UNIVERSITY OF CALGARY

Using a Soil Heat and Water Transport Model to Predict Soil Temperatures and Grass Mortality During a Fire

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF BIOLOGICAL SCIENCES

CALGARY, ALBERTA

SEPTEMBER, 2005

UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Using a Soil Heat and Water Transport Model to Predict Soil Temperatures and Grass Mortality During a Fire" submitted by Joanna Jadwiga Choczynska in partial fulfilment of the requirements of the degree of Master of Science.

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Abstract

The fate of belowground regenerative tissues is important to the survival of grasses during a wildfire. We looked at the potential of fires to impact the bud distributions of three tallgrass species (*Andropogon gerardii*, *Sorghastrum nutans*, and *Panicum virgatum*). Soil heating is described by physical processes of heat and water transport and combined with bud distributions to determine the proportion of buds expected to be heated to lethal temperatures. We considered factors including soil moisture, texture, mineral thermal conductivity, maximum soil surface temperature and fire residence time. Our results show that lethal temperatures are only reached to depths of 1 or 2 cm, and at least 30% of buds remain below lethal temperature. It takes several hours of heating at a high temperature to kill all buds, which is an unrealistic condition in a grass fire. This implies that grasses are expected to survive direct heat effects from a fire.

Acknowledgements

First, I would like to thank my supervisor Ed Johnson for guiding me through this degree and offering invaluable advice and support.

I would also like to thank Jim Davidson and Shane Richards for their tremendous help with computer programming and numerical simulations.

This project would not have been possible without all the people who assisted with my field work. Paul Zedler from the University of Wisconsin-Madison was invaluable in helping with the logistical arrangements of my stay at Madison. Mark Martin from the Department of Natural Resources helped me to find research sites and spent a lot of time answering my questions. The staff at the University of Wisconsin-Madison also offered advice and provided me with accommodations and research sites. In particular, I would like to acknowledge the assistance of Mark Leach, Larry Ring, and Steve Glass. Finally, I would like to thank my field and lab assistants: Lisa O'Donnell, Anne-Katrin Heine, Danielle Hegedus, and Heather Suttie, who put in many hours collecting and analyzing samples.

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List of Symbols, Abbreviations and Nomenclature

A	variable in temperature curve model
C_h	volumetric specific heat of soil, J m^{-3} K^{-1}
d_g	geometric particle mean diameter, µm
D_v	vapour diffusivity in air, m^2 s^{-1}
D_{vo}	standard value for diffusivity at 0 °C and sea level pressure, 2.12 x 10^{-5} m^2 s^{-1}
f_w	empirical weighting function
g_a	soil particle shape factor
g_c	soil particle shape factor
h	relative humidity
H_v	latent heat of vaporization, J kg^{-1}
H_{vv}	latent heat of vaporization, J mol^{-1}
I	intensity, kW m^{-1}
j	height above soil surface, m
k	proportionality factor, 4.47 $m^{5/3}$ $kW^{-2/3}$
k_a	weighting factor for air
k_m	weighting factor for mineral fractions
K_v	vapour conductivity, kg m^{-1} Pa^{-1} s^{-1}
k_w	weighting factor for water
L_f	flame length, m
m_t	fraction of silt
M_w	molecular mass of water, 0.018 kg mol^{-1}
m_y	fraction of clay

p	partial pressure of water vapour in the soil, Pa
p^*	saturation vapour pressure of water in the pore, Pa
P	atmospheric pressure, Pa
P_0	sea level pressure, 101325 Pa
q	the rapidity of the transition from air- to water-dominated conductivity
q_0	power for recirculation function
r	dimensionless temperature
R	gas constant, 8.31 J mol^{-1} K^{-1}
s	slope of the saturation vapour pressure vs. temperature function, Pa K^{-1}
t	time, s
t_r	time, rescaled to equal zero at maximum surface temperature, s
U	rate of fire spread, m s^{-1}
x_a	fraction of air, m^3 m^{-3}
x_m	fraction of mineral soil, m^3 m^{-3}
z	thickness of soil layer, m
α	tortuosity correction, 0.66
β	entrainment constant, 0.16
$\hat{\beta}$	variable in temperature curve model
γ	cooling constant
ε	eccentricity
η	vapour flow enhancement factor
θ	volume fraction of soil water, m^3 m^{-3}
θ_I	extrapolated value of water content when $\psi = -1$ J kg^{-1}, m^3 m^{-3}

θ_a	water content of air dry soil, $m^3\ m^{-3}$
θ_s	saturation water content, $m^3\ m^{-3}$
θ_{wo}	water content at which water starts to affect thermal conductivity, $m^3\ m^{-3}$
λ	thermal conductivity of soil, $W\ m^{-1}\ K^{-1}$
λ_a	thermal conductivity of air, $W\ m^{-1}\ K^{-1}$
λ_m	thermal conductivity of mineral soil, $W\ m^{-1}\ K^{-1}$
λ_w	thermal conductivity of water, $W\ m^{-1}\ K^{-1}$
ρ_w	density of water, 1000 $kg\ m^{-3}$
$\hat{\rho}$	molar density of air, $mol\ m^{-3}$
$\hat{\rho}_0$	standard value for density at 0 °C and sea level pressure, 44.65 $mol\ m^{-3}$
Θ	soil temperature, K
Θ_0	standard temperature, 273.15 K
Θ_{303}	303 K
ψ	water potential, $J\ kg^{-1}$
ψ_0	water potential of oven dry soil, $-10^6\ J\ kg^{-1}$

USING A SOIL HEAT AND WATER TRANSPORT MODEL TO PREDICT SOIL TEMPERATURES AND GRASS MORTALITY DURING A FIRE

1.1 Introduction

Grasslands are characterized by surface fires which occur annually or every few years (Bond and van Wilgen 1996). This is a result of the morphology of grass: leaves are produced and die throughout the season, providing a fine fuel with a high surface area to volume ratio (Bond and van Wilgen 1996, Cheney and Sullivan 1997). There is very little organic matter (duff) at the soil surface (Cheney and Sullivan 1997). Grass leaves can lose moisture rapidly and allow the fire to spread quickly with very little smoldering combustion occurring (Cheney and Sullivan 1997).

Grasses contain regenerative tissues (buds) in the crown, on aboveground stems called stolons, at the base of crowns (located at or just below the soil surface), and on underground organs called rhizomes (Figure 1). Not all species have stolons and rhizomes, although rhizomes are a common feature of many species (Mueller 1941, Volland and Dell 1981). Aboveground matter (crowns and stolons) is consumed during a fire (Bragg 1982), and the grass' survival depends on the ability to resprout from surviving tissues. The buds from which the grasses regrow must be affected in order to bring about a change in the population (Reyes 2004), since the seed bank is not a significant contributor to post-fire regrowth (Benson et al. 2004). In this study we focus on buds that are on rhizomes. The buds on the rhizomes have a few centimeters of soil directly above them (Weaver 1958, Kucera and Dahlman 1968). Heat transfer through soil has been studied extensively and an existing model can be readily applied. Grasses can also resprout from other surviving buds (at the base of the crown, or aboveground), but the process of how these buds die is a much more complicated problem and will not be addressed in this study. We chose to study big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*) because the *Andropogon-Panicum-Sorghastrum* system is considered some of the most common community type in the North American tallgrass prairie (Risser et al. 1981, Howe 1994). These species have a widespread geographic range and high rate of occurrence (Schaffner 1913, Curtis 1959, Vogel et al. 1985), and are rhizomatous (Sims et al. 1971, McKendrick et al. 1975).

There are many reports of changes in grassland species composition following a fire (e.g. Kucera 1981, Gibson et al. 1993). Plant response to a fire can be due to either the fire itself or due to the postfire conditions (Robberecht and Defossé 1995), and while most studies do not differentiate between the two, in this study we are only concerned with direct fire effects. Although fires typically heat only the top few centimeters of the soil (Kucera 1981), it has been estimated that 90% of rhizome mass is found in the top 2.5 cm of the soil (Kucera and Dahlman 1968), which means that soil heating could be crucial to the survival of buds. Furthermore, when the upper 2 cm of soil and plant matter were manually removed, grass recovery was greatly hindered (Ramsay and Oxley 1996), again suggesting that the fate of the top soil layers is important.

Grasslands contain varying soil textures (Hole 1976, USDA 1978), mineral contents (Vázquez de Aldana et al. 1996, Alonso and García-Olalla 1997), and moisture regimes (Barnes and Harrison 1982, Umbanhowar Jr. 1992). Given that previous studies deemed soil properties to be important in determining temperatures (Peter 1992, Balatsos

1994), and that heating in soils is often variable (Balatsos 1994, Reyes 2004), we need to investigate how soil properties affect grass mortality.

Although numerous soil heat transfer models are available (Albini et al. 1996), a general assessment of the potential of fire to kill grass buds has not been performed. Soil heating studies that address wildfires only model the conditions that exist during a limited number of heating experiments performed in the laboratory (e.g. Dimitrakopoulos and Martin 1990, Peter 1992, Campbell et al. 1995). The heating at the soil surface is not usually representative of a grass fire (e.g. Dimitrakopoulos 1988), extreme conditions are not addressed, and combinations of various factors are not often studied. Lastly, none of these studies examine the proportion of buds expected to survive the fire.

The soil temperature profile needs to be combined with a vertical bud distribution to determine what proportion of buds will be exposed to lethal temperatures. Information on belowground buds is not commonly found in the literature due to difficulty in obtaining such data (Pecháčková et al. 1999). Most studies either count the total number of buds in a sample without looking at their vertical distribution (e.g. Noble et al. 1979, Benson et al. 2004), or they look at root, rhizome, or total plant biomass with depth (e.g. Rodríguez et al. 1995, see Titlyanova et al. 1999 for summary). These studies divide the soil profile into layers which are 10 or more centimeters thick, which is too coarse of a resolution for looking at buds during a fire, given that only the top few centimeters of the soil experience any temperature increase.

The objective of this research is to look at the potential of fire to directly affect grasses by heating the buds found on rhizomes. This involves modeling heat transfer through the soil and comparing temperature distributions to rhizome bud distributions.

We bound the problem by selecting realistic inputs to represent a range of grass fire and soil conditions that can be expected in the field. Specifically, we chose to vary maximum surface temperature, fire residence time, soil moisture, texture, and mineral content (represented by thermal conductivity). Based on the above summary of the literature, we hypothesized that fire and soil properties have the potential to affect depths of lethal heat penetration, and the resultant bud death. Higher surface temperatures, longer fire residence times, increased soil moistures, finer soil textures, and higher thermal conductivities should result in greater depths of lethal heat penetration, and hence higher percentages of bud death. Soil moisture in particular is an important factor to consider because water is twenty times more conductive than air (Balatsos 1994) and previous studies emphasized differences between the heating of a dry versus a wet soil (e.g. Dimitrakopoulos 1988, Peter 1992, Balatsos 1994). Additionally, we also wanted to establish the amount of heating required to kill all the buds. We thus modeled soil heating at a constant rate to obtain lethal temperatures throughout the soil profile.

1.2 Soil heat transfer model

The model by Campbell et al. (1994, 1995) was tested by Balatsos (1994), Campbell et al. (1995), and Albini et al. (1996), and was shown to perform well in a range of conditions. The model is based on a previous model by Aston and Gill (1976) and it also incorporates concepts from a model by de Vries (1963). It is more physically based than other soil heat transfer models. In particular, it includes changes in soil moisture, unlike other models that assume a dry soil (e.g. Richon 1987). Various soil types can be represented by changing inputs such as mineral thermal conductivity, soil density, and fraction of silt and clay. Furthermore, the numerical simulations are stable over many conditions.

The model divides the soil profile into horizontal layers, and predicts the heat and water budget for each layer for a given number of time steps (Figure 2). Modeling soil heat transfer also requires modeling water concentration and movement, because water has a large heat of vaporization and hence can strongly affect heat transfer (Albini et al. 1996). The model is one-dimensional, which means it only considers vertical heat and water transport. Richon (1987) found that expansion to a two-dimensional model does not significantly improve predictions.

Two major equations make up the Campbell et al. model: heat transport and storage, and water transport and storage. The equation of soil heat transport and storage in a soil layer is

$$C_h \frac{\partial \Theta}{\partial t} - H_v \rho_w \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial \Theta}{\partial z}\right) \tag{1.1}$$

where C_h is the volumetric specific heat, Θ is soil temperature, t is time, H_v is the latent heat of vaporization, ρ_w is the density of water, θ is the volume fraction of soil water, z is the thickness of soil layer, and λ is the thermal conductivity of soil. The first term in equation 1.1 represents the heat that is stored by the soil layer, the second term is the heat that is used to evaporate water, and the third term is the heat that is conducted to the soil layer.

