Conceptual Approach to Temperature in the EDYS Model

Prepared for:

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1.0 Introduction

Temperature significantly influences plant dynamics, as well as a variety of processes that occur in soil (Sandor and Fodor 2012). Breaking of dormancy in the spring, seed germination, growth, and the onset of dormancy are all affected by temperature differences. In the soil, temperature influences microbial activities, evaporation rates, and the uptake of nutrients by plants. These processes are driven largely by soil temperature, and less so by ambient air temperature. Aboveground tissue loss due to late freezes in spring or early frost in autumn appears to be driven more by ambient air temperature than soil temperature. Consequently, both air temperature and soil temperature are necessary to drive temperature related processes in the EDYS model.

Currently, the EDYS model does not explicitly incorporate temperature effects on these processes. Instead, temperature is currently integrated into several plant parameters (Coldren et al. 2011), including those that control the breaking of dormancy (*GreenOutMonth*), when seeds are allowed to germinate (*SeedSproutMonth*), onset of dormancy (*DieBackMonth*), and monthly maximum growth rates (*MonthlyGrowthPercent*). In all these cases, temperature is factored in based on long-term averages, and so any annual variation greater than one month in duration is not adequately simulated. Early arrival of warm weather cannot drive early green out in the model, nor can a late spring freeze produce loss of aboveground biomass due to frozen tissue. Also, changes in plant phenology due to climate change may not be realistically projected into the future without mid-simulation changes in the above plant parameters. Changes in parameters mid-simulation would necessitate code modifications, effectively eliminating the ability of EDYS users to evaluate scenarios involving temperature differences over time. In response to these issues, a conceptual model for incorporating temperature into EDYS has been developed, and is described in detail below.

2.0 Previous Approaches

To drive the full range of biological responses to temperature will require incorporating both air and soil temperature into the model architecture. Air temperature is widely available as part of NOAA's online data for weather and climate across the United States. That dataset typically consists of both minimum and maximum daily temperatures. Like precipitation data, the period of record can be spotty, but missing values can be estimated in a manner similar to the production of a precipitation period of record, as we have done with previous applications of the EDYS model. On the other hand, soil temperature is not available from weather or climatic data sets through sources such as NOAA. Instead, those values must be estimated on a daily basis for the entire period of record.

A number of researchers have attempted to address the impact of temperature on biological processes in an ecosystem. These studies have taken a variety of forms, from mechanistic modeling approaches to statistical models, and even some efforts to take advantage of machine learning techniques for calculating soil temperature. Without going into great detail, these efforts fall into one of two main categories, each described as follows.

2.1 Heat Units and Growing-Degree Days (GDD)

The accumulation of heat units appears to drive the timing of some biological processes (McMaster and Wilhelm 1997) and has been simulated for some agricultural crops in order to determine optimum planting and harvesting dates. The idea behind this concept is that after a period of time with mean daily temperatures above a species-specific base temperature, then conditions should be appropriate for various phenological phenomena to occur. One example would be the breaking of dormancy in spring. Mathematically, heat units are calculated as follows:

$$HU = \sum_{i=1}^{SL} GDD_i \tag{1}$$

$$GDD = \left(\frac{T_{max} + T_{min}}{2}\right) - T_{base} \tag{2}$$

Where:

SL is season length in days,
T_{max} is maximum daily temperature,
T_{min} is minimum daily temperature, and
T_{base} is species' base temperature.

It is possible for GDD to be negative, and so two different correction factors have been devised:

1. $GDD = MAX\left\{0, \frac{T_{max} - T_{min}}{2} - T_{base}\right\}$ (3)

$$2.\ GDD = MAX\begin{bmatrix} & \frac{T_{base}+T_{min}}{2} - T_{base}\ when\ T_{max} < T_{base} \\ 0, & \frac{T_{base}+T_{max}}{2} - T_{base}\ when\ T_{min} < T_{base} \\ & \frac{T_{max}+T_{min}}{2} - T_{base}\ when\ T_{min} \geq T_{base} \end{bmatrix} \quad (4)$$

These corrections factors, although similar, can result in differences as high as 83% or more (McMaster and Wilhelm 1997), with the proper method relying heavily on the crop species in question and the local climate (Elnesr et al. 2013).

Additionally, a threshold heat unit value is required for each plant species. Once the accumulated heat units exceed the threshold, then processes such as green out and germination can begin.

Use of heat units would allow EDYS to conform to the approach widely used with agricultural crops to determine optimal conditions, such planting times in order to maximize yield. Conceptually, the same approach could be used with native vegetation to calculate when a species should break dormancy. However, three factors argue against the use of this approach in EDYS. First, T_{base} values and threshold heat units are available in the literature for some row crops and vegetables, but values for individual native plant species will be lacking, and may be difficult to obtain. Second, the high error rates stated above cast uncertainty on the validity of this approach when used in simulations of predominantly native vegetation. Last, this approach does not appear applicable to processes such as rates of microbial activity in the soil. Instead, it will require calculation of soil temperature separately from heat units.

2.2 Estimating Soil Temperature

Obviously, the use of soil probes to measure soil temperature at different depths would be ideal. However, this instrumentation is not practical on a landscape level situation, or across long-term temporal scales. Instead, soil temperature will need to be estimated in some manner to be available to drive the simulated biological processes. There are numerous approaches that have been attempted, several of which are described below.

2.2.1 Simulating Heat Flux

The most realistic approach to soil temperature may be the simulation of radiant energy as it reaches the vegetation and soil and its movement between components of the model. The movement of energy into and through soil layers is determined by the following relationship:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\frac{\partial^2 T}{\partial z^2} \quad (5)$$

Where:

T is soil temperature (°K),
k is thermal conductivity (W/m°K),
ρ is bulk density of the soil,
c is specific heat capacity of soil (J/g°K),
z is soil depth (m), and
t is time.

This approach can give accurate predictions of heat flux at the soil surface with use of incident shortwave and longwave thermal radiation (Kang et al. 2000). Unfortunately, this approach has proven difficult to apply across heterogeneous landscapes. It requires two parameters, soil thermal conductivity and specific heat capacity, that vary spatially and may require calibration for each soil series in a model application, as well as the plant communities associated with each.

2.2.2 Simulating Radiant Energy Reaching the Surface

The radiant energy that reaches the Earth's surface, under clear-sky conditions, can be calculated as:

$$R = \left(\frac{24}{\pi}\right) * 4.921 * ecc * [wT * sin(dec) * sin(\gamma) * cos(dec) * sin(wT) * cos(\gamma)] \quad (6)$$

Where:

ecc is earth's eccentricity correction factor,
w is earth's constant angular velocity,
T is time frequency,
dec is solar declination, and
γ is latitude.

