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The Influence of Ambient Temperature on Green Roof R-values

Bryce Kevin Cox
Portland State University

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The Influence of Ambient Temperature on
Green Roof R-values

by

Bryce Kevin Cox

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Mechanical Engineering

Thesis Committee:

Graig Spolek, Chair
Derek Tretheway
Huafen Hu

Portland State University
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Abstract

Green roofs can be an effective and appealing way to increase the energy efficiency of buildings by providing active insulation. As plants in the green roof transpire, there is a reduction in heat flux that is conducted through the green roof. The R-value, or thermal resistance, of a green roof is an effective measurement of thermal performance because it can be easily included in building energy calculations applicable to many different buildings and situations. The purpose of this study was to determine if an increase in ambient temperature would cause an increase in the R-value of green roofs. Test trays containing green roof materials were tested in a low speed wind tunnel equipped to determine the R-value of the trays. Three different plant species were tested in this study, ryegrass (*Lolium perenne*), sedum (*Sedum hispanicum*), and vinca (*Vinca minor*). For each test in this study the relative humidity was maintained at 45% and the soil was saturated with water. The trays were tested at four different ambient temperatures, ranging from room temperature to 120°F. The resulting R-values for sedum ranged from 1.37 to 3.28 ft²h°F/BTU, for ryegrass the R-values ranged from 2.15 to 3.62 ft²h°F/BTU, and for vinca the R-values ranged from 3.15 to 5.19 ft²h°F/BTU. The average R-value for all the tests in this study was 3.20 ft²h°F/BTU. The results showed an increase in R-value with increasing temperature. Applying an ANOVA analysis to the data, the relationship between temperature and R-value for all three plant species was found to be statistically significant.

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Nomenclature

C – constant evaporative heat flux

h – effective heat transfer coefficient including convection and radiation

h_{fg} – latent heat of evaporation

h_m – convective coefficient for mass transfer

K – thermal conductivity

L – characteristic depth of green roof

m – evaporation flow rate

P_{sat} – saturation pressure

P_{wv} – partial pressure of water vapor

q – heat flux

q_{conv} – convective heat flux

q_{cond} – conductive heat flux

q_{evap} – heat flux due to evaporation

q_{total} – total heat flux

$R_{combined}$ – R-value for convection and evaporation

R_{cond} – R-value associated with conduction

R_{conv} – convective R-value

R_{ideal} – ideal gas constant

R_{total} – total R-value

T_{Cold1} – temperature of cold space air for tray 1

T_{Cold2} – temperature of cold space air for tray 2

T_{Hot1} – temperature of hot space air for tray 1

T_{Hot2} – temperature of hot space air for tray 2

T_{C} – temperature of cold space

T_{S} – temperature of green roof surface

T_{∞} - ambient temperature

V_{∞} - free stream velocity

φ_{∞} - relative humidity of free stream

ρ – density

ρ_{wv} – water vapor density

Chapter 1 Background

Green Roof Benefits

While green roofs, also called vegetated roofs, have been around for a long time, their popularity has increased greatly in the last few years. The roofs of the Multnomah County Central Library in Portland, Oregon, (see Figure 1.1) and the Mountain Equipment Co-op located in Toronto, Ontario (see Figure 1.2) are just two examples of green roofs that have been installed in recent years (Oregon Department of Environmental Quality, 2010; Jespersen, 2006). This new interest in green roofs has come from the greater understanding of the many ways that green roofs can benefit buildings and their surrounding environment.

Figure 1.1 Portland Central Library Roof

Figure 1.2 Mountain Equipment Co-op Building

Green roofs are helpful in reducing and controlling storm water runoff in urban areas. Runoff is a critical issue in urban environments because the impervious surfaces like concrete buildings and cement roads do not allow rainwater to be absorbed into the ground, but instead cause it to be rapidly channeled into waterways. This can cause flooding, erosion and other problems (Stone, 2004). Mentens et al. (2006) conducted a survey of published green roof data on water runoff and concluded that an extensive green roof with median soil depth of 100mm can reduce annual runoff by 45%. VanWoert et al. (2005) performed tests on a conventional roof with gravel ballast, a green roof with plants, and a third roof that was a green roof without any plants. The green

roofs, with and without vegetation, retained significantly more rainwater than conventional roofs.

Urban heat island effect is an increase of ambient temperature in urbanized areas due to artificial materials in the urban environment retaining more heat than the naturally occurring surroundings. This increases energy demands of buildings by requiring the air conditioning system to work harder to overcome the increased temperatures. This effect can also have harmful effects on human health. Alexandria and Jones (2008) created a model of an urban environment to examine the effects of vegetated roof and walls on ambient temperature. They found that a reduction of up to 11°C could be achieved. This means that green roofs can be a valuable tool in combating the urban heat island effect. The main cause of the decreased roof temperature is evaporation of water in the soil and transpiration by green roof plants. This reduction in temperature reduces the heat flux into buildings and in this way green roofs can be active insulation. This phenomenon is discussed more thoroughly in Chapter 2.

Another reason green roofs are being used in buildings is to improve aesthetics. The vegetation in a green roof can be a refreshing contrast to typical construction materials. Flowering plants can be used to add color and variety. The Steinhaus hotel in Austria, pictured in Figure 1.3, is an example of using local plants to help the building fit in with the natural landscape (Oberinger, 2009).

Green roofs can also improve aesthetics by reducing indoor noise pollution. Green roofs were included in a numerical model of traffic noise propagation. The results showed that green roofs can significantly reduce the amount of noise from traffic that enters a building (Vanrenterghem and Botteldooren 2009).

Figure 1.3 The Steinhaus Hotel

Green Roof Composition

There are two types of green roofs that are commonly used, extensive and intensive. Extensive green roofs are also called ecoroofs. Figure 1.4 shows the layers that makeup an ecoroof. It consists of a growing medium with low maintenance plants like grass or other ground cover that do not require irrigation. Under the growing medium is a drainage area, a root barrier, and a waterproof membrane which lies on top of the structural roof material. An intensive green roof is similar in makeup to an ecoroof but it is designed with a larger growing medium for larger plants like trees and shrubs. Intensive green roofs require more maintenance and are more expensive.

Figure 1.4 Green Roof Makeup

Chapter 2 Heat Transfer in Green Roofs

During summer conditions a green roof behaves as active insulation on a building. This chapter outlines a model used to approximate the thermal behavior of green roofs in order to better understand and predict green roof performance.

Model Development

Figure 2.1 shows a simple representation of the heat flux associated with a green roof. The term q_{conv} represents both the radiation and convection on the green roof. The latent heat that is removed from the roof by evapotranspiration is represented by q_{evap} . The conduction through the green roof is represented by q_{cond} .