The equation for water transport and storage is

$$\rho_w \frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{K_v}{1 - p/P} \frac{\partial p}{\partial z}\right) \tag{1.2}$$

where K_v is the vapour conductivity, p is the partial pressure of water vapour in the soil, and P is the atmospheric pressure. Water flow is caused by a vertical pressure gradient. As the water vaporizes, it creates pressure which causes the vapour to rise upwards.

The remainder of the equations in the Campbell et al. model relate various soil and water properties to temperature and water content, and are given in Appendix A.

1.3 Surface temperature

The Campbell et al. soil model requires a surface time-temperature curve to be inputted as the upper boundary condition. We modeled a variable surface temperature curve, as would be expected in a grass fire, and a constant surface temperature curve, as an attempt to find a treatment that would kill all the buds in the soil.

A typical curve observed during a fire is right skewed, and we used equations described by Mercer and Weber (2001) to represent it. See Appendix B for a model description. The highest recorded maximum surface temperatures in grass fires are in the order of 700 °C (Daubenmire 1968, McPherson 1995). Typically, maximum temperatures are reached within seconds after the temperature begins to increase from ambient, while the cool-off period lasts several minutes (e.g. Archibold et al. 1998, Morgan 1999, Mabli 2001). Although the Mercer and Weber model was designed for depicting temperatures above a source of heat, the resultant curves have the same shape as those observed in grass fires.

Additional constant surface temperature simulations were conducted to establish a boundary for killing all buds throughout the soil profile. This is not necessarily a realistic representation of a grass fire, although it can be used to represent conditions when high residence times may exist, e.g. during slash burning or artificial heating. We allowed for 10 minutes of soil heat-up, during which the temperature of the soil surface increased at a constant rate from ambient to the selected maximum temperature. Following the heat-up period, continued heating at a constant maximum surface temperature was simulated to occur for several hours.

1.4 Bud mortality

Since we assume that aboveground buds will be consumed by the fire, only the fate of belowground buds needs to be considered. It is commonly accepted that plant cells die when exposed to a temperature of 60 °C due to protein denaturation (Byram 1948, 1958, Heber and Santarius 1973; but see Dickinson and Johnson 2004). We assume that the buds will be the same temperature as the soil, and will respond instantaneously to changes in soil temperature due to their small size. We measured the lengths of the longest and shortest axes of buds using a digital calliper, and found these to be 3.8 ± 0.15 mm and 1.6 ± 0.06 mm for big bluestem ($n = 121$), 2.2 ± 0.10 mm and 1.1 ± 0.04 mm for indiangrass ($n = 96$), and 2.4 ± 0.13 mm and 1.1 ± 0.05 mm for switchgrass ($n = 96$). Although heat transfer from the soil to the bud could be modeled, given our findings that soil only heats up to depths of 1 or 2 cm during fires and that buds are found below those depths (see Results), such an analysis would not make much difference to our conclusions (see Discussion).

1.5 Methods

1.5.1 Approach

We simulated 48 different fire conditions (referred to as "Variable surface temperature") using the Mercer and Weber (2001) model for surface temperature and the Campbell et al. (1994, 1995) model for soil temperature. See Table 1 for summary. Conditions were selected to cover the expected range encountered in the field (see below). We conducted 24 further simulations using the Campbell et al. model with a constant temperature at the surface (referred to as "Constant surface temperature") to establish a boundary for killing all buds throughout the soil profile. See Table 2 for summary.

Temperature profiles were combined with vertical bud distributions for big bluestem, indiangrass, and switchgrass. For variable surface temperature simulations, the proportion of buds subjected to lethal temperatures is reported. For constant surface temperature simulations, the total heating time required to kill 100% of buds is reported.

1.5.2 Inputs

This section describes inputs selected for the simulations. Detailed lists are found in Appendices C and D for variable and constant surface temperature respectively.

Simulations were conducted with a time step Δt of 0.005 s and a vertical depth node size Δz of 0.002 m to a total depth of 0.20 m. These values were found by repeating the simulations with increasingly smaller node sizes until consistent results were obtained. Results were considered "consistent" when the depth of lethal heat penetration was constant between the simulations. A depth of 0.20 m is expected to contain most of the grass buds (Mueller 1941, Kucera and Dahlman 1968, Elder 2001).

1.5.2.1 Variable surface temperature (Mercer and Weber model)

Ambient air temperature was set to 20 °C and three maximum surface temperatures were selected: 60, 400, and 700 °C. The 60 °C was selected because it is the lowest temperature that can potentially cause the soil to heat up to 60 °C. The highest of these is what is usually cited as the upper boundary for grass fire temperatures (Daubenmire 1968, McPherson 1995). Given that there is a relationship between surface temperature and flame length (see Appendix B), the Solver feature in Microsoft Excel was used to solve for the chosen ΔT by changing flame length L_f. This yielded L_f values of 0.8, 3.6, and 5.3 m, which is consistent with flame length values observed in the tallgrass prairie (Trollope et al. 2002).

For each ΔT a short residence time (30 s heating, 180 s cooling) and long residence time (60 s heating, 600 s cooling) fire was simulated. These values were selected after reviewing time-temperature curves in the literature (e.g. Archibold et al. 1998, Morgan 1999, Mabli 2001). Values of fire spread $U = 0.5$ m s^{-1} and cooling constant $\gamma = 0.1$, and $U = 0.01$ m s^{-1} and $\gamma = 0.01$ were used for short and long residence time fires respectively. Previous studies show that the mean fire spread in the tallgrass prairie is 0.54 m s^{-1} in head fires and 0.01 m s^{-1} in back fires (Trollope et al. 2002). The values used in this study were therefore consistent.

The j value (Appendix B equations B.1 and B.5) represents the height above the flame. Although ideally it would be set to a value close to zero to reflect soil surface conditions, doing so caused the heating portion of the curve to be too sharp such that the desired period of heating would not take place. To reflect time-temperature curves in the literature (see references above) *j* was set to 3 m, which caused the shape of the curve to be more realistic. The resultant time-temperature curve was then used as the surface condition in the Campbell et al. model.

Figure 3 shows the time-temperature curves used.

1.5.2.2 Constant surface temperature

We used maximum surface temperatures of 200 and 1000 °C, and allowed for heating to occur for 1, 2, 3, 4, 5, and 10 hours. Maximum surface temperature was reached after 10 minutes of heating at a constant rate from an ambient temperature of 20 °C.

1.5.2.3 Campbell et al. model – variable surface temperature (Mercer and Weber model)

Initial soil temperature throughout the soil profile was set to 20 °C. Tallgrass prairie soil temperature at depths of 10 and 20 cm was measured to have a temperature of about 20 °C throughout the summer (Hulbert 1969).

Volumetric specific heat of the soil C_h was found by multiplying the specific heat of the soil (1849 J kg^{-1} K^{-1}; Incropera and DeWitt 2002) by the bulk density of the soil. Bulk densities of 1700 kg m^{-3} and 1000 kg m^{-3} were used for sand and clay respectively (Brady and Weil 1996).

"Wet" soil was defined as the field capacity, and a "dry" soil was wilting point of plants. Initial volume fractions of soil water θ throughout the soil profile were set to 0.06

m^3 H_2O/m^3 soil for wet sand, 0.37 m^3 H_2O/m^3 soil for wet clay, 0.01 m^3 H_2O/m^3 soil for dry sand, and 0.20 m^3 H_2O/m^3 soil for dry clay (Brady and Weil 1996). The latter two values were also used for the water content of air dry soil θ_a. Fires are unlikely occur in saturated conditions because wet vegetation will impede fire spread (Cheney and Sullivan 1997), hence a saturated soil treatment was not included.

Saturation water content θ_s is given by 1 – (bulk density/particle density) (Vomocil 1965). Particle density was set to 2650 kg m^{-3}, a value which does not vary much among soils (Brady and Weil 1996).

The thermal conductivity of mineral soil λ_m can be obtained by knowing the fractions of various minerals in the soil and their thermal conductivities. A representative value of soil thermal conductivity was not found in the literature. Quartz is a common component of soils and its thermal conductivity (8.8 W m^{-1} K^{-1}; de Vries 1963) was used for half of the simulations. Campbell et al. (1994) report λ_m in the order of 2 W m^{-1} K^{-1} for various soils. Given that other common soil components include feldspars and kaolinites, which have thermal conductivities of 2.3 W m^{-1} K^{-1} (Dean 1999, Shabbir et al. 2000) and 2.9 W m^{-1} K^{-1} (de Vries 1963) respectively, a value of 2 W m^{-1} K^{-1} is realistic and was used for the other half of the simulations. The model was not sensitive to changes in λ_m (see Results), therefore further refinement of this input was not performed.

We simulated a sandy soil by setting the fraction of silt m_t and the fraction of clay m_y to 0.05 each, and a clayey soil by setting m_t to 0.10 and m_y to 0.80 (Ghildyal and Tripathi 1987). Particles were assumed to be spherical and therefore had a soil particle shape factor g_a of 0.333.

Campbell et al. (1994) measured the power for recirculation function q_0 experimentally and obtained values in the range of 1.71 – 6.08. We used a mean value of 4.16.

Atmospheric pressure was kept constant at 101325 Pa. Other constants include water potential of oven dry soil ψ_0 (-10^{-6} J kg^{-1}), air vapour pressure (1000 Pa), vapour diffusivity (2.12 x 10^{-5} m^2 s^{-1}) soil tortuosity (0.66), and surface boundary layer resistance (20) (Campbell et al. 1995).

1.5.2.4 Campbell et al. model – constant surface temperature

We used a dry (0.01 m^3 H_2O/m^3 soil) sand (0.05 fraction silt and 0.05 fraction clay, bulk density of 1700 kg m^{-3}, θ_a of 0.01 m^3 H_2O/m^3 soil) and a dry (0.2 m^3 H_2O/m^3 soil) clay (0.1 fraction silt and 0.8 fraction clay, bulk density of 1000 kg m^{-3}, θ_a of 0.2 m^3 H_2O/m^3 soil). Mineral thermal conductivity was kept at 2.0 W m^{-1} K^{-1}. We used the same initial soil temperature, atmospheric pressure, specific heat, particle density, and q_0 as for the variable surface temperature simulations.

1.5.3 Numerical simulations and coding

A Turbo Pascal code of the Campbell et al. model was obtained from G.S. Campbell, and re-coded in C++. The C++ code is available upon request. As a boundary condition, the original model uses heat flux at the surface. However, because there is little information about heat flux during a grass fire, we chose to use surface temperature as the boundary condition. Other boundary conditions included air temperature, initial soil temperature and moisture, and soil temperature and moisture of the deepest layer.

There are two systems of partial differential equations that need to be solved. One set is for heat transfer, and this is a linear system solved by matrix inversion. The other set is for water potential, which is a non-linear system. The numerical approach used to solve it was based on the Linear Theory method of pipe network analysis (Wood and Charles 1972).

For each simulation, temperatures were averaged for each 1-cm interval by averaging temperatures and the maximum depth of lethal heat penetration (60 °C) was determined.

1.5.4 Bud distribution sampling

The bud distributions of big bluestem, indiangrass, and switchgrass were sampled at four sites per species in tallgrass prairie sites in or near Madison, Wisconsin. Big bluestem was sampled in the Curtis Prairie (3 sites) and the Grady Track (1 site) at the University of Wisconsin Madison Arboretum. Indiangrass was sampled at the Audubon Goose Pond State Natural Area (3 sites) and the Poynette State Game Farm (1 site). Switchgrass was sampled at the Audubon Goose Pond State Natural Area (1 site), Poynette State Game Farm (2 sites), and Rocky Run State Natural Area (1 site). The Curtis Prairie and Goose Pond sites are mostly loamy/clayey, while the Grady Track, Poynette, and Rocky Run sites are mostly sandy.

At each site, a relative monoculture of the species was located, and a 2 x 2 m grid was set up. A core sampler (AMS Split Core Sampler with Core Tip; Ben Meadows, Janesville, WI) 5 cm in diameter and about 30 cm in length was used to take soil cores.

Cores were taken in a grid pattern at 25 cm intervals, giving a total of 81 cores per site. Each core was wrapped in plastic wrap and aluminum foil, labeled, and frozen.

In the lab, the core was cut into 1-cm slices from 0 – 6 cm, 2-cm slices from 6 – 10 cm, and 4-cm slices from 10 – 18 cm. This was the finest resolution we could have obtained while maintaining accuracy (slicing the core into finer pieces would cause it to fall apart and too many buds would be split in two). Each slice was placed in a fine sieve and the soil was washed off, leaving behind the plant matter. The buds in each slice were counted.