This approach is commonly used (Halama et al. 2018) but suffers from the inability to incorporate topography and vegetation effects. When this approach is used, soil temperature is typically calculated as:

$$T_{soil}(z, d_n) = T_{AA} + A_{surf} * e^{-z/dd} * sin\left(w * d_n - \frac{z}{dd}\right) \quad (7)$$

Where:

$T_{soil}(z, d_n)$ is soil temperature at depth z for Julian day d_n,
T_{AA} is average annual soil temperature,
A_{surf} is the amplitude of surface fluctuations,
dd is damping depth, and
w is angular frequency of damping oscillations by day d_n.

Halama et al. (2018) modified this approach to include a measure of the radiant energy actually reaching the surface of a cell, taking into account differences in topography and shading by vegetation. They tested this approach at forested and clear cut sites in Oregon, with elevations ranging from 157 m to 1298 m. They saw improvements in calculating soil temperature at two different depths for all but one site, compared to actual sample data at all study sites. The one site was a grass lawn at the lowest elevation, where the modified approach performed worse than the original calculations. Additionally, they did not test this approach for plant communities with structures between mature forest (primarily Douglas-fir) and open sites (the one grass lawn and three clear-cuts).

This approach appears to have merit, but at this time needs additional testing. First, it has not been adequately tested on communities other than mature forest and clear-cuts, and with the one herbaceous community tested it performed more poorly. Second, damping of heat flux between layers is based on the volume to volume soil moisture content between adjacent layers. Test conditions in the model included only two soil layers, both with a depth of 15 cm, accounting for a total depth of only 30 cm. Soils in the EDYS model are typically simulated at finer scales near the surface (to better capture changes in the upper layers where most of the biological activity occurs), with a total depth of 20 m with 35 layers. How well their approach works with finer-scale delineation of soils remains to be seen. Finally, they did not address the impact of snowpack on soil temperature near the surface.

2.2.3 Empirical Relationships

The last general approach to determining soil temperature is based on an empirical relationship with air temperature. Zheng et al. (1993) found that air temperature correlates well with soil temperature, in large part because both derive from the energy balance at the soil surface. They used a range of study sites, covering a broad spectrum of climate conditions, to develop their air-soil temperature correlations, with sites located in Florida, Oregon, Michigan, Tennessee, Montana, Arizona, and Alaska. R^2-values for correlations at each site were high (typically > 0.92), indicating strong relationships between air and soil temperature.

Because of the time lag that occurs due to the relatively large heat capacity of soil (Zheng et al. 1993), they used a running average of mean daily air temperature as the independent variable in a simple linear regression. They tested running averages from 5 days up to 31 days, and concluded 11 days yielded the highest correlations. These were performed for soil depths of 10 cm.

The presence of snowpack alters heat flux at the surface, effectively damping soil temperature fluctuations and preventing soil temperature at the surface from rising above 0ºC. To compensate, they altered the relationship between air and soil temperature as follows:

With no snowpack:

$$Tsoil_n = [Tair_n - Tair_{n-1}] * M_2 + Treg_n \quad (8)$$

With a snowpack:

$$Tsoil_n = [Tair_n - Tair_{n-1}] * M_1 + Treg_{n-1} \tag{9}$$

Where:

$Tsoil_n$ is soil temperature at 10 cm depth on day n,
$Tair_n$ is average daily air temperature on day n,
$Tair_{n-1}$ is average daily air temperature on the previous day,
$Treg_n$ is soil temperature on day n obtained from the regression equation,
$Treg_{n-1}$ is soil temperature on day $n-1$ obtained from the regression equation,
M_1 is a scalar multiplier derived from the running average air temperature (=0.1), and
M_2 is a scalar multiplier derived from the running average air temperature (=0.25)

Zheng et al. (1993) then modified these relationships to account for vegetation, based on the Beer-Lambert law, where the amount of radiation transmitted through the canopy equals

$$e^{(-K*LAI)} \tag{10}$$

Where:

K is the extinction coefficient, and
LAI is leaf area index.

Kang et al. (2000) modified this approach to make it more generalizable across regions, effectively eliminating the need for determining linear regression coefficients. Instead of using an 11-day sliding window of average air temperature, they simply used average air temperature of the current day and of the previous day. In order to compensate for the damping effect of soil at depth, they added a damping ratio. They also added in the effect of the litter layer to moderate soil temperature, much in the same manner as Zheng et al. (1993) used leaf area index.

$$Ts_n = Ts_{n-1} + [Ta_n - Ts_{n-1}] * exp\left[-z\left(\frac{\pi}{rp}\right)^{1/2}\right] exp[-K(LAI + Litter)] \tag{11}$$

Where:

Ts_n is soil temperature at depth z on day n,
$Ts_{n-1}$is soil temperature at depth z on day $n-1$,
Ta_n is average air temperature on day n,
z is depth (cm),
r is thermal diffusivity (cm^2/sec),
p is period of temperature variation (sec),
K is extinction coefficient of Beer-Lambert law,
LAI is leaf area index, and
$Litter$ is equivalent to leaf area index for litter.

One shortcoming of Kang et al.'s (200) modification is the use of thermal diffusivity of soil, which may not be known for all the soil series used in a large-scale simulation of EDYS.

2.2.4 Summary

Soil temperature is required in EDYS in order to more realistically simulate multiple ecological processes. There are several valid approaches to achieving this, but the one that appears most promising currently is a modification of an empirical relationship with air temperature. Several reasons support adopting this approach. Air temperatures, both daily minimum and maximum, are widely available from NOAA weather stations. Developing regression coefficients is a relatively straightforward task. Back in 1991, NRCS established the Soil Climate Analysis Network (SCAN) with over 200 stations scattered across the United States. These sites typically record soil temperature at multiple depths, as well as corresponding air temperature. Regression coefficients can be determined from the nearest SCAN station, or based on several of the stations located near the model domain. If using a sliding window for air temperature, as per Zheng et al. (1993), parameters such as thermal diffusivity (Kang et al. 2000) will not be needed, reducing the calibration effort. Additionally, leaf and litter biomass are currently used in EDYS to modify evaporation rates due to shading effects. This method should be directly adaptable to moderating soil temperature near the surface due to differing levels of litter and aboveground plant biomass. Last, the empirical approaches of Zheng et al. (1993) and Kang et al. (2000) are the only ones that have incorporated snowpack and its impacts on soil temperature. While this capability is not an issue in the San Antonio River watershed, it will be in other parts of the world where EDYS might be applied, and as such, it cannot be ignored when implementing temperature.

