Table of Contents

Table of Figures

Table of Tables

Table of Equations

Introduction

The purpose of this project was to investigate, at the study plot scale, the potential of landscape scale treatments that could be used to reduce sublimation losses of critical water supply snowpack. The reduction of losses to sublimation would allow for an increase in the amount of water that makes it into surface water flows and water supply storage facilities filled by snowmelt runoff.

This project was performed by three senior environmental engineering undergraduate students at Northern Arizona University: Adam Bringhurst, Keri Williamson, and Kevin Werbylo. These three students worked under the name of Snowpack Engineering, which operated under the professional guidance of snow hydrologist, and Northern Arizona University Professor, Dr. Rand Decker, who also served as the client to this project. The original Project Proposal is included in Appendix A. This proposal covers the constraints of the project as well as the scope of services and exclusions.

Tasks for this project included writing an extensive background and research report on the importance of snowpack on a global, regional and local level, the design and setup of an experimental methodology to conduct study plot testing, the collection and analysis of data, the analysis of the cost of implementation for promising treatments, and the formation of conclusions and recommendations. Each of these tasks is documented in detail in this document.

Abstract

Snowpack, with respect to both depth and duration, plays an important role in shaping the climate and biota of Earth, as well as impacting the way humans live. Alterations to snowpack result in changes to precipitation and weather patterns. Intimately related to both the weather and the direct impacts of snow on the ground are changes in vegetation and, consequently, wildlife. Additionally, snowpack plays a vital role in regional and local water supplies and water storage for human populations.

In the state of Arizona, the Colorado River and the Salt River Drainage Basin are primarily fed by snowpack and provide nearly half of Arizona's water. Due to the arid climate of Arizona, approximately 80% of the snow water equivalent (SWE) in the snowpack never makes it into surface water runoff. Finding a treatment for snowpack which could reduce sublimation losses would be beneficial for watersheds which rely on snowpack as a large part of their water source.

The treatments tested by Snowpack Engineering included vertical compaction of the snowpack, spraying the snowpack with a coat of vegetable oil, and applying a layer of chipped Ponderosa Pines over the top of the snowpack in both thin and thick layers. Four study plots were set up on the Northern Arizona University campus in Flagstaff, Arizona to test the effectiveness of these treatments. One plot was set up in a meadow area, one in a forested area with about 90% canopy cover, and two were set up under roof structures. The plots in the meadow and canopy areas were used to compare the potential effectiveness of each treatment in each setting, while the roof structures were utilized in an attempt to prevent additional snow from falling on snowpack that had already been treated.

The data from the two roofed study plots was disregarded because of the correlation between where the study plots were located under the roof structures and the rate at which the snowpack melted. Specifically, it was found that the southern subplots received much more sun than the northern subplots, causing the southern subplots to melt much faster.

The subplots in the meadow and canopy areas did yield usable results. In meadow areas the control subplot, which went untreated, saw snowpack ablate at a rate of 0.26 inches of SWE per day, while the subplot treated with a thick blanket of biomass saw snowpack ablate at a rate of 0.04 inches of SWE per day. Further, at the end of the data collection period, the control plot had lost 100% of its original SWE, while the biomass treated plot only lost about 22% of its original SWE. In the canopied area, the control plot averaged a loss of 0.21 inches of SWE per day and the biomass plot averaged a loss of only 0.08 inches of SWE per day. At the end of the data collection period, the control subplot in the canopied area had lost 100% of its original SWE, while the biomass treated subplot lost 70% of its original SWE.

Based on the gathered results, it was determined that a thick layer of biomass (about three to four inches in depth) would help reduce sublimation losses of snowpack in both meadow and canopied areas. A cost analysis was performed to determine the price of application of the thick biomass blanket, and it was determined that one application would cost about $365.50 per acre of treated area. This extremely high cost of application makes the feasibility of implementing this treatment very difficult.

1.0 Background and Research

This section of the report is a detailed research paper on many broad topics in snow hydrology. The ultimate goal of this section is to demonstrate the importance of snowpack as it pertains to water resources, and to demonstrate the value of a treatment which could be used to increase the amount of water in surface flows. This research was performed by examining the relationship between snowpack and the environment, as reported in Section 1.1, and the importance of water on a local scale as reported in Section 1.2. Current treatments for limiting losses of snowpack due to sublimation was also researched and reported in Section 1.3.

1.1 Snowpack and the Environment

The role of both snowpack depth and duration is important to humans because of its implications on the climate, biota, and water supplies that people rely on for a comfortable existence. However, the implications snowpack has on each of these things does not fall universally into positive or negative impacts, but rather, snowpack plays a role in a complicated web of relationships between ecosystems locally, regionally, and globally.

For every influence snowpack has over another variable, the reverse is generally also true; meaning that a change in snowpack conditions can have countless effects over time. These impacts on the climate, vegetation, wildlife, and water resources are important to humans because they ultimately affect the way people live.

1.1.1 Climate

Snowpack results from specific weather conditions; a change in climate directly affects snowfall and subsequently, snow depth. However, snowpack depth and endurance also take part in shaping weather conditions.

There is a global trend towards less snow at low altitudes in the past 50 years[1]. Thus, the disappearance of snowpack has been widely monitored and the effects closely watched. In one study taking place near the Brooks Range in Alaska, deep snow cover in the arctic tundra correlated to an overall decrease in annual CO_2 emissions[2]; this is important because carbon dioxide is a greenhouse gas recognized by the United States Environmental Protection Agency (EPA) as likely contributing to global climate change[3]. Both the moist and dry tundra sampled in the study showed higher rates of CO_2 emissions in the winter but lower rates in the summer, which ultimately made the emissions decrease significantly in the dry tundra, and slightly reduce the annual CO_2 emissions of the moist tundra[2].

Snowpack endurance also plays a role in seasonal events; it is known that deep snowpack lasts longer than shallow snowpack[4]. In the last 65 years, North America and Northern Eurasia have experienced spring peak river flows approximately 1-2 weeks earlier in the year than before due to the earlier melting of shallower snowpack[1]. The earlier peaks in river flows make water resource management more difficult because much of the demand for water comes in the summer and autumn months.

Additionally, it has been observed that in the years of deep Eurasian snow cover, less precipitation falls later in the year, resulting in a weaker Indian Monsoon during the rainy months[5]. A weak Indian

Monsoon affects global wind circulation and diminishes trade winds. Additionally, the weak Indian Monsoon contributes to poor regional crop yields because much of the annual precipitation in the area comes from the monsoon season[5].

1.1.2 Vegetation

Snowpack can affect vegetation and crops both negatively and positively, as well as make no difference at all. The effect of snowpack on vegetation is related to the climate, in addition to the individual species affected by the snowpack.

Studies conducted in Utah, intended to determine whether winter cloud-seeding in the Uinta Mountains would have major impacts on the biota, found that plant production, as well as total plant cover, was significantly less in heavier snowpack areas. A 10% increase in snowpack corresponded to an approximate 4.7% decrease in overall plant production[4]. Additionally, studies in the Medicine Bow Mountains in the Rockies, where snow fences were used to create deeper snowpack, also found that plant productivity and cover were generally reduced with the increase in snowpack over a three to five year study period[7]. Similar studies in subalpine meadows of Montana found that increased snowpack, and the subsequently later snowmelt date, delayed growth in the spring and shortened the overall growing season, resulting in a reduction in the overall biomass by the end of the season[7].

More evidence of negative impacts of snowpack comes from the subarctic areas of Eurasia where high winter precipitation and later snowmelt dates, limits the growing season of conifers, as evidenced in their reduced tree ring widths[6]. Other effects observed in Utah studies included a decrease in soil depth and organic matter corresponding to increasing snowpack[4].

In contrast, those same studies in Utah found that the number of species per plot and the total flowering period of the plants increased with an increasing depth in snowpack[4]. In Montana, studies found that additional snowfall increased the amount of water and nutrients entering the soil and probably facilitated litter decomposition and mineralization in the dry, subalpine meadow that was studied[8]. One study based in the western United States found that a 10% increase in snowpack correlated to a roughly 1.7 day delay in the snowmelt date[4].

In central Siberia, it was found that deeper snowpack and later snowmelt dates are related to higher normalized difference vegetation index (NDVI) values. Higher NDVI values indicate greater vegetative cover and are an indicator of plant productivity. In Siberia, the vegetation distribution followed a gradient of snowpack distribution, probably due to the thermal insulation effects that snow cover provides for the ground during the coldest periods of the winter, and the availability of water in the summer[8].

There are many cases of conflicting evidence on the relationship between snowpack and vegetation; one such explanation of the diverse response of plants may be related to the soil moisture content in the growing season. Studies indicate that where soil moisture is lacking in growing season, deeper snowpack correlates to greater plant cover and production. Where moisture is adequate, deep snowpack depresses plant cover and decreases plant production[4]. Additionally, some species prefer heavy snowpack, some prefer light snowpack, and some have no preference. However, the number of species that prefer late release snow has been found to be low compared to species that prefer early release[4].

1.1.3 Wildlife

Snowpack, especially with regard to depth and density, factors into the movement and energy requirements of wildlife; this impacts where they migrate, raise young, and populate. In addition, the influences of snowpack on wildlife are strongly related to the impacts on vegetation for species that forage.

Foragers, such as deer, elk and caribou, are limited in their habitat because snow tends to decrease the availability of food[9]. In studies of caribou, it was also found that because snowpack delayed the start of the growing season, in which plants are at their most nutritious levels, a change of snowpack patterns could offset the date at which the growing season starts. This affects caribou because they may arrive at foraging grounds when plants are not at their most nutritious levels[10].

Additional studies in Colorado found that snow depth influences elk movement in the winter because they tend to avoid the deeper areas except when forced to use them[11]. This has been supported with studies in Alaska on the limitation of locomotion for deer due to deep snow[9]. Studies on Colombian Black-Tailed Deer in British Columbia found that snow restricts the winter habitat of deer because of several factors including the reduced availability of forage and the increased energy and time required for movement[12].

Snowmelt patterns are related to the selection of migration routes and calving sites for caribou in Alaska[10]. The areas with the highest density of calving caribou are related to areas of high plant biomass. Late snowmelt plots had lower ratios of carbon to nitrogen than the early melting and control plots, which indicate higher nitrogen content in the soil. Nitrogen can be a limiting factor in plant growth and thus, the late snowmelt plots may have less plant biomass available for the caribou, deterring them from using the site for calving[10].

Furthermore, mammals such as wolverines have had populations declining with decreasing snowpack[13]. The reasons for this are not quite known but may be due to the increased survival rates of their prey in winters of decreased snowpack since wolverines are common scavengers and are thus dependent on other species mortality rates. Snowpack even plays a role in the populations of insects. Because snow acts as an insulator, snow cover generally reduces insect mortality rates over winter[14].