1.6 Results

We present the following information to address the hypothesis that fire and soil properties affect soil temperature and bud death, and to gain insight into how much heat is required to kill all the buds:

1) Variable surface temperature simulation results – depths of lethal heat penetration (60 °C) for the simulations
2) Constant surface temperature simulation results – depths of lethal heat penetration for the simulations
3) Maximum soil temperature profiles for variable surface temperature simulations that received the most heating (maximum surface temperature of 700 °C and residence time of 660 s)
4) Time-temperature curves at 0, 1, 2, and 3 cm soil depths for the two variable surface temperature simulations that received the most heating and were the most different from each other (dry sand with a thermal

conductivity of 8.8 W m^{-1} K^{-1} and wet clay with a thermal conductivity of 2.0 W m^{-1} K^{-1})

5) Bud distributions of three species at four sites each

6) Percentages of buds expected to die during the variable surface temperature simulations

7) Total time required to kill 100% of buds during constant surface temperature simulations.

1.6.1 Simulations – variable surface temperature (Mercer and Weber model)

Each of the 48 simulations had one of 3 outcomes: no lethal heat penetration into the soil, lethal heat penetration to 1 cm, and lethal heat penetration to 2 cm (Table 3). All simulations with a maximum surface temperature of 60 °C failed to attain lethal temperatures in the soil. Simulations having a maximum surface temperature of 400 °C, as well as those with a maximum surface temperature of 700 °C and a residence time of 210 s had lethal temperatures to 1 cm. The only exception is one wet clay treatment with a maximum surface temperature of 400 °C and a residence time of 660 s, which had lethal temperatures at 2 cm. Simulations with a maximum surface temperature of 700 °C and a residence time of 660 s all had lethal temperatures to 2 cm.

1.6.2 Simulations – constant surface temperature

There were 24 simulations with 15 different lethal heat depth outcomes (Table 4). Sand and clay heated at 200 °C had lesser lethal depths than sand and clay heated at 1000 °C. The lethal depths reached by the 200 °C simulations for both sand and clay were about half of the lethal depths reached by the 1000 °C simulations for each corresponding heating time. One hour of heating caused lethal temperatures at 4 cm for sand and 3 cm for clay at a surface temperature of 200 °C, and at 7 cm for sand and 8 cm for clay at a surface temperature of 1000 °C. Each additional hour of heating usually only increased the lethal heat penetration by 1 or 2 cm. Increasing the heating time from 5 to 10 hours only increased the lethal heat penetration by 1 cm for clay at 1000 °C, 2 cm for clay at 200 °C, and 3 cm for sand at 200 and 1000 °C. After ten hours of heating, lethal soil depths ranged from 9-10 cm for clay heated at 200 °C to 18-19 cm for sand heated at 1000 °C.

1.6.3 Maximum soil temperature profiles – variable surface temperature

Maximum soil temperature rapidly declined with soil depth (Figure 4). Most of the temperature increase occurred in the first centimeter of the soil. Although the simulations had different maximum soil temperatures in the first centimeter, the curves all converged in the second centimeter, and the lethal temperature of 60 °C was attained at approximately the same depth (about 2 cm) for all the simulations. Typically, sand had a higher temperature than clay, dry soil had a higher temperature than wet soil, and soil with a thermal conductivity of 8.8 W m^{-1} K^{-1} had a higher temperature than soil with a thermal conductivity of 2 W m^{-1} K^{-1}.

1.6.4 Time-temperature curves – variable surface temperature

Greater soil depths had increasingly flatter time-temperature curves, indicating lower temperatures at these depths, and had the peak of the curve shifted to the right, indicating an increased delay between the temperature peak at the soil surface and the temperature peak in the given layer (Figure 5). The two soil types (dry sand with a thermal conductivity of 8.8 and wet clay with a thermal conductivity of 2) displayed the same trends, although the sandy soil heated to greater temperatures.

1.6.5 Bud distributions

For all species and all sites, most buds were found within 4 cm of the soil surface (Figures 6 to 8), but all contained considerable percentages of buds beyond 2 cm. On average big bluestem buds were closer to the surface than those of the other two species. All species displayed some variation between sites. Most notably, big bluestem site 1 had about twice as many buds in the top centimeter than site 3, indiangrass site 4 had most of its buds deeper than the other indiangrass sites, and switchgrass site 4 had most of its buds closer to the surface than the other switchgrass sites while switchgrass site 3 had most of its buds deeper than the other switchgrass sites.

1.6.6 Percent bud death – variable surface temperature

We know from section 1.6.1 that lethal temperatures (60 °C) during variable surface temperature simulations only occur at 1 or 2 cm. For each species and site we present the percentage of buds that occur to these depths and hence would be expected to die (Table 5).

When combining the temperature distributions from the variable surface temperature simulations with the bud distributions, only 14 to 34% of big bluestem, 5 to 14% of indiangrass, and 2 to 36% of switchgrass buds will be subjected to lethal temperatures at 1 cm. When lethal temperatures occur at 2 cm, 55 to 71% of big bluestem, 33 to 45% of indiangrass, and 13 to 72% of switchgrass buds will be subjected to lethal heating. No simulation resulted in 100% bud death.

1.6.7 Time required to kill buds – constant surface temperature

For big bluestem, heating at 200 °C required 3 hours in order to kill most buds for both sand and clay (Table 6). Heating at 1000 °C required 1 hour of heating in most cases. Site 2, which had buds at greater depths than the other sites, required a few hours longer in each case except for clay at 1000 °C.

For indiangrass, heating at 200 °C required 10 or more hours in most cases for both sand and clay (Table 6). Heating at 1000 °C required anywhere between 1 and 10 hours for sand, and between 1 and 10+ hours for clay. Site 3, which had buds closer to the surface, only required 1 or 2 hours of heating.

For switchgrass, heating at 200 °C required between 3 and more than 10 hours for sand and clay (Table 6). Heating at 1000 °C required between 1 and 10+ hours.

1.7 Discussion

The physical mechanisms by which the belowground buds of grasses survive fires have not been demonstrated before. Vague, qualitative assessments such as "the soil is a good insulator" (e.g. Young 1982, Bond and van Wilgen 1996) have been used to explain why grasses survive fires. At the same time, soil heating studies (e.g. Peter 1992, Balatsos 1994, Campbell et al. 1995) suggest that soil has the potential to heat up to high temperatures and hence kill the belowground vegetation. These studies are more concerned with validating their model with some experimental data, seldom address the range of fire and soil conditions that exist in the field, and never consider the distribution of underground plant organs. Their findings are therefore difficult to extend to general, realistic situations for the purpose of examining fire effects on grass.

In contrast, we selected a well-established physically-based soil heat and water transport model and considered a range of fire conditions, including extreme situations, and their effect on soil temperatures. We then combined this with bud distributions for three tallgrass prairie species, which were selected due to their abundance in the tallgrass prairie. This allowed us to examine the expected grass bud death in a range of fires. We found that in all cases only the top 1 or 2 cm were heated to lethal temperatures and only buds found at those depths could be killed by heat from fires with realistic residence times of 210 and 660 s. It did not matter whether the soil was a clay or sand, wet or dry, or had a low or high mineral thermal conductivity. In terms of which factors most affect our soil temperatures, this study suggests that the surface temperature curve (fire residence time and maximum temperature) is important to soil heating, implying that aboveground factors such as amount, moisture content, and spatial patterns of aboveground biomass, as well as weather conditions are important. Belowground factors such as soil texture, mineral composition, and moisture are less important. We emphasize that we are making this conclusion only for the range of conditions encountered during grass fires, at the scale of about 1 cm, and as long as the belowground factors do not significantly influence the surface temperature curve.

Looking at the physical aspects of the soil model helps us to understand why soils do not heat up extensively in fires. The physical properties of a material, such as specific heat (amount of heat required to increase the temperature of the material by a degree) and thermal conductivity (amount of heat which passes through a cross section of the material per unit time) determine how much heat the material can hold and how much heat flows through it (Farouki 1986). The specific heat of soil (1849 J kg^{-1} K^{-1}; Incropera and DeWitt 2002) is higher than that of metals (about 200 to 800 J kg^{-1} K^{-1}; Holman 1990), and solids such as brick, stone, and concrete (about 800 J kg^{-1} K^{-1}; Holman 1990), indicating that soils are able to store a greater amount of heat energy. The maximum soil thermal conductivity found in this study (see Appendix A equation A.3) was 1 W m^{-1} K^{-1} for wet clay composed of quartz. This is not large when compared to highly conductive substances such as metals, which range from about 10 to 400 W m^{-1} K^{-1} (Holman 1990). As the soil heats it will dry, and the thermal conductivity will decrease further as air replaces water in the soil pores. However, all materials have the ability to heat up if enough heat is delivered to the surface, which makes it important to consider realistic fire conditions when addressing the effect of fires on soil heating.

All of our sampled bud distributions contained buds below 2 cm, and these buds would survive all of our simulated fire conditions and potentially reproduce following the fire. Bud distributions in the literature agree with this: although most buds and rhizomes are in the top layers, they do occur at depths of 5, 10, and 20 cm (Lemieux et al. 1993, Elder 2001, Reyes 2004), and a few studies found buds extracted from deep layers to be viable (e.g. Lemieux et al. 1993, Reyes 2004).

Grass populations still have the potential to be directly affected by fire, since buds near the surface were exposed to lethal temperatures, and species displayed varying percentages of bud survival. Our findings suggest that big bluestem has buds closer to the surface than indiangrass and switchgrass, although this is not a general conclusion as we did not measure sites where the three species coexist. We also suggest measuring other species which are subjected to fire.

Given the importance of fire residence time and maximum temperature, we suggest that further studies focus on a better representation of the fire, and incorporate processes such as vegetation combustion and fire spread. The Mercer and Weber (2001) model we used is not ideal, as it was developed for forest fires and describes the temperatures above a fire plume. We used it to represent the shape of the curves observed during grass fires, but the model does not describe why such a shape occurs and how it may vary among sites and conditions. Aboveground vegetation patterns vary in space and time due to grazing, weather patterns, topography, time-since-fire (Coppedge et al. 1998), changes in the proportion of sod and bunchgrass growth forms (Wink and Wright 1973), and changes in percent dead leaves (Bragg 1982), so the surface temperature curve may not be constant across the landscape. Furthermore, underground rhizomes buds correlate with aboveground vegetation (Horowitz 1973, Pecháčková et al. 1999) and are not necessarily spatially uniform (Bell and Tomlinson 1980), and if the aboveground pattern makes a difference to the surface temperature curve, some buds may be exposed to different heat than others. Thus, patterns of vegetation growth should be studied as well. As mentioned in our introduction, grasses contain buds other than those on rhizomes. To complete this analysis, the survival of these buds in a fire should be assessed.

An implication of our findings is that one cannot realistically expect to use heat from a fire as a means of the controlling belowground bud distributions of grasses. Even if the grass receives a setback, it will not be destroyed. We would like to emphasize that if fire has any potential to eradicate a grass species, it will be through indirect effects. In order to use heat as a tool, it must be applied to the soil for hours. It takes several hours of heating for the soil to reach lethal temperatures which would cause most of the buds to die. Most likely such a solution is impractical for land management, unless the area is small and there is an artificial heat source available. Smoldering combustion is another process which extends the length of soil heating, and has been found to be an important factor affecting soil heating in other ecosystems such as chaparral (Odion and Davis 2000). It is generally believed that smoldering combustion does not occur in grasslands, although there are suggestions that it may occur when heavy fuel loads are present (Wright 1971, Cheney and Sullivan 1997, Paysen et al. 2000). However, as can be seen from our constant surface temperature simulations, it would take extensive heating to affect the bud bank, thus even smoldering combustion is not expected to kill off the grass.

Our study suggests that soil's "insulating" properties are not the sole reason why grasses survive fire. Clearly, the short residence time and relatively low aboveground temperatures of the fire are two other reasons, which arise due to aboveground plant architecture and weather conditions. The physiology of belowground grass buds (the depth at which they are found) is another factor. Thus if this study were to be extended to other systems (e.g. shrublands and forests) or other organisms, the same conclusions may not apply, because a different temperature curve may very well cause underground organism death.

1.8 Conclusions

We presented a method of predicting soil temperatures based on fire and soil properties. We found that only the residence time and the surface temperature had an effect on the depth of lethal penetration, while changing other factors like soil texture or moisture had no effect on the final outcome (percent buds dead). The maximum depths that experienced lethal heating were about 2 cm. Given that buds are found below these depths, it can be concluded that grasses will survive fires. We do not recommend the use of controlled burns as a tool to kill invasive rhizomatous grasses directly. If fire has the potential to kill grass, it will be through indirect effects. To kill grass using heat, the soil must be heated for several hours, most likely using an artificial heat source.