Figure 2.1 Green Roof Heat Transfer

When steady state conditions are considered the heat fluxes are related by:

$$q_{\text{cond}} = q_{\text{conv}} - q_{\text{evap}} \quad (2.1)$$

The following equations are used to represent q_{cond} , q_{evap} , and q_{conv} :

$$q_{\text{cond}} = K \frac{(T_s - T_c)}{L} \quad (2.2)$$

$$q_{\text{evap}} = m \cdot h_{\text{fg}} |_{T_s} \quad (2.3)$$

$$q_{\text{conv}} = h(T_{\infty} - T_s) \quad (2.4)$$

The equation for the mass flow rate of water into the ambient air is:

$$m = h_m (\rho_{\text{wv } T_s} - \rho_{\text{wv } \infty}) \quad (2.5)$$

If the water vapor is treated as an ideal gas and it is assumed that the surface of the green roof is saturated, then the partial density of water at the surface is equal to the saturation pressure at the surface temperature.

$$\rho = \frac{P}{R_{\text{ideal}} T} \quad (2.6)$$

$$P_{\text{wv } T_s} = P_{\text{sat}} |_{T_s} \quad (2.7)$$

The partial density of the water vapor in the ambient air can also be found by using the ideal gas assumption and the definition of relative humidity.

$$P_{\text{wv } \infty} = \phi_{\infty} P_{\text{sat}} |_{T_{\infty}} \quad (2.8)$$

Substituting in the equation for mass flow and the partial pressures in the equation for q_{evap} gives:

$$q_{\text{evap}} = \frac{h_m}{R_{\text{ideal}} T_s} (P_{\text{wv } T_s} - \phi_{\infty} P_{\text{sat}} |_{T_{\infty}}) h_{\text{fg}} \quad (2.9)$$

The steady state heat flux equation becomes:

$$K \frac{T_s - T_c}{L} = h(T_{\infty} - T_s) - \frac{h_m}{R_i T_s} (P_{\text{wv } T_s} - \phi_{\infty} P_{\text{sat}} |_{T_{\infty}}) h_{\text{fg}} \quad (2.10)$$

Examination of the Model

In order to examine the validity of the model several cases were considered and the effects on the surface temperature T_s were examined. The case of zero evaporation was considered first, this case represents a standard roof. The equation for this case reduces to:

$$K \frac{T_s - T_c}{L} = h(T_\infty - T_s) \quad (2.11)$$

Solving for the surface temperature:

$$T_s = \frac{KT_c + hLT_\infty}{hL + K} \quad (2.12)$$

If the effective heat transfer coefficient was reduced to zero, T_s would be equal to T_c .

This is a reasonable result as conduction from the cold space to the surface would be the only heat transfer present. This would cause the surface temperature to be equal to the cold temperature when steady state was reached. If h were increased to infinity, then T_s would approach T_∞ . The convection would greatly dominate the conduction in this case, which would indeed cause T_s to approach T_∞ .

The next case considered included evaporation. For the moment, evaporation is to be assumed to be a constant C , in order to determine its influence on the heat transfer. By including the constant evaporation equation 2.11 becomes:

$$K \frac{T_s - T_c}{L} = h(T_\infty - T_s) - C \quad (2.13)$$

After solving for surface temperature it becomes:

$$T_s = \frac{KT_C + hLT_\infty - CL}{hL + K} \quad (2.14)$$

By comparing equation 2.13 to equation 2.11 for surface temperature with zero evaporation ($C = 0$) it can be seen that the value of T_s with evaporation will always be lower than the value of T_s without evaporation. This is consistent with physical behavior because evaporation will never increase the ambient temperature but it may cause it to decrease.

From equation 2.9 it can be seen that the evaporation is not constant. It is dependent on multiple variables but the main driving force comes from the difference in water vapor pressure between the free stream and the surface. As the difference between the two pressures increases, the evaporation rate increases.

$$q_{\text{evap}} = \frac{h_m}{R_{\text{ideal}} T_s} (P_{\text{wv}T_s} - \phi_\infty P_{\text{sat}}|_{T_\infty}) h_{\text{fg}} \quad (2.9)$$

Consider two different cases of an increasing ambient temperature, T_∞ , either constant absolute humidity or constant relative humidity in the ambient air. As the ambient temperature rises, the surface temperature will increase linearly and this will cause $P_{\text{wv}T_s}$ to increase exponentially. If the absolute humidity is held constant while the ambient temperature rises then $\phi_\infty P_{\text{sat}}$ will remain constant while $P_{\text{wv}T_s}$ increases at a constant rate. This will cause the rate of evaporation to increase greatly. In the second case, if relative humidity is maintained constant as the ambient air temperature increases then $\phi_\infty P_{\text{sat}}$ will increase along with $P_{\text{wv}T_s}$. It is not immediately obvious what will happen to the evaporation rate when both pressure values are increasing. This comparison will be looked at in more detail in Chapter 4.

Simplifying the Model

In heat transfer models it is very common to simplify complex problems by comparing the heat transfer to an electric circuit. In this analogy, the effect of each material is treated as a thermal resistance, called an R-value. A high thermal resistance causes low heat flux, just as a component of high resistance decreases the current flowing in a circuit. The equation for the thermal resistance for conduction is:

$$R_{\text{cond}} = \frac{L}{K} \quad (2.15)$$

and for convection:

$$R_{\text{conv}} = \frac{1}{h} \quad (2.16)$$

Substituting these R-values into the equations for q_{cond} (2.2) and q_{conv} (2.4) gives:

$$q_{\text{cond}} = \frac{(T_s - T_c)}{R_{\text{cond}}} \quad (2.17)$$

$$q_{\text{conv}} = \frac{(T_{\infty} - T_s)}{R_{\text{conv}}} \quad (2.18)$$

While using R-values in these equations does simplify them slightly, the usefulness of the R-value is that it greatly simplifies combined modes of heat transfer. For example, in the green roof model there is heat transfer by convection and heat transfer by evaporative cooling that both occur between the ambient air and the surface of the green roof. These two modes of heat transfer may be represented by a single thermal resistance in the following equation:

$$R_{\text{combined}} = \frac{(T_{\infty} - T_s)}{q_{\text{conv}} - q_{\text{evap}}} \quad (2.19)$$

Figure 2.2 shows the complete thermal circuit for the green roof with the combined R-value for convection and evaporation and a separate R-value for conduction.