1.1.4 Drinking Water Supply

Snowpack is not the only contributor to water supply because it is only a portion of the annual precipitation. Often times, when an area has a large amount of winter precipitation, there is a decrease in precipitation in other times of the year. However, many parts of the world rely heavily on snowpack for drinking water. In the western United States, snowmelt accounts for up to 75% of all drinking water supplies[15].

The Surface Water Supply Index (SWSI) is frequently used in the western United States as a hydrological drought indicator and takes into account snowpack, stream flow, precipitation, and reservoir storage[16].

Thus, snowpack plays a role in the determination of a hydrological drought. Snowpack analyses are often used to estimate future reservoir storage for the year.

In Canada, a 29% decrease in annual max daily stream flow has occurred due to temperature rise and increased evaporation with no change in precipitation rates[17]. The early spring shift in runoff leads to a shift in peak river runoff away from summer and autumn, which are normally the seasons with the highest water demand, resulting in difficulty managing water and ensuring it is available when demand requires it be[1].

1.2 Local Impacts of Snowpack

The state of Arizona is extremely dependent on water supply because of its desert climate. All economic activity in the state relies on a consistent supply of water[18]. Approximately half of the water used in the state originates from snowmelt. This includes the water allocated from the Colorado River, as well as water from the Salt River Drainage Basin, which includes the Salt River, the Verde River, and Tonto Creek[19].

The Colorado River is dammed at several locations to provide a network for water storage and distribution. This network ensures that the water, which is taken from the Colorado River, is available even in years of drought. However, the amount of water available from the Salt River Drainage Basin is extremely dependent on consistent snowfall. A very wet winter can fill the reservoirs to capacity, while a very dry winter will leave reservoirs depleted, which poses a problem for local water managers. The dependence that water users throughout the state have on snowpack is substantial, which is why treatments that have the potential to limit the losses of snowpack would be of great importance.

1.2.1 Arizona Water Usage

Arizona uses approximately seven million acre-feet of water annually. Of the seven million acre-feet, nearly three million acre-feet are from the Colorado River system and half of one million are snowmelt from the Salt River Drainage Basin. Together, these two basins account for nearly half of the water usage in the state[19]. The Salt River Drainage Basin covers nearly 6,000 square miles and feeds snowmelt into six reservoirs for storage and distribution[20]. The four storage reservoirs along the Salt River, from upstream to downstream are: Theodore Roosevelt Lake, Apache Lake, Canyon Lake, and Saguaro Lake. The two reservoirs along the Verde River are Horseshoe Reservoir and Bartlett Reservoir. The storage capacity of the six reservoirs is about 2.3 million acre-feet, and the median recharge for the two river systems is about 0.7 million acre-feet[20].

Water released from the two river systems enters a diversion dam that divides the flow into two canals; the Arizona Canal and the South Canal. These two canals are diverted several times until they reach agricultural lands or municipal water treatment facilities[21]. Water usage in the state of Arizona is typically categorized into three different uses: agricultural, industrial, and municipal. Nearly 70% of the water in Arizona is used for agriculture, 25% for municipal use, and 5% is used by industry[19]. In addition to water storage and distribution, the snowmelt runoff from the two river systems is also used to generate electricity[21].

1.2.2 Impacts of Forest Health

The effects of snowpack on forest health and on the different habitats in the high country of Arizona are important. Drought years can be correlated to greater forest fire risks and greater fire destruction[22]. The worst forest fire in the history of Arizona is attributed to a snow water equivalent in the snowpack more than 85% below the average annual snow water equivalent[22]. Snowpack affects not only the forest, but also the inhabitants therein.

Wildlife, which depends on a healthy forest for its livelihood, will benefit from good snowpack years and struggle during drought years. Many of the forest inhabitants are herbivores, and without the regeneration of healthy undergrowth, the entire food chain of the forest can suffer. Forest health is dependent on snowpack, whether it is the plant life, the animal life, or the risk of forest fire.

1.2.3 Why Treatments will be Beneficial

Snowpack is a very important factor for water usage in the state of Arizona. It plays a crucial role for the livelihood of its population. If there is a snowpack treatment which will effectively keep snow on the ground through the winter, instead of allowing it to sublimate, it would be of great value to a water dependent system that is already over-allocated.

1.3 Current Treatments at Limiting Losses

Currently, there are several techniques that can be implemented to help increase snow precipitation, increase peak snowpack, or slow the melting process of the snowpack. However, there is minimal information pertaining directly to limiting sublimation losses of the snowpack.

1.3.1 Cloud Seeding

Cloud seeding is a method that promotes an increase in snow precipitation. It does so by supplying an ice nucleus for snow precipitation to form around, supporting the creation of snowflakes[23]. This method is widely used in the western United States.

1.3.2 Tree Thinning

Tree thinning is a forestry management practice that can increase peak snowpack because greater amounts of snow accumulate on the ground in lower-density forests[24]. A low density forest is a forest that has ample room for growth due to natural conditions or human interactions. In the Beaver Creek watershed, roughly 80 km south of Flagstaff, Arizona, vegetative management practices such as clear cutting, tree thinning, and removing strips of forest, were tested on several different forest types: Ponderosa Pine, Alligator Juniper, and Utah Juniper, to determine their effect on annual water yield[25]. All of these management practices led to increases in annual water yields ranging from 30-160%. Because a large amount of water comes from winter runoff, the results are directly related to how the vegetative management practices affect winter snowpack[25].

1.3.3 Fences and Woodchips

Methods that prolong winter snowpack include managing wind-driven snow and treating the snowpack before the melt season begins. Drift fences can be used to encourage the accumulation of snow in specific areas, leaving large drifts that last long into the melting season. Treatment, such as spreading a layer of wood chips over the snow before the melt season begins, slows the evaporation and sublimation of snow. A group of researchers found that in the Lake Tahoe area of the Sierra Nevada mountain range, spreading wood chips over the snow significantly lowered the rate at which snowpack melted[26]. In the conclusions of their findings, this group reported that covering snow with a thick layer of woodchips will result in benefits including, but not limited to, “increasing water yield from the snowpack by decreasing loss to evaporation and sublimation”[26]. More treatments should be tested to determine their level of potential at limiting losses of snowpack and increasing the amount of water that makes it into surface water and surface water storage facilities.

2.0 Experiment Methodology

This section of the report is a detailed account of the methodology *As Designed* and the methodology *As Performed* by Snowpack Engineering to measure the effectiveness of different treatments at limiting sublimation losses of winter snowpack.

2.1 Section 1 – As Designed

Section 1 of the methodology is the experiment methodology as it was designed by Snowpack Engineering. These are the methods that Snowpack Engineering designed in December 2010 and January 2011, and were to be carried out for the duration of the data collection period, given an adequate amount of snowpack.

2.1.1 Duration of the Experiment

Snowpack Engineering believed that the best time for data collection would be the coldest months of the winter. The cold conditions prevalent during these months would result in a larger amount of snow being lost to sublimation, compared to the spring melt season, where much of the snow would be lost to melting. Data collection is projected to start on January 18th, 2011 and end March 11th, 2011. Sublimation losses will be measured on an individual storm basis, as well as a continuous winter-long basis (see Section 2.1.3 for detailed information on how this will be executed).

2.1.2 Time Intervals for Data Collection

Given ideal winter conditions and an adequate snowpack (about 1 foot or greater), data collection is planned to take place every four days. The time interval for data collection can be increased or decreased based on the expertise judgment of Snowpack Engineering. For example, if conditions after a snow event are predominately cool and humid, the time between collections on each plot could be expanded to a weekly interval. Contrarily, if conditions after an event are warm, dry, and windy, data collection could occur every one or two days for a given plot.

2.1.3 Plot Setup

Each study plot will be 9’ x 9’, and will contain four 4’ x 4’ square-shaped subplots with a 1’ walkway between subplots. Each plot will contain three different treatments, one treatment per subplot, and one subplot which will be untreated to act as a control.

Snowpack Engineering plans to construct four separate study plots. Two of the study plots will be covered with a roof structure and two will be unroofed. The roof structures will be used to prevent additional moisture from falling onto the study plots once they have been treated. The idea is that snow captured from individual events will be monitored until it has totally been eliminated, giving a start to finish sample from which to analyze data. The two unroofed study plots will be located in areas where one plot represents an area with at least 50% canopy cover, and one plot represents an open meadow area. Treatments will be applied to snowpack in these study plots throughout the winter following storm events. For example, if one storm puts 24 inches of snow on the ground, and two weeks later a second storm puts six more inches of snow on the ground, treatments will be applied after each snow event, creating a layering of snowpack and treatments. This is representative of what will happen if treatments are applied at the landscape scale after each significant storm event.

2.1.4 Control Plot

Each study plot will contain a control as one of its subplots. This control subplot will be used to simulate snow that has gone untreated at the landscape scale. The control subplot will be used to determine the effectiveness of treatments at limiting sublimation losses.

2.1.5 Parameters Monitored and Tested

Snowpack Engineering will use the snow water equivalent (SWE) calculation to determine the amount of water contained in a given area of snowpack. The SWE is calculated by multiplying the depth of the snowpack by the density of the snowpack, and dividing this by the density of water. If done in this fashion, the SWE will be reported as a depth of water. This equation is expressed in Equation 1 below. For example, twelve inches of snowpack with a given density may be found to have an equivalent of three inches of standing water. The SWE will be the measurement used to compare the effectiveness of one treatment to the effectiveness of another, or to the control.

Equation 1: Snow Water Equivalent

$$SWE = \frac{density\ of\ snow * depth\ of\ snow}{density\ of\ water}$$

The snow water equivalent will be measured at two locations on each subplot. Ideally, one sample will be taken from the edge of the subplot and one from near the middle. Thus, each snow subplot will have two samples taken from it during each test for quality assurance.

To determine the density of the snow, Snowpack Engineering will construct a sampling tube similar to the Mount Rose Sampling Tube, out of metal piping. The tube will have markings on it that will allow Snowpack Engineering to measure the depth of snow wherever the sample is gathered. The sampling tube will be used to collect snow in the field; the depth of the snow will be noted and then the snow will be put in a beaker so it can easily be transferred to the environmental lab at Northern Arizona University. In the lab, the weight of the melted snow will be measured, and the density of the snow will be calculated using the weight of the snowmelt and the volume of snow extracted from the field. The snow water equivalent will then be calculated using the density, the depth of the sampled snow, and the known density of water.