We recommend that future studies focus on the physiology of the grasses. Questions such as bud viability, spatial distributions of grasses, and regrowth following a fire should be addressed. These studies must be conducted in the field. Secondly, a more detailed description of the surface temperature curve should be made.

1.9 Literature cited

Albini, F., M.R. Amin, R.D. Hungerford, W.H. Frandsen, and K.C. Ryan. 1996. Models for fire-driven heat and moisture transport in soils. U.S. Department of Agriculture Forest Service General Technical Report INT-GTR-335. Intermountain Research Station, Ogden, UT, USA.

Alonso, I. and C. García-Olalla. 1997. Mineral composition of soils and vegetation from six mountain grassland communities in northern Spain. Journal of the Science of Food and Agriculture 73: 200-206.

Archibold, O.W., L.J. Nelson, E.A. Ripley, and L. Delanoy. 1998. Fire temperatures in plant communities of the northern mixed prairie. Canadian Field-Naturalist 112(2): 234-240.

Aston, A.R., and A.M. Gill. 1976. Coupled soil moisture, heat and water vapour transfers under simulated fire conditions. Australian Journal of Soil Research 14: 55-66.

Balatsos, P.C. 1994. Pyrogenic heat flow into soils and heat-induced tissue damage of *Agropyron spicatum* during simulated fire. PhD. Thesis. University of Idaho, Moscow, ID, USA.

Barnes, P.W., and A.T. Harrison. 1982. Species distribution and community organization in a Nebraska sandhills mixed prairie as influenced by plant/soil-water relationships. Oecologia 52: 192-201.

Bell, A.D., and P.B. Tomlinson. 1980. Adaptive architecture in rhizomatous plants. Botanical Journal of the Linnean Society 80: 125-160.

Benson, E.J., D.C. Hartnett, and K.H. Mann. 2004. Belowground bud banks and meristem limitation in tallgrass prairie plant populations. American Journal of Botany 91(3): 416-421.

Best, K.F., J. Looman, and J.B. Campbell. 1971. Prairie Grasses Identified and Described by Vegetative Characteristics. Publication 1413, Canada Department of Agriculture, Swift Current, SK, Canada.

Bond, W.J., and B.W. van Wilgen. 1996. Fire and Plants. Chapman & Hall, London, United Kingdom.

Brady, N.C. and R.R. Weil. 1996. The Nature and Properties of Soils. 11th Edition. Prentice Hall, New York, NY, USA.

Bragg, T.B. 1982. Seasonal variations in fuel and fuel consumption by fires in a bluestem prairie. Ecology 63(1): 7-11.

Byram, G.M. 1948. Vegetation temperature and fire damage in the southern pines. Fire Control Notes 9(4): 34-36.

Byram, G.M. 1958. Some basic thermal processes controlling the effects of fire on living vegetation. U.S. Department of Agriculture Forest Service Research Notes No. 114. Southern Forest Experiment Station, Asheville, NC, USA.

Campbell, G.S., J.D. Jungbauer, W.R. Birdlake, and R.D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Science 158(5): 307-313.

Campbell, G.S., J.D. Jungbauer, K.L. Bristow, and R.D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Science 159(6): 363-374.

Cheney, P., and A. Sullivan. 1997. Grassfires: Fuel, Weather and Fire Behaviour. CSIRO Publishing, Collingwood, Australia.

Coppedge, B.R., D.M. Engle, C.S. Toepfer, and J.H. Shaw. 1998. Effects of seasonal fire, bison grazing and climatic variation on tallgrass prairie vegetation. Plant Ecology 139: 235-246.

Curtis, J.T. 1959. The Vegetation of Wisconsin. University of Wisconsin Press, Madison, WI, USA.

Daubenmire, R. 1968. Ecology of Fire in Grasslands. pp. 209-266 IN Cragg, J.B., editor. Advances in Ecological Research 5. Academic Press Inc., London, UK.

Dean, J.A. 1999. Lange's Handbook of Chemistry, 15th Edition. McGraw-Hill, New York, NY, USA.

de Vries, D.A. 1963. Thermal properties of soils. pp. 210-235 IN Van Wijk, W.R., editor. Physics of Plant Environment. North-Holland Publishing Company, Amsterdam, The Netherlands.

Dickinson, M.B., and E.A. Johnson. 2004. Temperature-dependent rate models of vascular cambium cell mortality. Canadian Journal of Forest Research 34: 546-559.

Dimitrakopoulos, A.P. 1988. Measuring and modeling heat transfer into forest soil during wildland fires. PhD. Thesis. University of California at Berkeley, Berkeley, CA, USA.

Dimitrakopoulos, A.P., and R.E. Martin. 1990. Measuring and modeling soil-temperature profiles during simulated wildland fire conditions. Proceedings of the International Conference on Forest Fire Research, Coimbra, Portugal, Volume B21: 1-17.

Elder, B.D. 2001. The effects of fire on the life history traits of tallgrass prairie forbs. PhD. Thesis. Kansas State University, Manhattan, KS, USA.

Farouki, O.T. 1986. Thermal Properties of Soils. Series on Rock and Soil Mechanics Vol. 11. Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Fuller, E.N., P.D. Schettler, and J.C. Giddings. 1966. A new method for prediction of binary gas-phase diffusion coefficients. Industrial and Engineering Chemistry 58: 19-22.

Ghildyal, B.P., and R.P. Tripathi. 1987. Soil Physics. John Wiley & Sons, New Delhi, India.

Gibson, D.J., T.R. Seastedt, and J.M. Briggs. 1993. Management practices in tallgrass prairie: large- and small-scale experimental effects on species composition. Journal of Applied Ecology 30: 247-255.

Heber, U., and K.A. Santarius. 1973. Cell death by cold and heat resistance to extreme temperatures. Mechanisms of hardening and dehardening. pp. 232-263 IN Precht, H., J. Christophersen, H. Hensel, and W. Larcher, editors. Temperature and Life. Springer-Verlag, Berlin, Germany.

Hole, F.D. 1976. Soils of Wisconsin. University of Wisconsin Press, Madison, WI, USA.

Holman, J.P. 1990. Heat Transfer. 7th Ed. McGraw-Hill Inc, New York, NY, USA.

Horowitz, M. 1973. Spatial growth of *Sorghum halepense* (L.) Pers. Weed Research 13: 200-208.

Howe, H.F. 1994. Managing species diversity in tallgrass prairie: assumptions and implications. Conservation Biology 8(3): 691-704.

Hulbert, L.C. 1969. Fire and litter effects in undisturbed bluestem prairie in Kansas. Ecology 50(5): 874-877.

Incropera, F.P., and D.P. DeWitt. 2002. Fundamentals of Heat and Mass Transfer, 5th Edition. John Wiley & Sons, New York, NY, USA.

Johnson, E.A. 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press, New York, NY, USA.

Kucera, C.L. 1981. Grasslands and Fire. pp 90-111 IN Mooney, H.A., T.M. Bonnicksen, N.L. Christensen, et al. Fire regimes and ecosystem properties: proceedings of the conference Dec 11-15 1978 in Honolulu, Hawaii. Washington, DC, USA.

Kucera, C.L., and R.C. Dahlman. 1968. Root-rhizome relationships in fire-treated stands of big bluestem, *Andropogon gerardi* Vitman. The American Midland Naturalist 80(1): 268-271.

Lemieux, C., D.C. Cloutier, and G.D. Leroux. 1993. Distribution and survival of quackgrass (*Elytrigia repens*) rhizome buds. Weed Science 41: 600-606.

Mabli, L.A. 2001. Modeling backing fires California grassland fuels. PhD. Thesis. University of California at Berkeley, Berkeley, CA, USA.

McKendrick, J.D., C.E. Owensby, and R.M. Hyde. 1975. Big bluestem and indiangrass vegetative reproduction and annual reserve carbohydrate and nitrogen cycles. Agro-Ecosystems 2: 75-93.

McPherson, G.R. 1995. The Role of Fire in the Desert Grasslands. pp. 130-151 IN McClaran, M.P. and T.R. Van Devender, editors. The Desert Grassland. University of Arizona Press, Tucson, AZ, USA.

Mercer, G.N., and R.O. Weber. 2001. Fire Plumes. pp. 225-255 IN Johnson, E.A., and K. Miyanishi, editors. Forest Fires: Behavior and Ecological Effects. Academic Press, San Diego, CA, USA.

Morgan, J.W. 1999. Defining grassland fire events and the response of perennial plants to annual fire in temperate grasslands of south-eastern Australia. Plant Ecology 144: 127-144.

Mueller, I.M. 1941. An experimental study of rhizomes of certain prairie plants. Ecological Monographs 11(2): 165-188.

Noble, J.C., A.D. Bell, and J.L. Harper. 1979. The population biology of plants with clonal growth. I. The morphology and structural demography of *Carex arenaria.* Journal of Ecology 67: 983-1008.

Odion, D.C., and F.W. Davis. 2000. Fire, soil heating, and the formation of vegetation patterns in chaparral. Ecological Monographs 70(1): 149-169.

Paysen, T.E., R.J. Ansley, J.K. Brown, G.J. Gottfried, S.M. Haase, M.G. Harrington, M.G. Narog, S.S. Sackett, and R.C. Wilson. 2000. Chapter 6: Fire in western shrubland, woodland, and grassland ecosystems. pp. 121-159 IN Brown, J.K., and J. Kapler, editors. Wildland Fire in Ecosystems: Effects of Fire on Flora. U.S. Department of Agriculture Forest Service General Technical Report RMRS-GTR-42-vol. 2. Rocky Mountain Research Station, Ogden, UT, USA.

Pecháčková, S., H.J. During, V. Rydlová, and T. Herben. 1999. Species-specific spatial pattern of below-ground plant parts in a montane grassland community. Journal of Ecology 87: 569-582.

Peter, S.J. 1992. Heat transfer in soils beneath a spreading fire. PhD. Thesis. University of New Brunswick, Fredericton, NB, Canada.

Ramsay, P.M., and E.R.B. Oxley. 1996. Fire temperatures and postfire plant community dynamics in Ecuadorian grass páramo. Vegetatio 124: 129-144.

Reyes, C.M. 2004. The feasibility of using prescribed burning to control reed canary grass (*Phalaris arundinacea* L.) populations in Wisconsin wetlands. MSc. Thesis. University of Wisconsin-Madison, Madison, WI, USA.

Richards, J.M. 1971. Simple expression for the saturation vapor pressure of water in the range –50 to 140°C. British Journal of Applied Physics 4: L15-L18.

Richon, J.-B. 1987. Heat transfer in soils exposed to fires. MSc. Thesis. University of New Brunswick, Fredericton, NB, Canada.

Risser, P.G., E.C. Birney, H.D. Blocker, S.W. May, W.J. Parton, and J.A. Wiens. 1981. The True Prairie Ecosystem. Hutchinson Ross Publishing Company, Stroudsburg, PA, USA.

Robberecht, R., and G.E. Defossé. 1995. The relative sensitivity of two bunchgrass species to fire. International Journal of Wildland Fire 5(3): 127-134.

Rodríguez, M.A., V.K. Brown, and A. Gómez-Sal. 1995. The vertical distribution of below-ground biomass in grassland communities in relation to grazing regime and habitat characteristics. Journal of Vegetation Science 6: 65-72.

Schaffner, J.H. 1913. The characteristic plants of a typical prairie. The Ohio Naturalist 13(4): 65-69.

Shabbir, G., A. Maqsood, and C.A. Majid. 2000. Thermophysical properties of consolidated porous rocks. Journal of Physics D: Applied Physics 33: 658-661.

Shiozawa, S., and G.S. Campbell. 1991. On the calculation of mean particle diameter and standard deviation from sand, silt, and clay fractions. Soil Science 152(6): 427-431.

Sims, P.L., L.J. Ayuko, and D.N. Hyder. 1971. Developmental morphology of switchgrass and sideoats grama. Journal of Range Management 24: 357-360.

Titlyanova, A.A., I.P. Romanova, N.P. Kosykh, and N.P. Mironycheva-Tokareva. 1999. Pattern and process in above-ground and below-ground components of grassland ecosystems. Journal of Vegetation Science 10: 307-320.

Trollope, W.S.W., L.A. Trollope, and D.C. Hartnett. 2002. Fire behaviour a key factor in the fire ecology of African grasslands and savannas. pp. 1-15 IN Viegas, D.X., editor. Forest Fire Research & Wildland Fire Safety. Millpress, Rotterdam, The Netherlands.

Umbanhowar Jr., C.E. 1992. Reanalysis of the Wisconsin prairie continuum. American Midland Naturalist 127(2): 268-275.

United States Department of Agriculture Soil Conservation Service. 1978. Soil Survey of Dane County, Wisconsin. Washington, DC, USA.

Van Wagner, C.E. 1973. Height of crown scorch in forest fires. Canadian Journal of Forest Research 3: 373-378.