Figure 2.2 Green Roof Thermal Circuit

A total R-value for several thermal resistances in series can be calculated by summing all of the thermal resistances.

$$R_{\text{total}} = \sum R_i \quad (2.20)$$

In this way an R-value that represents all of the heat transfer through the green roof can be easily determined and used to relate the total heat transfer to the two extreme temperatures, T_∞ and T_c . Since q_{cond} represents the heat transfer into the cooled space corresponding to the overall effective R-value, then the green roof R-value is defined as:

$$R = \frac{(T_\infty - T_c)}{q_{\text{cond}}} \quad (2.21)$$

This R-value is a very compact way to describe the total heat transfer of the system. This is why R-values are used so often in heat transfer. It is especially useful in building envelope calculations. Walls and roofs are an important part of a building envelope and they are made up of many layers of different materials each with different heat transfer

properties, like sheet rock, insulation etc. The idea of a total R-value greatly simplifies the calculation of the heat transfer through these composite walls and roofs. For this same reason the R-value of a green roof can be a useful way to quantify its thermal performance. If an R-value can be obtained that encompasses the complex behavior of the green roof then it can be easily included in the building envelope calculations for the heating and cooling loads. These loads could then be used to determine the energy performance of the building. The energy savings of the green roof can then be determined by comparing results of the calculations with and without the green roof. This information would be very useful in designing a building that includes a green roof.

Chapter 3 Review of Current Research

There have been multiple studies done to determine how green roofs affect the thermal performance of a building. Some of the factors that are investigated include plant type, soil depth, local climate, and soil moisture levels. As more is learned about green roofs the quality of green roof models will improve, allowing for more informed design decisions and more accurate energy models. The following is a survey of currently available green roof data.

In 2003 Liu and Baskaran published a study in which they measured temperature, heat flux, solar reflectance, soil moisture content, weather conditions, and storm runoff on a green roof in Ottawa, Ontario. Half of the roof was covered by bituminous roofing for use as a reference, while the other half was covered with an extensive green roof with a median soil depth of 150 mm. The green roof was planted with wildflowers the first year and Kentucky bluegrass the second year. Data was taken November 2000 through September 2002. The results showed that the green roof reduced the roof surface temperature significantly compared to the reference roof with the temperature of the reference roof reaching 40°C or greater on 601 days of the 943 days examined. The green roof surface temperature never reached 40°C during the study. The green roof also reduced heat gain in summer by 95% and reduced heat loss in winter by 26%.

A similar study was performed at the University of Central Florida (Sonne, 2006). The study was based on a building with a conventional light colored roof on one half and an extensive green roof planted with grasses and small plants native to Florida on the other half. The soil depth ranged from 150 to 200 mm. During the summer of 2005, specifically July 4 to September 1, the average maximum temperature of the conventional

roof was 54°C contrasted to 33°C average maximum for the green roof. The heat flux was estimated based on the measured temperatures and approximated R-values for the insulation. At the point of lowest insulation the heat flux for the conventional roof was estimated to be 0.41 BTU/ft²h. For the green roof the heat flux was 0.294 BTU/ft²h, overall reduction of 18%.

Pearlmutter and Rosenfeld (2008) studied the thermal performance of 160 mm deep bare soil that was placed over cement cells designed to represent buildings. They compared dry bare soil to soil that is wetted and shaded by either lightweight gravel or mesh placed over the soil. The dry soil had a maximum surface temperature of approximately 40°C and the wetted soil was 30°C while they were under hot and dry test conditions. The maximum temperature for the wetted soil with gravel shading and the wetted soil with mesh shading were both near 25°C. The authors concluded that these strategies are useful for cooling buildings located in hot, dry climates.

Green roof thermal performance in a wet and mild climate was investigated by Spolek (2008) in Portland, Oregon. A green roof was installed on the roof of a student housing building at Portland State University while a small portion of the roof was reserved for a rock ballast roof to be used for reference measurements. During typical summer conditions in Portland the green roof greatly reduced variations in surface temperature compared to the rock ballast surface and the outdoor ambient temperatures. The maximum and minimum surface temperatures for the green roof were 4-6 hours out of phase with the rock ballast surface and ambient temperature extremes. The data from winter and summer 2006 show that in winter there was a 13% reduction in heat flux and

in summer there was a 72% reduction in heat flux. This shows that even in mild climate conditions a green roof can be effective in reducing heat flux.

Bell and Spolek (2009) designed a wind tunnel specifically to determine the R-value of the green roofs when exposed to varying climatic conditions. The wind tunnel passed warm air over the top of the test trays and cold air across the bottom of the trays. The R-values were calculated by taking temperature measurements both above and below the trays and by measuring the heat flux going through the bottom of the trays. Sheet metal was folded to make trays that contained a drainage mat, root barrier, soil, and plants. Trays with vinca, ryegrass, clover, sedum and bare soil were tested. The warm air temperature, soil moisture content and soil depth were varied. The data listed in Table 3.1 shows that when the data from each test were averaged ryegrass resulted in the highest R-value and bare soil resulted in the lowest. Increasing the soil depth in trays without plants resulted in slightly higher R-values. The effect of varying soil depth for bare soil was a slight increase in R-value when the soil depth was increased. When the soil depth was varied in trays with plants there was no significant effect on the R-value. When the ambient air temperature was increased with constant absolute humidity, there was an increase in the resulting R-value. The authors noted that this is likely due to increased evapotranspiration. As soil moisture was increased the bare soil showed a small increase in R-value, while the vegetated trays showed a reduction in R-value.

Table 3.1 R-values from Bell and Spolek (2008)

Plant	Vinca	Clover	Ryegrass	Sedum	Bare Soil	Average
R-value (ft ² h°F/BTU)	2.22	2.34	2.78	1.76	1.58	2.14

Simmons et al. (2009) created several test cells each consisting of a metal frame platform that was fitted with substantial insulation. Each of the platforms was topped with one of three different types of roofs: a green roof planted with native plants, a black roof, and a white reflective roof. The green roofs were constructed with variations in substrate makeup, filter fabric, and drainage layer type to determine if these variables affected roof performance. These cells were placed in an open field in Austin, Texas. All of the green roof platforms showed reduction in temperature amplitude as well as a 1-3 hour shift in peak temperature, similar to the findings of Spolek (2008). On a warm day when the ambient temperature reached 33°C the black roof platforms reached 68°C, the white roof platforms reached 42°C and the green roof maximum temperatures ranged from 31-38°C. The different green roof compositions resulted in temperature distributions with a range in temperature as large as 15°C.