Equation 2: Density of Snow

$$(Density\ of\ Snow) = \frac{(beaker\ with\ snow) - (beaker\ without\ snow)}{(area\ of\ snow\ tube) * (depth\ of\ snow)}$$

Outside air temperature will also be monitored. This will be achieved by setting up data loggers to read and record the temperature of each site every 30 minutes. The temperature is an important parameter in this study because it will help determine when sublimation is responsible for the majority of the snowpack loss. For example, if the temperature does not rise above freezing but a decrease in SWE is observed, this can be almost entirely attributed to sublimation, as opposed to melting.

2.1.6 Location of Study Plots

Study plots will be located on the Northern Arizona University campus in an area known as the On Site Waste Water Treatment Program, which is a multi-acre facility with areas that will effectively represent a meadow and a densely canopied forest. This location is a short walk from the Engineering Building, which houses the environmental lab, where analysis of the samples will take place.

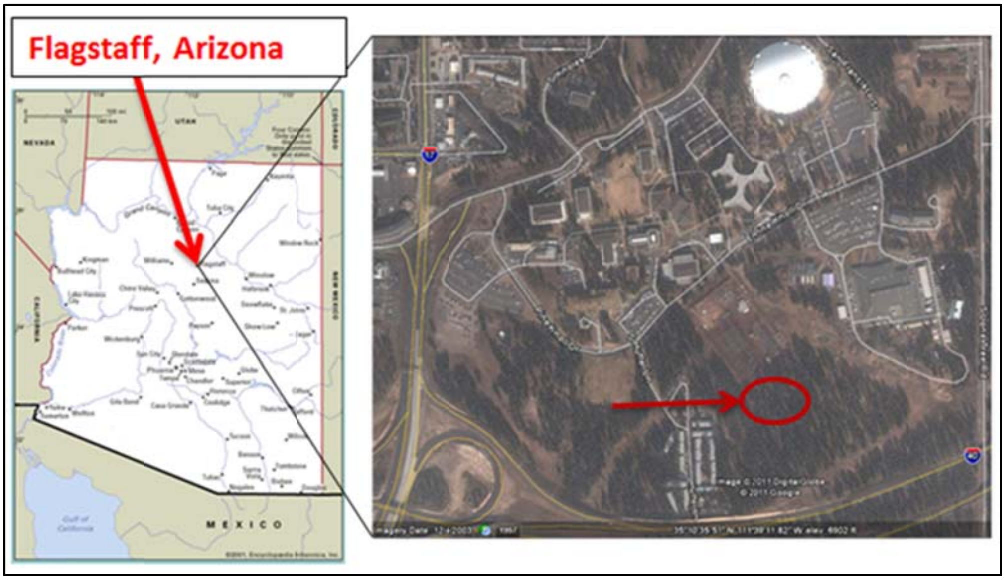


Figure 1: Location of study plots

2.1.7 Treatment Selection for Testing

The initial treatments which will be tested are: vertical compaction of the snowpack, covering the snowpack with biomass left over from forest thinning, and spraying the snowpack with vegetable oil. These treatments were selected because of a wide range of factors. Compaction was selected because it seems like a feasible treatment that can be easily applied at the landscape scale. Covering the snowpack with biomass also seems fairly feasible, since the materials are local and readily available. Spraying the snowpack with vegetable oil was selected because it is a unique treatment that has never before been considered for a similar project.

2.2 Section 2 – As Performed

Section 2 of the methodology is the experiment methodology as it was carried out by Snowpack Engineering. These are the methods that were actually performed at the study plots. The methods *As Performed* differed from the methods *As Designed* mainly due to warm, dry weather conditions during a majority of the proposed data collection period, as well as a limited period of data collection because of late snowfall events.

2.2.1 Duration of the Experiment

Snowpack Engineering began data collection on February 21st, 2011 by taking baseline snow water equivalent measurements and applying initial treatments to the snowpack. The data collection period began much later than the anticipated January 18th, 2011 start date because of extremely dry conditions. The Arizona Daily Sun, Flagstaff's local newspaper, reported that January 2011 was the second driest January on record for Flagstaff, Arizona[27]. The first significant snowfall of the data collection period took place on February 19th and 20th, 2011. This snow event deposited approximately 13 to 14 inches of snow on the ground at the study plot locations. Data collection began immediately following the exit of this storm system.

Shown below in Figure 2, is the Open Meadow study plot as it appeared on February 21st, 2011. As mentioned before, the picture documents about 13 to 14 inches of snow on the ground.

Figure 2: Open Meadow study plot on February 21st, 2011

The data collection period ended with final sampling of the roof plots, on March 11th, 2011, which was the end date originally established. Sampling ended on this day for two reasons: to give the research team adequate time to analyze and report results, and because warm conditions had eliminated most of the untreated and treated snowpack. Data collection ended for the Canopy plot on March 7th, 2011, and ceased at the Open Meadow plot on March 9th, 2011. Each of these plots saw data collection end earlier than the anticipated date because of a lack of testable snow present on the study plots.

Figure 3 on the next page shows the same Open Meadow study plot above in Figure 2 as it looked on the day that data collection was halted. As can be seen, there was not a measurable amount of snow on many of the subplots. The only snow still present in the plot was the snow covered by the biomass.

Figure 3: Open Meadow study plot on March 9th, 2011

2.2.2 Time Intervals for Data Collection

Initially, data collection took place every three days. For example, if a plot was sampled on Monday, it would again be sampled on Thursday. However, because of warm temperatures and a quickly diminishing snowpack, data collection occurred every other day for each plot. Near the end of the experiment, data collection on some plots took place every day.

2.2.3 Plot Setup

Each study plot was 9' x 9', and contained four 4' x 4' subplots with a 1' walkway between subplots. Each plot contained three different treatments, one treatment per subplot, and one untreated subplot which acted as a control. A picture of one study plot is shown in Figure 4. Each subplot is highlighted with red trim, and the 1' walkway is highlighted with a blue line down the center.

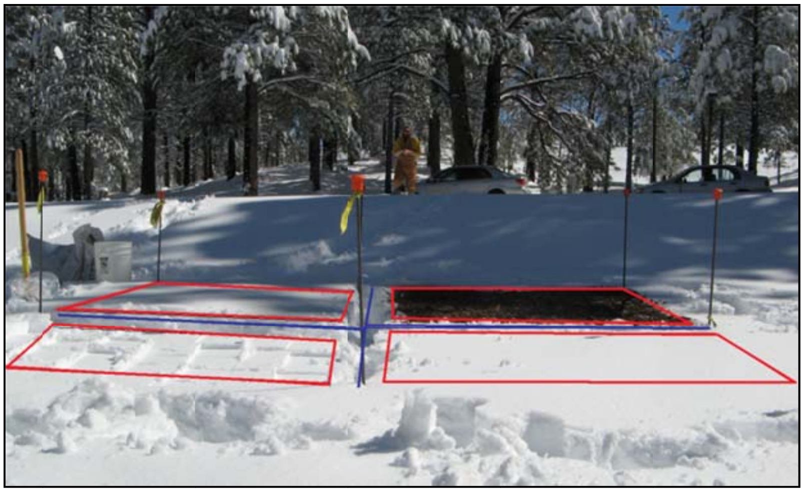


Figure 4: Study plot layout

Snowpack Engineering constructed four separate study plots. Two of the plots were covered with a roof structure, after snow fall events, and two were left unroofed. The roof structures were used to capture snowpack from individual snow events and prevent additional moisture from falling onto the study plots. The idea was that snow captured from individual events could be monitored until the snowpack from the given event was completely eliminated. Thus, for snowpack under a roof, treatments were only applied once, and monitored until the snowpack was completely depleted. A picture of the two roof structures is shown in Figure 5 below.

Figure 5: Roof structured study plots

After the first several days of sampling, Snowpack Engineering could visually see that direct sunlight was impacting the plots on the southern end of the roofed structures and causing more rapid snow loss than the plots at the northern end. When this was verified with data results, sun shading was put up on the south and west sides of both roofed structures on March 2nd. The shading used was a fabric sun screen cloth that still allowed some wind through but cut down direct sunlight to only a fraction of what it was originally. In spite of the shading, Snowpack Engineering continued to see the effects of sun infiltration visually and in the resulting data analysis.

The two unroofed study plots were located near the roofed sites, one in an area characterized by 80-90% canopy cover, and the other in an open meadow. The open meadow can be seen in Figure 2, which appeared previously in this document. Figures 6 and 7, on the following page, are pictures of the Canopy plot, as well as the actual canopy cover of the plot. Treatments were applied to the snowpack twice during the data collection period, once after each storm event, creating layers of snowpack and treatments. This was representative of a planned application of treatment at the landscape scale after every major storm event.

Figure 6: Canopy study plot

Figure 7: Canopy cover of the Canopy study plot

2.2.4 Control Plot

Each study plot contained one control subplot. The control subplot was used to simulate snow that went untreated at the landscape scale. The control was used to determine whether treatments were effective at limiting losses.

2.2.5 Parameters Monitored and Tested

Snowpack Engineering used the snow water equivalent calculation to determine the amount of water contained in a given depth of snowpack. The snow water equivalent was determined by dividing the weight of a given snow sample by the density of water and diving this value by the surface area of the sample tube used for collection. When performed in this fashion, the snow water equivalent was reported as a depth of water. For example, twelve inches of snowpack with a given density, may be found to be equal to three inches of standing water. The snow water equivalent was the value used to compare the effectiveness of one treatment compared to the effectiveness of another, or to the control. This method is slightly different than the method presented in the *As Designed* portion of the methodology because Snowpack Engineering believed that this method had less potential for error.

Equation 3: Snow Water Equivalent

$$SWE = \frac{\frac{weight\ of\ sampled\ snow}{density\ of\ water}}{surface\ area\ of\ sampling\ tube}$$

Sample spots were selected to best represent an average of the snow water equivalent for each subplot. The snow water equivalent was measured at two locations on each subplot; thus, each plot had eight snow water equivalent measurements taken during each test.

To take snowpack samples, Snowpack Engineering constructed a sampling tube from an 18” inch piece of 1 ¾” pipe. The sampling tube was driven into the snowpack with a small mallet until it was obvious that the tube had penetrated into the soil. The soil was removed from the tube and the withdrawn snow saved in a beaker. The depth of snow was noted to the nearest ½" using a simple 24" ruler. Figure 8, is a photograph of a Snowpack Engineering member sampling the study plot using the methods described.

Figure 8: Sampling study plots with constructed sampling tube

Once all samples had been taken in this manner, the beakers were transported to the environmental engineering lab on the campus of Northern Arizona University. A picture of beakers with samples in them is shown in Figure 9 below. In the lab, the beakers were weighed with the snow still in them. The snow was melted using a drying oven, the resulting water poured off, and the beaker, as well as any residual soil from the sample, was again weighed. Using the weight of the snow, the known density of water, and the calculated area of the sampling tube, the snow water equivalent of each sample was calculated as described above.

