts 20%. Also, dead plant material and microbes that exist on detritus can alter the nitrogen content of rain, decreasing the nitrogen's bioavailability to plants (Knapp and Seastedt 1986). Nitrogen fixation by free-living and symbiotic algae, and blue-green algae are important sources of nitrogen for tallgrass systems, but this fixation process is decreased on unburned plots (Knapp and Seastedt 1986).

There has been concern that repeated annual burning would eventually deplete available nitrogen resources, even though the physiological characteristics of the native prairie grasses cause a drawdown of soil nutrient levels, especially nitrogen (Risser *et al* 1981; Wilson and Gerry 1995). Unlike many weedy, invasive species, native prairie vegetation is adapted to low soil nitrogen levels; their physiological requirements create a positive feedback loop that promotes native vegetation. However, burning volatilizes approximately 1.5-2.0 g N/m^2/year from litter, equivalent to approximately two years worth of nitrogen inputs from rainfall (Knapp and Seastedt 1986; Scifres and Hamilton 1993). Only one to three percent of the nitrogen lost by combustion cannot be replaced by rain (Scifres and Hamilton 1993). However, this does not take into account the difference in nitrogen fixation between burned and unburned prairie, from changes in soil temperature and moisture, as well as inputs from other sources, such as ungulates (Hulbert 1988; Scifres and Hamilton 1993). Earthworms, an excellent source of soil nutrition, are less prevalent in areas with detrital accumulation (Knapp and Seastedt 1986). Evidence also shows that root systems in undisturbed prairie are not as good at removing bioavailable nitrogen from the soil as root systems on burned prairies. In the soil of burned prairies there are reservoirs of organic nitrogen, which suggests that increases in nitrogen levels exceed losses and nitrogen loss through periodic burning is compensated for by the benefits of detritus removal (Knapp and Seastedt 1986).

Grazing, one method of detritus compaction and removal, is intricately entwined with burning. Burning in tallgrass prairies increases bison (*Bison bison*) grazing three times more than would be expected if bison grazed randomly compared to unburned prairies (Vinton *et al* 1993). The preferential grazing of bison was most pronounced during the summer months, but was still evident into winter and fall (Vinton *et al* 1993). On a smaller scale, bison preferred patches on both burned and unburned landscapes that had a high dominance of big bluestem (*Andropogon gerardii*), low forbs species richness and diversity, and low plant species diversity. In other words, patches with high grass:forbs ratios (Vinton *et al* 1993). Burning is believed to modify bison grazing habits by making desirable plants more accessible and increasing their frequency. Preferential grazing is also attributed to increased grass production and high live:dead fuel ratios (Vinton *et al* 1993).

Fire and grazing are necessary and integral processes that maintain the productivity of tallgrass prairie by removing and preventing accumulation of detritus (Knapp and Seastedt 1986) and by shaping ecosystem composition (Bragg and Hulbert 1976). Burning serves to cause warm season grasses to begin growth earlier, grow faster, and produce more flowering stalks and tillers than unburned areas (Hulbert 1988; Knapp and Seastedt 1986).

Fuel Loads and Fuel Models

Of the three legs of the fire environment triangle--weather, topography, and fuels--only fuels are readily manipulated or altered by land managers. In addition, fuels are the driving factor behind fire behavior, which in turn influences plant and ecosystem response. As such, fuels become the focal point for studies of fire effects and behavior, or in management efforts meant to alleviate potentially dangerous levels of fuel. Therefore, it is important to be able to identify and characterize fuels in a way that is not only descriptive, but has meaning to others that may be involved in a prescribed burn situation. Fuel models are used to characterize fuels for the prediction of fire behavior and for fire danger ratings (Anderson 1982). The fire danger rating system works using weather records for each day along with fuel model data to predict daily and seasonal trends in fire risk. As fuel models for fire danger are not used for fire behavior prediction, they will receive no further mention.

Fuel models are generalizations of fuel characteristics that affect fire behavior, such as vegetation type loading, horizontal and vertical arrangement, and moisture (Wagtendonk 1991). The descriptive value of fuel models has increased as the number of fuel models has increased. In 1964 the Forest Service used two fuel models. In 1972 it increased to nine, then in 1978 to 20 fuel models. Although 20 fuel models are recognized, most fire behavior prediction models use a thirteen fuel model system (Table 2-1) described by Rothermel and Albini (Anderson 1982). These fuel models are organized into four groups based on the fuel that drives fire behavior: grasses, shrub, timber and slash (Anderson 1982).

Table 2-1: Descriptions of Fuel Models (Anderson 1982)

Fuel Model	Fuel Description	Grouping
1	Short grass (1 foot)	Grasses
2	Timber (grass and understory)	Grasses
3	Tall grass (2.5 feet)	Grasses
4	Chaparral (6 feet)	Chaparral/shrub
5	Brush (2 feet)	Chaparral/shrub
6	Dormant brush, hardwood slash	Chaparral/shrub
7	Southern rough	Chaparral/shrub
8	Closed timber litter	Timber
9	Hardwood litter	Timber
10	Timber (litter and understory)	Timber
11	Light logging slash	Slash
12	Medium logging slash	Slash
13	Heavy logging slash	Slash

Although there are thirteen models, only three apply to this research, fuel models 1-3, and the rest will receive no further mention. Fuel model 1 is short grass, the fine, porous grasses that are either cured or nearly cured and regulate fire spread. The rate of fire spread is rapid. Examples of typical ecosystems for fuel model 1 include grazed rangeland and short to mixed grass prairies. Timber and shrubs, when present, represent less than 1/3 of the area (Anderson 1982). Fuel Model 2 also relies on the fine cured or dead grasses to spread the fire. Woody species present contribute to the fire intensity. Shrubs and trees may cover 1/3 to 2/3 of the area in this model (Anderson 1982). Savannahs, old-fields, and prairies with substantial woody species encroachment represent this fuel model. Fuel Model 3, tall grass, has fires that are the most intense of all the grass groups. The stands are tall, averaging approximately one meter (Anderson 1982). Tallgrass prairies are an example of fuel model 3.

While standard methods for fuel assessment exist (Brown *et al* 1982; Anderson 1982) the potential influence of sampling scale and method on the results is rarely made explicit except in landscape level analysis (Key and Benson 2003). However, a basic premise of ecology is that the spatial patterns of habitats (or fuel models) and ecosystems in a landscape exert strong and sometimes dominant influences on the distribution and population dynamics of the flora and fauna (Andren 1994; St. Clair *et al* 1998), and that these readily observable patterns are the result of basic biophysical processes, such as disturbances (e.g., fire), climate, and soil processes (Bormann and Likens 1979; Allen and Hoesktra 1992). What makes this basic premise complicated for scientific study is that different patterns in the ecology of a landscape emerge at different spatial scales of sampling and analysis (Cale and Hobbs 1994; Stohlgren *et al* 1998; Bissonette 1997). The relationship between the scale of observation and the patterns researchers observe remains the "central problem in ecology" (Levin 1992: 1943). Thus, scale must be explicitly considered in any field assessment of fuel models or fuel loading.

Fuel Moisture

Fuel moisture is an important piece of information to consider when planning a prescribed burn. For ignition of fuel to occur, heat must be applied, but the high heat capacity of water absorbs heat and confounds the process. For ignition to be successful, fuel temperatures must be raised to 100°C and held until the moisture has been driven off (Scifres and Hamilton 1993).

There are several mechanisms by which fuel moisture affects the combustion process. When fuels combust, the physical components of the fuel are broken down into a combustible gaseous mixture by chemical processes. Water vapor, from the moisture content of the fuel, dilutes these combustible gases, delaying the production of a flammable layer of gasses. The flammability of the air and gas mixture is reduced. Fuel moisture also becomes water vapor when burned, and thus cools or extinguishes flames (Scifres and Hamilton 1993). In addition, moisture content buffers plant tissue against temperature increases. This buffer capacity increases the time needed to raise the temperature of the fuel to its ignition point and may slow down the burn as fuel moisture acts to smother flames (Wright and Bailey 1982; Scifres and Hamilton 1993). Also, high water content of fuel slows the decomposition of organic compounds under high temperatures. This process, known as pyrolysis, occurs at the surface of the fuel and is part of the combustion process. The gases released by pyrolysis are flammable and account for most of fire’s behavior (Scifres and Hamilton 1993). Additionally, water content of fuel absorbs heat as water moves through the layer of char. Char forms over the surface of the fuel and insulates the unburned portion of the fuel. The cooling causes char to form faster and insulate flammable plant material more readily. This function of water is more important when burning woody fuels than with grasses (Scifres and Hamilton 1993).

Another fuel characteristic to consider when planning a prescribed burn is how fuels react to varying environmental conditions, such as long-term precipitation and humidity patterns. Moisture levels in vegetation with large volumes and small surfaces areas, for example mature trees, respond slowly to environmental changes. However fine fuels, such as grasses and forbs, have small volume to surface area ratios, and thus respond quickly to changes in weather. The moisture content of these fuels is strongly influenced by environmental conditions, primarily wind, temperature, and relative humidity. Relative humidity and fuel moisture are closely related, as relative humidity has direct effect on fuel moisture (Wright and Bailey 1982). Wind tends to have a drying effect on fuel moisture, as does direct sun exposure. Air temperature can amplify the effects of wind: on warm days wind action has more of a drying effect than cooler days (Scifres and Hamilton 1993). Volume to surface area ratio generally classifies fuels. Dead fuels are classified by the rate, or time lag, at which they respond to changes in environmental conditions (Table 2-2). Being able to classify fuels gives prescribed fire personnel an indication of how the fire will spread and behave.

Table 2-2: Fuel Lag Time Classifications (Wright and Bailey 1982; Scifres and Hamilton 1993)

	Diameter	
Time Lag	English (in)	Metric (cm)
1-hour	<0.25	<0.6
10-hour	0.25-1	0.6-2.5
100-hour	1-3	2.5-7.6
1000-hour	3-8	7.6-20.3

One-hour fuel moisture content not only influences the rate and intensity of the burn, it also determines whether woody plants will ignite (Scifres and Hamilton 1993). It also influences fire behavior; for example, when fuel moisture is below 5%, spot fires are almost a certainty, but above 11% spot fires are rare. Fuel moisture between 7-8% is usually the threshold for avoiding ash and firebrands (burned woody material) from causing spot fires (Wright and Bailey 1982).

Weather Forecasting

When planning a prescribed burn, the important issues are weather, fuel, season, and time. The season and time of burn are the variables most readily controlled, and fuels are readily manipulated (Scifres and Hamilton 1993). Weather, however, cannot be influenced, requiring land managers wait for suitable conditions. A successful prescribed burn requires that aspects of weather particularly air temperature, wind direction and speed, relative humidity, and precipitation, be within strict parameters (Scifres and Hamilton 1993). These variables are often grouped under the term “fire weather.”

Given the importance of weather in prescribed burning and its variability, predicting weather conditions becomes an important issue. After the fires at Yellowstone National Park, the Secretary of Agriculture and the Secretary of the Interior organized a team to investigate fire policies and management. Among the recommendations of this council was more research into forecasting long-term weather conditions (Fujioka 1991). In 1989, the Forest Service emphasized a need for long-range weather forecasting to assist in prescribed burning. This information would allow land managers and prescribed burn planners to predict in advance weather related fire potentials, both beneficial and harmful (Fujioka 1991).

Air Temperature

Air temperature determines how much heat energy input is required to raise fuel temperatures to ignition point. As air temperature increases less heating is required to raise the temperature of fuels to ignition and fuel dries more quickly (Scifres and Hamilton 1993). The drying effects of wind are increased on hot days as opposed to cool days (Scifres and Hamilton 1993).

Generally, fire does not take and carry well in temperatures less than 4°C, but burns readily at temperatures above 21°C (NWCG 1989; Scifres and Hamilton 1993). Below 15°C the danger of firebrands and glowing embers starting spot fires decreases, while above 15°C the danger increases exponentially. Grasses generally will not carry a fire when temperatures are below 0°C, unless fuel loads are dense (Wright and Bailey 1982). Management objectives might require different types of burns that require air temperatures outside the general rule. For example, “cool” burns that remove rough herbaceous material and top kill small woody species, may be conducted near the low end of the air temperature recommended range. Conversely, “reclamation burns” that are conducted to do maximum damage to established woody plants may be conducted at temperatures closer to 32°C (Scifres and Hamilton 1993).

Both the duration of heat exposure and the maximum temperature of the burn are variables that will affect plant mortality. On hot, dry days, critical temperatures for plant mortality are more likely to be achieved and sustained than on cooler days. As always, when deciding air temperature parameters, safety must be a consideration (NWCG 1989; Scifres and Hamilton 1993).

Wind

The most substantial effect of wind is on the spread of the fire. Wind and slope determine the direction of fire spread. Head-fires burn with the wind and back-fires burn against the wind, which allows managers to use wind to modify fire behavior to meet their objectives. The rate of head-fire movement is always greater than that of the backfire, making head-fires the more dangerous of the two (Scifres and Hamilton 1993). Wind is a complex and potentially treacherous weather condition: some wind is required for an effective burn, but unless the wind is consistently within the prescription and from the proper direction, wind can turn an otherwise well-managed prescribed burn into a wildfire (NWCG 1989; Scifres and Hamilton 1993). In addition, fire creates its own localized air currents. Convective air currents will form as the fire heats the air. These air currents contribute to the flashy nature of fire (Scifres and Hamilton 1993).

The specific wind speed desired for burning varies based on the objectives of the burn. Greater wind speeds increase the rate of spread of fire. As wind speed increases it tips the flame from a vertical position to a more horizontal position. This position allows the flames to pre-heat the preceding fuels, decreasing the energy needed to achieve ignition. This action helps the flames bridge fuel discontinuity (Scifres and Hamilton 1993; Miller 1994).

According to Texas law, “burning must be conducted when the surface wind speed is predicted to be in the range of six to twenty-three miles per hour” (10 to 37 km/h) (30 Texas Administrative Code 111.201-111.221). Wind speeds of less than 6 km/h are not usually sufficient to supply enough oxygen for maximum combustion rate. Insufficient oxygen may lead to low fuel consumption and increased smoke production since fuels may not have high combustion efficiency (Scifres and Hamilton 1993). Wind speeds of at least 21 km/h are recommended for top-killing brush and removing dead woody fuel (Wright and Bailey 1982). Winds over 21 km/h may compromise the ability to control head-fires, but the rate at which head-fires move is not directly proportional to wind speed (Scifres and Hamilton 1993).