Teemusk and Mander (2009) examined the thermal performance of an extensive green roof in Tartu, Estonia. Their test roof consisted of a 100 mm substrate layer with 45% of the substrate layer covered by vegetation. The plants were made up of mostly sedum and a few other small plants. A reference roof of bituminous material located near the green roof was used. Temperature measurements were taken between June 2004 and April 2005 for both roofs. During the summer months the green roof surface temperature maximums were actually higher than those of the reference roof, but the temperatures inside the substrate layer were lower and fluctuated with much smaller amplitude than the reference roof. This indicates that even though the green roof surface temperatures were higher, it still improved the thermal performance of the roof because the actual roof membrane temperatures were lower. During the shoulder seasons the

green roof reduced the roof membrane's exposure to rapid temperature and rapid freezing. The authors also concluded that a green roof with a higher percentage of plant coverage would have lower surface temperatures in the summer and improved thermal performance.

Mathematical models of green roofs have been used to predict roof behavior and to test parameters that are difficult or even impossible to measure in actual roofs. Del Barrio (1998) created a model from basic differential equations for heat transfer based on three distinct regions: the structural roof material, the substrate and the canopy made by the vegetation. A sensitivity analysis of a green roof using weather data from January to October, 1982 in Athens, Greece was performed to determine the most important green roof parameters to reduce heat flux into the building during summer conditions. The result of this analysis shows that choosing a plant with leaves that cover a large amount of the green roof area is ideal as it reduces the solar radiation transmitted to the soil. Also a light soil should be used because it reduces the weight and thermal conductivity of the roof. Del Barrio concluded that the green roof did not actually cool the building. It only acted as a very good insulator. Another conclusion of the author is that it may be inappropriate to design a roof based solely on summer performance because it might result in significant problems during the winter season.

Another mathematical model for green roof performance was developed by Eumorfopoulou and Aravantinos (1998). Their model examined green roofs with low, medium and high plant heights on a roof with insulation and a roof without insulation. The results showed that for both cases, with or without insulation, the green roof reduces

thermal losses by about 50% with the highest plant level providing the largest reduction in thermal losses.

Ondimu and Murase (2007) combined an inverse finite-element method with a neural network analysis to determine the effective thermal conductivity of a moss mat that is commonly used in green roofs in Japan. The mat consisted of a moss grown with cotton wool on PVC netting. The model determined the thermal conductivity of the moss mat to be up to 24 W/mK at 100% water content and decreased with decreasing water content. The authors concluded that this method can be used to determine the thermal conductivity of many bio-materials such as those used in green roofs. Once the thermal conductivity is known then the R value based on conduction can be calculated.

In Singapore, Wong et al. (2003) conducted a study that estimated the R-value of 3 types of plants and then used those values to calculate the green roof's effects on cooling load and annual energy consumption. The R-values were estimated using the known R-value for the bare roof and temperature measurements taken on the surface of the roof and inside the building. The temperature measurements were taken in November, 2001. Three plants were chosen each to represent a typical plant type, Ophiogon for turfing, Raphis palm for shrubs and Erythrina for trees. Table 3.2 summarizes the R-values for the three plant types including substrate, drainage and protective layers. Each plant type also had a unique substrate depth that influences the R-values. The substrate moisture content for these values was 40%.

Table 3.2 R-values from Wong et al. (2003)

	Substrate Depth (mm)	R-value
		ft ² h°F/BTU
Ophiogon (turfing)	100	2.84
Raphis Palm (shrubs)	300	10.66
Erythrina (trees)	700	6.19

The data were then used in a model of a 5-story building that was analyzed using DOE-2 building energy simulation software. The addition of the green roofs resulted in a reduction of annual energy usage ranging from 1-15% and a reduction in cooling load of 17-79% with the shrubs achieving the maximum reductions.

Sailor (2008) created a software tool that uses DOE-2 based EnergyPlus to model green roof behavior. The software allows the user to input several variables important to green roof design and includes them in the building analysis. Results from the model were compared to data gathered from a green roof at the University of Florida and the model was able to accurately predict the green roof surface temperature. A sensitivity analysis was performed with the software examining high and low values of soil thickness, ratio of vegetation leaf area to ground area, and irrigation. The analysis was performed for two cities, Chicago, Illinois and Houston, Texas. Of all the tested parameters, the soil thickness had the largest effect on energy consumption. A thicker soil layer increases the insulation of the roof and helps both cooling loads during the summer and heating loads during the winter. This contrasts the findings of Bell and Spolek (2009). They found that for bare soil the increase in R-value with increasing soil depth was small and that increasing soil depth for vegetated roofs had no significant effect on R-value. Based on their findings soil depth should have little to no effect on the building loads.

Takakura et al. (2000) constructed multiple test cells with a 6 cm thick cement roof and 30 cm of air space underneath. Each of the sides was insulated with polystyrene. Four cells were made, one roof was left bare, one had 140mm of bare soil, one had turf planted in 140mm of soil and the last had ivy planted also in the same amount of soil. Thermocouples were placed on either side of the concrete roof, in the soil, on the soil surface and in the ivy canopy. Temperature measurements were taken for only 3 days during the summer of 1993. The measurements indicated that the leaf area and the evapotranspiration rate of the plants have a large effect on the heat transfer into the cells. A one-dimensional transient mathematical model was created with this study. The model was built by splitting the green roof into multiple layers and creating an ordinary differential equation for each layer. Although the model included effects of evapotranspiration, it was not accurate at high transpiration rates. The authors concluded that a more complex model of water movement through the soil, the plants and the atmosphere is necessary to improve the accuracy of this mathematical model of the test cells.

Niachou et al. (2001) investigated the thermal performance of a hotel located near Athens, Greece that was fitted with a green roof with various types of vegetation. Temperature data was taken from the unoccupied apartments during the summer of 2000. These temperature values were used along with material manufacturer's data to determine the U-value for the roof (which is the reciprocal of an R-value). The U-value was calculated for various points on the roof including where it was non-insulated, where there was moderate insulation and in locations where the roof was well insulated. Each of these cases was measured both with and without a green roof. The difference between

these values was used to calculate the average R-value of the green roof portion alone.

The values for the 3 cases are given in Table 3.3.

Table 3.3 R-values from Niachou et al. (2001)

	Green Roof R-value
	(ft ² h°F/BTU)
Non-insulated	2.545
Moderate Ins.	2.588
Well ins.	2.162

The calculated U-values were used in simulations performed with TRNSYS software to estimate the impact of the green roofs on annual energy consumption of the building.

The green roofs resulted in an annual reduction of up to 44% in heating and cooling energy use for the non-insulated section but the reduction decreases as the building insulation increases with an annual reduction of only 2% for the well insulated case.