Figure 9: Beakers with snow samples in the environmental lab

Snowpack Engineering used a Data Tech® data logger for recording temperature. One was set up on an adjacent tree in the Canopy site, one mounted to the underside of the roof structure for the roofed sites, and a third was set on a stump near the Open Meadow site. After completion of the experiment, the data loggers were retrieved and found to have temperature recordings exceeding a reasonable temperature value for the area. Because of this, Snowpack Engineering chose to disregard the temperature data in the experiment and not include it in the results or analysis.

2.2.6 Location of Study Plots

Study plots were located on the South Campus of Northern Arizona University in the On Site Waste Water Treatment Program area. This location is a multi-acre facility that has areas which effectively model a meadow and a dense canopied forest; also, it had available space for the roof structures. This area was a short walk from the Engineering Building, which houses the environmental lab where the samples were weighed.

2.2.7 Treatment Selection for Testing

The initial treatments that were tested were compaction of the snowpack, covering the snowpack with biomass left over from forest thinning (both thin and thick layers), and spraying the snowpack with vegetable oil. These are the same treatments that were proposed in the *As Designed* methodology.

For the study plot scale, compaction was performed using a hand tamper. A picture of the snowpack after it had been compacted is in Figure 10 below.

Figure 10: Study plot after compaction treatment

At first, a very thin layer of biomass was used; after it became apparent that this accelerated the melting of the snow, a thick biomass layer was used. Following the next storm event on February 27th, a three to four inch layer of biomass was applied to the subplots in the meadow, the canopy, and under the second roof structure. A picture of the biomass is shown in Figure 11 on the next page.

Figure 11: Biomass used for covering snowpack

Vegetable oil is used to prevent the evaporation of water in household applications, so it had scientific validity as a potential treatment. Vegetable oil was spread throughout the study plot using a hand pumped, pressurized weed sprayer bought at a local hardware store. Although the sprayer did not apply the oil in a thin mist as was expected, the sprayer was able to be used to apply a fairly uniform layer of oil onto the snowpack. A picture of the application of the vegetable oil is shown in Figure 12 below.

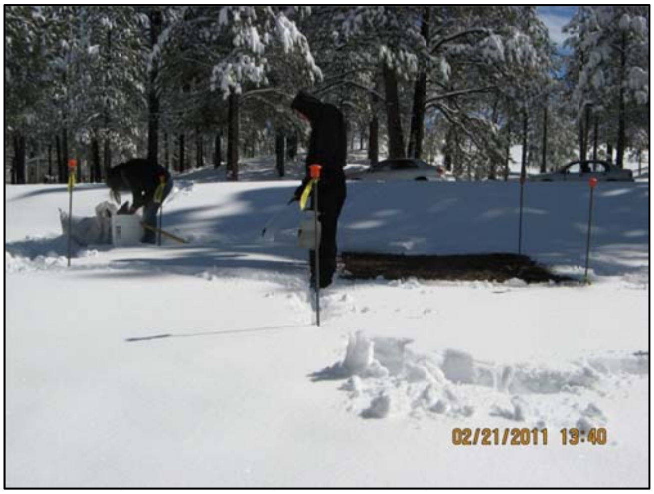


Figure 12: Application of vegetable oil onto snowpack

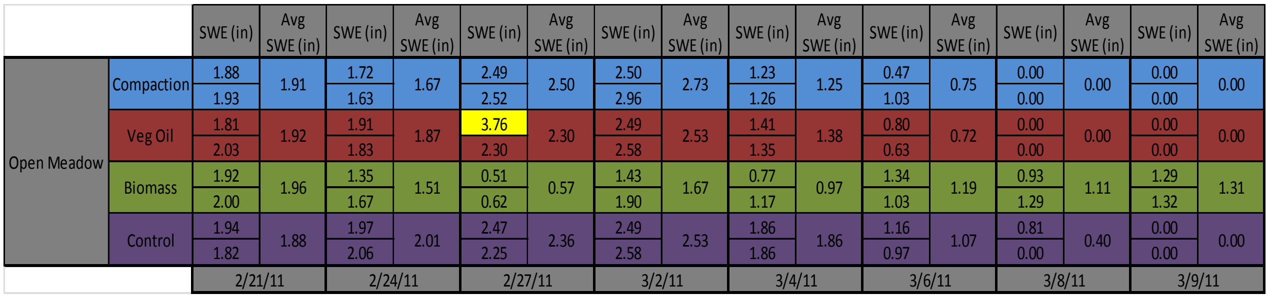
3.0 Data Collected

This section of the report is a presentation of the data as it was collected by Snowpack Engineering. The data, as presented in this section of the report, is a condensed version of the raw data that can be found in Appendix B and C of this report. Cells highlighted in yellow in the data tables are values which appeared to be outliers or were disregarded in the analysis due to sampling error.

3.1 Open Meadow Data

The following is a table of the results for the Open Meadow study plot. Sampling took place eight times on this plot during the data collection period. For each of the days in which sampling took place, eight snow water equivalent calculations were performed, two for each treatment. These results are reported in the column of the table titled *SWE*. The average of the two snow water equivalents for each treatment was reported in the column titled *Average SWE*. The highlighted cell in the vegetable oil column was a sampling error in which the sampling tube was not cleaned before a sample was taken, and did not factor into the SWE average for that day.

Table 1: Snow water equivalent for the Open Meadow study plot

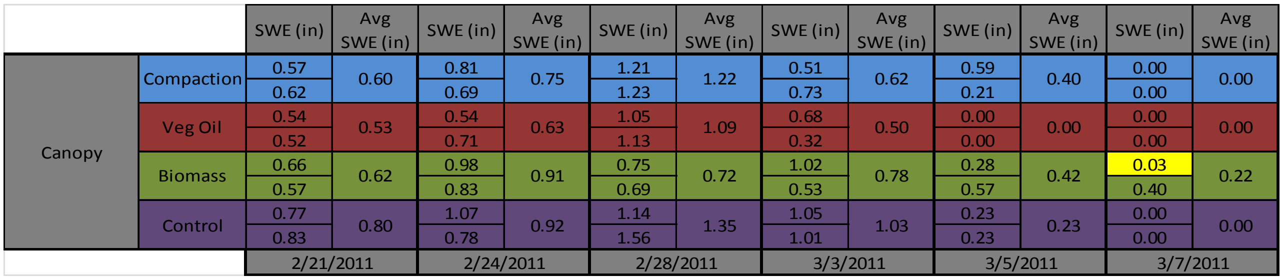


		SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)
Open Meadow	Compaction	1.88	1.91	1.72	1.67	2.49	2.50	2.50	2.73	1.23	1.25	0.47	0.75	0.00	0.00	0.00	0.00
		1.93		1.63		2.52		2.96		1.26		1.03		0.00		0.00	
	Veg Oil	1.81	1.92	1.91	1.87	3.76	2.30	2.49	2.53	1.41	1.38	0.80	0.72	0.00	0.00	0.00	0.00
		2.03		1.83		2.30		2.58		1.35		0.63		0.00		0.00	
	Biomass	1.92	1.96	1.35	1.51	0.51	0.57	1.43	1.67	0.77	0.97	1.34	1.19	0.93	1.11	1.29	1.31
		2.00		1.67		0.62		1.90		1.17		1.03		1.29		1.32	
	Control	1.94	1.88	1.97	2.01	2.47	2.36	2.49	2.53	1.86	1.86	1.16	1.07	0.81	0.40	0.00	0.00
		1.82		2.06		2.25		2.58		1.86		0.97		0.00		0.00	
		2/21/11		2/24/11		2/27/11		3/2/11		3/4/11		3/6/11		3/8/11		3/9/11	

3.2 Canopy Cover Data

On the following page is a table of the results for the Canopy study plot. Sampling took place six times on the Canopy study plot during the data collection period. The highlighted cell in the biomass row appeared to be low but was still used in the average SWE for the day because the other sample captured a high point in the snow under the biomass treatment.

Table 2: Snow water equivalent for the Canopy study plot



		SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)
Canopy	Compaction	0.57	0.60	0.81	0.75	1.21	1.22	0.51	0.62	0.59	0.40	0.00	0.00
		0.62		0.69		1.23		0.73		0.21		0.00	
	Veg Oil	0.54	0.53	0.54	0.63	1.05	1.09	0.68	0.50	0.00	0.00	0.00	0.00
		0.52		0.71		1.13		0.32		0.00		0.00	
	Biomass	0.66	0.62	0.98	0.91	0.75	0.72	1.02	0.78	0.28	0.42	0.03	0.22
		0.57		0.83		0.69		0.53		0.57		0.40	
	Control	0.77	0.80	1.07	0.92	1.14	1.35	1.05	1.03	0.23	0.23	0.00	0.00
		0.83		0.78		1.56		1.01		0.23		0.00	
		2/21/2011		2/24/2011		2/28/2011		3/3/2011		3/5/2011		3/7/2011	

3.3 Roof 1 Data

The following is a table of the results for Roof 1 study plot. Sampling took place ten times on the Roof 1 plot during the data collection period.

Table 3: Snow water equivalent for the Roof 1 study plot

		SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)
Roof #1	Compaction	1.81	1.81	1.81	1.76	1.99	1.94	1.97	1.96	1.96	1.81	1.67	1.55	1.16	1.18	1.37	1.19	1.10	1.09	0.61	0.72
		1.82		1.72		1.89		1.95		1.65		1.44		1.21		1.01		1.09		0.84	
	Veg Oil	1.70	1.91	1.86	1.76	1.95	1.67	1.86	1.80	1.60	1.53	1.07	1.10	0.69	0.68	0.65	0.50	0.36	0.34	0.00	0.00
		2.11		1.67		1.38		1.75		1.47		1.13		0.67		0.35		0.32		0.00	
	Biomass	1.65	1.73	1.50	1.50	1.53	1.47	1.39	1.48	1.14	1.10	0.97	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		1.82		1.03		1.41		1.56		1.06		1.04		0.00		0.00		0.00		0.00	
	Control	1.91	1.82	1.82	1.93	1.63	1.70	1.90	1.92	1.66	1.62	1.29	1.44	1.15	1.24	1.15	1.14	1.18	1.13	0.66	0.73
		1.74		2.04		1.76		1.93		1.59		1.59		1.33		1.14		1.07		0.80	
		2/21/2011		2/24/2011		2/27/2011		3/2/2011		3/4/2011		3/6/2011		3/8/2011		3/9/2011		3/10/2011		3/11/2011	

3.4 Roof 2 Data

The following is a table of the results for the Roof 2 study plot. Sampling took place ten times on the Roof 2 study plot during the data collection period.