The wind speed needed to supply oxygen to a burn and push the flames through fuel varies from site to site. Sites with low fuel loads (approximately 1,500 pounds/acre), poor fuel continuity, and fuel moistures greater than 25% may not be practical areas to burn, regardless of wind speed. Areas that have a moderate fuel load (approximately 2,000 pounds/acre), good fuel continuity, and low fuel moisture may require winds of 16 to 19 km/h. Moderate to heavy fuel loads (2,000-4,000 pounds/acre), good continuity, and low moisture may require only require wind speeds of 12.9 to 16.1 km/h. These estimates pertain to grasslands (fuel models 1-3), where the vegetation is mostly grasses with light shrub cover (Scifres and Hamilton 1993).

Relative Humidity

Relative humidity is a measure of the drying and wetting ability of the air in close contact with fuel and, therefore, the measure of atmospheric water content used by fire ecologists. Relative humidity is at least as important as wind speed when planning a prescribed burn because changes in fuel moisture, especially one-hour or fine fuel moisture, lags only slightly behind changes in relative humidity. Fuel moisture and relative humidity exist in a dynamic equilibrium (Scifres and Hamilton 1993). From 20 to

40% relative humidity, fires burn with approximately the same intensity. When relative humidity is below 20%, there is a serious danger of firebrands causing spot fires. When relative humidity is above 50% firebrands and glowing embers rarely start spot fires (Wright and Bailey 1982). Scifres and Hamilton (1993) cite a study by Cooper (1963) that recommends a relative humidity range from 30 to 60 percent for prescribed burning of one-hour fuels. However, as with other weather parameters, relative humidity ranges should be set based on the objectives of the prescribed burn. When “reclamation” is the goal, burning with a relative humidity of 30% or less may be acceptable, whereas “cool” maintenance burns may be conducted when relative humidity is 60% or more (Scifres and Hamilton 1993). However, burning in north Texas at greater than 60% relative humidity is, at best, difficult due to the smothering action of water vapor.

Smoke Production and Management

Smoke is generated by the incomplete combustion of flammable materials. Smoke from burning is composed of carbon, tar, liquids, gases, and particulates. Historically, the goal of smoke management was to alleviate nuisance conditions and avoid visibility issues in surrounding areas. Currently, smoke is still managed for those issues, but smoke management must also consider a variety of regional, state, and federal legislation governing air quality (NWCG 2001). Pollutants emitted during the burning process that are also regulated by the National Ambient Air Quality Standards are carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone, and particulate matter (NWCG 2001). The amount of smoke produced is commensurate with area burned, fuel loading, and fuel consumption (NWCG 2001). Additionally, the phase of combustion--preheating, flaming, glowing, and smoldering--affects the amount of emissions produced. Smoldering produces more emissions per quantity of fuel burned than the flaming phase. This is due to low efficiency and incomplete combustion (EPA 1996). Smoldering is less common in fuels that have a low surface area to volume ratio, such as grasses (NWCG 2001). Flaming is the most efficient stage of combustion; producing the least emissions and consuming the most fuel. Twenty to 90% of the fuel consumed during a fire is consumed during the flaming stage (NWCG 2001), while during the glowing phase carbon monoxide and carbon dioxide are still being produced, but no smoke is visible (Mahaffey and Miller 1994). Factors that influence combustion and combustion efficiency are the size, quantity and arrangement of fuels, meteorological conditions, and topography (EPA 1996). Quantitative smoke emissions are usually calculated from lab derived emission factors (EPA 1996; NWCG 2001).

Carbon dioxide (CO_2) and water (H_2O) are common emissions from the burning process, they are not technically pollutants, although carbon dioxide and water vapor are greenhouse gases and water vapor condenses into the visible white part of smoke. When combustion efficiency is low, carbon is not converted into carbon dioxide efficiently and more carbon is available to form other gases, such as carbon monoxide (NWCG 2001).

Carbon monoxide (CO) is the most abundant emission from wildland fires. It poses a serious threat to human health, because it binds preferentially to hemoglobin, over oxygen. Hemoglobin is the structure in red blood cells that normally carries oxygen (Marieb 1992). The EPA (1998) website warns that exposure to CO is associated with visual impairment, reduced work capacity, decrease in manual dexterity, decreased learning ability, and impairment when performing complex tasks. The negative effects depend on duration of exposure, concentration of CO, and level of physical activity during the window of exposure. Dilution of CO occurs quickly, so it does not usually pose a problem to surrounding areas, unless there is a temperature inversion that traps the CO near the ground (NWCG 2001).

Nitrogen oxides (NO_X) are produced when nitrogen in fuels is oxidized during the combustion process. Most fuels contain less than 1% nitrogen. About 20% of that nitrogen is converted to NO_X during combustion. NO_X is a ground level ozone precursor, and under certain weather conditions, may contribute to ground level ozone formation (NWCG 2001). According to the EPA (1998), NO_X reacts to form toxic chemicals, such as nitric acid, and also contributes to acid rain, cultural eutrophication, impairment of visibility by forming particles, and contributes to global warming.

Particulate matter (PM) produced during the combustion process may obscure visibility, absorb and act as a carrier of harmful gasses, and aggravate respiratory ailments. Ailments that may be aggravated include asthma, and chronic bronchitis. Additionally, PM may cause coughing, decreased lung function, and premature death (EPA 1998). Over 90% of the particulates produced during combustion are less than 90 μm and approximately 70% of all the particulates produced are less than 2.5 μm. The small particulates (<2.5 μm) may stay suspended in air for an extended period of time; this increases the chance of inhalation and allows the particulates to penetrate deep into the lung (EPA 1998; Wright and Bailey 1982). Particulates vary widely in size depending somewhat on the rate of energy release from the fire. For example, high intensity fires tend to have a strong bimodal distribution of particulate size with a peak at 3 μm and at greater than 10 μm (EPA 1996). Since particulates also absorb harmful gasses, they may deliver these toxins into the lungs (NWCG 2001). Additionally, particulates form soot, which can cause aesthetic and physical damage to porous materials, including historical treasures and landmarks (EPA 1998).

Sulfur dioxide (SO_2) is produced during combustion and may cause a variety of health and environmental impacts, primarily due to the way SO_2 reacts with other air borne substances. High levels of SO_2 may temporarily aggravate asthma and long-term exposure may cause respiratory illness and aggravate heart disease. Sulfur dioxide in the air may react with other airborne chemicals to form particulates and obscure visibility. Sulfur dioxide may also react with other chemicals to form acids that may react to form acid rain, snow, fog, or dry acidic particles. These acidic compounds can damage plants and crops, compromise water supplies, and damage buildings and cultural and aesthetic treasures (EPA 2003).

Health concerns associated with smoke exposure naturally call to attention the risk to personnel that work along the fireline. OSHA has Permissible Exposure Limits (PELs), set to protect most workers from adverse health effects over the course of their working life (NWCG 2001). There are more stringent guidelines set by the American Conference of Governmental Industrial Hygienists (ACGIH). These guidelines are set to protect most workers, but unlike the OSHA limits, are set without regard to economic feasibility. The ACGIH periodically updates its guidelines based on new health information and scientific advances, whereas some OSHA limits have not changed since the 1960s (NWCG 2001).

Studies have monitored fireline workers' exposure to smoke (Reinhart *et al* 2000; Reinhart and Ottmar 2000). Samples were collected from "the breathing zone," one-foot in front of workers' faces, while they worked a fire. The data were collected at 39 prescribed burns, and Reinhardt *et al* (2000) found that 10% of the firefighters had exposure levels of respiratory irritants and carbon monoxide that exceed OSHA exposure limits. A study conducted at wildfires, duplicating the prescribed burn smoke exposure study, found that 5% of firefighters were exposed to smoke concentrations exceeding limits (Reinhart and Ottmar 2000).

Equipment exists to help reduce fireline workers exposure to smoke. There are disposable respirators, but they tend to degrade over time with heat exposure. Another alternative is a half mask, but there is an associated potential for heat stress with all face masks. Full-face masks have the same heat stress problem, but have the benefit of eye protection. All respirators have the benefit of decreasing the risks of some types of exposure, but also have specific drawbacks. For example, all respirators have the deficiency of not being able to remove carbon monoxide from the air (NWCG 2001). Decisions about whether or not to wear a respirator or what type of respirator to wear must be made based on the situation and the benefits and limits of the respirator.

CHAPTER 3: METHODS

Study Area

The Lewisville Lake Environmental Learning Area (LLELA) comprises approximately 2000 acres, lying within the Cross Timbers and Prairies physiogeographic province of north central Texas (Figure 3-1). The climate is considered humid subtropical, with hot summers and mild winters. Average annual precipitation is 32 inches and is concentrated largely in spring and fall. The LLELA landscape (Figure 3-2) can be delineated roughly into four major ecosystem types: bottomland forests and adjacent wetlands (~1000 acres), upland grasslands of the Blackland Prairie (~800 acres), transitional shrublands (~200 acres) resulting from either cleared forests or fire suppressed grasslands, and aquatic systems of wetlands, creeks, and rivers.

Figure 3-1: The landscape of north central Texas near LLELA (photo 1998).

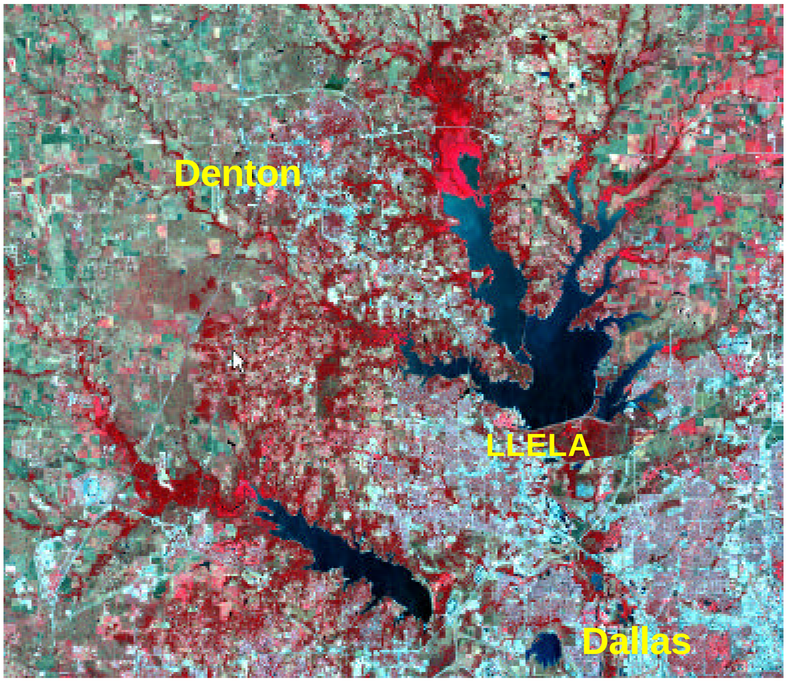
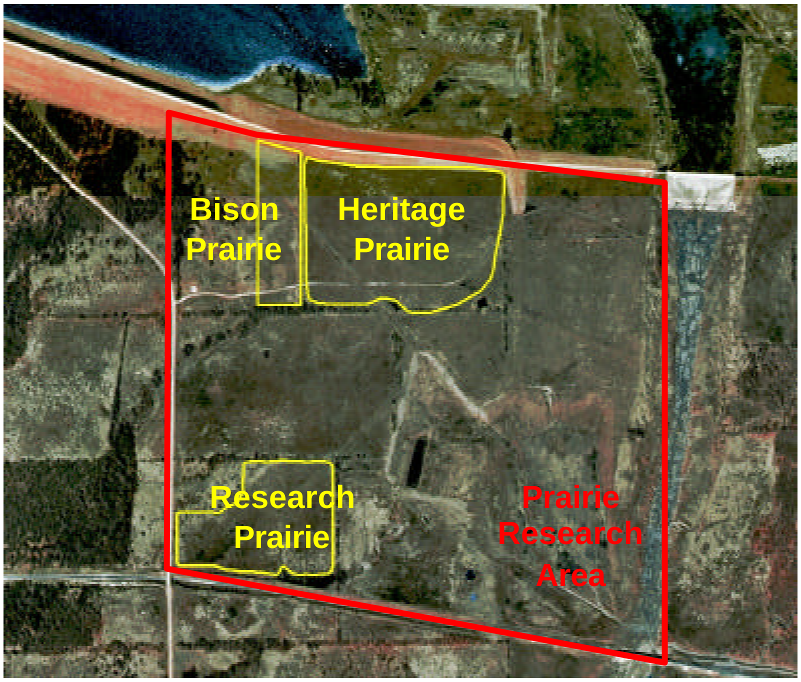


Figure 3-2: The Lewisville Lake Environmental Learning Area (photo 1995). The primary study areas for this project are delineated.



The prairie research area comprises approximately 300 acres within the LLELA lands (Figure 3-2). In February of 2002, approximately 35 acres of the prairie research area were treated with prescribed fire as an initial assessment of this project's potential. The assessment burn was very successful, and approximately 60-75 acres in three different burn units will be included in the prescription fire program. Areas intended for burning are referred to as burn units. The three burn units investigated during this study are the Bison Prairie Burn Unit, the Heritage Prairie Burn Unit, and the Research Prairie Burn Unit (Figure 3-2).

The Bison Prairie Burn Unit, according to calculations made using GPS data, is 10.3 acres, with a calculated fuel load of 2.7 tons of fuel per acre (relative acceptable error=15%, $p \leq 0.05$). Calculations of air pollution emissions were made based on 95% of fuel being consumed during burning (Scifres and Hamilton 1993).

The Heritage Prairie Burn Unit is 39.4 acres, based on GPS data, and has a fuel load of 2.58 tons per acre (relative acceptable error=15%, $p \leq 0.05$). Emissions were calculated using 95% consumption of available fuel.

The Research Prairie Burn Unit has a fuel load of 2.86 tons per acre (relative acceptable error=15%, $p \leq 0.05$), based on previous sampling data, and is 20.6 acres, based on GPS data. Again, consumption of fuel during burning is estimated to be 95%.