3.0 Conceptual Approach in EDYS

Implementing temperature in EDYS will require changes to four aspects of the model: input data, data structures, plant parameters, and ecological algorithms. Proposed changes to each of these is detailed below.

3.1 Input Data

The primary input data are air temperature and associated regression coefficients.

3.1.1 Air Temperature

Both minimum and maximum daily air temperature data sets will need to be built and code added to EDYS to read those data in monthly. The period of record will need to match the period of record for all precipitation data in a simulation.

3.1.2 Regression Coefficients

Linear regressions will need to be performed using SCAN data from locations near the EDYS domain being simulated. Mean daily air temperature (based on daily minimum and maximum values) will be used as the independent variable, while soil temperature at 10 cm (or 4 inches) will be used as the dependent variable. Use of the regression coefficients will allow EDYS to dynamically calculate daily soil temperature based not only on the relationship with mean air temperature, but also on the amount of aboveground leaf biomass and litter.

Provisions in EDYS should be implemented to allow for use of actual soil temperature data if those data are available. The most likely scenario for this option will be an application using a small-scale simulation domain that has been set-up for validation purposes. In this case, actual soil temperature will be used instead of the regression coefficients, in a manner similar to the use of air temperature.

3.2 Data Structures

The following data structures will be required to implement temperature in the EDYS model: minimum air temperature, maximum air temperature, soil temperature, green out day counter, germination day counter, dieback day counter, and maximum temperature day counter.

3.2.1 Minimum Air Temperature

An array for minimum air temperature (*MinAirTemp*) will be included in the global variable section of the model architecture, with a structure identical to that currently used for precipitation. It will include the following fields:

- Year,
- Month,
- Number of Days in the month, and
- 1 to 31 – values for daily minimum air temperature (using 0 to fill out the array for months with less than 31 days.

3.2.2 Maximum Air Temperature

An array for maximum air temperature (*MaxAirTemp*) will be included in the global variable section of the model architecture, with the same structure as for *MinAirTemp*, but containing values for daily maximum air temperature.

3.2.3 Soil Temperature

An array for soil temperature (*SoilTemp*) will be included in the plot-type record structure of EDYS (see Coldren et al. 2011) because differences in plant litter biomass will result in daily soil temperature values that will vary by plot-type. This array will contain up to 31 values for daily soil temperature, using a value of 0 to fill out the array for months with less than 31 days. At the start of each month, daily soil temperature will be calculated based on the predetermined regression equation, moderated by aboveground leaf biomass and litter biomass.

3.2.4 Green Out Day Counter

A day counter will be used to monitor conditions to determine when a species will break dormancy. *GODayCount* will be a running counter of consecutive days in which the daily soil temperature exceeds each plant species' Minimum Temperature (see Section 3.3.1 below). This counter will be species-specific, and because daily soil temperature is plot-type dependent, this value will be part of the plot-type record. The counter will be set to -1 upon green out to prevent the code from attempting multiple green-outs during a growing season, then reset to 0 upon dieback in preparation for green out the next growing season.

3.2.5 Germination Day Counter

A day counter will be used to monitor conditions to determine when seeds will be allowed to germinate. *GermDayCount* will be a running counter of consecutive days in which the daily soil temperature exceeds each plant species' Minimum Temperature (see Section 3.3.1 below). This counter will be species-specific, and because daily soil temperature is plot-type dependent, this will be part of the plot-type record. Since germination in EDYS is allowed to occur during a period of months, the counter will be set to -1 upon reaching the end of the germination window to prevent germination past the allowed time period. It will be reset to 0 upon dieback in preparation for germination the following growing season. Actual germination will be based on both *GermDayCount* and the amount of water seeds absorb during rehydration, a process which is currently included in EDYS algorithms.

3.2.6 DieBack Day Counter

A day counter will be used to monitor conditions to determine when a species will enter dormancy. *DieBackDayCount* will be a running counter of consecutive days in which the daily soil temperature falls below each plant species' Minimum Temperature (see Section 3.3.1 below). This counter will be species-specific, and because daily soil temperature is plot-type dependent, this value will be part of the plot-type record. The counter will be set to -1 upon dieback to prevent the code from attempting diebacks during dormancy, then reset to 0 upon green out in preparation for dieback at the conclusion of the current growing season.

3.2.7 Maximum Temperature Day Counter

A day counter will be used to monitor conditions when temperatures are too high for growth. *MaxTempCount* will be a running counter of consecutive days in which the maximum air temperature exceeds each plant species' Maximum Temperature (see Section 3.3.2 below). This counter will be species-specific, but not part of the plot-type record. The counter will be set to 0 at green out to allow for growth impacts during the growing season, and set to -1 upon dieback to prevent the code from attempting to limit growth due to high temperatures. While this last situation seems unlikely, including this check should help prevent triggering code that is unnecessary for cool-season species.

3.3 Plant Parameters

Several new plant parameters will be necessary to simulate temperature impacts on plant dynamics.

3.3.1 Minimum Temperature

MinTemp is a species-specific minimum soil temperature tolerance. When this value is exceeded for the appropriate number of days (see Green Out Window, Section 3.3.3 below), a plant species will break dormancy. When soil temperature drops below this value for the appropriate number of days (see DieBack Window, Section 3.3.5 below), a species will enter dormancy.

Estimates for *MinTemp* can be derived from average green-out dates and typical weather patterns for the previous number of days specified by *GreenOutWindow* below.

3.3.2 Maximum Temperature

Extended periods of temperatures above a species-specific maximum will cause plants to drastically reduce, or even stop, production. Cool-season plants are known to stop production at temperatures above 25ºC, while warm-season species can produce up to 38ºC (Hatfield and Prueger 2015). *MaxTemp* is a species-specific maximum temperature for production. This parameter may not be easily obtained for many native species, but differences in cool- and warm-weather species can be estimated. A default temperature of 40ºC may be used.

3.3.3 Green Out Window

GreenOutWindow is the number of consecutive days in which daily soil temperature will need to exceed the species-specific *MinTemp* for a species to break dormancy. Default is 14 days.

3.3.4 Germination Window

GerminationWindow is the number of consecutive days in which daily soil temperature will need to exceed the species-specific *MinTemp* for seeds to germinate. Default is 14 days.

3.3.5 DieBack Window

DieBackWindow is the number of consecutive days in which daily soil temperature will need to fall below the species-specific *MinTemp* to trigger a species entering dormancy. Default is 14 days.