Chapter 4 Project Description

The studies addressed in the previous chapter have repeatedly shown the thermal benefits of green roofs. Green roofs can reduce the maximum surface temperature of the roof. They reduce heat flux through the roof and reduce the energy consumption of buildings. What these studies lack are results that can be easily quantified. In most cases the values for temperature reduction or energy usage are unique to the building in the study. The data may not be useful in the design or analysis of a different building in a different location. The R-value of a green roof is important because it is a value that can be used in design settings and can be applied to many different buildings and situations.

Some studies do include information on R-values, or enough information to easily obtain them, however the current knowledge base is not sufficient (Wong et al. 2003, Niachou et al. 2001). The R-value of a green roof is determined by plant behavior which is dependent on plant type, age, health and many ambient properties like temperature, relative humidity and solar radiation. Each of these needs to be examined in order to better understand and predict green roof performance. This study examines the effect of increasing ambient air temperature with constant relative humidity.

Chapter 2 briefly examined increasing the ambient air temperature with either constant absolute humidity or constant relative humidity and its effect on the evaporation heat transfer. As can be seen in equation 2.9 the difference between the water vapor pressure at the roof surface and the pressure in the ambient air is the main driving force in evaporation. As the ambient temperature rises, the surface temperature will increase linearly and this will cause P_{wvT_s} to increase exponentially. If the absolute humidity is held constant while the ambient temperature raises then $\varphi_{\infty} P_{sat}$ will remain constant while P_{wvT_s}

increases at a constant rate. This will cause the rate of evaporation to increase greatly. In the second case, if relative humidity is maintained constant as the ambient air temperature increases then $\phi_{\infty} P_{\text{sat}}$ will increase as well. It is not immediately obvious what will happen to the evaporation rate when both pressure values are increasing.

$$q_{\text{evap}} = \frac{h_m}{R_{\text{ideal}} T_s} (P_{\text{wv}T_s} - \phi_{\infty} P_{\text{sat}} |_{T_{\infty}}) h_{\text{fg}} \quad (2.9)$$

Figure 4.1 is a psychrometric chart that illustrates the process of increasing the ambient air temperature with a constant absolute humidity. The gray line is the path of increasing ambient air temperature. Starting from the point of 75°F and 45% relative humidity the red line follows the wet bulb line until saturation is reached. The absolute humidity at this point is related to the water vapor pressure at the roof surface. The black line marks this humidity level. The difference in the absolute humidity of the ambient air and the roof surface is the distance between the black and gray lines. The second red line indicates what the surface humidity would be at an ambient air temperature of about 90°F. The second black line indicates the new absolute humidity of the surface. The distance between this black line and the gray line is much greater. This indicates that the driving force for evaporation is much greater as the ambient air temperature increases with constant absolute humidity.

Figure 4.1 Increasing Temperature with Constant Absolute Humidity

Figure 4.2 is a psychrometric chart illustrating the process of increasing the ambient temperature while maintaining a constant relative humidity. The gray path follows a line of constant relative humidity and represents the path of increasing ambient air temperature. The black lines in this case also represent the absolute humidity of the green roof surface. The horizontal red lines indicate the absolute humidity of the ambient air. The gap between the horizontal red lines and the black lines indicate the driving force for evaporation. There is almost no increase in the gap between the black and red lines as temperature is increased.

PSYCHROMETRIC
CHART
Normal Temperature
I-P Units
SEA LEVEL
BAROMETRIC PRESSURE: 29.921 in. HG

Figure 4.2 Increasing Temperature with Constant Relative Humidity

The purpose of this study is to determine how the R-value of a green roof changes as temperature increases while the relative humidity is maintained constant. If evaporation were to increase, the R-value for the green roof would increase because the heat flux into the roof would be reduced. According to the model, this is not likely to be the case. For this study the null hypothesis is that there will be no change in R-value due to the increasing temperature with constant relative humidity. The test hypothesis is that the plants will transpire at an increased rate with increasing temperature, even though the pressure gradient driving evaporation does not increase significantly. This will increase evaporative cooling which would increase the R-value of the roof.

Three types of plants were used in this study: ryegrass (*Lolium perenne*), sedum (*Sedum hispanicum*) and vinca (*Vinca minor*). The sedum, pictured in Figure 4.3 is one of the plants most commonly used in green roofs because it has low irrigation requirements for sustained growth (Jones and Liptan, 2008). This indicates that it transpires at a low rate. It was suspected that vinca and ryegrass would result in higher R-values than sedum because of sedum's low transpiration rate. The sedum does not grow very densely but it does have small leaves that provide some shading. This is helpful in blocking radiation, but air can flow under the leaves causing higher rates of convective heat transfer. As can be seen in Figure 4.4, ryegrass grows tall and dense, not allowing much air flow near the soil surface. This reduction in air flow near the soil surface likely reduces the heat transfer by convection and increases the R-value for the grass. A disadvantage is that it provides little shading compared to the other plants. The vinca, pictured in Figure 4.5, grows taller than the sedum and is spread out, allowing more air to flow under its leaves and stems. Vinca would likely have the most heat transfer by convection but it shades the soil better than the sedum and ryegrass.

Figure 4.3 Green Roof Sedum

Figure 4.4 Green Roof Ryegrass

Figure 4.5 Green Roof Vinca

Chapter 5 Test Procedure

Equipment

The tests for this study were performed in a low speed wind tunnel designed for thermal testing of green roof materials. Figure 5.1 shows a schematic of the wind tunnel. It is designed to test two trays containing green roof plants. The upper portion is designed to simulate summertime climate conditions over the trays. It is fitted with a heater and a humidifier in order to control temperature and humidity. The lower portion generates cooled air that is passed below the trays, simulating a cooled building space. Duct work separates the hot and cold spaces. Heat flux sensors are located under the green roof trays. The plant trays are placed in the heated space on a sheet metal shelf. Both the heated and cooled spaces have two thermocouples for air temperature measurement and the heated space also has two relative humidity sensors placed near the two thermocouples. A Plexiglas door provides access to the trays. Figure 5.2 is a photograph of the test apparatus.

Figure 5.1 Wind Tunnel Drawing

The plant trays for the wind tunnel were made of steel and were rectangular in shape. They measured 8.5" high with a 24"x 23.5" base. A Henry DB-50 liner that includes a drainage layer and a root barrier was used to line the trays. The substrate was made up of an approximately 150 mm (6 in) thick layer of ProGro extensive mix soil. Two trays of each plant were tested for replication. The approximate plant height for the ryegrass was 165 mm (6.5 in), for the vinca was 89 mm (3.5 in) and the sedum was 76 mm (3 in), each measured from the soil surface.