Prairie Vegetation

The literature of fire effects on the vegetation that is common across LLELA's prairies was explored and a database developed categorizing important species based on how they are affected by fire and how they might be expected to respond given certain fire prescriptions. Climate and seasonal influence on vegetation response to fire was investigated. This information may be used to predict potential fire effects on the vegetation located in the burn units.

Fuel Load and Fuel Models

Fuel loads and fuel models in prairie and shrubland areas were sampled to understand how changes in method of assessment and scale of assessment modify sampling results. Two hundred fifty two points were sampled within the three burn units. Using a Trimble® v5.12 GPS Unit, 87 points were placed on a 50 m x 50 m fixed-point grid over the Bison and Heritage Burn Units. The Research Prairie Burn Unit had been previously mapped into 40 x 40 meter plots with a 5-meter buffer between each plot; therefore the Research Prairie grid used the center of each plot for the assessment site. The other 126 points were placed randomly over the same burn units, so that each burn unit had an equal number of grid and random points. At each point, assessments were made of (a) qualitative fuel loading within 1-meter of the point, based upon previous quantitative data gathered from the area, and (b) the appropriate Anderson fuel model within 1-meter of the point and within 25-meters of the point.

Qualitative fuel loadings were rated as one of six categories: none, low, low-medium, medium, medium-high, and high. Based on data collected for the fuel moisture study (below), each qualitative fuel load has the following approximate weight range (Table 3-3).

Table 3-3: Approximate Weight Ranges for Qualitative Fuel Load Categories

Qualitative Category	Approximate Weight Range ($g/900\ cm^2$)	Approximate Weight Range (tons/acre)
None	0	0
Low	1-40	0.05-2.0
Low-medium	40-80	2.0-4.0
Medium	80-120	4.0-6.0
Medium high	120-160	6.0-8.0
High	>160	>8.0

Data were analyzed using the G-Test (SAS 8.2© 1999-2001). Grid and random assessments for fuel load and fuel models were compared to assess whether the resulting map was significantly different for data collected using a grid or random method. Also, fuel model assessments at 1-meter and 25-meter radii were tested to determine whether the resulting map was significantly different for data collected using 1-meter and 25-meter radii.

Spatial analysis and comparisons were made using ArcGIS 8.3®. Data points were used to create raster files based on one of the evaluations made for each point (for example fuel loading), then the rasters were converted to polygons with the point being the centroid of the polygon. Point data were extended using a grid based allocation function that extended each point's attributes to a location midway to each of its neighbors. ArcGIS then calculated the area for each field variable and the calculated areas were used to generate statistics.

The grid-based survey method with the 25-meter assessment radius provided nearly complete coverage of the 3 burn units, and thus represents the closest approximation of the distribution of fuel model types across the study area without resorting to mapping every square meter within the unit. At 25-meters from a point on the grid, there would be no overlap in assessment, however when using a random point system there is potential for overlap.

Fuel Moisture

Stratified random fuel samples were collected, along a random azimuth, from LLELA's prairie research areas using a 30 by 30 cm reference frame. An azimuth was chosen from a random number table generated by Microsoft® Excel©. The azimuth determines the direction from the edge, through the center of the plot where samples were taken. Representative fuel samples were then collected along the azimuth. All standing, 1-hour fuels within a 30 cm by 30 cm frame were collected for weighing and drying. At the time of collection, a hand-held Kestrel® 3000 Pocket Weather Meter was used to measure temperature, relative humidity, and wind speed. After samples were collected they were weighed to determine initial weight. The samples were then dried in an 80°C oven for twenty-four hours. Fuel moisture was calculated by subtracting the dry weight of the fuel from the initial weight of the fuel divided by the dry weight (weight $_{(initial)}$ – weight $_{(dry)}$ / weight $_{(dry)}$) (Scifres and Hamilton 1993; Miller 1994).

Simple linear regression was used to create a statistical model to determine 1-hour fuel moisture from weather variables. Maximum R^2 improvement multiple regression analysis was used to create a statistical model to determine 1-hour fuel moisture from all recorded weather variables. Then dry weights were used to calculate total fuel loading for the burn units sampled. This fuel loading data was used to calculate the qualitative categories employed in the fuel load study.

In addition, a fuel moisture station was set up for 10-hr, 100-hr fuels, and 1000-hr fuels, so that fuel moistures could be directly compared with on-site fire weather data. A sling psychrometer and a hand-held Kestrel 3000 Pocket Weather Meter were used to collect fire weather data. Fuel sticks were used to assess woody fuel moisture. Fuel sticks are wooden dowels that act as surrogates for woody plants. Two sets of standard 10-hr fuel sticks and a calibrated scale were placed at the sampling station on the roof of the EESAT building. This site was chosen to avoid people and animals tampering with the sticks, since protocol requires the sticks be arrayed 12 inches above wood chip or hard wood litter. Also, protocol for fuel moisture sticks require the sticks be exposed to sunlight from 9:00 am to 3:00 pm (Brown *et al* 1982). Data collected from the moisture sticks were not applied directly to LLELA, but used to determine relationships between woody fuel moisture and weather variables.

Ten-hour fuel moisture sticks are dowels that are 47 cm in length and 1.27 cm in diameter. A 100-hr fuel moisture stick was also placed at the sampling station. The 100-hour stick is 47 cm in length and 3.8 cm in diameter. The 1000-hr fuel stick was 91 cm in length by 10 cm in diameter. A calibrated scale was used to assess 10-hr fuel moisture in one stick set. Before measurements were taken, the calibration of the scale was checked using a 100 g weight, provided with the scale. Once calibration was verified, the 10-hour sticks were hung from the scale. Before reading the results the pivot was gently tapped to make sure the scale had stopped adjusting. A handheld electronic moisture meter (Protimeter® Surveymaster® SM Hand-held Moisture Meter) was used to assess fuel moisture levels in the second 10-hr stick set as well as in the 100-hr stick. Measurements for all the moisture sticks were taken at least twice weekly, except during times of rapid weather change, such as after a front moved through the area, when measurements were taken every two hours. At the time of fuel moisture measurements, temperature, relative humidity, wind speed and wind direction were recorded. Maximum R^2 improvement multiple regression analysis was used to create a statistical model to determine 10-hr fuel moisture, 100-hour fuel moisture, and 1000-hr fuel moisture by assessing weather variables.

Weather Forecasting

Historic fire weather data was collected from the National Weather Service for the time frame from December 1996-April 2003 to obtain information on prescribed burn windows for Denton, Wise, Collin, and Hunt Counties. This time frame was the only time that had sufficiently detailed weather records for the purpose of analysis for prescribed fire planning. This information was used to predict opportunities to conduct prescribed burns based on historic probabilities, and to allow the managers of nature preserves to plan around adverse weather conditions and avoid unnecessary expenditures on cancellations of planned prescribed burns. Historic weather was organized into a database, and then queries were used to extract data that meet the criteria for safe and effective prescribed burning (Table 3-4). The following weather prescription was derived from Scifres and Hamilton (1993), and Wright and Bailey (1982):

Table 3-4: Weather Prescription for Prescribed Burning at LLELA

Parameter	Minimum	Maximum
Temperature (°C)	4	21
Relative Humidity (%)	30	60
Wind Speed (km/h)	6	24

Preferred wind direction is site specific and relies on directing smoke away from smoke sensitive areas (Wright and Bailey 1982; Scifres and Hamilton, 1993).

In order to qualify as a burn day, weather had to be within prescription for four consecutive hours and have no precipitation. Burn season in north Texas is January through March (Woodward 2003, personal communication). Data were collected from December through April to cover all of burn season and provide a cushion of information for managers whose prescription may require burning during the off-season.

Smoke Production and Management

For each fuel type (grassland, forest, etc.) there are estimated emission factors for each NAAQS regulated pollutant that may be emitted during the course of the burn. Fuel loads were calculated based on information collected during the sampling for 1-hour fuel moisture (above). Fuel loads were calculated with a 15% potential acceptable error and $p \leq 0.05$. Total emissions per pollutant are calculated based on predicted fuel consumption and from there may be reported as lb/acre of pollutant or lb pollutant per burn unit (Mahaffey and Miller 1994).

CHAPTER 4: RESULTS

Prairie Vegetation

Little Bluestem (*Schizachyrium scoparium* Michx.)

Little bluestem is a warm season, fire-adapted grass. It is considered one of the four primary grasses that comprise tallgrass prairies (Bragg and Hulbert 1976). Little bluestem is adapted to spring, fall, and winter fires, when the plant has stored sufficient below-ground carbohydrates to regenerate. Fire during these times generally results in beneficial effects on little bluestem, except in dry years, when fire effects are less pronounced (Wright 1974). During the growing season, little bluestem is damaged by fire because the below ground carbohydrate stores are diminished (Bragg 1982, Ewing and Engle 1988).

Spring burning is known to increase flowering, specifically late spring burning, before growth has begun (Hulbert 1969; Hulbert 1988). These effects of fire include an increase of above- and below-ground biomass resulting from increased light penetration, nutrient cycling, and increased soil temperature (Dhillon *et al* 1988; Hulbert 1988). The beneficial effects of burning on little bluestem seem to extend from one to three growing seasons after the fire (Wright 1974) (Table 4-1).

Big Bluestem (*Andropogon gerardii* Vitman)

Big bluestem is another of the four major tallgrass prairie grasses. It is a rhizomatous, warm season, fire-adapted species (Bragg and Hulbert 1976). Burning consumes the above ground portion of plant, and new growth occurs from below-ground rhizomes (Weaver 1968). Big bluestem derives the most benefit from burns occurring during dormancy, primarily spring. Big bluestem burned in the late spring shows the most increase in above-ground biomass compared to unburned stands or stands burned at other times of the year (Towne and Owensby 1984). Burning during the active growing season results in slower, less vigorous plant re-growth (Ewing and Engle 1988).

The benefits of burning on big bluestem include earlier growth, faster development and increased above-ground biomass. Increases in flowering stems have also been reported following burning (Annala and Kapustka 1982). The benefits of burning are attributed to increased light penetration and soil warming from litter reduction (Knapp 1985; Knapp and Gilliam 1985; Hulbert 1988). Increased soil temperatures promote root growth and activity, which in turn promotes shoot production (Peet *et al* 1975; Knapp and Seastedt 1986). Increased photosynthetic activity and leaf thickness have been reported for big bluestem in recently burned areas (Knapp 1985) (Table 4-1).

Indiangrass (*Sorghastrum nutans* Nash.)

Indiangrass is the third grass considered to define tallgrass prairies (Bragg and Hulbert 1976). Like other warm season, fire adapted grasses; indiangrass benefits most from late spring burns, prior to the beginning of the growing season. Some of the benefits derived from late spring burning include increases in stem density (Dubis *et al* 1988), flowering stems (Annala and Kapustka 1982), and basal cover (Owensby and Smith 1979). Following fire, seeds are generally absent from the soil and sprouting occurs from rhizomes (Abrams and Hulbert 1987), making indiangrass vulnerable to the timing and intensity of fires. Fires that occur during the growing season, when below-ground carbohydrate stores are low, have a detrimental effect on plant recovery. Also high intensity fires during the growing season have a short-term, negative impact on tiller growth. Low intensity fires during the growing season appear to have little or no detrimental effects (Ewing and Engle 1988) (Table 4-1).

Switchgrass (*Panicum virgatum*)

Switchgrass is a warm season, rhizomatous grass and the fourth species that comprises tallgrass prairies (Bragg and Hulbert 1976). When burned, the above-ground portion of the plant is consumed, but below-ground rhizomes are preserved and allow for re-growth. Burning during dormancy allows for maximum benefits to the plant, while burning during the growing season is detrimental. During the growing season, switchgrass carbohydrate stores are low and its growth points (apical meristems) are elevated above the soil surface and may be damaged or consumed by fire. If the apical meristems are consumed, growth will be initiated from the rhizomes, which require carbohydrates stores (Sims *et al* 1971).

Burning during dormancy increases basal cover and biomass slightly to moderately, with the most benefits occurring with late spring burning, prior to growth. Late spring burning is also reported to have increased seed stalk production. In North Dakota, mid-May burning increased seed stalk production more than two fold during the following growing season (Olsen 1975).

Switchgrass responds less favorably to fire than other warm season, fire-adapted grasses. Knapp (1985) compares the fire response of big bluestem with that of switchgrass, attributing the more modest response of switchgrass to its growth form. Switchgrass has a higher reproductive shoot:vegetative shoot ratio than big bluestem resulting in a less leafy plant. Also, switchgrass litter does not mat down as big bluestem litter does, so solar radiation is able to warm the soil and reach new shoots of switchgrass. This results in pre- and post-burn environments for switchgrass not varying as much as they might for other grasses (Knapp 1985) (Table 4-1).

Dropseed (*Sporobolus asper* Michx.)

Dropseed is a native grass, which tends to out-compete other tallgrass prairie species when disturbance has been removed. This dropseed is less desirable than other Tallgrass Prairie species because it is not considered one of the primary four grasses (Bragg and Hulbert 1976). Early spring burns tend to favor rough dropseed (Anderson *et al* 1970) and studies in southeast Texas have shown an increased biomass spring burning (Wink and Wright 1973). Studies in southern Texas show an increase in rough dropseed following fall burns also (Collins 1987) (Table 4-1).

Johnsongrass (*Sorghum halepense*)

Johnsongrass is a non-native, warm-season, rhizomatous grass, native to the Mediterranean. When burned, the top portion of the grass is consumed by fire, but deep rhizomes allow re-growth following fire. One study of Johnsongrass in Georgia showed an increase in Johnsongrass biomass following mid-March burning. Following the burn, Johnsongrass was also the dominant grass in the burned plots (Odum *et al* 1974). However, an unpublished study cited in Grace *et al* (2001: 48) showed a "substantial reduction in Johnsongrass" and an increase in little bluestem following late April burning. This study may suggest that Johnsongrass is vulnerable to time-specific fires based on growth cycles (Grace *et al* 2001). Studies at LLELA suggest Johnsongrass can be harmed by backfires and helped by headfires in late winter/early spring burns (Barry 2003, personal communication) (Table 4-1).

Japanese brome (*Bromus japonicus* Thunb.)