Table 4: Snow water equivalent for the Roof 2 study plot

		SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)	SWE (in)	Avg SWE (in)
Roof #2	Compaction	1.81	1.81	2.10	2.13	1.39	1.41	0.95	0.94	0.54	0.47	0.33	0.30	0.00	0.00
		1.82		2.15		1.44		0.93		0.41		0.27		0.00	
	Veg Oil	1.70	1.91	2.06	2.10	1.65	1.55	1.32	1.15	1.01	0.79	0.50	0.53	0.00	0.00
		2.11		2.15		1.44		0.99		0.56		0.56		0.00	
	Biomass	1.65	1.73	2.16	2.04	1.78	1.64	1.72	1.87	1.22	1.20	1.35	1.43	0.84	1.10
		1.82		1.93		1.49		2.01		1.19		1.52		1.37	
	Control	1.91	1.82	2.29	2.27	1.73	1.72	2.31	1.80	1.40	1.34	0.93	1.03	0.43	0.65
		1.74		2.25		1.71		1.28		1.29		1.12		0.87	
		2/28/2011		3/3/2011		3/5/2011		3/7/2011		3/9/2011		3/10/2011		3/11/2011	

4.0 Data Analysis

The following section documents the analyses performed on the data as it was collected for each of the four study plots. Section 4.1 presents data analysis from the Roof 1 plot, Section 4.2 presents data analysis from the Roof 2 study plot, Section 4.3 presents data analysis from the Canopy study plot and Section 4.4 presents data analysis from the Open Meadow study plot.

4.1 Roof 1

The following three sections present analyses performed on the data as collected at the Roof 1 study plot. Section 4.1.1 presents the data over the entire duration of the data collection period, while Sections 4.1.2 and 4.1.3 present the data for the *Accumulation Period* and the *Loss Period* of the snowpack, respectively.

4.1.1 Roof 1 Entire Duration of Data Collection

Data collection took place at the Roof 1 study plot from February 21st, 2011 to March 11th, 2011. Although this data collection period encompassed two significant storm events, the roof over the plot was utilized to capture snow from only the first storm event, which occurred on February 19th and 20th. Figure 13 shows that ten samples were taken during the data collection period. The thin biomass plot was only sampled seven times because the snow in this plot was completely ablated by March 8th.

Figure 13, on the next page, is a graphical representation of the snow water equivalent versus time for each of the four subplots in the Roof 1 study plot.

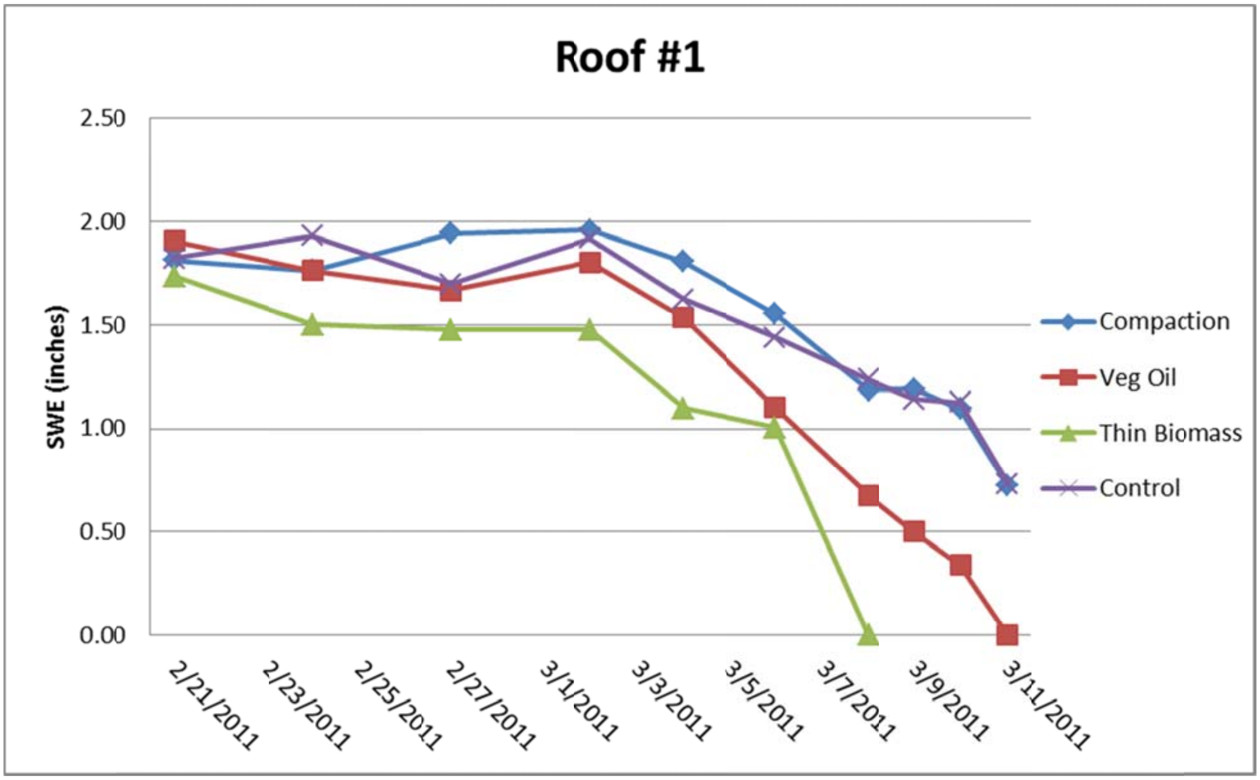


Figure 13: SWE versus time for the Roof 1 study plot

The snow on the thin biomass and vegetable oil subplots had completely ablated on March 8th and March 11th, respectively. However, on March 11th, the control and the compaction subplots still had an average of 0.73 and 0.72 inches of water present on each plot, respectively. Further, the graph shows two distinct trends in the data. The first trend takes place from February 21st to March 2nd, and can be categorized by a mild negative slope for the vegetable oil and thin biomass, and a slightly positive slope for the compaction and control data. This period will be referred to as the *Accumulation Period*. The second trend in the data can be categorized by a significant increase in negative slope for the data from each of the four subplots. This trend takes place from March 2nd to March 11th, and will be referred to as the *Loss Period*.

To make analysis of the data more meaningful, the analysis was performed for the *Accumulation* and *Loss* periods independently. The emphasis of the data analysis was focused on the *Loss Period* due to the fact that the treatments were designed to limit sublimation losses of snowpack, and the *Accumulation Period* does not illustrate much loss in SWE.

4.1.2 Roof 1 Accumulation Period

The graph of the snow water equivalent for each of the four subplots under Roof 1 from February 21st through March 2nd is shown in Figure 14 on the next page.

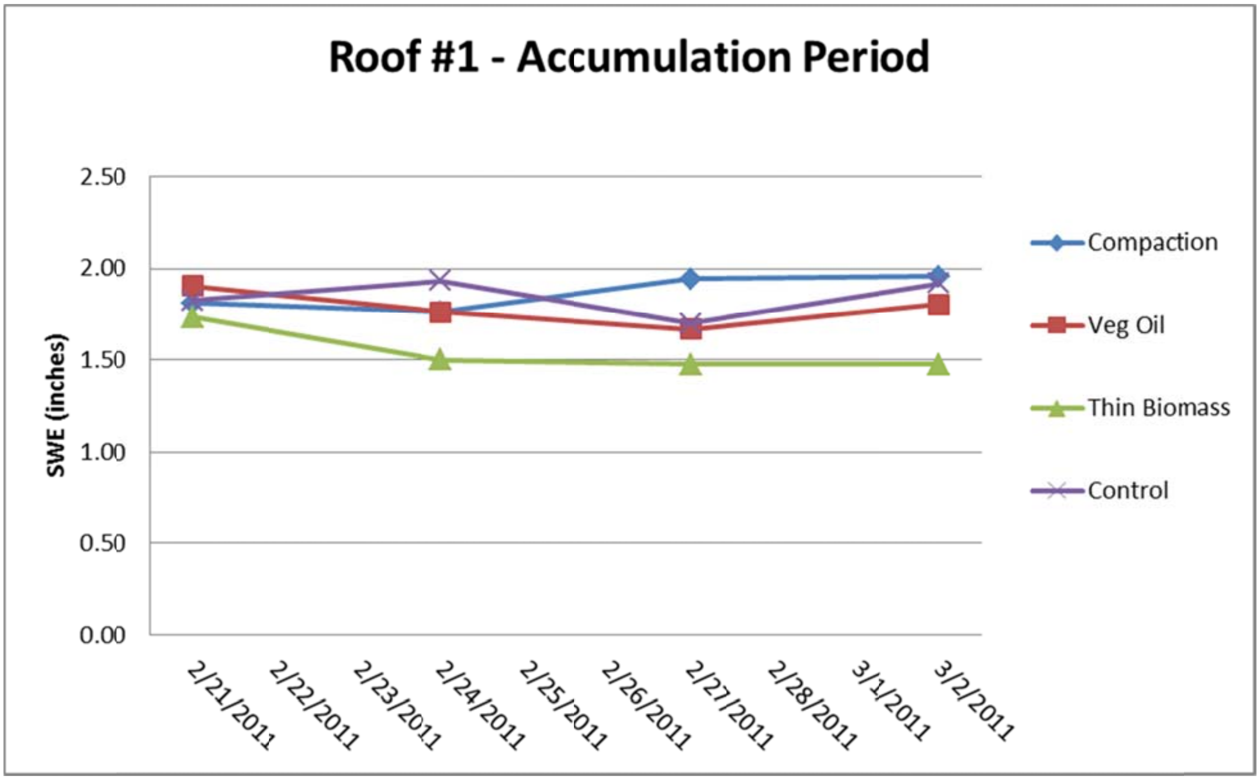


Figure 14: SWE versus time for the Roof 1 study plot

The SWE for each of the subplots decreased slightly or increased slightly during this time period. The compaction subplot saw an increase of 0.15 inches of SWE, while the control saw an increase of 0.10 inches of SWE. The vegetable oil and thin biomass subplots saw a decrease in SWE of 0.11 and 0.25 inches, respectively.

There were very minimal losses during the *Accumulation Period* in the Roof 1 study plot. The lack of losses and in the case of the compaction treatment and the control, the increase in SWE, is attributed to windblown snow infiltration from the storm event on February 26th and 27th. The pictures shown in Figure 15 and 16 on the following page support this theory. Additional snow accumulation can be seen on the applied treatments in both pictures. Each picture was taken on the afternoon of February 27th, the day the storm event ended.

Figure 15: Possible contamination of the Roof 1 study plot

Figure 16: Possible contamination of the Roof 1 study plot

Based on these observations, and the data collected, a detailed data analysis was only performed on the *Loss Period* of the data.