Vázquez de Aldana, B.R., M.E. Pérez Corona, A. García Ciudad, and B. García Criado. 1996. Mineral content in semiarid grassland systems as affected by community structure and soil characteristics. Acta Œcologica 17(3): 245-259.

Vogel, K.P., C.L. Dewald, H.J. Gorz, and F.A. Haskins. 1985. Improvement of switchgrass, indiangrass and eastern gamagrass – current status and future. pp. 51-62. IN Range plant improvement in western North America. Proceedings of the 38th Annual Meeting of the Society for Range Management, February 14, Salt Lake City, UT, USA.

Volland, L.A., and J.D. Dell. 1981. Fire effects on Pacific Northwest forest and range vegetation. U.S. Department of Agriculture. Pacific Northwest Region, Portland, OR, USA.

Vomocil, J.A. 1965. Porosity, pp. 299-314 IN Black, C.A., editor. Methods of Soil Analysis, Part 1. American Society of Agronomy, Madison, WI, USA.

Weaver, J.E. 1958. Prairie Plants and their Environment: A Fifty-Year Study in the Midwest. University of Nebraska Press, Lincoln, NE, USA.

Wink, R.L., and H.A. Wright. 1973. Effects of fire on an ashe juniper community. Journal of Range Management 26(5): 326-329.

Wood, D.J., and C.O.A. Charles. 1972. Hydraulic network analysis using linear theory. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 98(HY7): 1157-1170.

Wright, H.A. 1971. Why squirreltail is more tolerant to burning than needle-and-thread. Journal of Range Management 24: 277-284.

Young, R.P. 1982. Fire as a vegetation management tool in rangelands of the Intermountain region. pp. 18-31 IN Monsen, S.B., and N. Shaw, editors. Managing Intermountain Rangelands – Improvement of Range and Wildlife Habitats. Proceedings of Symposia: September 15-17, 1981, Twin Falls, Idaho, June 22-24, 1982, Elko, Nevada. U.S. Department of Agriculture Forest Service. General Technical Report INT-157. Intermountain Forest and Range Experiment Station, Ogden, UT, USA.

Table 1: All possible combinations of the following factors resulted in 48 different variable surface temperature simulations.

Fire or soil property	**Possible variables**		
Fire residence time (s)	short (210)	long (660)	
Maximum surface temperature (°C)	60	400	700
Soil moisture (m^3 H_2O/m^3 soil)	low (0.01 – sand; 0.2 – clay)	high (0.06 – sand; 0.37 – clay)	
Soil texture (fraction silt and clay)	sand (0.05 silt and 0.05 clay)	clay (0.1 silt and 0.8 clay)	
Mineral thermal conductivity (W m^{-1} K^{-1})	low (2)	high (8.8)	

Table 2: All possible combinations of the following factors resulted in 24 different constant temperature simulations.

Heating or soil property	Possible variables					
Time of heating (hours)	1	2	3	4	5	10
Maximum surface temperature (°C)	200			1000		
Soil texture (fraction silt and clay)	sand (0.05 silt and 0.05 clay)			clay (0.1 silt and 0.8 clay)		

Table 3: Maximum soil depths (cm) which experienced temperatures of 60 °C or higher during fire ("variable surface temperature") simulations.

Maximum depth which reached 60 °C (cm)	Simulation # (refer to Appendix C)	Description
none	1, 4, 7, 10, 13, 16, 19, 22, 25, 28, 31, 34, 37, 40, 43, 46, 49	all maximum surface temperature of 60 °C
1	2, 3, 5, 8, 9, 11, 14, 15, 20, 21, 23, 26, 27, 29, 32, 33, 35, 38, 39, 41, 44, 45, 47	all short residence time with maximum surface temperatures of 400 and 700 °C, and long residence time with maximum surface temperatures of 400 °C (except for one listed under 1 – 2 cm).
2	6, 12, 17, 18, 24, 30, 36, 42, 48	long residence time. All but one have a maximum surface temperature of 700 °C. The other one is a wet clay with λ_m = 8.8 W m^{-1} K^{-1} and a maximum surface temperature of 400 °C.

Table 4: Maximum depths (cm) which experienced temperatures of 60 °C during simulations of heating (“constant surface temperature”) simulations.

Total heating time (hours)	**Sand (200 °C)**	**Sand (1000 °C)**	**Clay (200 °C)**	**Clay (1000 °C)**
1	4	7	3	8
2	5	10	5	11
3	6	12	6	13
4	7	14	7	15
5	8	16	7	16
10	11	19	10	17

Table 5: Percentages of buds expected to die if lethal temperature occurs at 1 cm and 2 cm soil depths.

Species	Site #	Soil depth (cm)	
		1	2
Big bluestem	1	33.6	71.3
	2	21.3	54.5
	3	13.5	55.5
	4	26.4	60.1
Indiangrass	1	4.9	39.5
	2	13.5	45.1
	3	12.1	44.3
	4	5.8	32.7
Switchgrass	1	5.3	32.0
	2	6.2	43.6
	3	2.2	12.8
	4	36.2	71.9

Table 6: Time of heating (hours) required to kill 100% of buds at each site during constant surface temperature simulations.

Species	Site #	Sand (200 °C)	Sand (1000 °C)	Clay (200 °C)	Clay (1000 °C)
Big bluestem	1	3	1	3	1
	2	5	2	5-10	1
	3	3	1	3	1
	4	3	1	3	1
Indiangrass	1	5-10	2	10	2
	2	10+	5-10	10+	10+
	3	2	1	2	1
	4	10+	5-10	10+	10+
Switchgrass	1	5	2	5-10	1
	2	3	1	3	1
	3	10+	4	10+	4
	4	10+	5-10	10+	10+

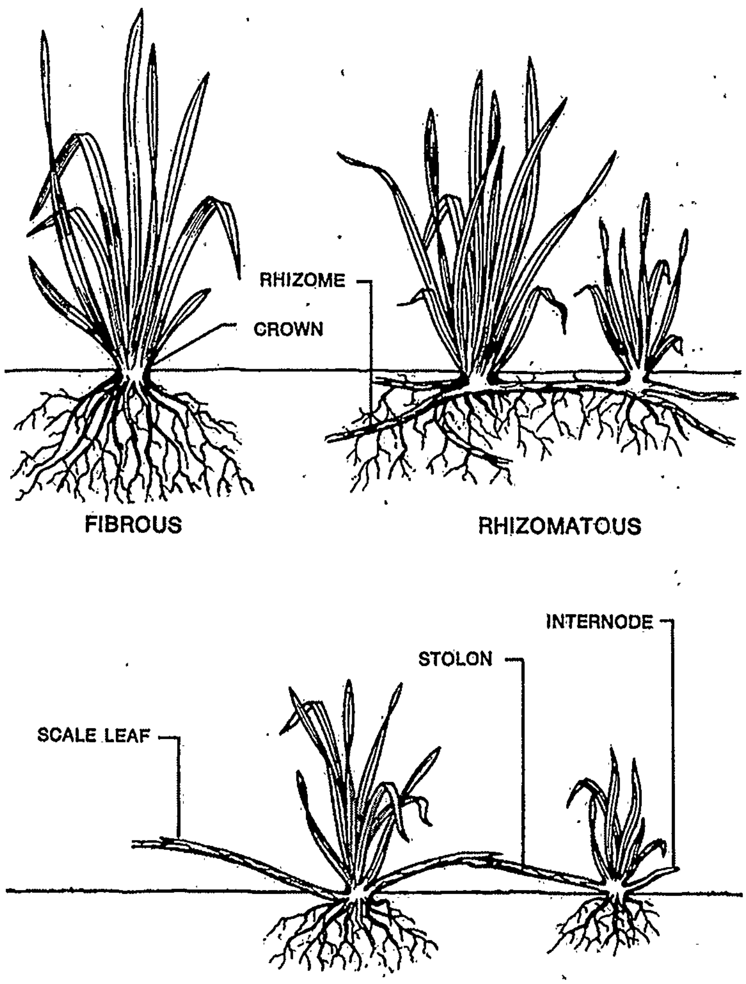

Figure 1: Morphology of grass. Figure is from Best et al. 1971.

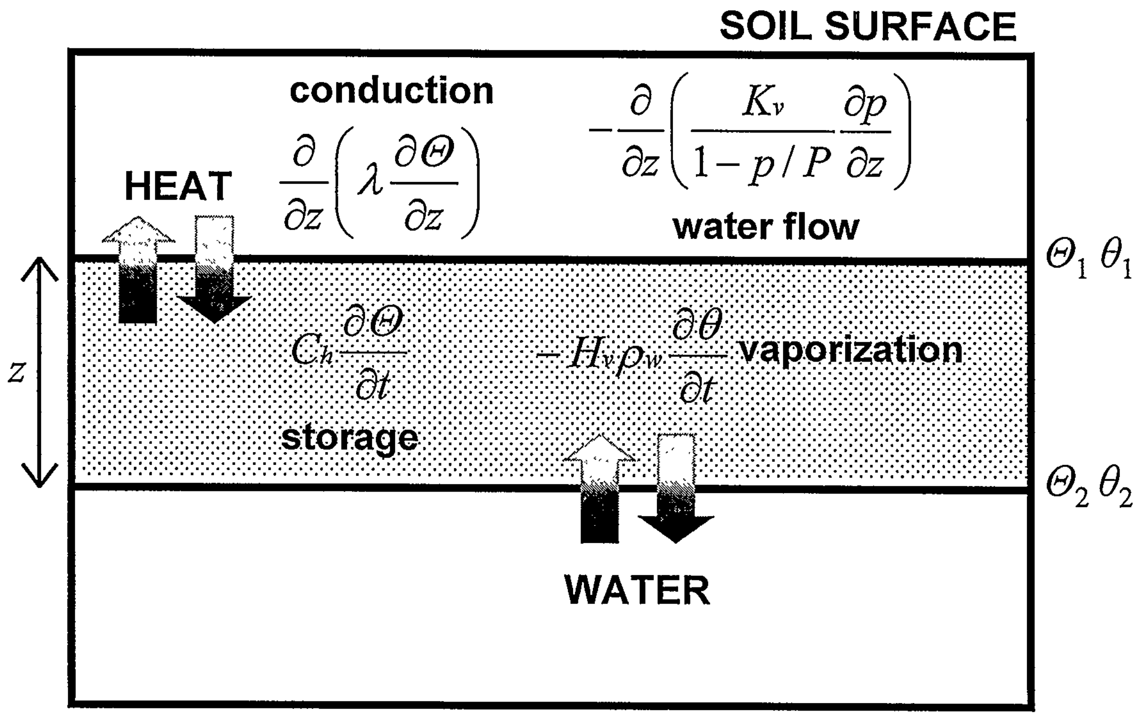

Figure 2: Heat and water budgets of a layer of soil. The symbols are defined in the text. Heat is conducted through the soil, stored by the soil, or used to vaporize water. Upward water flow occurs due to a pressure gradient that forms when the water vaporizes.