Japanese brome is a non-native, cool-season annual. It has become invasive in prairie habitats where grazing and burning have been removed (Whisenant 1985). Japanese brome seeds prolifically and has the most successful germination during high rainfall years, because germination relies on litter accumulation to retain soil moisture (Grace *et al* 2001).

Generally, fire kills the majority of Japanese brome plant and consumes seeds retained by the plant. The effects of burning generally last one to two years depending on annual rainfall (Whisenant *et al* 1984; Whisenant 1985). In wet years, the effects of fire are minimal, probably because soil moisture is high enough to allow for seed germination even without the protection of a layer of plant litter. Therefore, surviving seed banks and high soil moisture will minimize the impacts of fire on Japanese brome. In dry years, when plant litter is consumed, reduced soil moisture will not allow seeds to germinate, reducing the following year's crop (Whisenant 1985) (Table 4-1).

King Ranch Bluestem (*Bothriochloa ischaemum* Keng.)

King Ranch bluestem is a non-native grass imported from Asia for grazing forage. It has most popularly been used at the King Ranch, resulting in the common name. There are little data on fire response but research suggests the species is reasonably tolerant of fire. It is uncertain if burning can be used as a tool to control the growth or spread of the species (Grace *et al* 2001) (Table 4-1).

Table 4-1: Summary of Prairie Vegetation Response to Prescribed Burning

Plant	Desirable species	Potential Fire Response	Conditions for Response
Little bluestem	Yes	+	Before growth begins
Big bluestem	Yes	+	Before growth begins
Switchgrass	Yes	+	Before growth begins
Indiangrass	Yes	+	Before growth begins
Dropseed	No	+	Spring and fall burning
Johnsongrass	No	-	Hot fires, late spring
Japanese brome	No	-	Average to low rainfall years
KR bluestem	No	+/-	Unknown conditions

Mapping Fuel Loads and Fuel Models

Bison Prairie Burn Unit

The area of the Bison Prairie (BP) Burn Unit (Figure 4-2) is 4.2 hectares (10.3 acres). The landscape is fuel model 1 (short grass) and it is dominated primarily by prairie dropseed (*Sporobolus asper*), silver bluestem (*Bothriochloa sacchariodes*), and a variety of annual forbs. Areas designated as fuel model 2 contain mesquite trees (*Prosopis glandulosa*) scattered amidst short and medium sized grasses, including dropseed and Johnsongrass (*Sorghum halepense*). Fuel model 3 (tall grass) patches are mostly dominated by thick stands of Johnsongrass.

Surveying the unit using a grid-based survey method and 1-meter survey radius resulted in 45% of the unit being classified as low-medium fuel loads. The medium fuel load had the second most area covered. Using a random survey method, 69% of the site was identified as having low fuel loading, and 23% was identified as having low-medium fuel loading (Table 4-3).

Figure 4-2: Overview of Burn Unit Fuel Loads (1-Meter Assessment Radius) and Fuel Models (25-Meter Assessment Radius) Using a Grid-Based Survey Method

Bison Prairie Fuel Load Distribution

Bison Prairie Fuel Model Distribution

Heritage Prairie Fuel Load Distribution

Heritage Prairie Fuel Model Distribution

Research Prairie Fuel Load Distribution

Research Prairie Fuel Model Distribution

Legend:

- ■ Low
- ■ Low-Medium
- ■ Medium
- ■ Medium-High
- ■ High

Legend:

- ■ FM 1
- ■ FM 2
- ■ FM 3

When the Bison Burn Unit was surveyed for fuel models using a grid-based survey method, only fuel model 1 was detected at a 1-meter survey radius; however, at a 25-meter assessment radius, fuel models 1 and 2 were recorded (Table 4-4). At a 25-meter assessment the majority of the unit was identified as being fuel model 1, although 13% was identified as fuel model 2. Fuel model three was not represented.

The random survey of the Bison Burn Unit, with a 1-meter survey radius, identified 88% of the site as fuel model 1, and 12% of the site as fuel model 3. With a 25-meter assessment radius, the site was identified as 41% fuel model 1, 40% fuel model 2, and 19% fuel model 3. The primary source of change was the reclassification of fuel model 1 (Table 4-4).

A comparison of 1-meter radius assessment area reveals that regardless of the survey method, grid-based or random, fuel model 1 was the dominant fuel model. The only difference being, with the random survey method, 12% of the site was identified as fuel model 3, compared to 0% with the grid-based survey method. Fuel model 2 was not identified using either survey method (Table 4-4).

Comparing the 25-meter assessment radius between the two survey methods, grid-based and random, the primary source of change is the reclassification of fuel model 1. Fuel model 2 was identified as covering 40% of the site using the random survey method, while with the grid-based survey method fuel model 2 was not identified (Table 4-4).

Table 4-3: Overview of the Bison Burn Unit Fuel Load Percent Area with Different Survey Methods

Fuel Load	Grid-based	Random
Low	20%	69%
Low-Medium	47%	23%
Medium	26%	8%
Medium-High	7%	0%
High	0%	0%

Table 4-4: Overview of Bison Burn Unit Fuel Model Percent Area with Different Survey Methods and Assessment Areas

	Grid-based		Random	
Fuel Model	1-m Radius	25-m Radius	1-m Radius	25-m Radius
1	100%	87%	88%	41%
2	0%	13%	0%	40%
3	0%	0%	12%	19%

Heritage Prairie Burn Unit

The Heritage Prairie (HP) burn unit (Figure 4-2) comprises 16.0 hectares (39.4 acres) dominated by fuel model 1. The area covered by this fuel model, like the Bison Prairie, is dominated by prairie dropseed, silver bluestem, and annual forbs. Fuel models 2 and 3 are also represented in this unit. Areas represented by fuel model 2 mostly contain mesquite trees and a variety of graminids, short and tall. Areas that are represented by fuel model 3 are mostly dominated by thick stands of Johnsongrass.

When the Heritage Prairie was surveyed using a 25-meter radius, grid-based method, 70% of the site was identified as having a low fuel load, and 19% was identified as having a low-medium fuel load. Conversely, using a 25-meter radius, random survey method identified 55% of the Heritage Prairie as having a low fuel load and 31% as having a low-medium fuel load. For both survey methods a medium-high fuel load was not identified, and 3% of the site was identified as high loading for both survey methods (Table 4-5).

The 1-meter radius, grid-based survey of the Heritage Prairie for fuel models identified 93% of the unit as fuel model 1. Using a 25-meter assessment radius, 81% of the unit was identified as fuel model 1. Fuel model 2 had the least coverage for both the 1-meter and the 25-meter assessment radii, at 1% and 7%, respectively. Fuel model 3 had 6% and 12% coverage for the 1-meter assessment and 25-meter assessment radii, respectively (Table 4-6).

Using the random survey method to evaluate fuel models gave a similar picture of the burn unit regardless of assessment radius. The 1-meter survey radius identified 59% of the unit as fuel model 1, 2% as fuel model 2, and 39% as fuel model 3. The 25-meter survey radius identified 49% of the prairie burn unit as fuel model 1, 2% as fuel model 2, and 49% as fuel model 3.

Comparison of the 1-meter radius assessment between survey methods shows a decrease in fuel model 1 coverage from the grid-based survey to the random survey method (Table 4-6). The random survey method reclassified some of fuel model 1 to fuel model 3. For both survey methods, fuel model 2 is the least represented.

Using a 25-meter assessment radius and the grid-based survey method resulted in 81% of the unit being classified as fuel model 1, whereas 49% of the unit is classified as fuel model 1 using a 25-meter radius assessment, and random survey method. The change occurs primarily in the representation of fuel model 3; using a grid-based survey method only shows fuel model 3 covering 12% of the burn unit. The 25-meter random assessment indicates fuel model 3 covers 49% of the unit (Table 4-6).

Table 4-5: Overview of the Heritage Burn Unit Fuel Load Percent Area with Different Survey Methods

Fuel Load	Grid-based	Random
Low	70%	55%
Low-Medium	19%	31%
Medium	8%	11%
Medium-High	0%	0%
High	3%	3%

Table 4-6: Overview of Heritage Burn Unit Fuel Model Coverage with Different Survey Methods and Assessment Areas (Percent of Total Area Covered)

	Grid		Random	
Fuel Model	1-m Radius	25-m Radius	1-m Radius	25-m Radius
1	93%	81%	59%	49%
2	1%	7%	2%	2%
3	6%	12%	39%	49%

Research Prairie Burn Unit

The Research Prairie Burn Unit (Figure 4-2) is an 8.3 hectare (20.6 acres) prairie. Fuel models 1 and 3 comprise the majority of the unit. In terms of species composition, fuel model 1 is dominated by dropseed and forbes such as broomweed (*Gutierrezia dracunculoides*), prairie tea (*Croton monanthogynus*), and goldenrod (*Solidago ulmifolia*). Fuel model 3 is composed predominately of Johnsongrass, K.R. Bluestem (*Bothriocloa ischaemum*), Japanese brome (*Bromus japonicus*), and small patches of little bluestem (*Schizachyrium scoparium*).

Using a 25-meter radius assessment, grid-based survey method, 48% of the Research Prairie Burn Unit was identified as having a low fuel load, 34% as having a low-medium fuel load, 14% as having a medium fuel load, and 4% as having a medium-high fuel load. The random survey method showed similar results, with 52% being identified as having a low fuel load, 39% as having a low-medium fuel load, and 9% as having a medium fuel load (Table 4-7). The random survey method did not identify any areas as having a medium-high or high fuel load. The grid-based survey method did not identify any high fuel loads.

The grid-based survey method with a 1-meter assessment radius identified the Research Prairie as being 67% fuel model 1, 5% fuel model 2, and 28% fuel model 3. In comparison, the 25-meter assessment radius identified the burn unit as 42% fuel model 1, 24% fuel model 2, and 34% fuel model 3 (Table 4-8). The primary difference between the two assessment radii is the reclassification of fuel model 1 to fuel model 2 from the 1-meter assessment radius to the 25-meter assessment radius.

The random survey method with a 1-meter assessment radius classified the Research Prairie as 79% fuel model 1, 2% fuel model 2, and 19% fuel model 3. The 25-meter assessment area identified the prairie as 38% fuel model 1, 45% fuel model 2, and 17% fuel model 3. The differences in area are again attributable to the reclassification of fuel model 1 to fuel model 2 in the 25-meter assessment radius compared to the 1-meter assessment radius (Table 4-8).

When looking at the 1-meter assessment radius, comparing the grid-based survey to the random survey method, there is a shift from fuel model 3 to fuel model 1. In the grid based survey method, 67% of the area is identified as fuel model 1, compared to 79% with the random survey method. In comparison, the grid based survey method identified 28% of the area as fuel model 3, compared to 19% with the random survey method.

The 25-meter radius assessment area with the grid-based survey method identified 24% of the burn unit as fuel model 2, where the random survey method identified 45% of the unit as fuel model 2. The other point of contention between the two survey methods for the Research Prairie is the difference between the areas identified as fuel model 3. The grid-based survey method identified 34% of the prairie as fuel model 3 and the random method identified 17% as fuel model 3 (Table 4-8).

Table 4-7: Overview of the Research Burn Unit Fuel Load Percent Area with Different Survey Methods

Fuel Load	Grid-based	Random
Low	48%	52%
Low-Medium	34%	39%
Medium	14%	9%
Medium-High	4%	0%
High	0%	0%

Table 4-8: Overview of Research Burn Unit Fuel Model Percent Area with Different Survey Methods and Assessment Areas

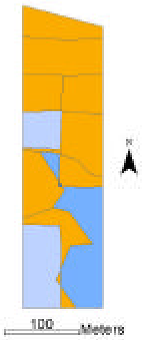
	Grid		Random	
Fuel Model	1-m Radius	25-m Radius	1-m Radius	25-m Radius
1	67%	42%	79%	38%
2	5%	24%	2%	45%
3	28%	34%	19%	17%

Comparison of Survey Methods

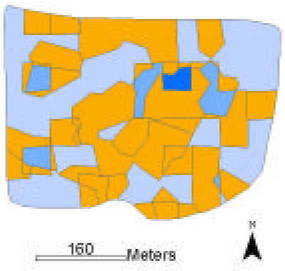
Comparisons were made to test whether the method used to collect data, either grid or random, had a statistically significant influence on the resulting map ($p \leq 0.05$). For each assessment, the resulting categorical counts were compared using a G-Test (SAS 8.2© 2001) (Table 4-9).

Figure 4-10: Comparison of Grid-Based and Random Fuel Load Survey Methods

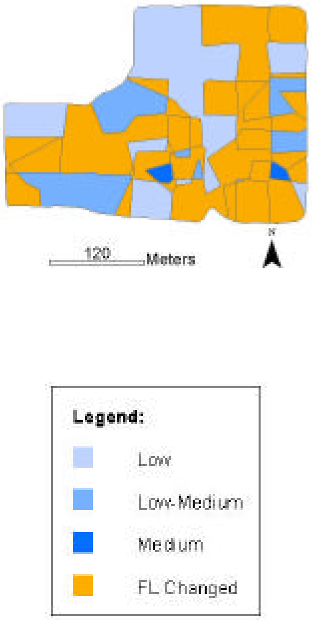
Bison Prairie



Heritage Prairie



Research Prairie



For fuel loading, only the Bison Prairie showed a statistically significant difference between the grid and random assessment methods (Table 4-9). The Bison Prairie also had the smallest number of sampling points of all the burn units. The majority of the difference occurred in the low and low-medium fuel loads. Looking at the percent change, the Bison Unit experienced almost a 100% difference in classification between the grid and random assessment method for fuel load. The Heritage Prairie Unit and the Research Prairie Units experienced only a 33% difference and a 17% difference respectively (Figure 4-10).