4.1.3 Roof 1 Loss Period

The graph of the snow water equivalent for each of the four subplots on the Roof 1 plot from March 2nd through March 11th is shown in Figure 17 below.

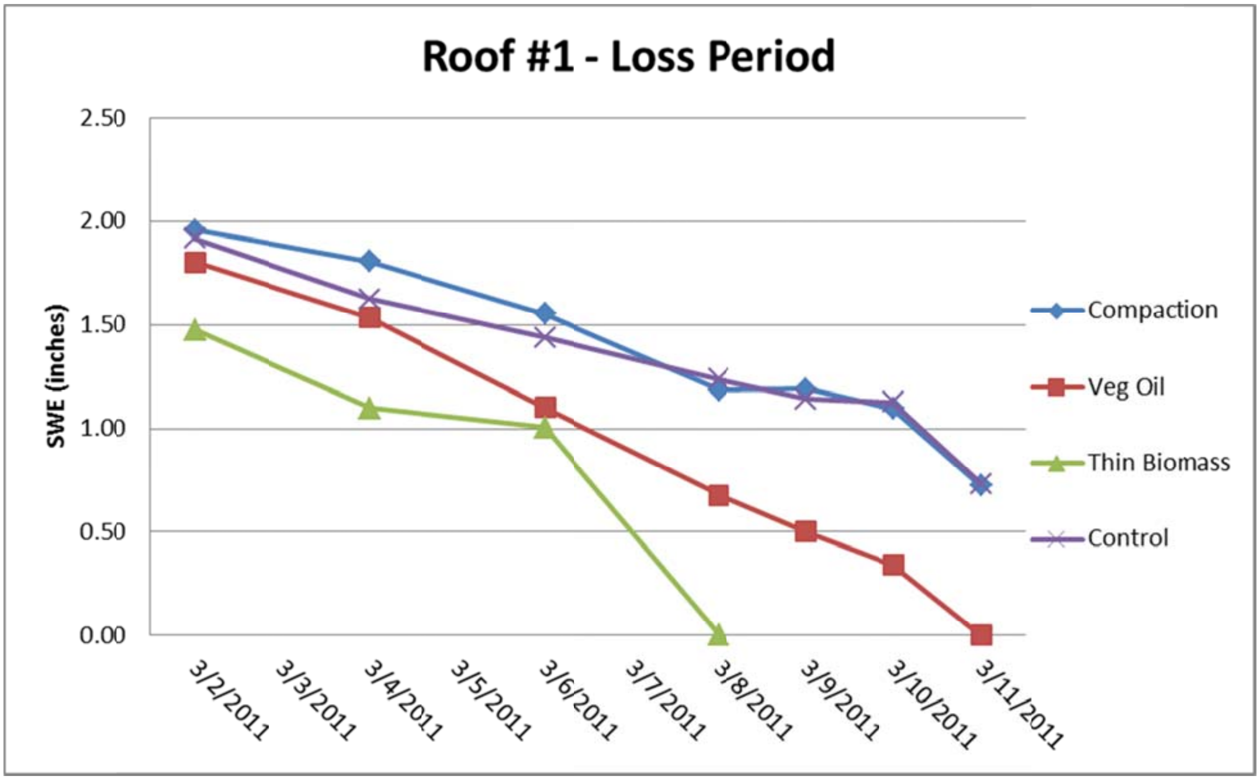


Figure 17: SWE versus time for the Roof 1 study plot

The thin biomass treatment subplot and the vegetable oil treatment subplot, experienced complete ablation of the snowpack much quicker than the control subplot and the subplot treated by compaction. The thin biomass subplot was completely ablated by March 8th, and the vegetable oil subplot was completely ablated by March 11th.

Figures 18 through 20 will present each treatment's linear regression line compared to the linear regression line of the control plot. This will provide a comparison of the effectiveness of a given treatment to the control.

Likewise, tables 5 through 7, which accompany figures 18 through 20, will show the slope and the coefficient of determination (R^2) for each linear regression line. The slope of the regression line represents that average loss of SWE (in inches) per day. The coefficient of determination (R^2) was used to support the validity of the data. The R^2 value ranges from 1.0 to 0, where 1.0 represents data that is perfectly represented by the linear regression line, and 0 represents an absence of correlation between the linear regression line and the actual data points.

Figure 18 below compares the linear regression line of the study plot treated by compaction to the linear regression line of the control plot.

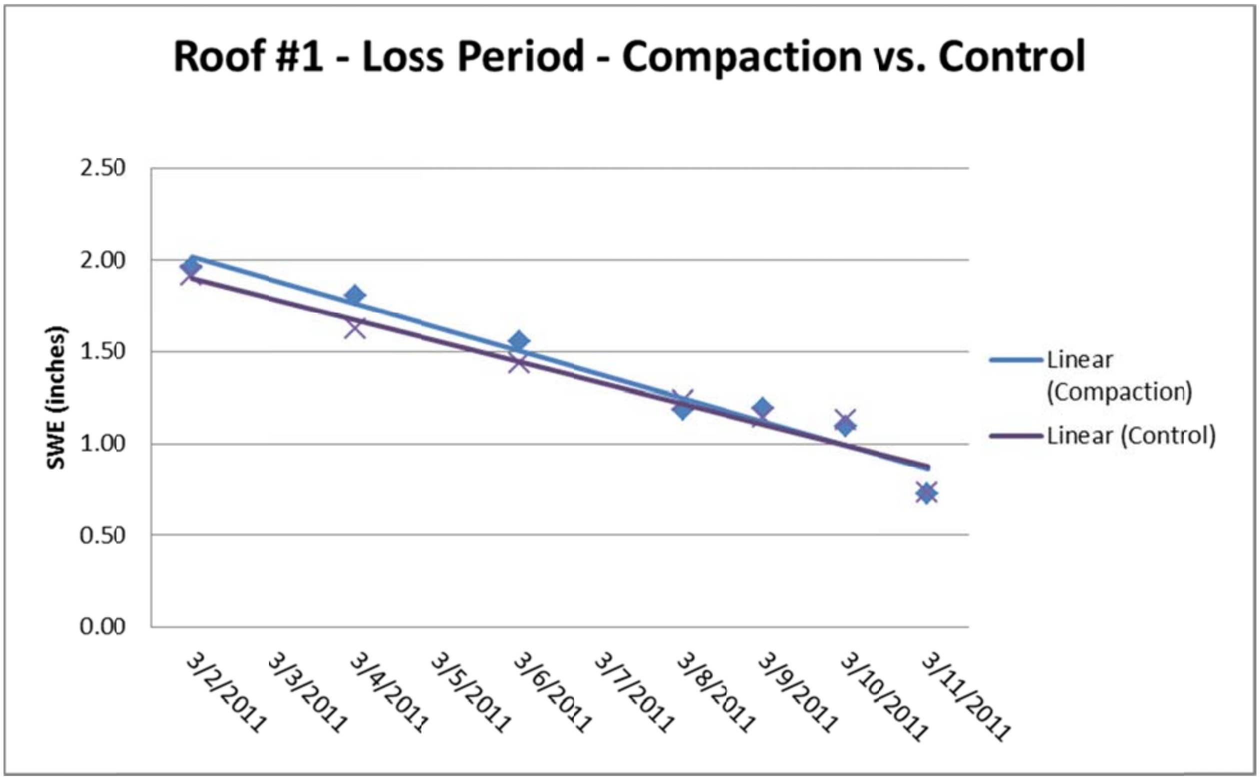


Figure 18: SWE linear regression line for compaction treatment versus the control

Table 5 below shows the slope and R^2 value of the regression line for the control and compaction subplots.

Table 5: Slope and R^2 values for compaction and control subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.11	0.95
Compaction	-0.13	0.96

As shown in Table 5, the compaction subplot saw an average rate of SWE loss of 0.13 inches per day, while the loss rate of the control plot was 0.11 inches per day. The R^2 values for the control and compaction plot were 0.95 and 0.96, respectively, showing a minimal amount of variance, and a strong correlation between the linear regression line and the actual data.

Figure 19 below shows both the linear regression line of the subplot treated by vegetable oil and the linear regression line of the control subplot.

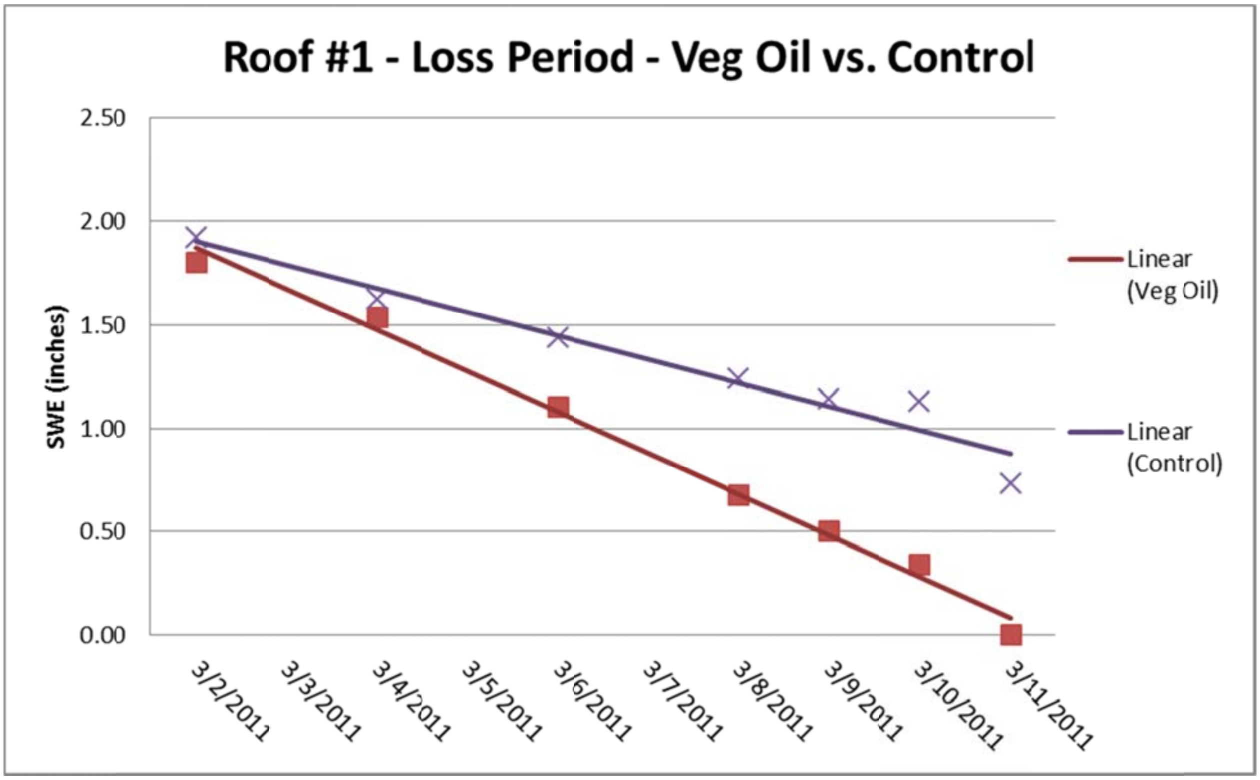


Figure 19: SWE linear regression line for vegetable oil treatment versus the control

Table 6 below shows the slope and R^2 value of the regression line for the control and vegetable oil subplots.