3.3.6 MaxTemp Window

MaxTempWindow is the number of consecutive days that a plant species can tolerate air temperatures above its species-specific *MaxTemp* before new growth is curtailed. Default is 3 days.

3.4 Ecological Algorithms

The following ecological algorithms in EDYS will need to be modified to implement temperature effects.

3.4.1 Green Out

When any plant species in the model is dormant, code will be invoked to check whether any of those dormant species will green out. This condition must be checked at the start of each month.

If *GODayCount* exceeds *GreenOutWindow*, then that species will break dormancy that month. Monthly maximum growth rate (*MonthlyGrowthPercent*, see Coldren 2011 et al. for details) may need to be adjusted if green out occurs and the monthly maximum growth rate equals 0.0. A default value of 0.1 will be used to allow some growth to occur that month.

3.4.2 Germination

If seeds have not germinated for any species, a check will be made as to whether soil temperature conditions are sufficient to allow germination. This condition must be checked at the start of each month.

If *GermDayCount* exceeds *GerminationWindow*, then the seeds of that species will be allowed to germinate. Actual germination rates will also depend on the absorption of soil moisture by the seeds, the proportion of seeds that are allowed to germinate during any one month (*SeedSproutProp*, see Coldren et al. 2011 for details), and the amount of biomass currently in the seed bank.

3.4.3 Die Back

When any plant species in the model is actively growing, code will be invoked to check whether conditions are conducive for any of those species to enter dormancy. This must be checked at the start of each month.

If *DieBackDayCount* exceeds *DieBackWindow*, then that species will enter dormancy that month. Monthly maximum growth rate (*MonthlyGrowthPercent*, see Coldren 2011 et al. for details) may need to be adjusted if the growing season lasts longer than expected and the monthly maximum growth rate equals 0.0. A default value of 0.1 will be used for *MonthlyGrowthPercent* that month. The *SeedSetMonth* window (see Coldren et al. 2011 for details) may need to be adjusted if dieback occurs earlier than normal, allowing seeds and fruiting bodies to mature appropriately. If so, *SeedSetMonth[2]* will be overridden for that growing season and the code used to process seed maturation and seed drop will be invoked.

3.4.4 Reduction in Growth from High Temperatures

During the growing season for a plant species, code will be invoked to check whether daily maximum air temperatures are sufficiently high to limit growth. This condition will be checked daily within the growing season.

If *MaxTempCount* exceeds *MaxTempWindow*, then potential production (*PotProd*, see Coldren et al. 2011 for details) will be proportionally scaled downward based on *MaxTempCount*, relative to the length of the respective month. This approach will allow some growth if *MaxTempCount* is less than the number of days in that month.

3.4.5 Tissue Loss from Late Spring Freezes

Late spring freezes can cause tissue loss, particularly if a species has already broken dormancy. Those new tissues are tender and more susceptible to freezing conditions, and can include buds, stems, shoots, leaves, and roots (Malmqvist et al. 2018). After a species has greened-out in the model, daily *MinAirTemp* will be monitored and if it drops below freezing (0ºC), some amount of new growth will be lost. These losses will include leaves, stems, fine roots, seedling shoots, and seedling roots. The amount of loss will depend on the length of time that temperatures fall below freezing, as well as which soil layers are impacted. For soil layers with temperatures below freezing, losses will be 33% loss of new growth for one day, 67% loss for two days, and 100% loss for three days, as well as which soil layers.

3.4.6 Tissue Loss from Early Fall Frosts

Early Fall frosts can also cause tissue loss, as with late Spring freezes. The amount of loss will be 10% per day that *MinAirTemp* drops below freezing. Tissues impacted will be leaves, fruiting bodies, fine roots, seedling shoots, and seedling roots.

3.4.7 Decomposition Rate

Rates of soil microbial activity are also impacted by soil temperature. Pietikainen et al. (2005) found maximum growth rates of both fungi and bacteria at 25-30ºC, with somewhat linear declines at temperatures both above and below.

Decomposition in EDYS occurs daily, so decomposition rates will be modified as follows:

- at soil temperature of 0ºC and below,
- Linear increase of rate from 0.0-1.0 up to 25ºC,
- Maximum at 25-30ºC, and
- Linear decline from 1.0 at 30ºC down to 0.0 at 45ºC and above.

3.4.8 Snow Melt Rate

In EDYS, snow melt rate is currently set to a constant value that does not vary during a simulation. However, temperature is known to impact the rate at which snow melts, but it is a complex relationship. Two approaches for simulating snow melt rate have been devised (USDA 2004). The first is an energy balance approach that is computationally intensive, and realistically beyond the needs of EDYS at this time. The second is the degree-day method that uses the following equation:

$$M = C_m(T_{air} - T_{base}) \tag{12}$$

Where:

M is snow melt rate (mm/day),
C_m is degree-day coefficient (mm/degree-day C),
T_{air} is mean daily air temperature, and
T_{base} is base temperature (typically 0°C).

Values for C_m range from 1.6 to 6.0 mm/degree-day C, and a value of 2.74 mm/degree-day C is often used when site-specific data are lacking.

In EDYS, snow melt rate will be modified to match the degree-day method, using the average value of 2.74 mm/degree-day C for C_m.

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Appendix

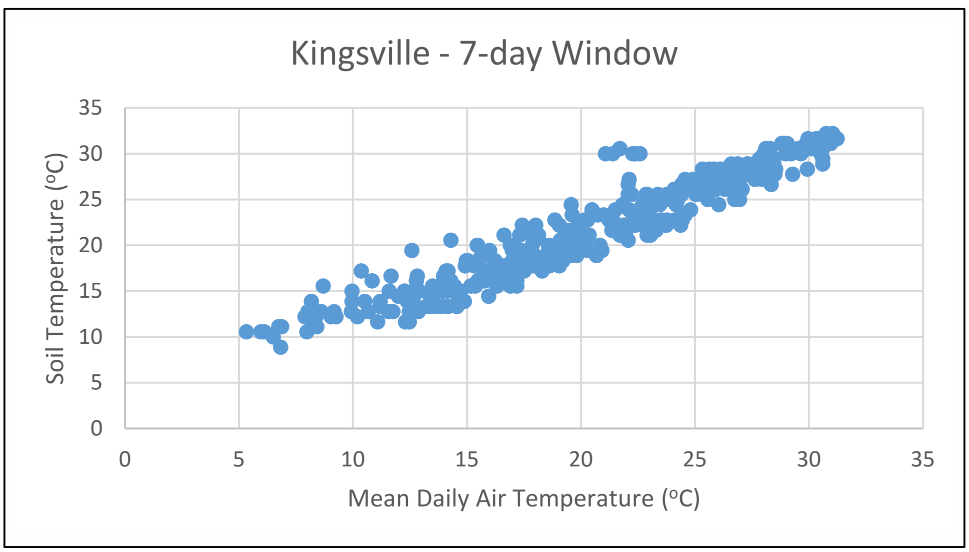
Below are examples of Air Temperature-Soil Temperature linear regressions from 5 sites in Texas. Data are from NRCS SCAN sampling stations. All regressions use recorded soil temperature at 4 inch depths except Port Aransas with soil temperature probes located at 10 cm depth. The independent variable for each regression is a sliding window of mean air temperature for a previous number of days. Shown below are regressions for 7-day, 11-day, and 14-day sliding windows. All sliding windows include the current day's observations. For example, a 7-day sliding window on July 7 includes 1-7 July.