Table 4-9: Summary of Probabilities from G-Test Log-Likelihood Ratio Comparing Grid v. Random Survey Method

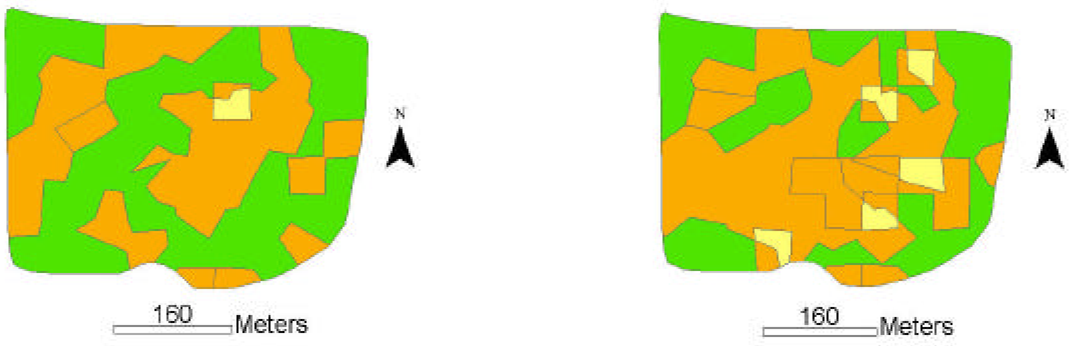
		Probability (p)		
	n	Fuel Load	Fuel Model (1m)	Fuel Model (25 m)
Bison Prairie	16	*0.0230*	0.0882	*0.0016*
Research Prairie	39	0.6645	0.5765	*0.0096*
Heritage Prairie	71	0.1828	*<0.0001*	*<0.0001*
Bison + Heritage	87	0.6416	*<0.0001*	*<0.0001*

When fuel models were assessed within a 25-meter radius from a point, all comparisons revealed a significant difference in the results from the two survey methods (Table 4-9 and Figure 4-10). The Research Prairie showed a 41% change in classification. The Bison Unit showed the greatest percent change with 93% of the total area being reclassified; 47% of the area that was reclassified was in fuel model 1.

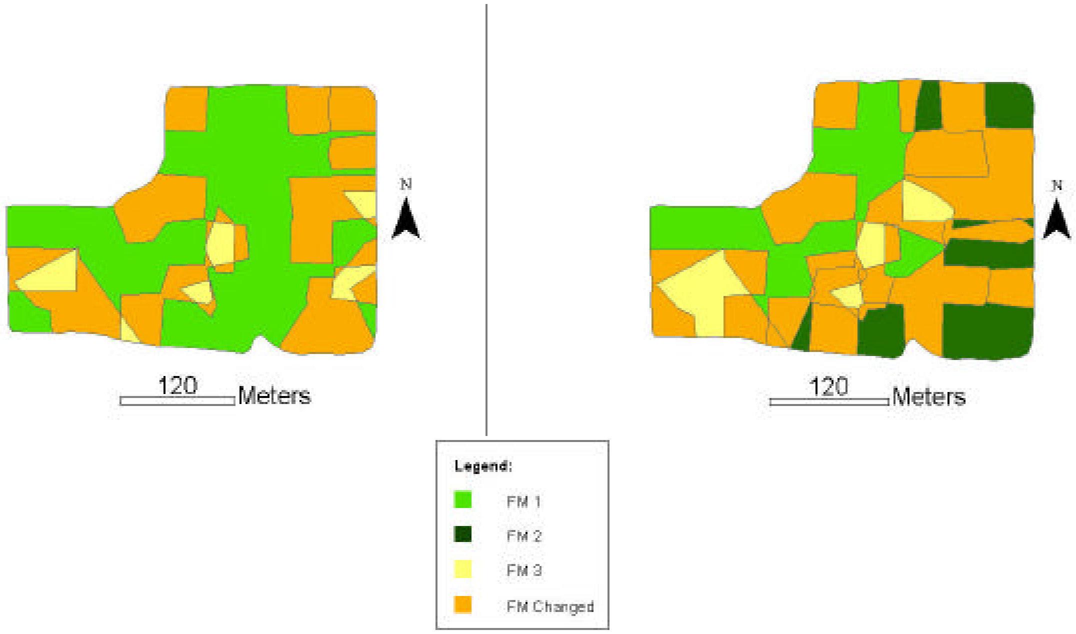
Figure 4-10: Comparison of Grid-Based and Random Survey Methods of Fuel Models

Bison Prairie 1-m Radius Assessment Bison Prairie 25-m Radius Assessment

Heritage Prairie 1-m Radius Assessment Heritage Prairie 25-m Radius Assessment



Research Prairie 1-m Radius Assessment Research Prairie 25-m Radius Assessment



Comparison of Fuel Model Assessment Area

The G-Test (SAS 8.2© 2001) was used to compare whether assessing fuel models at 1-meter or 25-meters had a significant influence on the resulting map ($p \leq 0.05$) (Figure 4-12). For each burn unit the categorical count data from the 1-meter assessment and the 25-meter assessment were compared, keeping the assessment method, grid or random, the same (Table 4-11).

Although there are no clear cut patterns in the statistical results (Table 4-11), the majority of the tests reflect a statistically significant difference between fuel models assessed at a 1-meter radius from a point and fuel models assessed at a 25-meter radius from a point. The only burn unit not to show statistical significance using either assessment method was the Heritage Prairie. The Heritage Prairie showed a 26% change in classification using the grid assessment method and 20% change using the random assessment method. A possible explanation for this is that the Heritage Prairie has been burned in the last 3 years and the unit may still be experiencing burn effects (Figure 4-12).

Table 4-11: Summary of Probabilities from G-Test Log-Likelihood Ratio Comparing Fuel Model Assessment at 1-meter and at 25-meters

		Probability (p)	
	n	Grid	Random
Bison Prairie	16	0.0882	*0.0006*
Research Prairie	39	*0.0320*	*<0.0001*
Heritage Prairie	71	0.0913	0.1711
Bison + Heritage	87	*0.0291*	*0.0016*

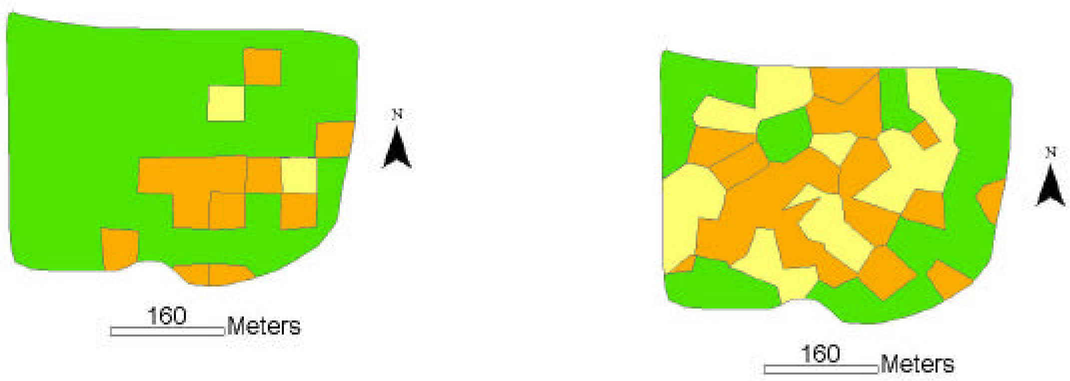
Figure 4-12: Comparison of 1-Meter Radius and 25-Meter Radius Fuel Model Assessment Area

Bison Prairie Grid-Based Survey Method

Bison Prairie Random Survey Method

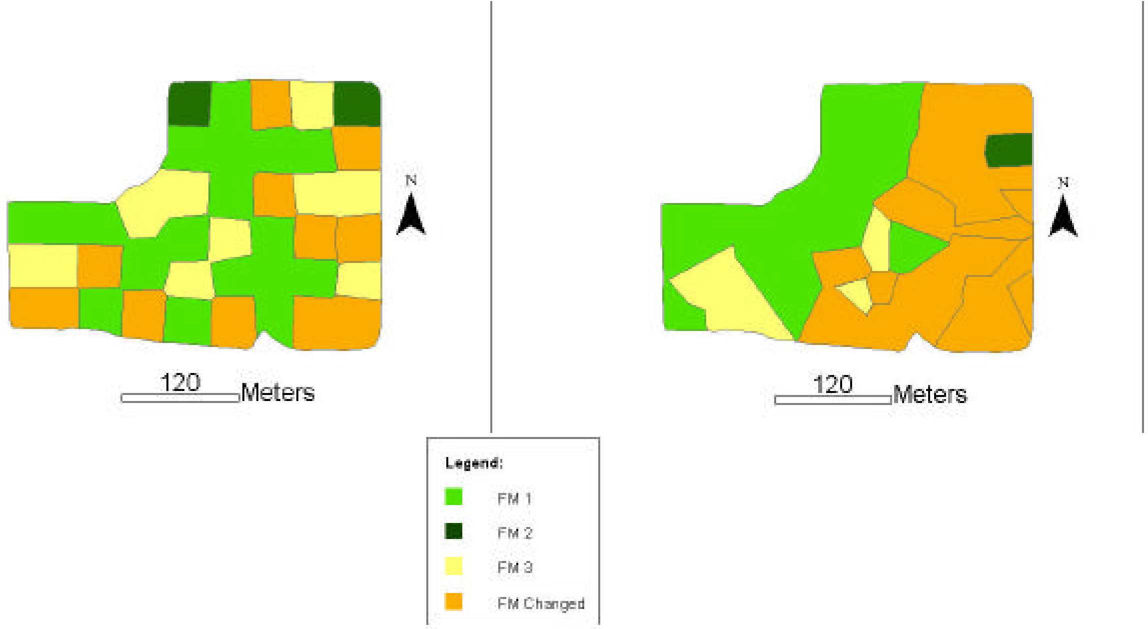
Heritage Prairie Grid-Based Survey Method

Heritage Prairie Random Survey Method



Research Prairie Grid-Based Survey Method

Research Prairie Random Survey Method



Fuel Moisture

1-Hour Fuel Moisture

Data collected for 1-hour fuel moisture exceeded the parameters set for a safe prescribed burn to insure that any statistical model resulting from the study could be applied to a prescribed burn situation without extrapolation, except relative humidity. The relative humidity measured during the study was the only variable that did not cover the full range of relative humidity allowed in the weather prescription; the prescription allows relative humidity to be as low as 30%, but due to a wet winter, the lowest relative humidity recorded was 39%. Wind speed ranged from 6.4 mph to 27.4 km/h, covering the entire range of allowable wind conditions for burning. Figures 4-13, 4-14, and 4-15 illustrate the temperature, relative humidity, and wind speed conditions recorded during the study. Temperatures range from –1.4 to 21.6°C with an average temperature of 13.6°C and a standard deviation of 6.9°C. Relative humidity ranged from 39 to 89%, with the average relative humidity being 63% (standard deviation ± 16.3%). The average wind speed for the study time was 14.5 km/h and standard deviation ± 6.9 km/h.

A simple linear regression to predict fuel moisture from relative humidity produced the following statistically significant ($p=0.0425$, $R^2=0.30$) model: 1-Hour Fuel Moisture= 8.43 + 0.14 (relative humidity [%]). Although this model is statistically significant, the low R^2 indicates it has a low predictive value, in other words, the model has statistical, but probably not ecological significance.

Figure 4-13: Temperature Range for 1-Hour Fuel Moisture Collection Period

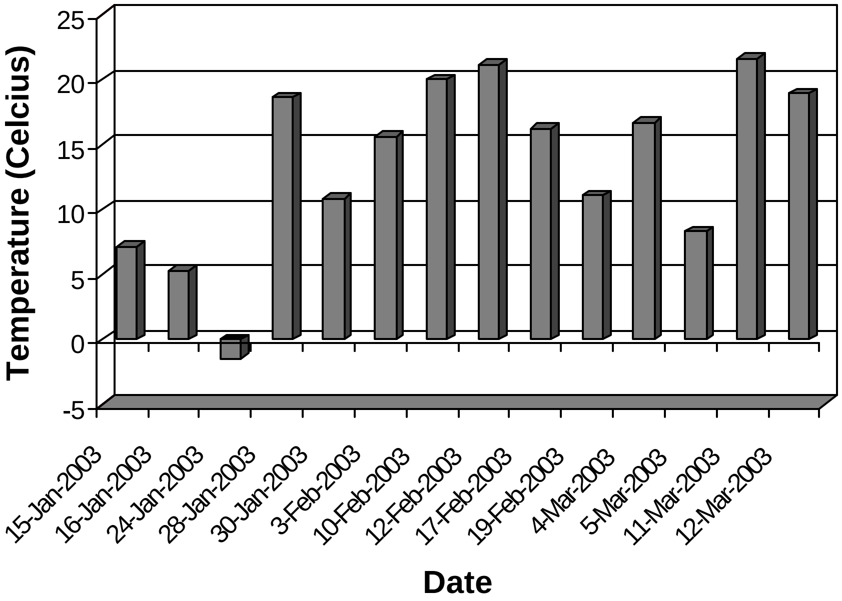


Figure 4-14: Relative Humidity Range for 1-Hour Fuel Moisture Collection Period

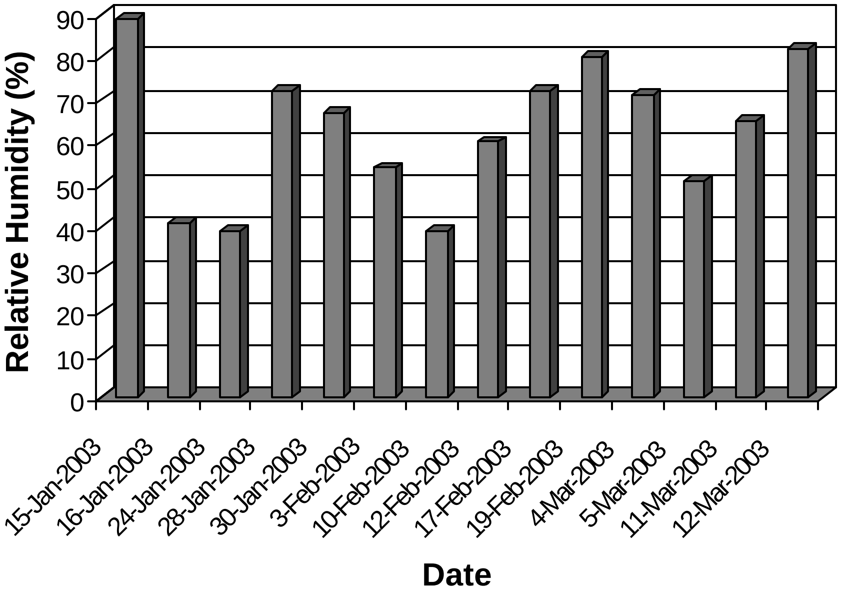
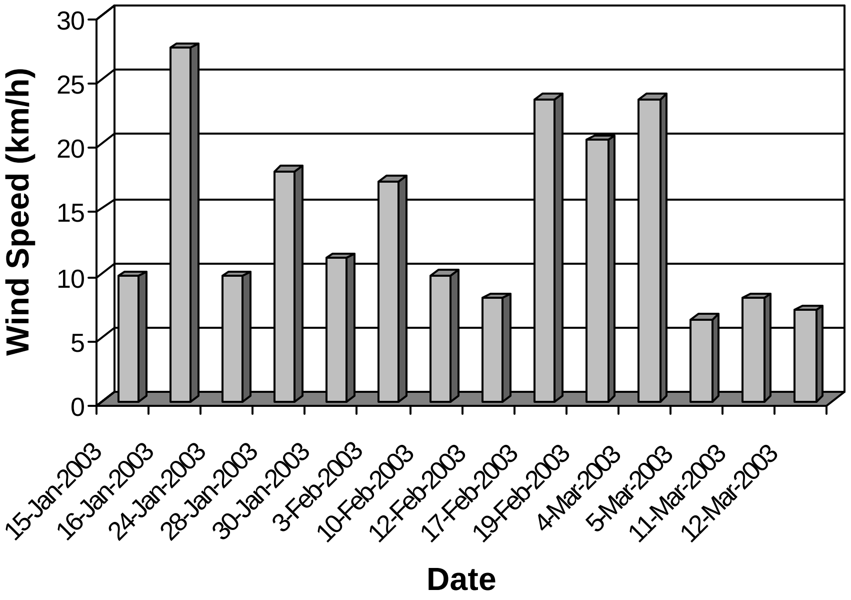