Figure 5.2 Photograph of Wind Tunnel

Table 5.1 outlines the hardware used in the testing. Thermocouples with a PVC coating were chosen to protect them from the soil and moisture. The thermocouples in the heating space were each covered with a radiation shield, shown in Figure 5.3, that was designed to let in air flow but block most of the radiation from the heating coils upstream. The thermocouples were all wired to thermocouple modules on a National Instruments DAQ chassis. The heat flux and relative humidity sensors were wired to a universal analog input that was located on the same chassis. The chassis was then connected to a Dell laptop via USB. Data was collected using LabVIEW Signal Express.

Table 5.1 Hardware List

Hardware	Company	Model Number	Type
Heater	Heatrex	545575	28 KW Electric Duct Heater
Heater Controller	Delta		DTB Series
Humidifier	DRISTEEM	VM99-16	Vapormist Electric 48 lb/hr capacity
Air Conditioner	LG	LWHD 1500ER	15000 BTU
Thermocouple	Omega	TC-PVC-T-24-180	T with PVC coating
Relative Humidity Sensor	Omega	HX71-V1	
Heat Flux Sensor	Vatell	BF03	Thermopile
DAQ	National Instruments	cDAQ-9172	USB Chassis
Digital Inputs	National Instruments	NI 9211	Thermocouple Module
Analog Inputs	National Instruments	NI 9219	Universal Analog Input
Computer	Dell	Latitude	Laptop

Figure 5.3 Radiation Shields

The top image is a side view of the thermocouples and relative humidity sensors. The bottom image is a view of the thermocouple inside the radiation shield.

Test Procedure

To control the moisture content of the soil for each test, the trays were watered excessively and all of the excess water was allowed to drain away so that the soil was initially quasi-saturated. This state was used because it was easy to reproduce and it allowed for plenty of water available for evaporation.

Four different set temperatures were tested: room temperature, 87°F, 103°F and 120°F. Each plant type was tested twice at each set temperature for replication. For all of these tests the air conditioner was set at its lowest temperature setting. The relative humidity setting was chosen based on two constraints, the ambient relative humidity of the laboratory and the output capacity of the humidifier. If the set temperature is increased while the humidifier is running at full capacity the relative humidity will decrease, so using a low value for relative humidity would allow for higher set temperatures. The relative humidity for the tests could not be below the relative humidity in the lab, so the minimum controllable relative humidity was found to be 45%. This is the value that was used for each test, but because the humidifier could not be run without monitoring, the humidity was not set to 45% until about two hours after each test had begun.

A single test consisted of room temperature trays being placed inside the test apparatus. The trays were then watered until there was a significant amount of water draining off the bottom of the trays. The warm ambient air temperature was then set at the desired level for that test and the air conditioner was turned on. Each test was done at a single ambient air temperature and the tests were performed in a random order.

Approximately two hours after the temperature was set the humidifier was turned on and the humidity set at the desired level.

The conditions remained constant after the humidifier was set until a steady state was reached. This was determined to occur when the heat flux and R-value remained constant for at least 45 minutes, which took approximately 4-8 hours to achieve. The last 2000 seconds (33 minutes) of data were used in calculating the results. Figure 5.4 is a set of plots from a sedum test with set temperature of 87°F that represents the testing process. The initial heat flux spikes as the temperature in the cooled space rapidly decreases. The magnitude of the heat flux then decreases as the base of the tray cools until a steady state temperature gradient is established through the soil bed. In the plot of relative humidity the sudden increase in relative humidity corresponds to the humidifier beginning to function. It is then adjusted to and held at the value of 45%. This specific test lasted approximately 6 hours.

The R-value of each tray was calculated using the temperatures from the thermocouples that were placed above and below the tray and the heat flux from the sensor underneath the tray. The equation for the average R-value is:

$$R = \frac{1}{2} \left(\frac{T_{\text{Hot1}} - T_{\text{Cold1}}}{q_1} + \frac{T_{\text{Hot2}} - T_{\text{Cold2}}}{q_2} \right) \quad (5.1)$$

Figure 5.4 Example Test Data

Chapter 6 Results and Discussion

In order to obtain the R-value for only the trays and the green roof materials inside, the thermal resistance for the test device due to convective, conductive and contact resistance was needed. This was found by running the apparatus without any test trays in the device. The value was found to be $0.71 \text{ ft}^2\text{h}^\circ\text{F}/\text{BTU}$. The thermal resistance was assumed to remain constant and was subtracted from of the resulting R-value for each test.

Only a single viable test was performed for vinca at the 103°F set temperature. All other temperatures were tested with replication for each plant. The final R-values are listed in Table 6.1 by plant type and set temperature. The raw test data is available in Appendix A.

Table 6.1 Measured R-values

	Set Temperature	Measured Temperature	R-value
	$^\circ\text{F}$	$^\circ\text{F}$	$\text{ft}^2\text{h}^\circ\text{F}/\text{BTU}$
Vinca	room temperature	81.2	3.15
	room temperature	82.0	3.45
	87	86.8	3.64
	87	86.8	4.49
	103	97.5	4.13
	120	107.2	4.76
	120	104.3	5.19
	Average:		4.12
Ryegrass	room temperature	78.2	2.15
	room temperature	82.0	2.77
	87	86.9	3.01
	87	87.4	2.42
	103	94.7	3.43
	103	95.6	3.78
	120	105.7	3.58
	120	107.1	3.62
	Average:		3.10

Sedum	Set Temperature	Measured	R-value
		Temperature	
	room temperature	83.1	1.93
	room temperature	81.8	3.07
	87	87.6	1.37
	87	87.6	1.79
	103	99.1	2.50
	103	99.5	2.10
	120	115.3	3.28
	120	111.6	2.91
Average:			2.37

Vinca had the highest average value of the three plants at 4.12 ft²h°F/BTU. The overall average for all tests was 3.2 ft²h°F/BTU. All of the R-values for the three plants in this study fall in the range of 1.37 to 5.19 ft²h°F/BTU. Table 6.2 is a list of the average R-values for published R-values and the results for this study. The work of Niachou (2001) and the work of Bell and Spolek (2009) are very similar in magnitude to the results of this study. The results from Wong et al. (2003) are larger in magnitude than the other studies. This is likely due to the intensive green roof used by Wong et al. as opposed to the extensive green roofs used in the other studies. The intensive green roof included larger plants and larger substrate depth. When the large amount of variability in these biological systems is considered, the results from this study align well with currently published data.