Table 6: Slope and R^2 values for vegetable oil and control subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.11	0.95
Vegetable Oil	-0.20	0.99

The study plot treated with vegetable oil averaged a loss of 0.20 inches of SWE per day, which was a higher loss rate than that of the control plot. The R^2 value for the subplot treated with vegetable oil was 0.99, showing a very strong correlation between the regression line and the actual data.

Figure 20 below shows the linear regression line of the study plot treated by thin biomass blanketing to the linear regression line of the control subplot.

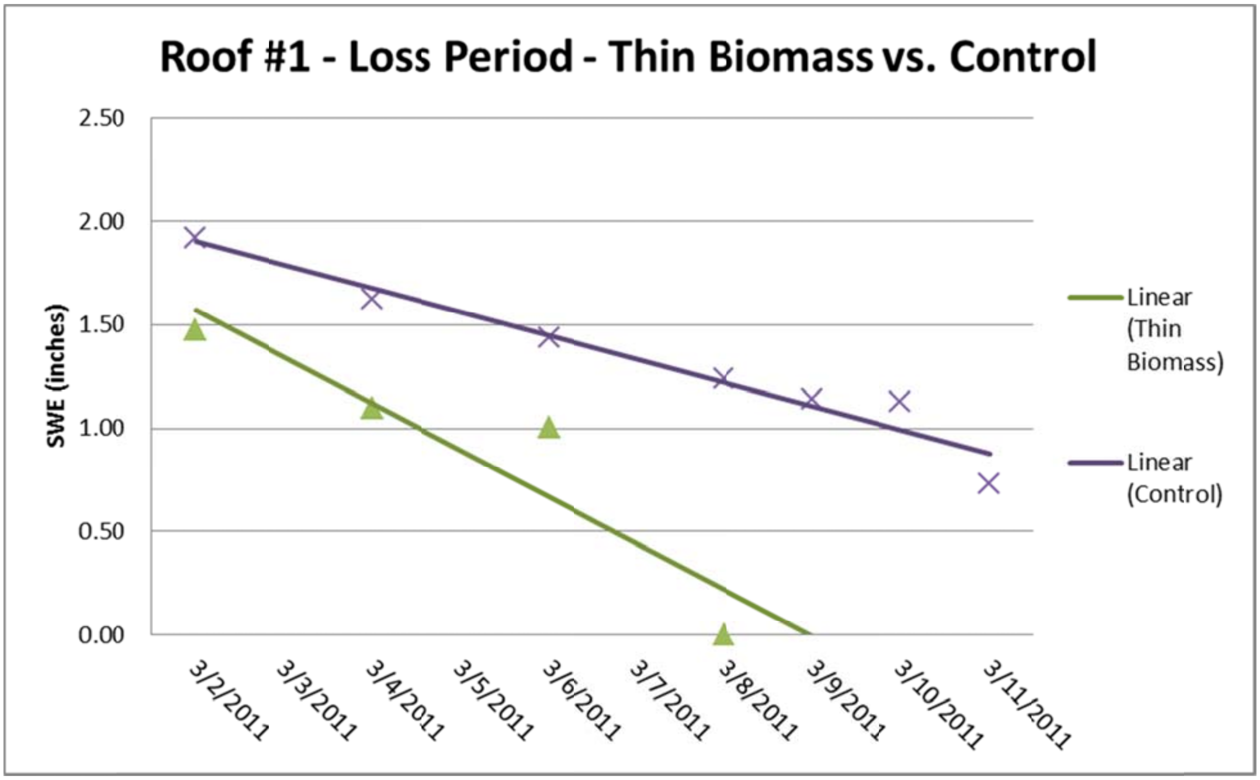


Figure 20: SWE linear regression line for the thin biomass treatment versus the control

Table 7 below shows the slope and R^2 value of the regression line for the control and the thin biomass subplots.

Table 7: Slope and R^2 values for thin biomass and control subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.11	0.95
Thin Biomass	-0.23	0.86

As is noted in the table above, the study plot treated with thin biomass blanketing averaged a loss of 0.23 inches of SWE per day. The R^2 value for the subplot treated with thin biomass was 0.86.

As team members from Snowpack Engineering were collecting data samples, there seemed to be a visible relationship between location of the treatment in the roofed study plots, and how fast their snowpack was melting. Snow was melting faster in the southern portion than in the northern portion of the roof structures. Sun contamination of the southern two study plots was documented as a major issue. Shown in Figure 21 below, is a picture of the Roof 1 study plot showing the effects of sun contamination in the southern subplots. Because this was identified as an influencing factor on the data, Snowpack Engineering attempted to remediate the design by screening the southern and western sides of the roof structures with a woven cloth shade. The shading did not seem to solve the sun contamination problem as the data below will show.

Figure 21: Sun contamination in the Roof 1 study plot

A comparison of the average SWE between north and south plots was used to incorporate the solar effect into data analysis. The data, which is based on the averages and their associated rates of loss, further validated Snowpack Engineering's concerns about the effect the sun had on the Roof 1 study plot. The results of this comparison are shown in Figure 22 on the next page.

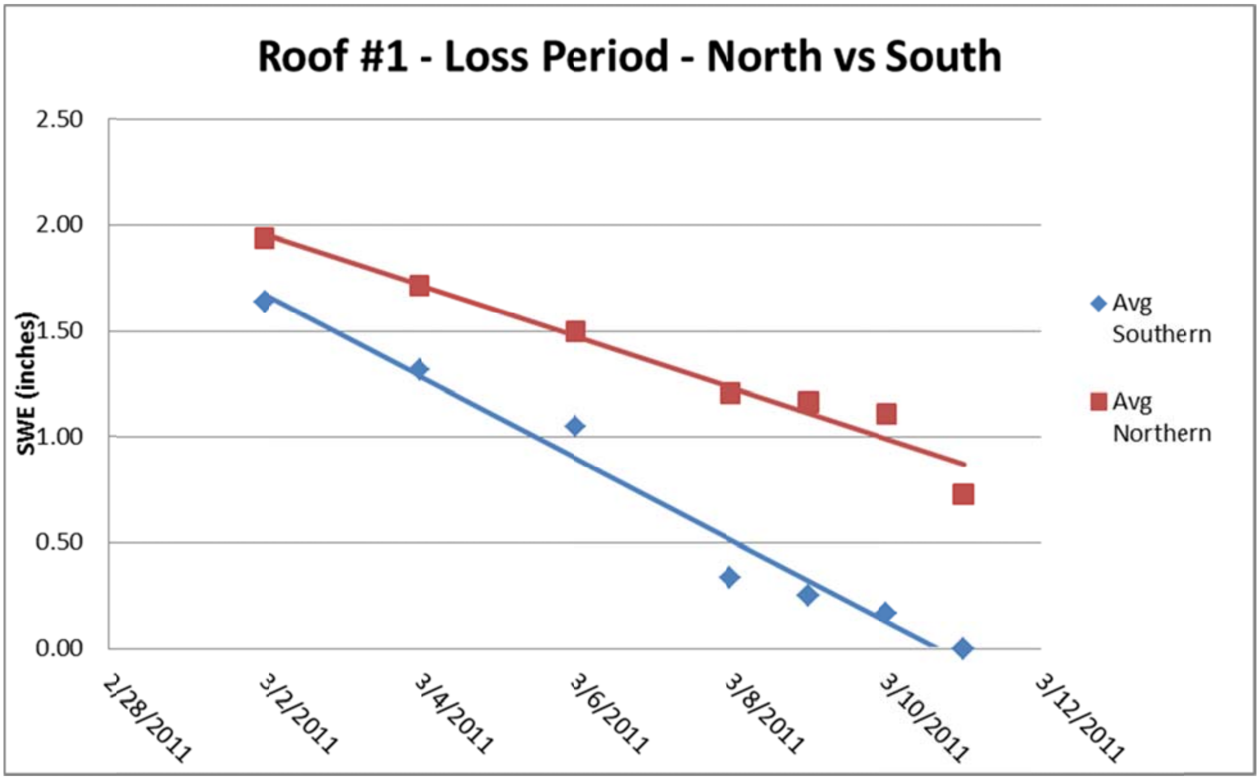


Figure 22: SWE for the northern and southern subplots

Table 8 below shows the slope and R^2 value of the regression lines for the southern and northern subplots.

Table 8: Slope and R^2 values for southern and northern subplots

	Slope (inches SWE/day)	**R^2 Value**
Northern Subplots	-0.12	0.96
Southern Subplots	-0.19	0.97

The average loss of SWE per day for subplots in the northern portion of the roofed plot was 0.12 inches, while the average loss of SWE per day for subplots in the southern portion of the roofed plot was 0.19 inches of water. The R^2 values for the northern and southern plots were 0.96 and 0.97, respectively, showing a strong correlation between the best fit line and the data points. This data shows a very strong correlation between where the subplots were located and the loss rate of snow water equivalent. For this reason, most of the above data was ignored when determining effective treatments at limiting sublimation losses.

4.2 Roof 2

The following two sections present analyses performed on the data collected at the Roof 2 study plot. Section 4.2.1 presents the data over the entire duration of the data collection period. Section 4.2.2 presents the data for the *Loss Period*.

4.2.1 Roof 2 Entire Duration of Data Collection

Data collection took place at the Roof 2 study plot from February 28th, 2011 to March 11th, 2011. This period started right after the completion of the second significant storm of the overall data collection period, which took place on February 26th and 27th. Seven samples were taken during this time. Figure 23 below is a graphical representation of the snow water equivalent versus time for the four subplots in the Roof 2 study plot.