Figure 4-15: Wind Speed Range for 1-Hour Fuel Moisture Data Collection Period



A Maximum-R^2 Improvement, multiple regression, yielded the following statistically significant (F=16.73, p=0.0005, R^2= 0.75) model: 1-Hour Fuel Moisture=18.82 - 0.24 (temperature [°F]) + 0.19 (relative humidity). The variable wind speed was eliminated from the model, because it did not contribute substantially to R^2.

It should be noted that all regression models were calculated in Fahrenheit for temperature, percent for relative humidity, and miles per hour for wind speed. This was done because field instruments for forestry use those units. This is also true for 10-, 100-, and 1,000-hour fuel moisture regression models.

10-Hour Fuel Moisture

Weather data for the 10-hour, 100-hour, and 1000-hour fuels were collected simultaneously, so the following weather information applies to all woody fuel data. Data were collected from January through March and during that time recorded temperatures ranged from –4.4 to 24.4ºC. The mean temperature was 8.4°C with a standard deviation of ± 7.3°C (Figure 4-16). The range of temperatures recorded during the study covers the acceptable range of temperatures for burning. Relative humidity ranged from 31% to 82% with the mean being 54.7% and a standard deviation of ± 17.5% (Figure 4-17). The actual low end for the acceptable range of relative humidity for prescribed burning is 30%, so the range of data collected does not entirely cover the acceptable range. Recorded wind speeds range from 6.8 to 35.7 km/h, with an average of 14.5 km/h and a standard deviation of ± 7.1 km/h (Figure 4-18). The range of data collected for wind speed almost covers the entire range of allowable wind speed range for prescribed burning. The actual range is from 6.4 to 24.1 km/h, so the collected data missed the bottom end of the spectrum by 0.4 km/h.

Ten-hour fuel moisture was measured two ways, with a Protimeter and with a calibrated scale. The measurements taken with the scale and the Protimeter varied somewhat over the course of the experiment, but more often than not the scale measured higher moisture content than the Protimeter.

Figure 4-16: Temperature Range for Woody Fuel Moisture Data Collection Period

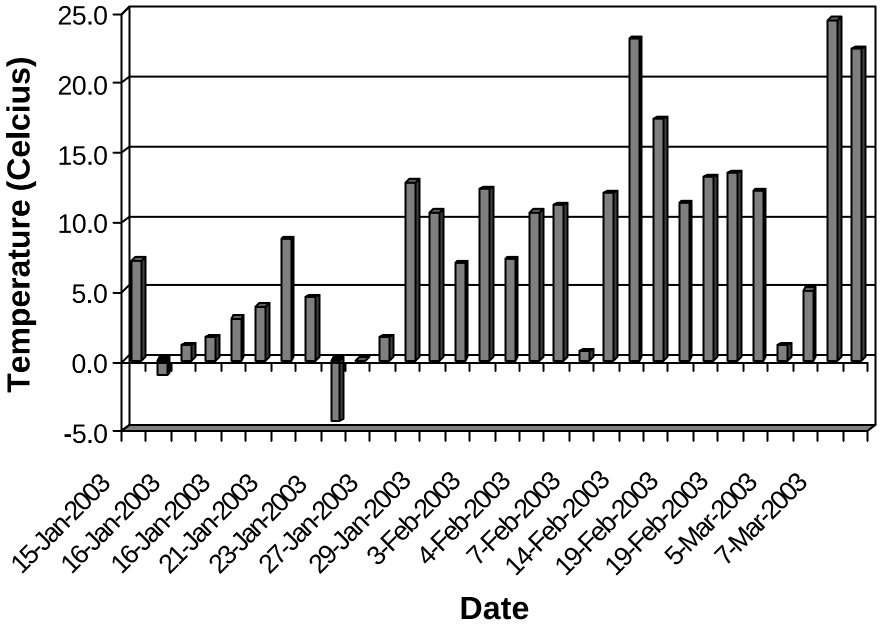


Figure 4-17: Relative Humidity Range for Woody Fuel Moisture Data Collection Period

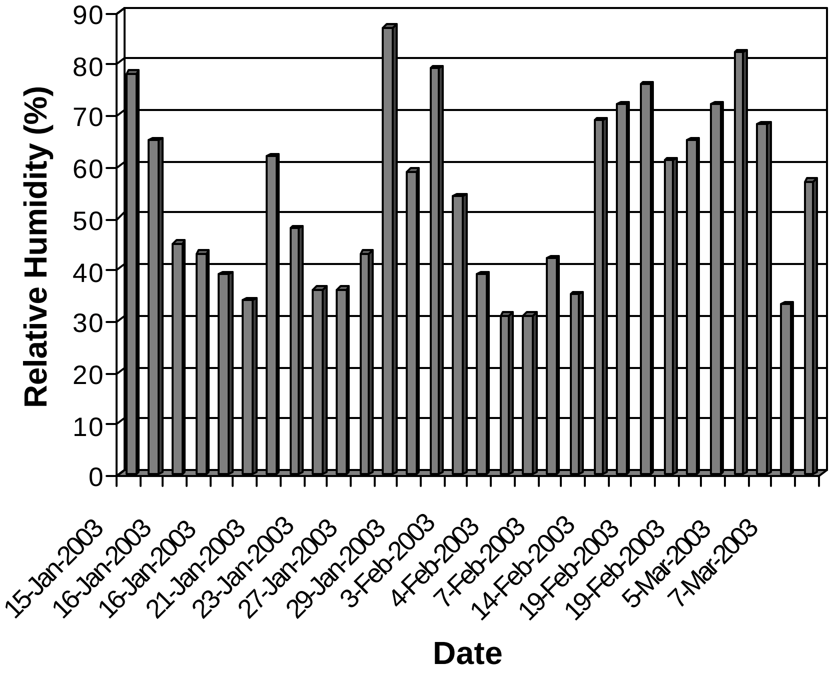
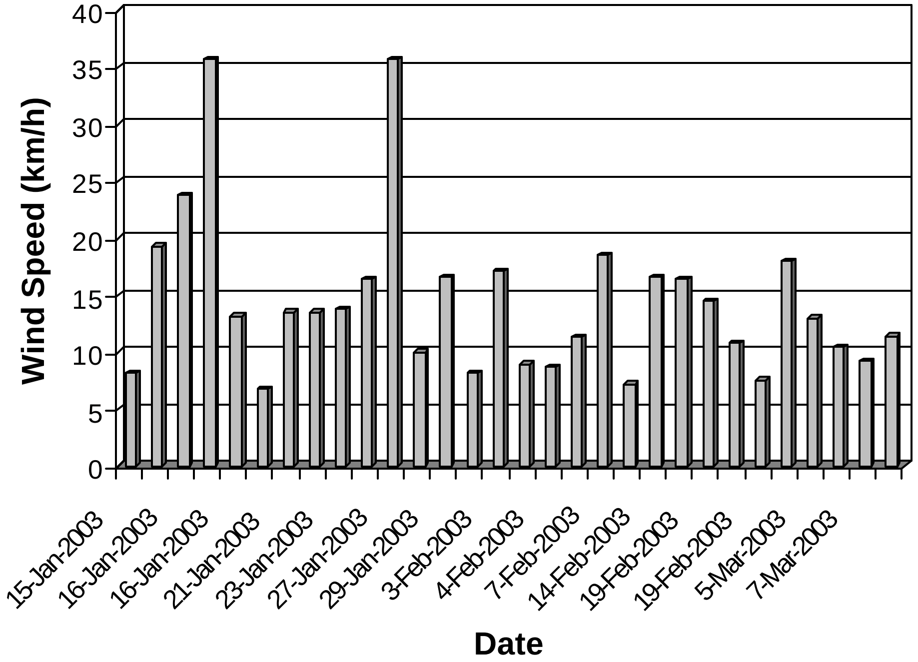


Figure 4-18: Wind Speed Range for Woody Fuel Moisture Data Collection Period



A Maximum-R^2 Improvement multiple regression yielded the following statistically significant ($F=12.58$, $p=<0.0001$, $R^2= 0.51$) model: 10-Hour Fuel Moisture (scale)=9.04 - 0.07 (temperature [°F]) + 0.14 (relative humidity [%]) + 0.26 (wind speed [mph]). This model predicts fuel moisture based on the readings given by the calibrated scale. This model is statistically significant, but again, a low R^2 indicates a low predictive value.

A Maximum-R^2 Improvement multiple regression yielded the following statistically significant model ($F=8.00$, $p=0.0019$, $R^2= 0.37$): 10-Hour Fuel Moisture (Protimeter)=6.01 + 0.09 (relative humidity [%]) + 0.28 (wind speed [mph]). The variable temperature was eliminated from the model, because it did not contribute substantially to improving the coefficient of determination. The model for predicting fuel moistures that coincide with Protimeter readings has even less predictive value than the model that generates fuel moistures based on scale readings.

100-Hour Fuel Moisture and 1,000-Hour Fuel Moisture

A Maximum-R^2 Improvement multiple regression model for 100-hour fuel moisture, yielded the following statistically significant model ($F=11.10$, $p=0.0003$, $R^2= 0.45$): 100-Hour Fuel Moisture=9.52 + 0.05 (relative humidity [%]) + 0.06 (wind speed [mph]). The variable temperature was excluded from the model, because it did not contribute substantially to the coefficient of determination.

A Maximum-R^2 Improvement, multiple regression model for 1,000-hour fuel moisture, yielded the following statistically significant model ($F=11.16$, $p=0.0003$, $R^2= 0.45$): 1,000-Hour Fuel Moisture=9.50 + 0.05 (relative humidity [%]) + 0.06 (wind speed [mph]). The variable temperature was excluded from the model, because it did not contribute substantially to the coefficient of determination.

Predicted Weather Windows

December

A general analysis of the data for the month of December from 1996-2002 showed that temperatures ranged from –8. 0°C to 27°C. The mean temperature for December was 8.0°C with a standard deviation ± 11°C. Relative humidity ranged from 13% to 100% with the mean being 69% and standard deviation ± 20%. Wind speed varied from 0 km/h to 52 km/h and the mean was 15.5 km/h (Tables 4-20 to 4-22).

Over the course of seven years, during the month of December, 60% of burn opportunities occurred as single days and 35% occurred as two to four consecutive days. Twice, or 5% of the time, the window for burning was six days long, but both six day windows occurred in one year. There were seven days, that in the last seven years were acceptable for burning more than 50% of the time: December 7, 13, 14, 17, 26, 27, and 28. Only two days never occurred as burn opportunities, based on weather conditions: December 3, and 11.

January

In January (1997-2003) temperatures ranged from –12 to 28°C and the mean temperature was 8°C ± 11°C. Relative humidity ranged from 13-100% and the mean was 70%. The standard deviation for relative humidity was ± 21%. Wind speed ranged from 0 to 56 km/h. The mean wind speed was 15.8 km/h and the standard deviation was ± 9.1 km/h (Tables 4-20, 4-21, and 4-22).

For the month of January, there were three days that were acceptable burn days more than 50% of the time: January 6, 22, and 23. January 1, 2, 12, 13, and 28 never occurred as burn days over the last seven years. Of the 38 burn windows in January, 21 occurred as single days, 12 as two day windows, and five as three to five day windows.

February

For February 1997-2003, the temperature ranged from -11 to 29°C. The mean temperature was 10°C and the standard deviation was ± 11°C. The relative humidity ranged from 11-100% and the mean was 69% with a standard deviation of 21%. Wind speed was varied highly from 0 km/h to 70 km/h, the mean was 16.5 km/h with a standard deviation of 9.6 km/h (Tables 4-20 to 4-22).

For February there were 36 burn windows, twenty-two windows occurred as single days, ten as two day windows, and four as three to four day windows. February 15, 24, and 28 were never good burn days, based on weather records. February 2, 3, 5, and 22 were acceptable for burning more than 50% of the time in the last seven years.

March

For the month of March (1997-2003), the average temperature was 13°C and ranged from –9 to 31°C. The standard deviation for temperature was ± 11°C. Relative humidity ranged from 10% to 100%. The mean humidity was 70% with a standard deviation of 19%. The range of wind speeds recorded was even broader than February winds, ranging from 0 km/h to 78 km/h. The mean wind speed was 17.5 km/h and standard deviation equaled 9.9 km/h (Tables 4-20 to 4-22).

In March there were four days that more than 50% of the time were acceptable burn days: March 6, 9, 12, and 26. There were also four days that were not acceptable burn days over the years that the data covers those were: March 14, 18, 28, and 29. In

March, 54% of burn days occur singly, and 46% occurred in groups of two to four consecutive days.