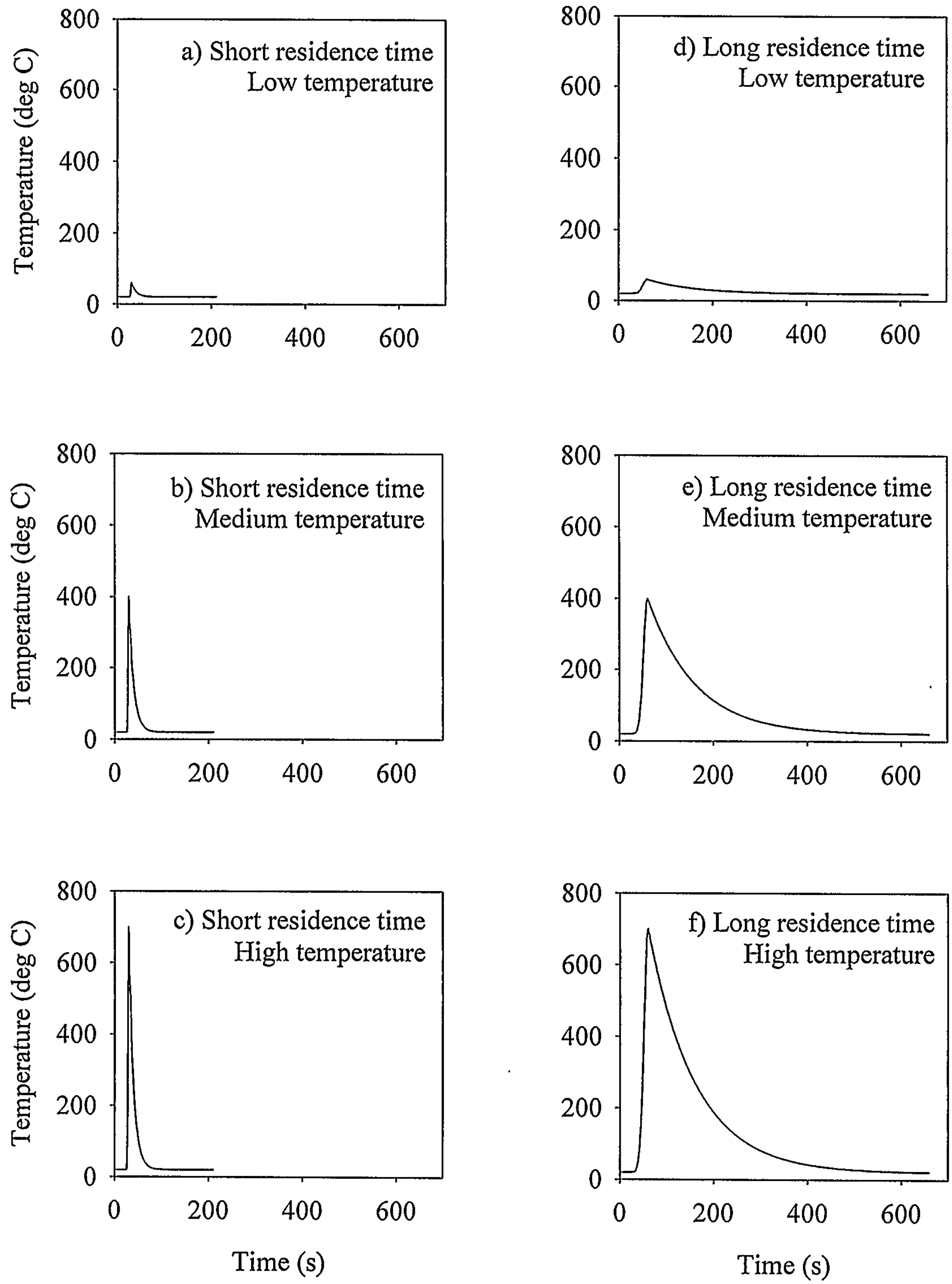

Figure 3: Time-temperature curves used in the variable surface temperature simulations.

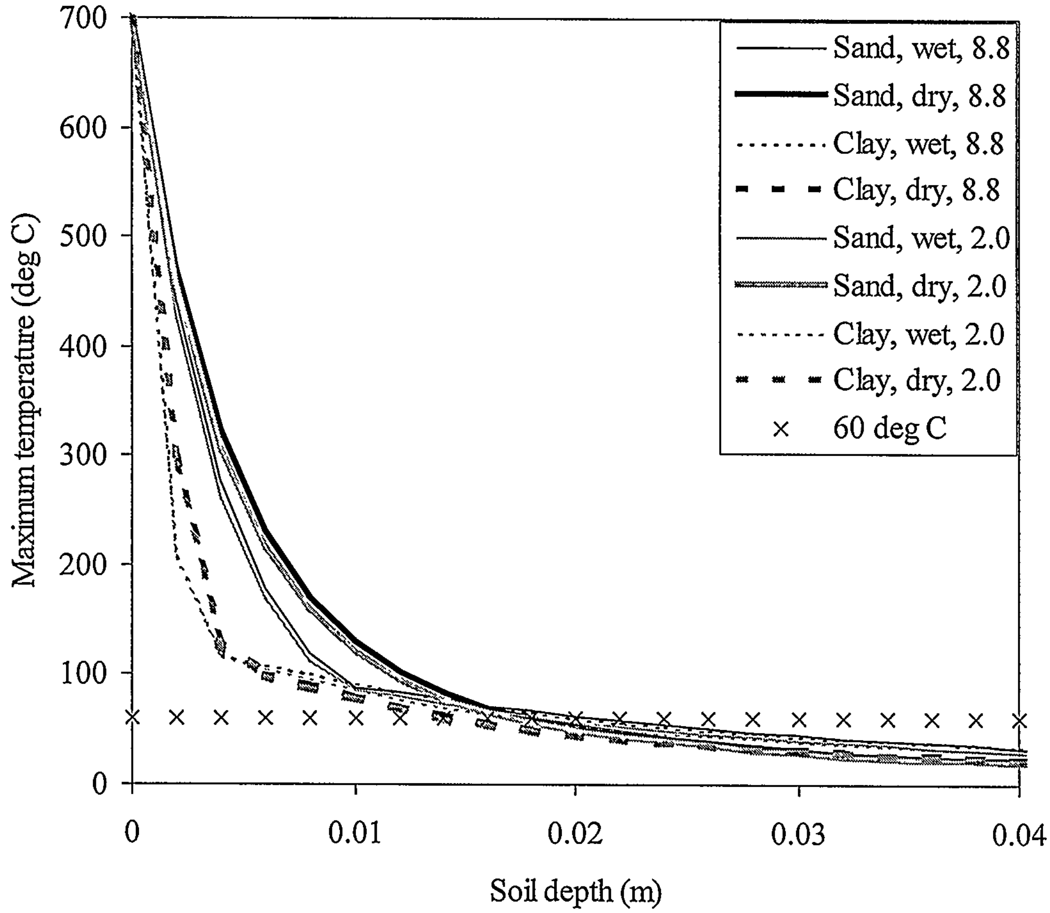

Figure 4: Maximum soil temperatures (°C) attained throughout the soil profile for variable surface temperature simulations with a maximum surface temperature of 700 °C and a residence time of 660 s. The number in the legend indicates mineral thermal conductivity (W m^{-1} K^{-1}).

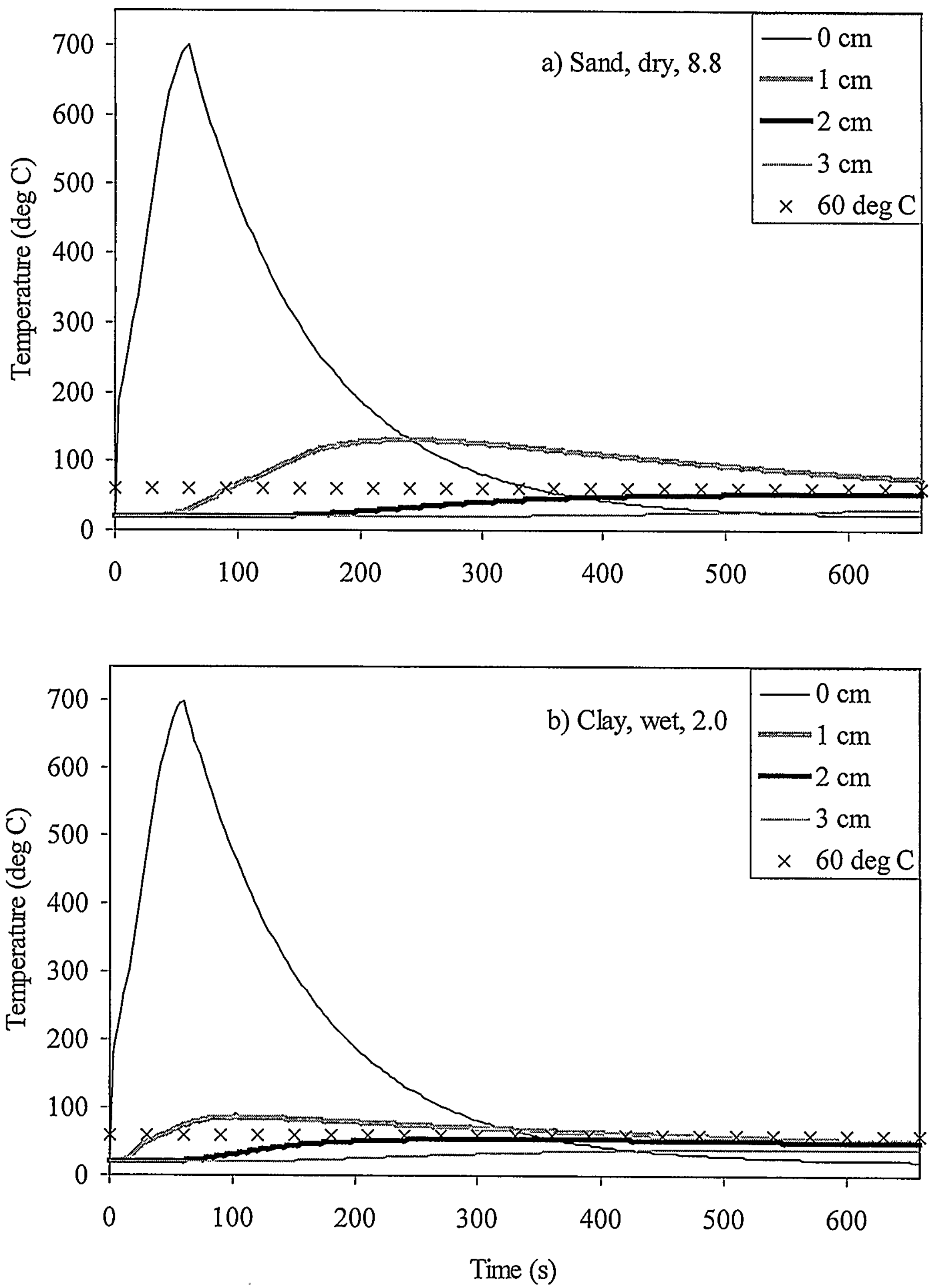

Figure 5: Time-temperature curves observed at various depths of the soil profile for two variable surface temperature simulations with a maximum surface temperature of 700 °C and a residence time of 660 s. The values 8.8 and 2.0 refer to the mineral thermal conductivity (W m^{-1} K^{-1}).

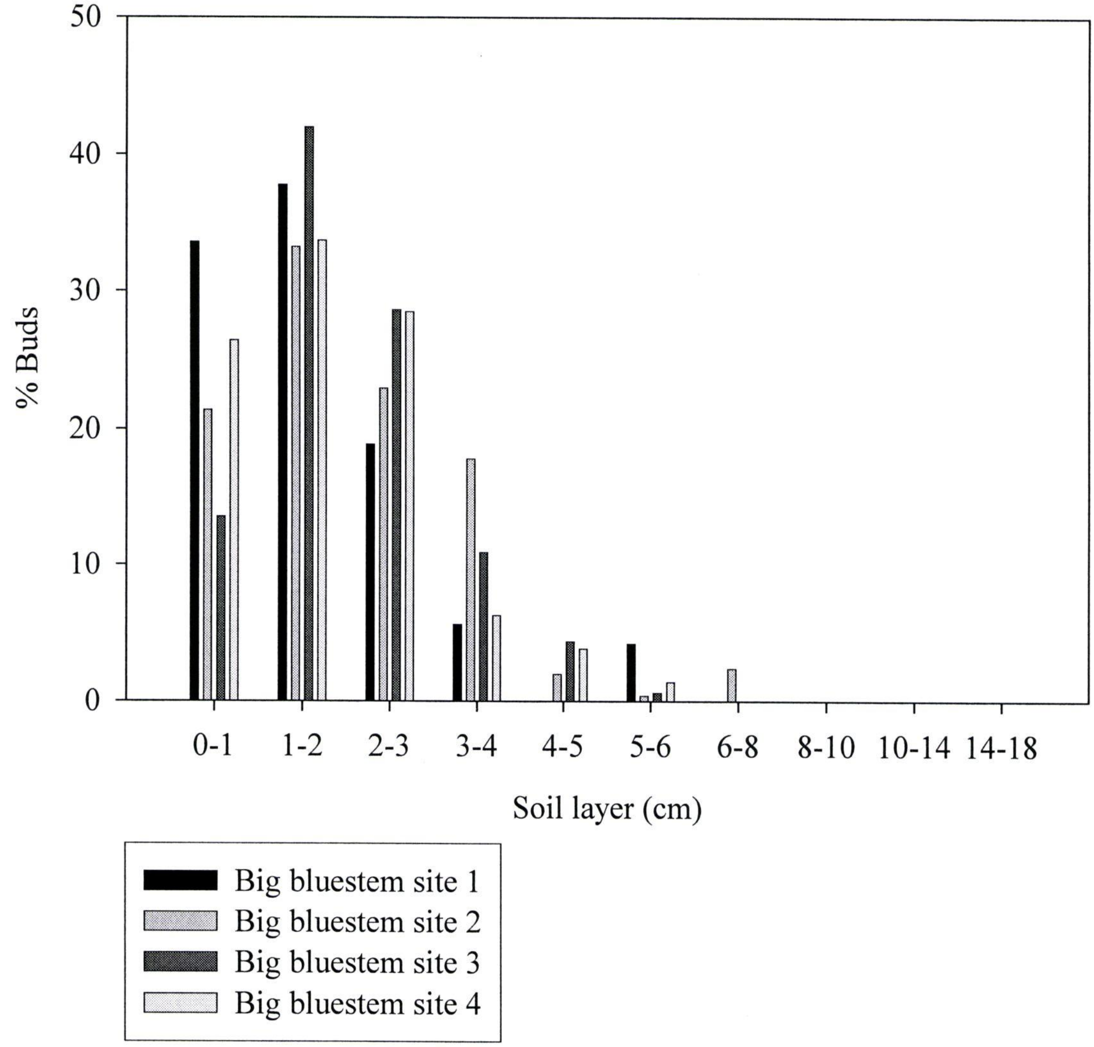

Figure 6: Bud distributions at four big bluestem sites.