Table 6.2 Average R-values

Author:	Bell and Spolek (2009)	Wong (2003)	Niachou (2001)	This study
R (ft ² h°F/BTU):	2.14	6.56	2.43	3.20

Figure 6.1 is a plot of R-value vs. measured ambient temperature for vinca. The R-values range from 3 to 5 ft²h°F/BTU. A linear curve fit shows a positive correlation of R-value and temperature. The data in this plot supports the hypothesis that an increase in temperature will increase the R-value of the plants. To statistically test the hypothesis an analysis of variance, or ANOVA, was performed using Minitab statistical software. The test compares data from several groups and uses the variance of the data set to determine if there is a significant difference in the means of each group. In the case of this study the groups are the three different set temperatures (the 103°F test was excluded from statistical calculations because it was not replicated). The complete results for all statistical analysis in this study can be found in Appendix B. A one-way ANOVA test was used. The analysis concluded that given a confidence level of 95% there is enough evidence to reject the null hypothesis. In other words, temperature does have a significant impact on R-value for vinca.

Figure 6.1 Vinca R-values

After the ANOVA analysis, a Tukey test was then used to compare each set temperature in pairs. The test uses information from the ANOVA analysis to determine if there is a significant difference in R-value between any of the pairs of set temperatures. For vinca at the confidence level of 95% there was a significant difference between the R-values for each of the ambient air temperature levels.

Figure 6.2 shows R-value vs. measured ambient temperature for ryegrass. A linear fit to the data shows an upward trend in R-value with increasing temperature, which is evidence for confirming the test hypothesis for ryegrass. The range of R-values for ryegrass is 2-4 ft²h°F/BTU, which is slightly lower than the range for vinca. The slopes of the linear curve fits for the two plant species are very similar. A one-way ANOVA analysis indicated that the null hypothesis should be rejected for ryegrass with a confidence level of 95%. Increasing temperature will increase the R-value of ryegrass in a significant manner.

Figure 6.2 Ryegrass R-values

A Tukey test was performed using the ryegrass data as well. With a 95% confidence level there is a significant difference in R-value between each temperature level except there was no significant difference between the R-values at 103°F and 120°F for ryegrass.

Figure 6.3 is a plot of R-value vs. measured ambient temperature of the tests performed with sedum. The values range from just over 1 to just over 3 ft²h°F/BTU. Sedum has the lowest R-values of the three plants tested. One possible reason why the sedum resulted in the lowest R-values is the low water consumption of sedum. It uses less water which means that it must transpire less water. This would cause a reduction in evaporative cooling when compared to the other plants, resulting in a lower R-value. Another possible reason for the low values from the sedum is its health. It should be noted that when the sedum was tested it was not in good health. About 50% of the two trays was still vital and healthy looking but the other half was shriveled and discolored. Figure 6.4 is a photograph showing both the healthy and unhealthy portions of the sedum. Figure 6.5 is a close up of a portion of the unhealthy sedum. It is possible that the health of the sedum may have impacted the resulting R-values.

Figure 6.3 Sedum R-values

Statistical analysis for the sedum was also performed using a one-way ANOVA analysis. The results show enough evidence to reject the null hypothesis and accept that the R-values for sedum increase significantly with temperature with an 95% confidence level. A Tukey test was performed on the sedum data. This test showed that there was a significant difference between the R-values for all of the different ambient air temperatures.

Figure 6.4 Healthy and Unhealthy Sedum

Figure 6.5 Unhealthy Sedum

Figure 6.6 is a plot of temperature and R-value for all three plant species tested. The trend lines for each of the three plant types are also included. The three types of plants each show a similar response to increasing temperature that supports the test hypothesis. For each plant the R-value increases as the ambient temperature increases. This plot also clearly shows the difference in thermal performance of the plants. Vinca produced the highest R-values, sedum the lowest, and ryegrass between the two. ANOVA analysis was performed to determine if plant species has a significant effect on R-value. The analysis results indicate that there is a significant difference between R-value and plant species with a confidence level of 95%.

Figure 6.6 R-values For All Three Plants

Chapter 7 Conclusion

Green roofs can be an effective and appealing way to increase the energy efficiency of buildings. The R-value, or thermal resistance, of a green roof is an effective means of measuring thermal performance of the green roof because it can be easily input in building energy calculations and applied to many different buildings and situations. The R-values for test green roofs with each of the three different plant species was tested in this study, ryegrass (*Lolium perenne*), sedum (*Sedum hispanicum*) and vinca (*Vinca minor*). The results showed an increase in R-value with increasing temperature. When the data was analyzed using an ANOVA analysis, the relationship between temperature and R-value for all three plant species were found to be significant. When relative humidity was maintained at 45%, the soil was saturated with water, the temperature was varied from room temperature up to 120°F the R-values for sedum ranged from 1.37 to 3.28 ft²h°F/BTU, for ryegrass the R-values ranged from 2.15 to 3.62 ft²h°F/BTU, and for vinca the R-values ranged from 3.15 to 5.19 ft²h°F/BTU. The average R-value for all the tests in this study was 3.20 ft²h°F/BTU.

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Appendix A Raw Test Results

The test data used to calculate the R-value for each run are included in Table A.1. Since each test was replicated, the letter “a” refers to the first test and the letter “b” refers to the second test at the given set temperature. Two sets of measurements were taken for each test. In the table the number “1” refers to the data for the first tray and “2” refers to the data for the second tray. T_C refers to the temperature measured in the cold space and T_H refers to the temperature measured in heated space. The temperatures are all listed in °C. Flux refers to the heat flux through the bottom of the tray and is listed in W/m^2 . The negative heat flux indicates that heat is going from the heated space into the cooled space.

It should be noted that for the higher temperature tests the actual measured temperatures were lower than the set temperatures. This is likely due to two factors. The first is infiltration which occurs because of the negative pressure in the wind tunnel. The second and perhaps the more significant factor is the evapotranspiration performed by the plants which causes evaporative cooling of the air in the test section. The evidence indicating evapotranspiration as the main cause of the temperature decrease is that the measured temperatures for the sedum are higher than the others and the sedum likely transpired less than the other two plants, which might be why the measured temperatures for sedum are higher.