1. Kingsville

A. 7-day Sliding Window:

$$T_{soil} = 0.8923T_{air} + 3.5861 \qquad \text{(A-1)}$$

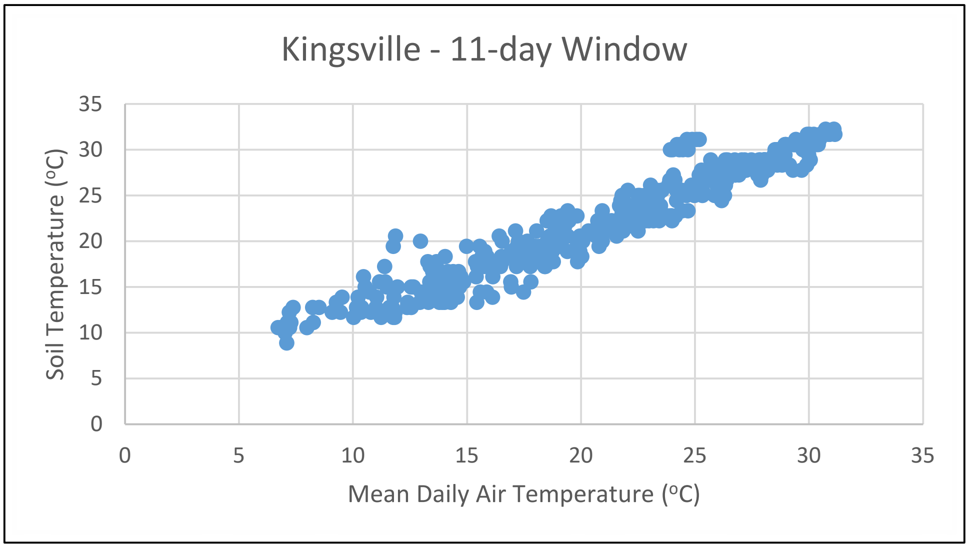
$$r^2 = 0.9182$$



B. 11-day Sliding Window:

$$T_{soil} = 0.9105T_{air} + 3.1737 \quad \text{(A-2)}$$

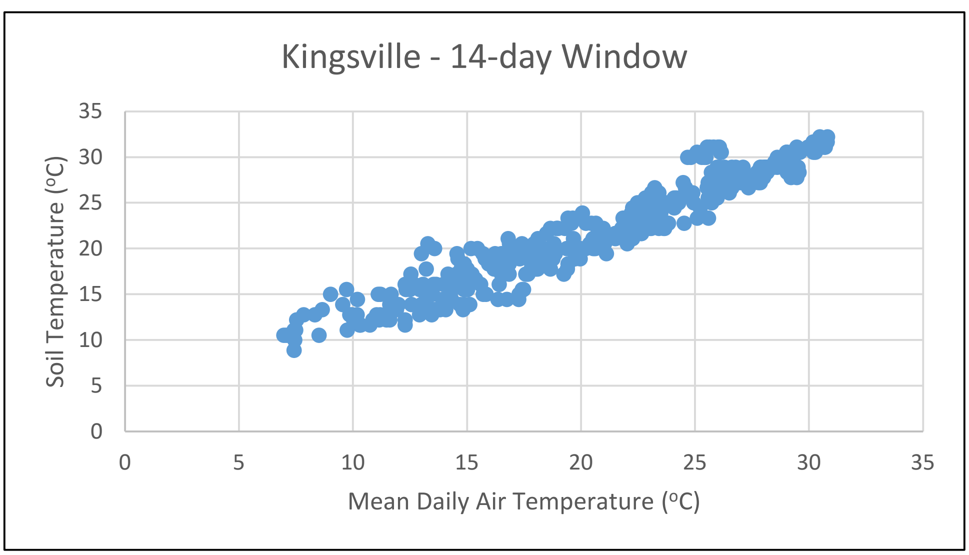
$$r^2 = 0.9247$$



C. 14-day Sliding Window:

$$T_{soil} = 0.9191T_{air} + 2.9813 \quad \text{(A-3)}$$

$$r^2 = 0.9275$$

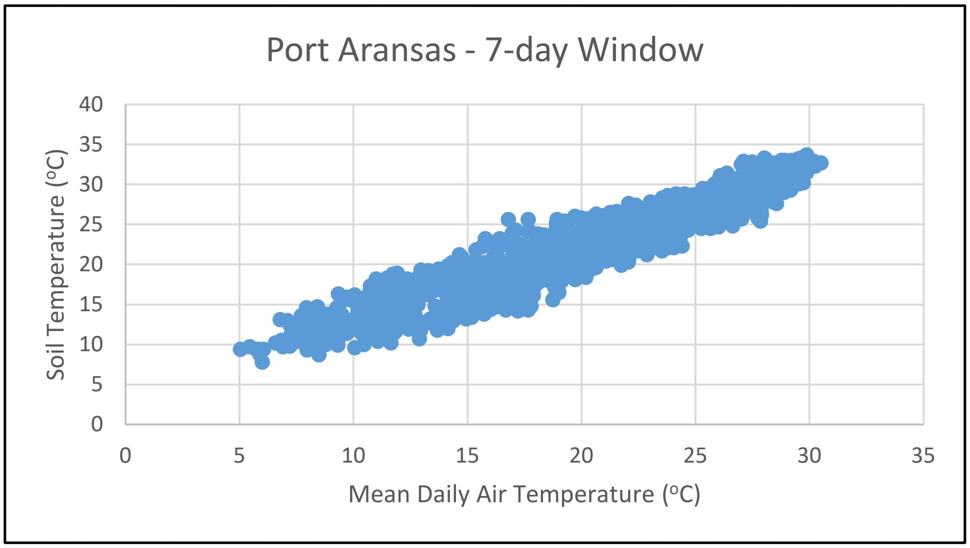


2. Port Aransas

A. 7-day Sliding Window:

$$T_{soil} = 0.9374T_{air} + 3.5689 \quad \text{(A-4)}$$