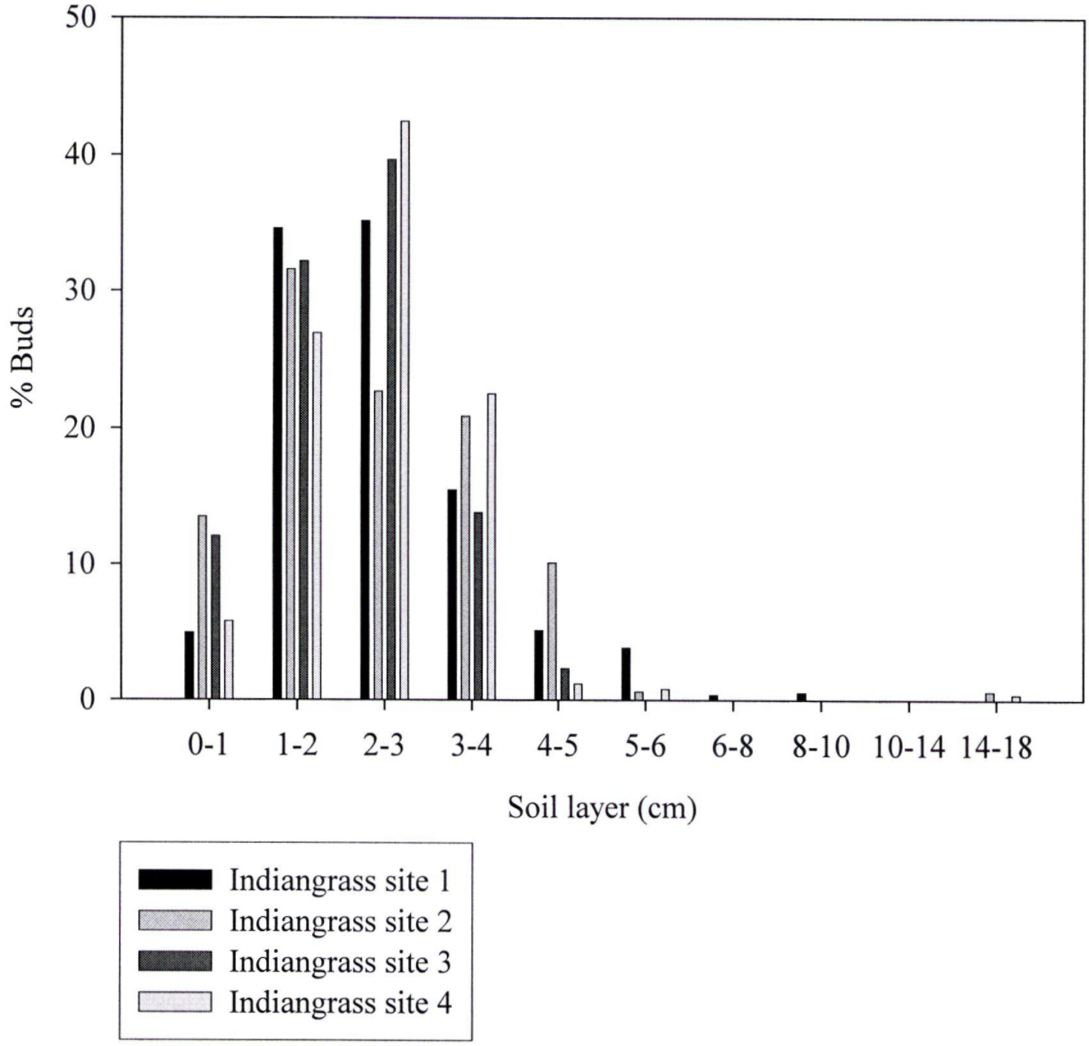

Figure 7: Bud distributions at four indiangrass sites.

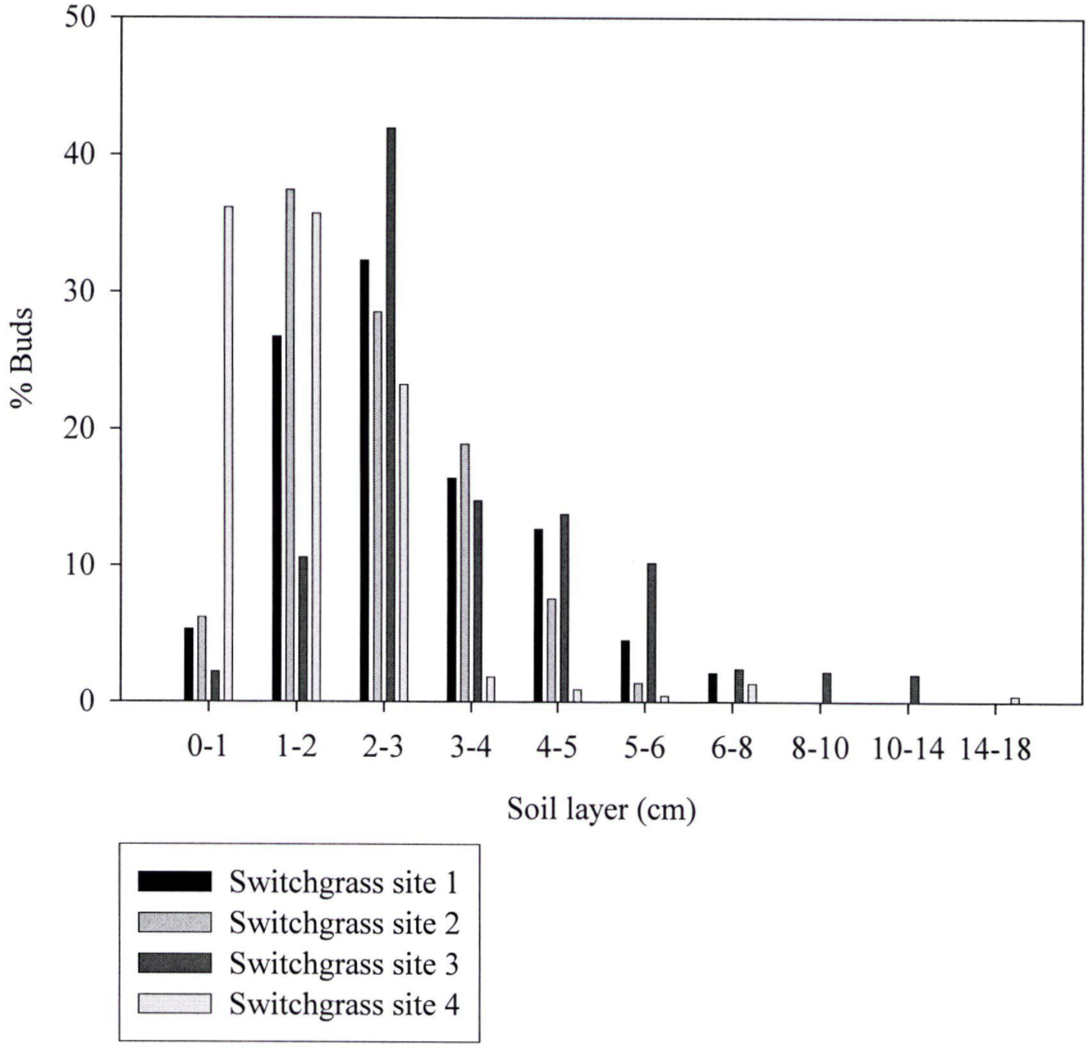

Figure 8: Bud distributions at four switchgrass sites.

APPENDIX A – CAMPBELL ET AL. MODEL EXPLANATION

See papers by Campbell et al (1994, 1995).

The following model description is divided into three parts: heat transport and storage, thermal conductivity submodel, and water transport and storage.

A.1 Heat transport and storage

The equation for soil heat transport and storage is

$$C_h \frac{\partial \Theta}{\partial t} - H_v \rho_w \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial \Theta}{\partial z}\right) \qquad \text{(A.1)}$$

where C_h is the volumetric specific heat, Θ is soil temperature, t is time, H_v is the latent heat of vaporization, ρ_w is the density of water, θ is the volume fraction of soil water, z is the thickness of soil layer, and λ is the thermal conductivity of soil.

In equation A.1,

$C_h \frac{\partial \Theta}{\partial t}$ is the heat stored in the soil layer

$-H_v \rho_w \frac{\partial \theta}{\partial t}$ is the heat that is used to evaporate water

and $\frac{\partial}{\partial z}\left(\lambda \frac{\partial \Theta}{\partial z}\right)$ is the heat that is conducted to the soil layer.

The latent heat of vaporization H_v is given by

$$H_v = 45144 - 48(\Theta - 273.15) - 0.018\psi \qquad \text{(A.2)}$$

where ψ is the water potential, obtained from equation A.21.

A.2 Thermal conductivity submodel

The thermal conductivity λ is found using a model similar to de Vries (1963), which assumes that total thermal conductivity of the soil is based on the proportions and thermal conductivities of its components. Thermal conductivity is given by

$$\lambda = \frac{k_w \theta \lambda_w + k_a x_a \lambda_a + k_m x_m \lambda_m}{k_w \theta + k_a x_a + k_m x_m} \tag{A.3}$$

where k_w, k_a, and k_m are the weighting factors for water, air, and mineral soil, θ is the fraction of water (from equation A.21), x_a and x_m are the fractions of air and mineral soil, and λ_w, λ_a, and λ_m are thermal conductivities of water, air, and mineral soil.

To obtain the weighting factors, Campbell et al. (1994) defined a "fluid" thermal conductivity λ_f. At a soil water content of θ_{wo} and greater, water will become a more significant contributor to soil thermal conductivity than soil air. This water content is dependent on soil properties, and in particular the particle diameter (see equation A.10). The "fluid" thermal conductivity describes the relative contributions of air and water thermal conductivities.

$$\lambda_f = \lambda_a + f_w \left(\lambda_w - \lambda_a \right) \tag{A.4}$$

where f_w is an empirical weighting function. This function ranges from 0 in dry soil (so that $\lambda_f = \lambda_a$ in equation A.4) to 1 in saturated soil (so that $\lambda_f = \lambda_w$ in equation A.4). It is given by

$$f_w = \frac{1}{1 + \left(\frac{\theta}{\theta_{wo}} \right)^{-q}} \tag{A.5}$$

where q is the rapidity of the transition from air- to water-dominated conductivity and θ_{wo} is the water content at which water starts to affect thermal conductivity. The exponent q is found by

$$q = q_0 \left(\frac{\Theta}{\Theta_{303}} \right)^2 \tag{A.6}$$

where Θ_{303} is 303 K, and q_0 is a constant obtained from measuring thermal conductivity and from nonlinear least square fits. It depends on the soil type (Campbell et al. 1994).

Based on nine soil samples, Campbell et al. (1994) determined a relationship between θ_{wo} and geometric mean particle diameter d_g:

$$\theta_{wo} = 0.267 d_g^{-0.2} \tag{A.7}$$

The diameter is calculated using the method of Shiozawa and Campbell (1991) using the relationship

$$d_g = \exp\left(5.756 - 3.454 m_t - 7.712 m_y\right) \tag{A.8}$$

where m_t and m_y are the fractions of silt and clay.

Using the "fluid" thermal conductivity, the weighting factors are

$$k_a = \frac{1}{3}\left[\frac{2}{1 + \left(\frac{\lambda_a}{\lambda_f} - 1 \right) g_a} + \frac{1}{1 + \left(\frac{\lambda_a}{\lambda_f} - 1 \right) g_c} \right] \tag{A.9}$$

$$k_w = \frac{1}{3}\left[\frac{2}{1 + \left(\frac{\lambda_w}{\lambda_f} - 1 \right) g_a} + \frac{1}{1 + \left(\frac{\lambda_w}{\lambda_f} - 1 \right) g_c} \right] \tag{A.10}$$

$$k_m = \frac{1}{3}\left[\frac{2}{1+\left(\frac{\lambda_m}{\lambda_f}-1\right)g_a}+\frac{1}{1+\left(\frac{\lambda_m}{\lambda_f}-1\right)g_c}\right] \tag{A.11}$$

where g_a and g_c are soil particle shape factors. In the de Vries model, there are three shape factors, g_a, g_b, and g_c which sum to 1 and correspond to the ratios of axes a, b, and c of soil particles. Assuming that the soil particles are elliptical in shape, g_b=g_a, and g_c=1 – 2g_a. Campbell et al. (1994) state that g_a must be found empirically, but they found that its value has "little effect, except in dry soil". Like q_0, g_a varies by soil type, and Campbell et al. (1994) obtained this value from measuring thermal conductivity and from nonlinear least square fits.