April

For the month of April 1997-2003, air temperature ranged from 2 to 33°C. The mean temperature was 16°C and the standard deviation was 6°C. The mean relative humidity was 63% and standard deviation was 26%. The range of relative humidity was 17-100%. Wind speeds varied from 0 to 59 km/h and the mean was 17.6 km/h with a standard deviation of 9.7 km/h (Tables 4-20 to 4-22).

In April, there were no days that were acceptable for burning that occurred more than 50% of the time, based on weather conditions, over the last seven years. April 4 and 17 were both good burn days 43% of the time, and had the highest frequency of any of the days. There were nine days that did not meet the criteria for good burn days during any of the years. These days were concentrated toward the end of the month. In April 75% of the burn days occurred singly, and 25% occurred in groups of two to three.

Overall Season

Overall, December had the most burn windows, days or consecutive days that had acceptable weather conditions for burning. January had the second most burn windows, then February, then March, and then April, which is expected as burn season winds down. Analyses of weather data for December yielded some trends about how often burn days (i.e. consecutive days that had acceptable weather conditions for burning occurred). Based on the collected data, December has the most burn days (Table 4-19), even though December is not often considered as part of the official burn season in north Texas due to the timing of frosts.

Table 4-19: Mean Number of Burn Days Per Month
(December 1996- April 2003)

Month	Mean (days/month)	Range (days/month)
December	11	7-15
January	9	5-15
February	8	5-10
March	8	5-13
April	4	1-9

Table 4-20: Comparison of Temperature Variation by Month
(December 1996- April 2003)

Month	Temperature (°C)			
	Minimum	Maximum	Mean	St. Dev.
December	-8.0	27	8	11
January	-12	28	8	11
February	-11	29	10	11
March	-9	31	13	11
April	2	33	16	6

Table 4-21: Comparison of Relative Humidity Variation by Month
(December 1996- April 2003)

Month	Relative Humidity (%)			
	Minimum	Maximum	Mean	St. Dev.
December	13	100	69	20
January	13	100	70	21
February	11	100	69	21
March	10	100	70	19
April	17	100	63	26

Table 4-22: Comparison of Wind Speed Variation by Month
(December 1996- April 2003)

Month	Wind Speed (km/h)			
	Minimum	Maximum	Mean	St. Dev.
December	0	52	15.5	8.9
January	0	56	15.8	9.1
February	0	70	16.5	9.6
March	0	78	17.5	9.9
April	0	59	17.6	9.7

Smoke Production

The Bison Prairie Burn Unit can be expected to produce over 11,727 kg of carbon monoxide and 123,874 kg of carbon dioxide, but these are the major emissions of burning. Sulfur dioxide and NO_X are some of the more minor emissions produced and can be expected to produce only 68 kg and 253 kg, respectively. Emissions of particulate matter are 977 kg for $PM_{2.5}$ and 1,140 kg for PM_{10} (Table 4-23).

Table 4-23: Emissions For Bison Prairie

Pollutant	kg/hectare	Total emissions (kg)
CO	830	11,727
CO_2	8,761	123,874
CH_4	39	554
$PM_{2.5}$	70	977
PM_{10}	81	1,140
SO_2	5	68
NO_X	18	253

The Heritage Prairie Burn Unit is the largest burn unit at LLELA. Burning should produce 118,369 kg of CO_2 and more than 11,206 kg of CO. Approximately 64 kg of SO_2 will be emitted and 241 kg of NO_X, a precursor for ground-level ozone, will be emitted. Particulate matter emitted during burning should be less than 1,100 kg for both $PM_{2.5}$ and PM_{10} (Table 4-24).

The Research Prairie Burn Unit is the second largest burn unit. The greatest emission from burning the Research Prairie will be CO_2 at 131,214 kg, followed by CO with 12,423 kg of emissions. Particulate matter is the next largest emission with $PM_{2.5}$ emissions being about 1,035 kg and PM_{10} being 1,208 kg. Methane (CH_4) emissions will be approximately 586 kg and NO_X will be 268 kg. The smallest emission is of SO_2 at 72 kg (Table 4-25).

Table 4-24: Emissions For Heritage Prairie

Pollutant	kg/hectare	Total emissions (kg)
CO	793	11,206
CO_2	8,371	118,369
CH_4	37	529
$PM_{2.5}$	66	934
PM_{10}	77	1,090
SO_2	5	64
NO_X	17	241

Table 4-25: Emissions For Research Prairie

Pollutant	lb/acre	Total emissions (kg)
CO	879	12,423
CO_2	9,279	131,214
CH_4	42	586
$PM_{2.5}$	73	1,035
PM_{10}	85	1,208
SO_2	6	72
NO_X	19	268

CHAPTER 5: DISCUSSION

Prairie Vegetation

The effects of prescribed fires on prairie species are highly variable and highly dependent on the time of year of the burn, as well as the annual and fire weather conditions. Many native species respond favorably to treatment with prescribed fire, but so do less desirable native grasses and non-native grasses. To receive the maximum restoration benefits from prescribed fire, careful timing and attention to weather conditions are essential.

The four primary Tallgrass Prairie grasses--little bluestem, big bluestem, indiangrass, and switchgrass--are all reported to respond favorably to burning. However, some non-native, nuisance species are also reported to respond favorably to burning, particularly Johnsongrass and dropseed. According to the literature, all the species discussed are damaged by fire during green-up, when they first begin to put out shoots. Japanese brome is cool season grass; it tends to begin growing earlier than the native warm season grasses. To eliminate or compromise Japanese brome, fire can be timed for when it is vulnerable, without damaging native desirable species. However, during rainy years, burning to eliminate or control Japanese brome will not be effective. Dropseed is a native, fire adapted graminid. It is reported to respond favorably to fire, but research is unclear as to how burning may tip the scale of competition between dropseed and more desirable native species. Johnsongrass poses more of a problem because it is a warm season, fire adapted grass. There is some evidence Johnsongrass may be controlled, while favoring native grasses, by proper timing of burning (Grace *et al* 2001; Barry 2003, personal communication) without additional mechanical treatment or herbicides. It is unclear how King Ranch (K.R.) bluestem responds to fire, because not enough research has been done in this area. Burning to eliminate or control K.R. bluestem may not be effective and could have precisely the opposite of the desired effect. Overall, the literature suggests late spring burning benefits the native, desirable plant species the most and inflicts damage on non-native and non-desirable plant species.

Fuel Loads and Fuel Models

Each survey method has benefits as well as drawbacks. Grid-based surveys give complete coverage of the area being studied; and by varying the distance between the points, a more or less detailed image of the study area can be collected. One associated problem, however, is efficiency. A complete detailed study of an area, especially large areas, may not be financially viable, or the best use of personnel. Another potential problem is that plant distributions tend to be patchy, rather than uniform. A grid that is too large may miss some of the patchiness of a landscape. When conducting this survey, it became apparent that small patches were under-represented in the final map using the grid-based method with a 1-meter assessment radius. The final products gave a more homogenous picture of the burn units, when in actuality each burn unit had a complex mixture of fuel loads and fuel models.

Random surveys have more potential for capturing patchy distributions because the collection points are of varying distances from each other. Additionally, random sampling may be more cost effective and efficient because fewer points can be used without intentionally neglecting regions of the study area. Random sampling may neglect some areas, as is the nature of random point selection, but stratified random sampling can be employed to assure adequate cover of large study areas. In this study, stratified random sampling was not employed because the burn units were relatively small (<50 acres).

During the course of data collection, using only a 1-meter assessment radius did not capture the complexity of the landscape and oversimplified the final map, regardless of the survey method. Varying fuel loads and fuel models were closely integrated, and a 1-meter radius survey allowed a narrow snapshot of the landscape to unduly influence the final map. It essentially made an area with a 1-meter radius representative of the total area between the points (i.e., 50 m in the grid). This led to a more homogenous output map. This is best illustrated using the Research Prairie: comparison between the 1-meter radius survey distance and the 25-meter radius survey distance showed a 50% change in area classification using the grid method. Using the random assessment method, there was an 86% change in area classification. Both changes occurred primarily in the reclassification of fuel model 1 to fuel model 2. In the Bison Unit, the changes in classification also occur primarily from fuel model 1 to fuel model 2.

One possible explanation for this is that unless a point lands on or very near a tree or shrub, assessing fuel models at 1-meter will miss fuel model 2. Then, when an area was classified using a 25-meter assessment radius fuel model 2 was easier to identify, so fuel model 1 and fuel model 3 were reclassified as fuel model 2. Another possible explanation has to do with perspective. When looking into the distance, fuels appear homogenous. It is sometimes difficult to determine if grasses are short or tall, or if the terrain has dipped or elevated. This is why fuel loading was not assessed at a 25-meter radius. Fuel load was determined based on density of the fuel as well as fuel height. At 25 meters it is difficult to tell how dense the fuel is or whether the height is from change in elevation or change in plant height.

When conducting the 25-meter radius survey, it became apparent the survey area was not homogenous. The fuel model was chosen based on which fuel model covered at least half the area and would most influence fire behavior. The larger survey area seemed to pick up small patches of different fuel models that may be important in predicting fire behavior. This method, as previously stated, also picks up fuel model 2, which may be under-represented with a 1-meter radius survey. However, with the 25-meter assessment radius, there was a certain amount of subjectivity involved. Sometimes two or even all three fuel models were represented in a given area and background knowledge of fire behavior became an import factor in assigning a fuel model. For example, in an area where fuel model 1 and fuel model 3 were equally represented, fuel model 3 was chosen because it is a more hazardous fuel model when burning. This means that plans based on this fuel model will be more conservative than plans based on fuel model 2 (Anderson 1982).

The grid-based survey method with the 25-meter assessment radius provided nearly complete coverage of the 3 burn units, and thus should represent the closest approximation of the distribution of fuel model types across the study area without resorting to mapping every square meter within the unit. The only problem is that although this system provides complete coverage of the area, the centroids of the polygons in the grid-based system, are an artificial construct. The points are placed artificially so that patches may be divided between polygons, and thus their full influence on fire behavior not be represented. For example, a patch of fuel model 3 may be divided into two polygons and represent less than half of each polygon. The polygon may be assigned a fuel model 1, whereas if the point had fallen in the center of the fuel model 3 patch, it may have been represented as fuel model 3 on the final map. Using a random survey method alleviates this problem somewhat. Although patches of plant life are usually distributed in patchy fashion, a random distribution would be expected to find these patches more than a grid-based distribution, unless the grid was small.

Fuel Moisture

1-Hour Fuel Moisture

Knowing 1-hour fuel moisture is an important aspect of determining fire behavior. The 1-hour fuels carry the fire and determine the rate of spread, fire intensity, and whether or not woody fuels may be consumed (Rothermel 1983; Scifres and Hamilton 1993). Usually, assessment of 1-hour fuel moisture requires 24 hours drying time, and samples have to be collected, weighed, dried, and then re-weighed to calculate moisture content. Having a statistical model for predicting 1-hour fuel moisture is a useful tool for predicting fire behavior and effects, as it allows for real time estimations.

There are many factors that affect 1-hour fuel moisture, but three variables are usually credited with having the most influence: temperature, relative humidity, and wind speed (Miller 1994). Temperature and relative humidity are closely related. Also, warm temperatures increase fuel temperature, which in turn causes water vapor to diffuse away from plants, drying them. Relative humidity functions in a dynamic equilibrium with plant material, since moisture readily penetrates and escapes. Wind has a drying effect by removing water vapor from the plant surfaces (Miller 1994). Other variables for predicting fuel moisture are sometimes included, for example: shading by clouds or forest canopy. Shading affects the amount of solar radiation that reaches fuels which, in turn, influences fuel moisture. Cloud cover was not measured in this study because its effects vary depending on other variables, such as aspect, slope, and day length (Rothermel 1983). The co-correlation of all these variables makes it difficult to use them in multiple regression analyses.

There are, however, "rule of thumb" methods for determining fine fuel moisture. These short cuts rely on relative humidity playing a dominant role in influencing fuel moisture. One such "rule" is fuel moisture equals the relative humidity divided by 5 (FM=RH/5) (Rothermel 1983). To determine if a "rule of thumb" could be established for north Texas, a simple linear regression was performed using measured 1-hour fuel moistures and measured relative humidity. Although a statistically significant model was found, the low coefficient of determination (R^2=0.30) indicates only 30% of the variability in fuel moisture can be accounted for by variability in relative humidity. This gives the model low predictive value, and also suggests that the RH/5 rule may be too simplistic for use in north Texas, at least during the winter burn season.

A multiple regression, involving multiple weather variables, increases the predictive value of the statistical model. The coefficient of determination indicates 75% of the variability in fuel moisture can be explained by variability in temperature, and relative humidity. Wind speed was not included in the model because it did not substantially increase the predictive value of the model.

10-Hour Fuel Moisture

Ten-hour fuel moisture was measured using a calibrated scale and a Protimeter. The scale was tested because that is what the U.S. Forest Service uses to report 10-hour fuel moisture, and the Protimeter was tested as an alternative to using the scale.

A multiple regression analysis of scale derived data yielded a statistically significant model. The coefficient of determination indicates that 51% of the variability in 10-hour fuel moisture can be accounted for by variability in temperature, relative humidity, and wind. Since 10-hour fuels have a 10-hour lag time for changing moisture, one would not expect a high degree of predictability from measuring current weather conditions. The regression analysis used weather data collected when fuel moisture was measured, to determine if there was a way to predict 10-hour fuel moisture under those conditions. Under a worst-case scenario, where a burn escapes or in a wildfire situation when local 10-hour fuel moisture information is unavailable, a predictive statistical model for fuel 10-hour fuel moisture would be valuable for predicting fire behavior.