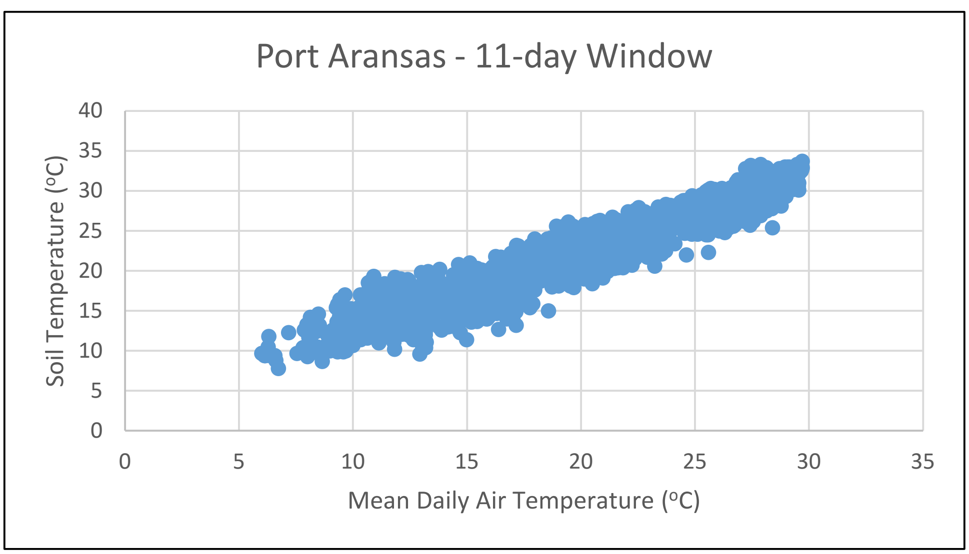
$$r^2 = 0.9162$$



B. 11-day Sliding Window:

$$T_{soil} = 0.9528T_{air} + 3.2483 \quad \text{(A-5)}$$

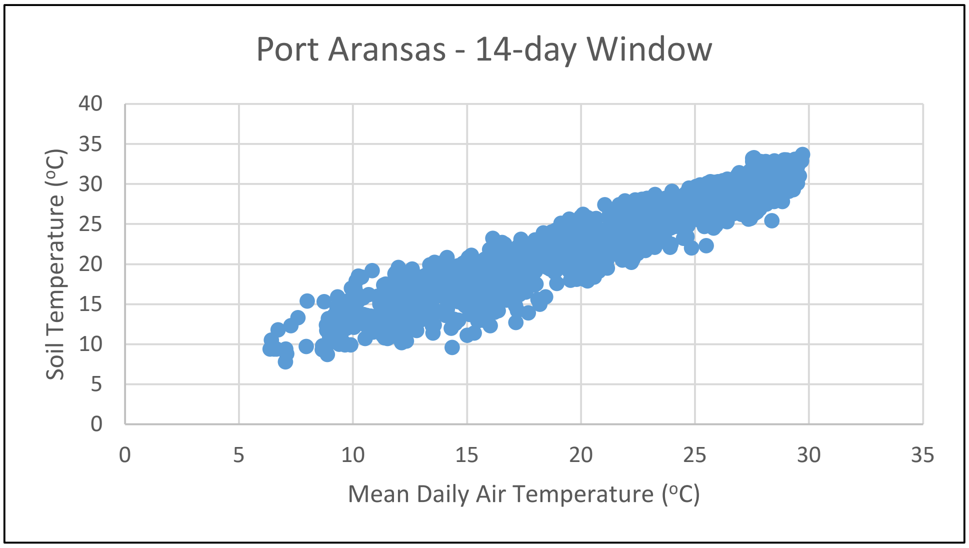
$$r^2 = 0.9081$$



C. 14-day Sliding Window:

$$T_{soil} = 0.9576T_{air} + 3.1580 \quad \text{(A-6)}$$

$$r^2 = 0.9047$$

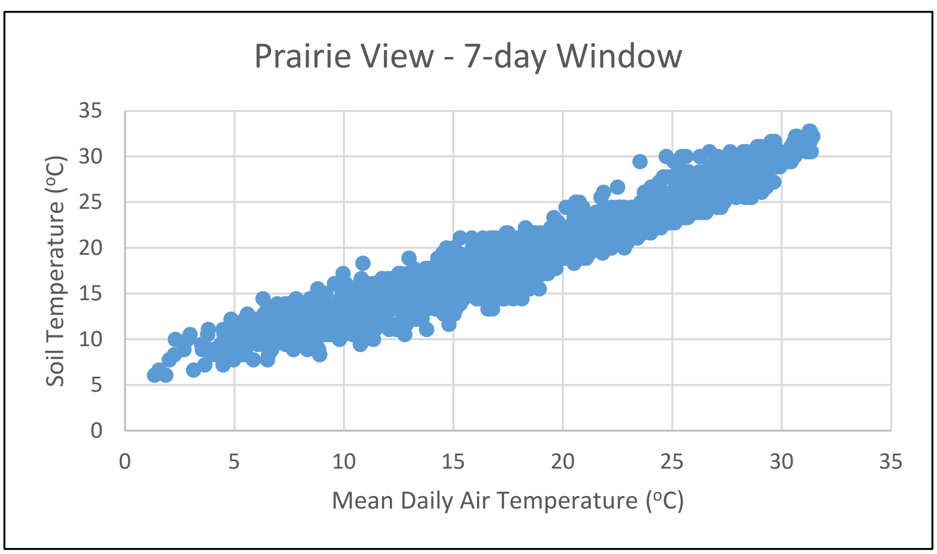


3. Prairie View

A. 7-day Sliding Window:

$$T_{soil} = 0.8063T_{air} + 4.6584 \quad \text{(A-7)}$$

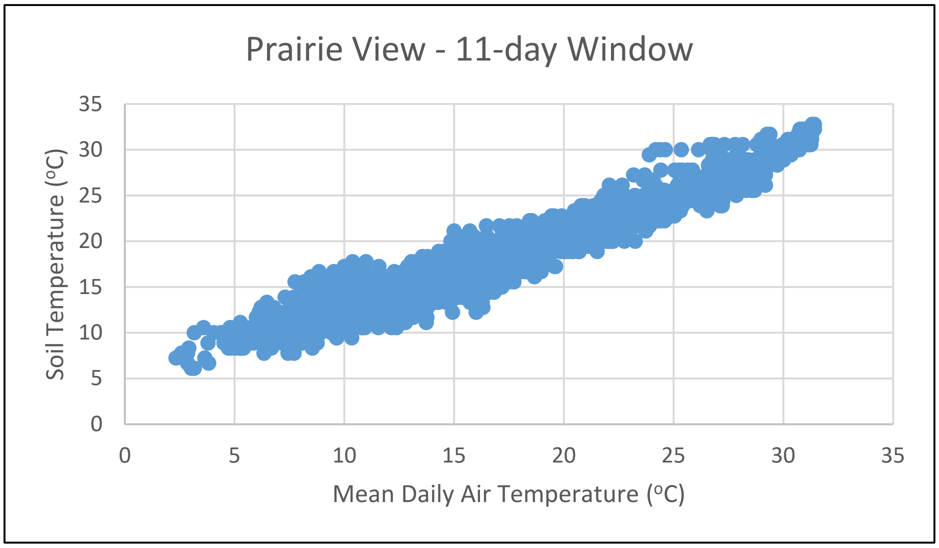
$$r^2 = 0.9354$$



B. 11-day Sliding Window:

$$T_{soil} = 0.8201T_{air} + 4.3941 \quad \text{(A-8)}$$

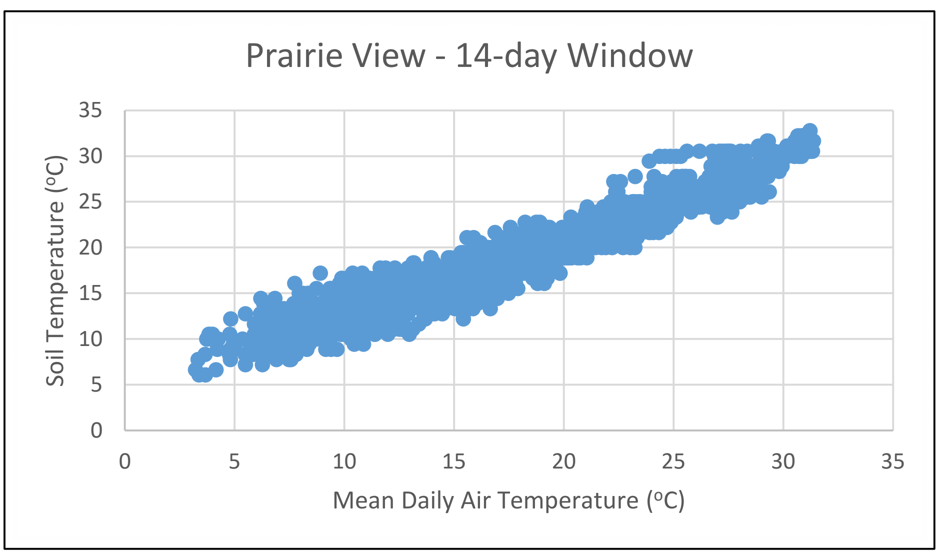
$$r^2 = 0.9326$$



C. 14-day Sliding Window:

$$T_{soil} = 0.8258T_{air} + 4.2834 \quad \text{(A-9)}$$

$$r^2 = 0.9307$$

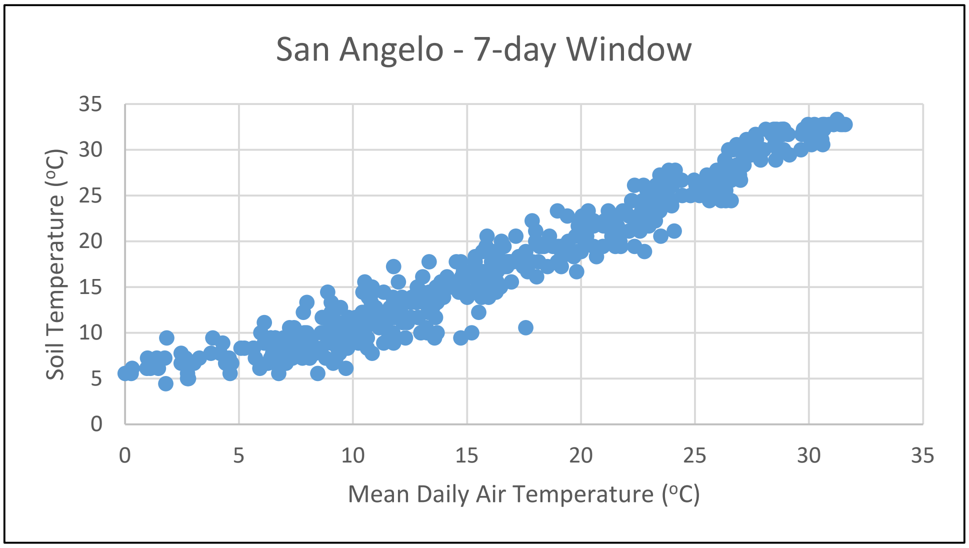


4. San Angelo

A. 7-day Sliding Window:

$$T_{soil} = 0.9692T_{air} + 1.5865 \quad \text{(A-10)}$$

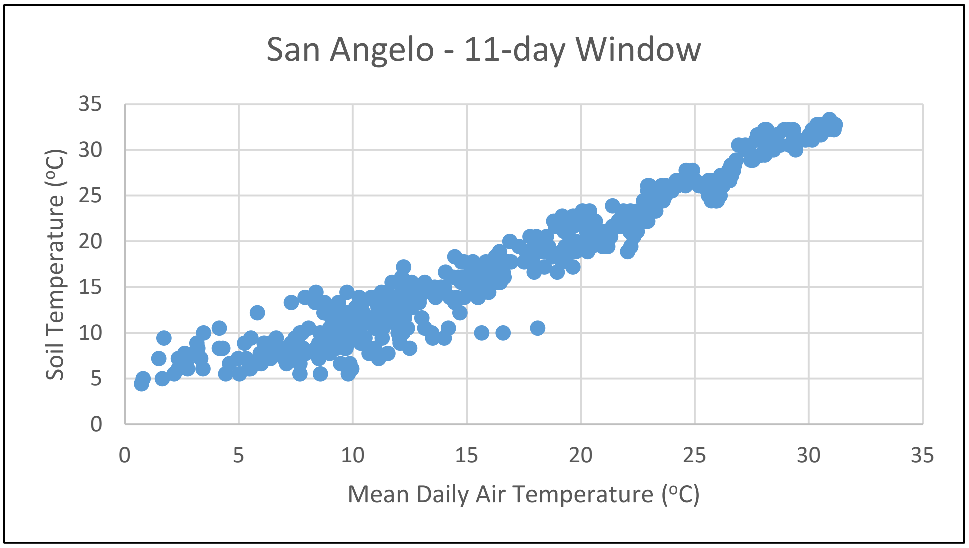
$$r^2 = 0.9418$$



B. 11-day Sliding Window:

$$T_{soil} = 0.9841T_{air} + 1.2868 \quad \text{(A-11)}$$

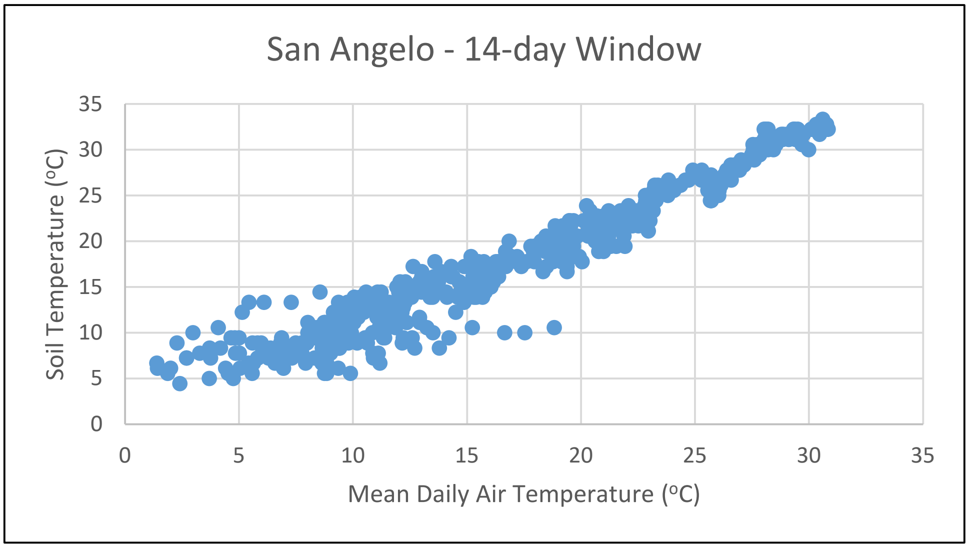