The equation for the air filled pore space is

$$x_a = \theta_s - \theta \tag{A.12}$$

where θ_s is the saturation water content and θ is the water content from equation A.21. The fraction of mineral soil x_m is then found by subtracting θ and x_a and from 1.

The thermal conductivity of water is given by

$$\lambda_w = 0.554 + 2.24\times10^{-3}(\Theta - 273.15) - 9.87\times10^{-6}(\Theta - 273.15)^2 \tag{A.13}$$

The thermal conductivity of air is based on a similar model by de Vries (1963) for a saturated pore. Campbell et al. added a humidity term to de Vries' model, and the resultant equation is

$$\lambda_a = \frac{H_{vv} h f_w \hat{\rho} D_v s}{P - hp^*} \tag{A.14}$$

where H_{vv} is the latent heat of vaporization of water, $\hat{\rho}$ is the molar density of air, D_v is the vapour diffusivity in air, P is atmospheric pressure, p^* is the saturation vapour pressure of water in the pore, and s is the slope of the saturation vapour pressure vs. temperature function. Note the latent heat of vaporization (H_{vv}) is given in units of J mol^{-1} rather than J kg^{-1} as in equation A.2. The formula is

$$H_{vv} = 45144 - 48(\Theta - 273.15) \qquad \text{(A.15)}$$

Molar density of air is dependent on temperature and pressure and is found by

$$\hat{\rho} = \hat{\rho}_0 \left(\frac{P}{P_0}\right)\left(\frac{\Theta_0}{\Theta}\right) \qquad \text{(A.16)}$$

where $\hat{\rho}_0$ is the standard value for density at 0 °C and sea level pressure, P_0 is the sea level pressure, and Θ_0 is the standard temperature.

The vapour diffusivity is also temperature and pressure dependent and follows the formula

$$D_v = D_{vo}\left(\frac{P_o}{P}\right)\left(\frac{\Theta}{\Theta_0}\right)^{1.75} \qquad \text{(A.17)}$$

where D_{vo} is the standard value for diffusivity at 0 °C and sea level pressure. The use of the 1.75 exponent is explained by Fuller et al. (1966).

The saturation vapour pressure is obtained from a modified version of the Richards equation (Richards 1971):

$$p^* = 101325\exp\left(r\left(13.3016 + r\left(-2.042 + r\left(0.26 + 2.69r\right)\right)\right)\right) \qquad \text{(A.18)}$$

where $r = 1 - 373.15/\Theta$ is a dimensionless temperature.

The slope in equation A.14 is

$$s = \frac{373.15p^*\left(13.3015 - 4.082r + 0.78r^2 + 10.76r^3\right)}{\Theta^2} \qquad \text{(A.19)}$$

A.3 Water transport and storage

The equation for water transport and storage is the second main equation of the model:

$$\rho_w \frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{K_v}{1 - p/P}\frac{\partial p}{\partial z}\right) \qquad \text{(A.20)}$$

where K_v is the vapour conductivity and p is the partial pressure of water vapour in the soil. Water flow is caused by a vertical pressure gradient. As the water vaporizes, it creates pressure which causes the vapour to rise upwards. The term $(1 - p/P)$ is called the Stefan correction and is required as a mass flow factor because the upward flow of gas causes it to accumulate at the surface and evaporate away from the surface.

The water content θ is expressed as a function of the water potential

$$\theta = \theta_1\left[1 - \frac{\ln(-\psi)}{\ln(-\psi_0)}\right] \qquad \text{(A.21)}$$

where θ_1 is the extrapolated value of water content when ψ = -1 J kg^{-1} and ψ_0 is the water potential of oven dry soil.

Campbell et al. (1995) state that the water potential is related to temperature, but were unsuccessful at finding a suitable relationship and hence assumed that water potential is independent of temperature.

The θ_1 value can be obtained from

$$\theta_1 = 6.3\theta_a \qquad \text{(A.22)}$$

where θ_a is the water content of air dry soil.

The partial pressure of water vapour is obtained from

$$p = hp^* \qquad \text{(A.23)}$$

where h is the relative humidity, and p^* is given by equation A.18.

Relative humidity is given by

$$h = \exp\left(\frac{M_w \psi}{R\Theta}\right) \qquad \text{(A.24)}$$

where M_w is the molecular mass of water and R is the gas constant.

The vapour conductivity is given by

$$K_v = \frac{\alpha x_a \eta M_w D_v}{R\Theta} \qquad \text{(A.25)}$$

where α is a tortuosity correction, and η is a vapour flow enhancement factor given by

$$\eta = 1 + 2\left(f_w k_a\right) \qquad \text{(A.26)}$$

APPENDIX B – VARIABLE SURFACE TEMPERATURE

Mercer and Weber (2001) describe the heating process as:

$$\Delta T = \frac{A}{j}\exp\left(-t_r^2 / \hat{\beta}^2 j^2\right) \qquad \text{(B.1)}$$

where ΔT is the change in surface temperature, j is the height above the soil surface, and t_r is time rescaled so that it equals zero at maximum temperature. It is negative during heating and positive during cooling. A and $\hat{\beta}$ are variables.

The variable A is given by

$$A = kI^{2/3} \qquad \text{(B.2)}$$

where k is the proportionality factor found by Van Wagner (1973), and I is intensity found according to the equation (Johnson 1992):

$$I = 259.83\left(L_f\right)^{2.174} \qquad \text{(B.3)}$$

where L_f is flame length.

The variable $\hat{\beta}$ is given by

$$\hat{\beta} = \beta / U \qquad \text{(B.4)}$$

where β is an entrainment constant and U is the rate of fire spread.

The cooling process is described by

$$\Delta T = \frac{A}{j}\exp\left(-\gamma t_r\right) \qquad \text{(B.5)}$$

where γ is a cooling constant . The ratio A/j is equal to the maximum ΔT.

APPENDIX C – INPUTS USED FOR VARIABLE SURFACE TEMPERATURE SIMULATIONS

	Mercer and Weber							Campbell et al.				
sim #	**max temp**	**time of heating**	**time of cooling**	L_f	U	γ	**initial** θ	θ_a	**bulk density**	m_t	m_y	λ_m
1	60	30	180	0.75	0.5	0.1	0.06	0.01	1.7	0.05	0.05	8.8
2	400	30	180	3.55	0.5	0.1	0.06	0.01	1.7	0.05	0.05	8.8
3	700	30	180	5.29	0.5	0.1	0.06	0.01	1.7	0.05	0.05	8.8
4	60	60	600	0.75	0.01	0.01	0.06	0.01	1.7	0.05	0.05	8.8
5	400	60	600	3.55	0.01	0.01	0.06	0.01	1.7	0.05	0.05	8.8
6	700	60	600	5.29	0.01	0.01	0.06	0.01	1.7	0.05	0.05	8.8
7	60	30	180	0.75	0.5	0.1	0.01	0.01	1.7	0.05	0.05	8.8
8	400	30	180	3.55	0.5	0.1	0.01	0.01	1.7	0.05	0.05	8.8
9	700	30	180	5.29	0.5	0.1	0.01	0.01	1.7	0.05	0.05	8.8
10	60	60	600	0.75	0.01	0.01	0.01	0.01	1.7	0.05	0.05	8.8
11	400	60	600	3.55	0.01	0.01	0.01	0.01	1.7	0.05	0.05	8.8
12	700	60	600	5.29	0.01	0.01	0.01	0.01	1.7	0.05	0.05	8.8
13	60	30	180	0.75	0.5	0.1	0.37	0.2	1	0.1	0.8	8.8
14	400	30	180	3.55	0.5	0.1	0.37	0.2	1	0.1	0.8	8.8
15	700	30	180	5.29	0.5	0.1	0.37	0.2	1	0.1	0.8	8.8

16	60	60	600	0.75	0.01	0.01	0.37	0.2	1	0.1	0.8	8.8
17	400	60	600	3.55	0.01	0.01	0.37	0.2	1	0.1	0.8	8.8
18	700	60	600	5.29	0.01	0.01	0.37	0.2	1	0.1	0.8	8.8
19	60	30	180	0.75	0.5	0.1	0.2	0.2	1	0.1	0.8	8.8
20	400	30	180	3.55	0.5	0.1	0.2	0.2	1	0.1	0.8	8.8
21	700	30	180	5.29	0.5	0.1	0.2	0.2	1	0.1	0.8	8.8
22	60	60	600	0.75	0.01	0.01	0.2	0.2	1	0.1	0.8	8.8
23	400	60	600	3.55	0.01	0.01	0.2	0.2	1	0.1	0.8	8.8
24	700	60	600	5.29	0.01	0.01	0.2	0.2	1	0.1	0.8	8.8
25	60	30	180	0.75	0.5	0.1	0.06	0.01	1.7	0.05	0.05	2.0
26	400	30	180	3.55	0.5	0.1	0.06	0.01	1.7	0.05	0.05	2.0
27	700	30	180	5.29	0.5	0.1	0.06	0.01	1.7	0.05	0.05	2.0
28	60	60	600	0.75	0.01	0.01	0.06	0.01	1.7	0.05	0.05	2.0
29	400	60	600	3.55	0.01	0.01	0.06	0.01	1.7	0.05	0.05	2.0
30	700	60	600	5.29	0.01	0.01	0.06	0.01	1.7	0.05	0.05	2.0
31	60	30	180	0.75	0.5	0.1	0.01	0.01	1.7	0.05	0.05	2.0
32	400	30	180	3.55	0.5	0.1	0.01	0.01	1.7	0.05	0.05	2.0
33	700	30	180	5.29	0.5	0.1	0.01	0.01	1.7	0.05	0.05	2.0
34	60	60	600	0.75	0.01	0.01	0.01	0.01	1.7	0.05	0.05	2.0
35	400	60	600	3.55	0.01	0.01	0.01	0.01	1.7	0.05	0.05	2.0
36	700	60	600	5.29	0.01	0.01	0.01	0.01	1.7	0.05	0.05	2.0
37	60	30	180	0.75	0.5	0.1	0.37	0.2	1	0.1	0.8	2.0

38	400	30	180	3.55	0.5	0.1	0.37	0.2	1	0.1	0.8	2.0
39	700	30	180	5.29	0.5	0.1	0.37	0.2	1	0.1	0.8	2.0
40	60	60	600	0.75	0.01	0.01	0.37	0.2	1	0.1	0.8	2.0
41	400	60	600	3.55	0.01	0.01	0.37	0.2	1	0.1	0.8	2.0
42	700	60	600	5.29	0.01	0.01	0.37	0.2	1	0.1	0.8	2.0
43	60	30	180	0.75	0.5	0.1	0.2	0.2	1	0.1	0.8	2.0
44	400	30	180	3.55	0.5	0.1	0.2	0.2	1	0.1	0.8	2.0
45	700	30	180	5.29	0.5	0.1	0.2	0.2	1	0.1	0.8	2.0
46	60	60	600	0.75	0.01	0.01	0.2	0.2	1	0.1	0.8	2.0
47	400	60	600	3.55	0.01	0.01	0.2	0.2	1	0.1	0.8	2.0
48	700	60	600	5.29	0.01	0.01	0.2	0.2	1	0.1	0.8	2.0

APPENDIX D – INPUTS USED FOR CONSTANT SURFACE TEMPERATURE SIMULATIONS

sim #	max temp	time of heating	m_t	m_y
49	200	1	0.1	0.8
50	200	2	0.1	0.8
51	200	3	0.1	0.8
52	200	4	0.1	0.8
53	200	5	0.1	0.8
54	200	10	0.1	0.8
55	1000	1	0.1	0.8
56	1000	2	0.1	0.8
57	1000	3	0.1	0.8
58	1000	4	0.1	0.8
59	1000	5	0.1	0.8
60	1000	10	0.1	0.8
61	200	1	0.05	0.05
62	200	2	0.05	0.05
63	200	3	0.05	0.05
64	200	4	0.05	0.05
65	200	5	0.05	0.05
66	200	10	0.05	0.05

67	1000	1	0.05	0.05
68	1000	2	0.05	0.05
69	1000	3	0.05	0.05
70	1000	4	0.05	0.05
71	1000	5	0.05	0.05
72	1000	10	0.05	0.05