Data collected from the Protimeter readings of fuel moisture varied slightly from the data collected from calibrated scale. This changed the statistical model and R^2 values obtained from a multiple regression of the data. The coefficient of determination for the statistical model using Protimeter data (R^2=0.37) indicates only 37% of variability in 10-hour fuel moisture can be accounted for by variability in temperature, relative humidity, and wind speed; this is opposed to the scale data, which had an R^2=0.51. The lower coefficient of determination for the Protimeter data compared to the coefficient of determination for the data collected by the scale could have occurred from the way the Protimeter measured fuel moisture. The Protimeter has 1.0-cm prongs that are driven into the wooden dowels to read interior moisture content. The diameter of the wooden dowels is 1.1-cm. It is possible that using the Protimeter to measure the moisture content of the wooden dowel allowed for the moisture content of the edge of the dowel to unduly influence the overall moisture content. Towards the edge of the dowel, moisture content would change faster than the center, based on relative humidity.

Based on the length of the Protimeter prongs relative to the diameter of the 10-hour wooden dowels, the Protimeter may not be the best tool for measuring 10-hour fuel moisture content. Lack of an effective rapid assessment tool makes a predictive statistical model for 10-hour fuel moisture all the more important.

100-Hour Fuel Moisture and 1000-Hour Fuel Moisture

Neither 100-hour fuels nor 1000-hour fuels are usually considered the dangerous, or a determining factor, in how fire spreads or behaves. The exception to this is under conditions of severe fire weather, such as high winds and low relative humidity (Rothermel 1983). Predicting fuel moisture for these classes of fuels is less reliant on statistical models because of rapid assessment tools, like the Protimeter, designed to measure moisture in heavy fuels. This is fortunate, because the long lag-time for weather conditions to affect fuel moisture makes it difficult to develop a statistical model for them. A multiple regression analysis did determine a statistically significant fuel model for both the 100-hour and the 1000-hour fuels, but both had only moderate coefficients of determination, 0.45 and 0.45, respectively. This suggests using an instrument to predict fuel moisture for these classes may be the better alternative for obtaining fuel moisture.

Weather Forecasting

Caution should be used when interpreting results of weather data analysis, for several reasons. First, the data only covers a span of seven years; the focus of meteorology is forecasting and the availability of detailed, archived data is somewhat limited. Second, the forecasting of potential burn windows means extrapolating from existing data. As any statistician might say, “interpolate at will, extrapolate with caution” (Beitinger 2000).

Tables 4-20, 4-21, and 4-22 compare the ranges, means, and standard deviations of the months that the weather data covers. Several trends become apparent when viewing the tables. From December to April there is not only a warming trend, but variation in temperature decreases, indicating temperature is stabilizing. One cause of this may be a reduction in severe weather as the months move into summer. Also relative humidity is comparable for all the months; however, April has a slightly larger standard deviation, indicating more variability in the range of relative humidity. Furthermore, maximum wind speed increases through March, and then decreases in April, but mean wind speed is comparable for all months except December. April has the highest mean wind speed; this means the data may be slightly skewed to the high end of the range, suggesting April may be too windy for burning.

During each month, except April, there are a number of days that occurred as potential burn days > 50% of the time during the time frame of the data. Rather than focus on the exact dates of days, it is important to focus on potential trends. In December it is notable that both days that did not meet the criteria during the data frame for prescribed burning occurred in the beginning of the month, rather than later in the month. Since December is actually before the beginning of prescribed burn season, this is as expected. In January, the days that have a 0% occurrence for meeting prescribed burn weather criteria occur primarily in the beginning of the month. Two of the three days that met prescribed burn weather criteria occurred late in the month. In February, the days that were most likely to be burn days occur in the first half of the month, and the days that did not meet burn criteria occur in the latter half of the month. So, based on the data, the end of January and the beginning of February seem to have a high potential for good burn weather. During March, days that were most likely to meet the criteria for burning occurred primarily in the first half of the month, and days that never meet the criteria occurred primarily in the last half of the month. Since March is the end of burn season, this is a reasonable expectation. March is also the beginning of spring rains in the area and a time of rapid weather change. In April, no days occurred greater than 50% of the time as meeting burn weather criteria, but more days at the end of the month failed to meet the criteria than at the beginning of the month (Table 5-1).

Restoration burning that relies on fire to eradicate non-native plants, such as Johnsongrass and Japanese brome, requires late spring burning. Late spring would be early March and into April in north Texas. These are the months that have the least opportunity to burn. However, based on field observation, Johnson grass begins to green-up in late February when, historic weather data has shown, there may be an opportunity to burn.

Table 5-1: Burn Window Frequency Data

	December	January	February	March	April
1		⊗			
2		⊗	☆		⊗
3	⊗		☆		
4					
5			☆		
6		☆		☆	
7	☆				
8					
9				☆☆	
10					⊗
11	⊗				⊗
12		⊗		☆	
13	☆	⊗			
14	☆			⊗	
15			⊗		
16					
17	☆				
18				⊗	
19					⊗
20					⊗
21					
22		☆	☆		⊗
23		☆			
24			⊗		⊗
25					
26	☆			☆	⊗
27	☆☆				
28	☆☆	⊗	⊗	⊗	
29				⊗	
30					⊗
31					

⊗= 0% occurrence as potential burn days
☆= >50% occurrence as potential burn days
☆☆= >70% occurrence as potential burn days

Smoke Production and Management

One of the primary concerns about prescribed fire, after safety, is the emission of pollutants during burning. Pollution emissions are a matter for concern not only for air quality purposes and visibility issues, but because they can threaten public health. Smoke is composed of hundreds of chemicals, but only a few criteria pollutants have associated National Ambient Air Quality Standards, particulate matter, sulfur dioxide, nitrogen dioxide, ozone, carbon monoxide, and lead (NWCG 2001). The EPA (2003) has listed the Dallas-Fort Worth Metro area as non-attainment for ozone. Fire is not a major source of ozone, but it does produce NO_X, a precursor for ozone. The pollutants of concern when burning are particulate matter, sulfur dioxide, nitrogen dioxide, and carbon monoxide.

To illustrate the smoke impacts of prescribed or wildland fire on air quality, it is useful to compare the pollutant emissions to those of automobiles. Based on Texas Department of Transportation data in the counties of Denton, Dallas, Tarrant, and Collin, 74,558,144 miles are driven per day (NCTCOG 2002). Based on the emissions factors (Table 5-1), some comparisons can be made between prescribed burn emissions and driving distance and time.

Table 5-2: Amount of Pollutant Emitted by Automobile per Mile Driven (NCTCOG 2002)

Pollutant	lb of pollutant per mile driven
CO	0.055
CO_2	0.7788
CH_4	0.000143
$PM_{2.5}$	0.0000968
PM_{10}	0.0000682
SO_2	0.0000154
NO_X	0.0033

As tables 5-3 to 5-5 demonstrate, the impacts from each prescribed fire would emit less pollution than the average day of driving in the four county area. Of all the pollutants, PM_{10} is produced most, but is still only the equivalent of half a day, or less, of driving. NO_X is a precursor to ozone, for which the metroplex is in non-attainment, but an equivalent amount of NO_X is emitted every six minutes in the metroplex. CO_2 is a greenhouse gas, which may contribute to global warming. In the metroplex, every six minutes automobiles emit an equivalent amount of CO_2 as prescribed fires at LLELA would. These comparisons are not meant to trivialize the contribution of prescribed fire to air pollution, but to put the effects of prescribed burning in perspective with other air quality concerns.

Table 5-3: Comparisons of Potential Air Pollution from Bison Prairie Burn Unit and Automobile Emissions

Pollutant	Miles that must be Driven to Equal Fire Emissions (miles)	Driving Time Needed to Equal Fire Emissions in minutes (hours)
CO	470,095	12 (0.2)
CO_2	350,662	6 (0.1)
CH_4	8,538,042	162 (2.7)
$PM_{2.5}$	22,258,264	432 (7.2)
PM_{10}	36,857,771	714 (11.9)
SO_2	9,677,045	186 (3.1)
NO_X	168,668	6 (0.1)

Table 5-4: Comparisons of Potential Air Pollution from Heritage Prairie Burn Unit and Automobile Emissions

Pollutant	Miles that must be Driven to Equal Fire Emissions	Driving Time Needed to Equal Fire Emissions in minutes (hours)
CO	449,201	6 (0.1)
CO_2	335,077	6 (0.1)
CH_4	8,158,573	156 (2.6)
$PM_{2.5}$	21,269,008	408 (6.8)
PM_{10}	35,219,648	678 (11.3)
SO_2	9,246,955	180 (3.0)
NO_X	161,172	6 (0.1)

Table 5-5: Comparisons of Potential Air Pollution from Research Prairie Burn Unit and Automobile Emissions

Pollutant	Miles that must be Driven to Equal Fire Emissions	Driving Time Needed to Equal Fire Emissions in minutes (hours)
CO	497,952	12 (0.2)
CO_2	371,442	6 (0.1)
CH_4	9,044,000	174 (2.9)
$PM_{2.5}$	23,577,273	456 (7.6)
PM_{10}	39,041,935	756 (12.6)
SO_2	10,250,500	198 (3.3)
NO_X	178,663	6 (0.1)

Even though the smoke impacts are not great compared to other sources of pollution, smoke management strategies should still be employed. There are basically three strategies to manage smoke emissions—avoidance, dilution, and emissions reduction (NWCG 2001).

Emissions avoidance is achieved by scheduling burns when meteorological conditions will direct smoke away from smoke sensitive areas. For example, at LLELA burning is only conducted with a south to southeast wind, this directs smoke away from sensitive areas, such as metropolitan areas, major roadways, and DFW International Airport. By using wind direction, these areas are able to avoid emissions all together.

Emissions can also be redistributed, or diluted, by burning when atmospheric conditions are conducive to dispersal. When the atmosphere is unstable, dispersal will be improved. Mixing height is the distance smoke will rise before it begins to disperse substantially. The higher the mixing height the dispersed emissions will be. In the past, burns at LLELA have been planned for when the mixing height is at least 1,000 meters. Also, smaller units can be burned over several days. The problem that may arise with the latter strategy is running out of good burn days before a unit can be completely burned.

One technique to lessen emissions is to reduce the area burned; this method is most effective when it does not merely delay the release of emissions. For this to have a true impact on air quality, the area to be burned should be reduced using a combination of treatments, such as mosaic burning or isolating fuels so they don’t burn (NWCG 2001). Fuel loads may also be reduced to decrease emissions; again the goal is to reduce, not delay emissions. This can be accomplished by mechanical removal of fuels or the introduction of ungulates. Reducing fuel production can decrease emissions by shifting species composition to those less likely to burn, or to burn more efficiently producing less smoke. This method of smoke reduction is not as applicable, in the short-term, at the LLELA burn units. A shift in species composition is a goal, and burning is one method that will be employed to achieve this. Then, over time, burning will decrease the occurrence of woody species and as a result reduce fuel production. The last technique for reducing emissions is increasing combustion efficiency. The flaming phase of combustion is more efficient than the smoldering phase; therefore, increasing flaming and decreasing smoldering can reduce emissions. Using backing fires and burning at the low end of the weather prescription for relative humidity, will increase flaming and decrease smoldering. Additionally, rapid mop-up, or extinguishing of smoldering fuels, will contribute to reduced emissions. One of the best options for land management and smoke management is to burn the units often. This reduces fuel loads and decreases emissions.

There are also methods for delaying emissions, rather than reducing emissions. Reducing the fuel consumed does not lead to a true reduction in emissions; it only results in a delay of emissions. This may serve some air quality goals, but delay management goals. Burning when fuel moisture is high enough so that some vegetation is not affected will result in the unit having to be burned again to accomplish management goals. Burning before new fuels appear may also interfere with land management goals. Burning should occur when it will benefit desirable species the most. Burning early to avoid new fuels may have little to no effect on desirable species, or a detrimental effect.

Conclusion

Prescribed burning is valuable land management technique for re-introducing fire into lands that have been degraded by fire suppression practices. Many ecosystems have degraded by fire exclusion, but among the most degraded are the prairies (Morgan 2003). Like much of the tallgrass prairies of the Midwest, the Blackland prairie region of Texas has been modified to the point that it is nearly extinct. Once, the Blacklands stretched across 12 million acres, from the Red River to San Antonio; today less than one-tenth of one percent remains (Diamond and Smeins 1993; Sharpless and Yelderman 1993). Following the regional and national pattern, the most degraded environment of north Texas is its former prairie.

Based on prairie vegetation response, burning is a practical, cost-effective method for restoring native species, and reducing or eliminating non-desirable species. Based on the historic weather data analysis, it also probable that opportunities to burn, based on weather, will occur when burning will be most effective for restoring prairie species (late February to early March).

Knowing fuel loads and fuel models for a burn unit is both a fire management and fire safety issue. Fuel loading may affect the weather conditions required for safe and effective burning. Fuel models, as they were used in this research, are important for predicting fire behavior. Fuel loads can only be evaluated on a small scale (1 meter) and extrapolated to a larger area. Evaluating fuel loads over a large distance is deceptive because it is not possible to tell how densely the fuel is arranged, which will affect estimates of fuel loads. However, evaluating fuel models is more accurate over a larger distance (25 meters). Evaluating fuel models over a small area (1 meter radius) was biased against fuel model 2. The survey method used for the assessment of fuel load and fuel model also affected the results of the study. A random survey method for assessment seemed to pick up more of the patchiness of landscape as opposed to a grid-based system. Also, a random or stratified random sampling method would be more feasible for large study areas.

Fuel moisture is a determining factor in fire behavior; however, predicting fuel moisture, especially 1-hour fuel moisture, can be time consuming and require special equipment. Based on the research 1- and 10-hour fuel moisture can be calculated from statistical models, but 100- and 1,000-hour fuel moisture require instrumentation to determine fuel moisture. However, 100- and 1,000- hour fuel moistures do not have a strong an influence on fire behavior, except during extreme fire weather conditions.

Smoke production for prescribed burning is a concern for nuisance issues, as well as, air quality and public health issues. Some pollutants emitted during burning are comparable to average daily automobile emissions, but some are higher. Smoke emissions can be somewhat reduced during burning using weather and management techniques. In north Texas the primary air quality concern is ground level ozone, but the production of ground level ozone precursors produced by burning at LLELA are comparable to the average precursor emitted every six to twelve minutes by automobiles in the Metroplex daily.

Although the focus of this research is the implementation of prescribed burning, the ultimate goal of restoration should not be forgotten. Before a prescription for burning can be written management goals should be defined. When defining management goals it is important to keep in mind that management strategies should be adaptive. Management goals should be based on previous results and strategies for achieving goals should be modified accordingly.

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