$$r^2 = 0.9422$$



C. 14-day Sliding Window:

$$T_{soil} = 0.9892T_{air} + 1.1687 \quad \text{(A-12)}$$

$$r^2 = 0.9392$$

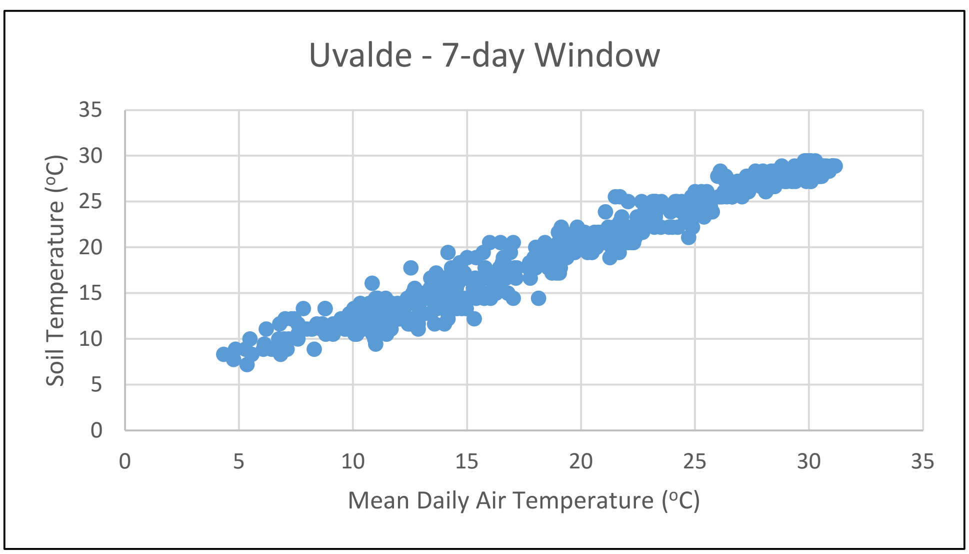


5. Uvalde

A. 7-day Sliding Window:

$$T_{soil} = 0.8408T_{air} + 3.4623 \quad \text{(A-13)}$$

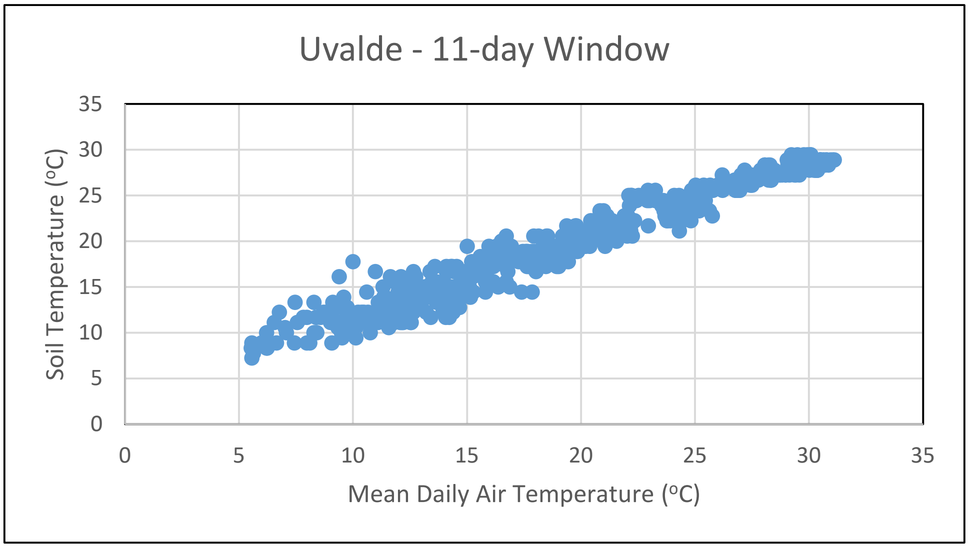
$$r^2 = 0.9529$$



B. 11-day Sliding Window:

$$T_{soil} = 0.8482T_{air} + 3.2710 \quad \text{(A-14)}$$

$$r^2 = 0.9507$$



C. 14-day Sliding Window:

$$T_{soil} = 0.8514T_{air} + 3.1803 \quad \text{(A-15)}$$

$$r^2 = 0.9486$$