Table A.1 Raw Test Data

Ambient Temperature Set Point	Test	Sedum			Ryegrass			Vinca		
		T _H	T _C	Flux	T _H	T _C	Flux	T _H	T _C	Flux
Room Temperature	1a	27.51	10.32	-29.78	25.54	11.30	-29.34	27.25	10.27	-25.82
	2a	27.80	10.18	-23.83	25.75	11.24	-28.25	27.42	10.16	-24.96
	1b	28.80	11.23	-40.34	28.09	13.08	-23.34	27.73	10.00	-25.45
	2b	27.94	11.16	-34.43	27.42	12.95	-25.24	27.88	9.86	-23.92
30 °C	1a	31.64	10.41	-60.65	30.69	12.40	-28.17	30.88	10.78	-29.54
	2a	30.10	10.33	-52.02	30.33	12.31	-27.57	29.99	10.69	-23.07
	1b	31.24	8.80	-54.03	31.22	10.56	-35.96	31.07	10.99	-22.32
	2b	30.49	8.71	-47.04	30.36	10.50	-38.04	29.81	10.89	-20.70
39 °C	1a	38.64	12.61	-45.60	35.09	12.37	-39.02	37.57	12.01	-29.13
	2a	35.98	12.56	-42.20	34.59	12.29	-25.73	35.23	11.88	-28.78
	1b	38.99	9.85	-59.06	35.68	12.36	-28.97			
	2b	36.01	9.72	-53.35	35.04	12.25	-29.80			
49 °C	1a	43.44	12.71	-47.98	38.27	11.37	-40.15	40.25	11.17	-30.71
	2a	49.16	12.69	-48.21	43.66	11.53	-38.24	40.07	11.08	-25.93
	1b	42.81	11.09	-55.08	37.77	11.24	-40.71	39.59	11.77	-33.53
	2b	45.60	11.01	-49.79	45.63	11.18	-39.85	43.99	11.67	-29.93

Appendix B Statistical Results

For each of the three plant species tested in this study an ANOVA analysis was done, followed by a General Linear Model using a Tuckey test. For the ANOVA part of the analysis the important output is a value labeled P. A statistically significant result is indicated by a value for P that is less than α , where α is defined as $\alpha = 1 - \text{CL}$, i.e. for a 95% confidence level, α will be 5%. The results of the Tuckey test are intervals that are created for each pairing. If the interval does not include zero, then there is a significant difference between the two groups in that pair. A linear regression was also performed for R-value vs. temperature for each species, not necessarily to determine goodness of fit, but to show that R-value has a non-zero slope when plotted versus temperature. That was determined to be the case for each species when a confidence level of 95% was used.

Results for the statistical analysis of sedum:

One-way ANOVA: R-value versus Temperature

Source	DF	SS	MS	F	P
Temperature	3	1878.015	626.005	2976.90	0.000
Error	6412	1348.362	0.210		
Total	6415	3226.376			

S = 0.4586 R-Sq = 58.21% R-Sq(adj) = 58.19%

				Individual 95% CIs For Mean Based on Pooled StDev	
Level	N	Mean	StDev	-----+-----+-----+-----+-----	
1	1604	3.2077	0.7047		*)
2	1604	2.2927	0.2646	*)	
3	1604	3.0138	0.2597	*)	
4	1604	3.8083	0.4550		*)
				-----+-----+-----+-----+-----	
				2.40	2.80 3.20 3.60

Pooled StDev = 0.4586

Tukey 95% Simultaneous Confidence Intervals

All Pairwise Comparisons among Levels of Temperature

Individual confidence level = 98.97%

Temperature = 1 subtracted from:

Temperature	Lower	Center	Upper
2	-0.9565	-0.9149	-0.8734
3	-0.2355	-0.1939	-0.1524
4	0.5590	0.6006	0.6422

Temperature = 2 subtracted from:

Temperature = 3 subtracted from:

Regression Analysis: R-value versus Temperature

The regression equation is
R-value = 2.45 + 0.252 Temperature

Predictor	Coef	SE Coef	T	P
Constant	2.44991	0.01990	123.11	0.000
Temperature	0.252279	0.007266	34.72	0.000

S = 0.650723 R-Sq = 15.8% R-Sq(adj) = 15.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	510.43	510.43	1205.43	0.000
Residual Error	6414	2715.95	0.42		
Total	6415	3226.38			

Results for the statistical analysis of vinca:

One-way ANOVA: R-value versus Temperature

Source	DF	SS	MS	F	P
Temperature	3	1811.838	603.946	1920.90	0.000
Error	4410	1386.540	0.314		
Total	4413	3198.378			

S = 0.5607 R-Sq = 56.65% R-Sq(adj) = 56.62%

Pooled StDev = 0.5607

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Temperature

Individual confidence level = 98.97%

Temperature = 1 subtracted from:

Temperature = 2 subtracted from:

Temperature = 3 subtracted from:

Regression Analysis: R-value versus Temperature

The regression equation is
R-value = 3.62 + 0.505 Temperature

Predictor	Coef	SE Coef	T	P
Constant	3.62468	0.01892	191.61	0.000
Temperature	0.504764	0.007342	68.75	0.000

S = 0.591603 R-Sq = 51.7% R-Sq(adj) = 51.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1654.2	1654.2	4726.38	0.000
Residual Error	4412	1544.2	0.3		
Total	4413	3198.4			

Results for the statistical analysis of Ryegrass:

One-way ANOVA: R-value versus Temperature

Source	DF	SS	MS	F	P
Temperature	3	1710.586	570.195	1898.68	0.000
Error	6412	1925.595	0.300		
Total	6415	3636.182			

S = 0.5480 R-Sq = 47.04% R-Sq(adj) = 47.02%

Pooled StDev = 0.5480

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Temperature

Individual confidence level = 98.97%

Temperature = 1 subtracted from:

Temperature	Lower	Center	Upper	-----+-----+-----+-----+-----
2	0.2057	0.2554	0.3050	(*)
3	1.0953	1.1450	1.1946	(*)
4	1.0943	1.1440	1.1936	(*)
				-----+-----+-----+-----+-----
				-0.60 0.00 0.60 1.20

Temperature = 2 subtracted from:

Temperature	Lower	Center	Upper	-----+-----+-----+-----+-----
3	0.8399	0.8896	0.9393	(*)
4	0.8389	0.8886	0.9383	(*)
				-----+-----+-----+-----+-----
				-0.60 0.00 0.60 1.20

Temperature = 3 subtracted from:

Temperature	Lower	Center	Upper	-----+-----+-----+-----+-----
4	-0.0507	-0.0010	0.0487	(*)
				-----+-----+-----+-----+-----
				-0.60 0.00 0.60 1.20

Regression Analysis: R-value versus Temperature

The regression equation is
R-value = 2.73 + 0.432 Temperature

Predictor	Coef	SE Coef	T	P
Constant	2.72735	0.01766	154.46	0.000
Temperature	0.432151	0.006448	67.03	0.000

S = 0.577405 R-Sq = 41.2% R-Sq(adj) = 41.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1497.8	1497.8	4492.46	0.000
Residual Error	6414	2138.4	0.3		
Total	6415	3636.2			