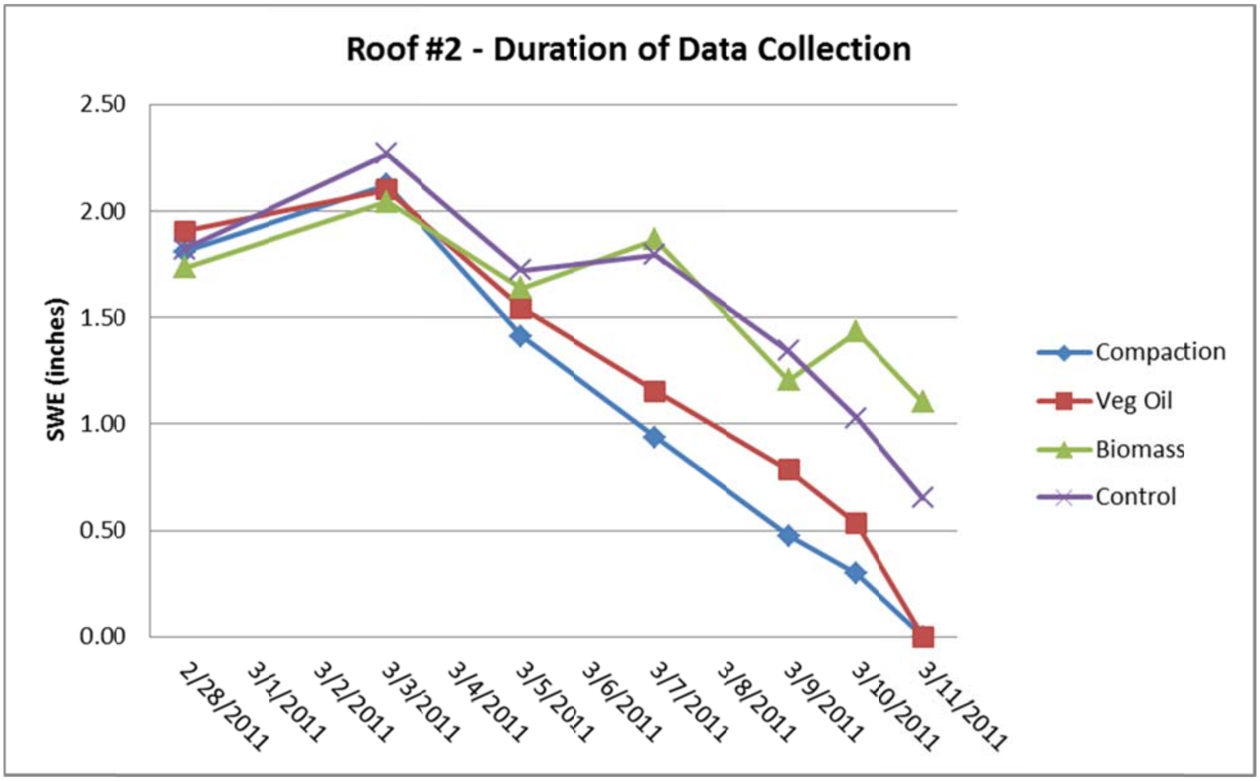


Figure 23: SWE versus time for the Roof 2 study plot

The snow on the compaction and vegetable oil study plots had completely ablated by March 11th. However, on March 11th, the biomass and control plots still had an average of 1.10 and 0.65 inches of SWE, respectively. There is a consistent increase in SWE values from February 28th to March 3rd, even though a storm event did not occur during this time period. Because this study was looking at losses of snowpack, and because the increase in SWE between February 28th and March 3rd is unexplained, only the data during the *Loss Period* of the snowpack was analyzed. This period takes place from March 3rd to March 11th.

4.2.2 Roof 2 Loss Period

The graph of the snow water equivalent for the four subplots under Roof 2 from March 3rd through March 11th is shown in Figure 24 below. The compaction treatment plot, as well as the vegetable oil treatment plot, experienced complete ablation of the snowpack much quicker than either the snowpack treated with a thick biomass blanket or the control plot. At the completion of the data collection period, the thick biomass plot and the control plot still had 1.10 and 0.65 inches of SWE, respectively.

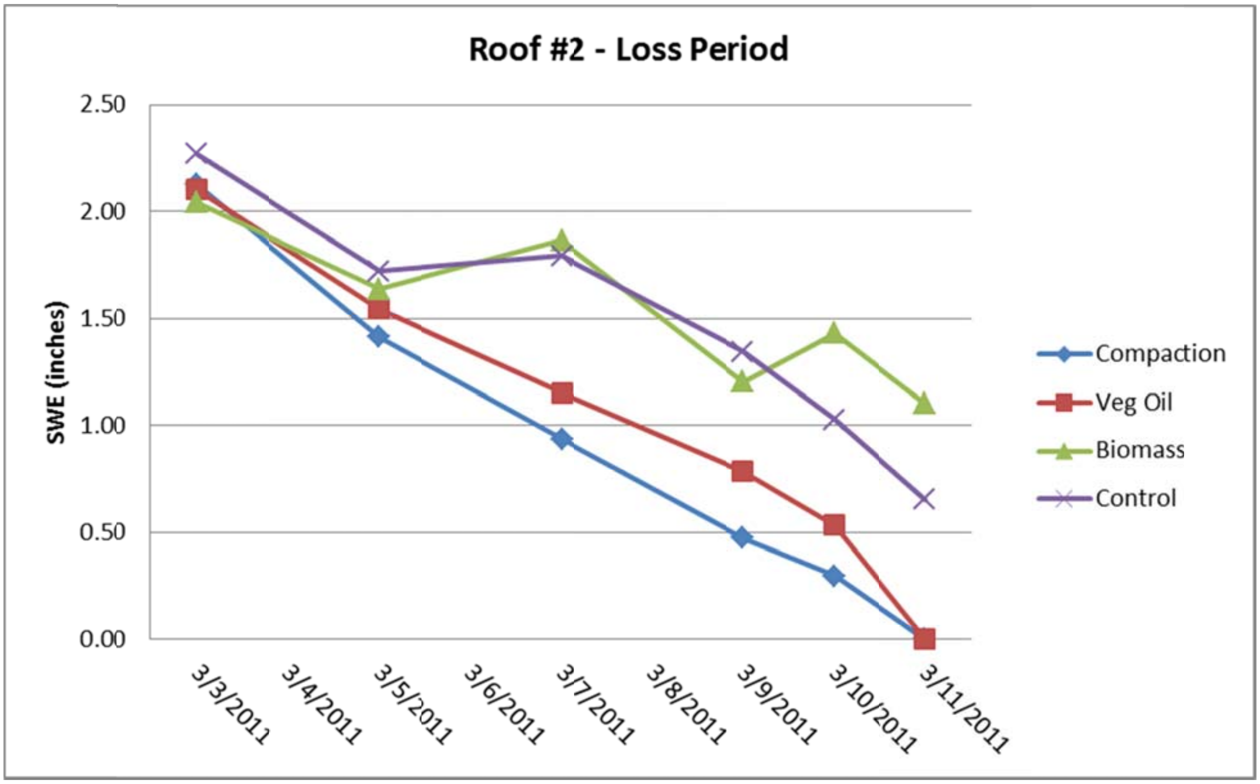


Figure 24: SWE versus time for the Roof 2 study plot

Figure 25 on the following page shows a comparison of the average rate of SWE loss between the compaction subplot and the control.

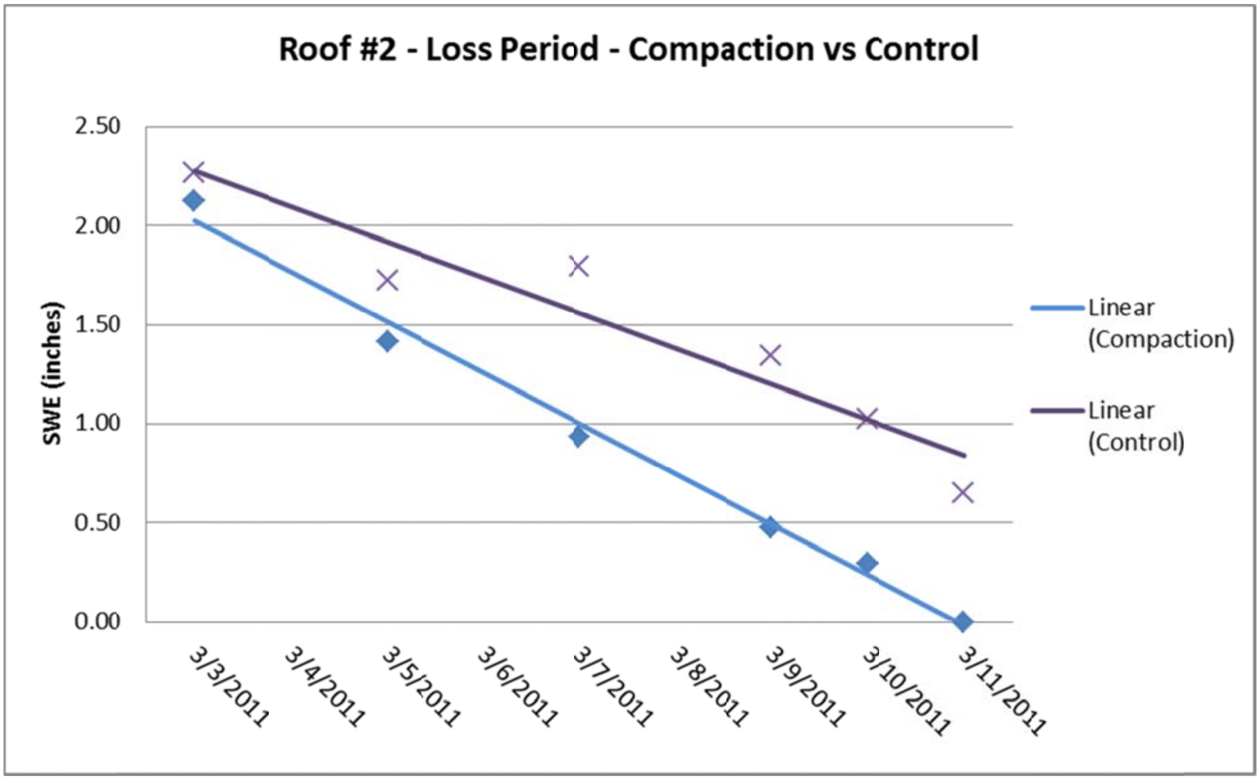


Figure 25: SWE linear regression line for compaction treatment versus the control

Table 9 below shows the slope and R^2 value of the regression lines for the control and compaction subplots.

Table 9: Slope and R^2 values for control and compaction subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.18	0.91
Compaction	-0.26	0.99

As shown in Table 9, the compaction subplot saw an average SWE loss of 0.26 inches per day, while the loss rate of the control plot was 0.18 inches per day. The R^2 values for the control and compaction plot were 0.91 and 0.99, respectively, showing a minimal amount of variance and a strong correlation between the linear regression line and the actual data.

Figure 26 on the following page shows the linear regression line representing the average rate of SWE loss from the study plot treated by vegetable oil compared to the average rate of SWE loss from the control subplot.

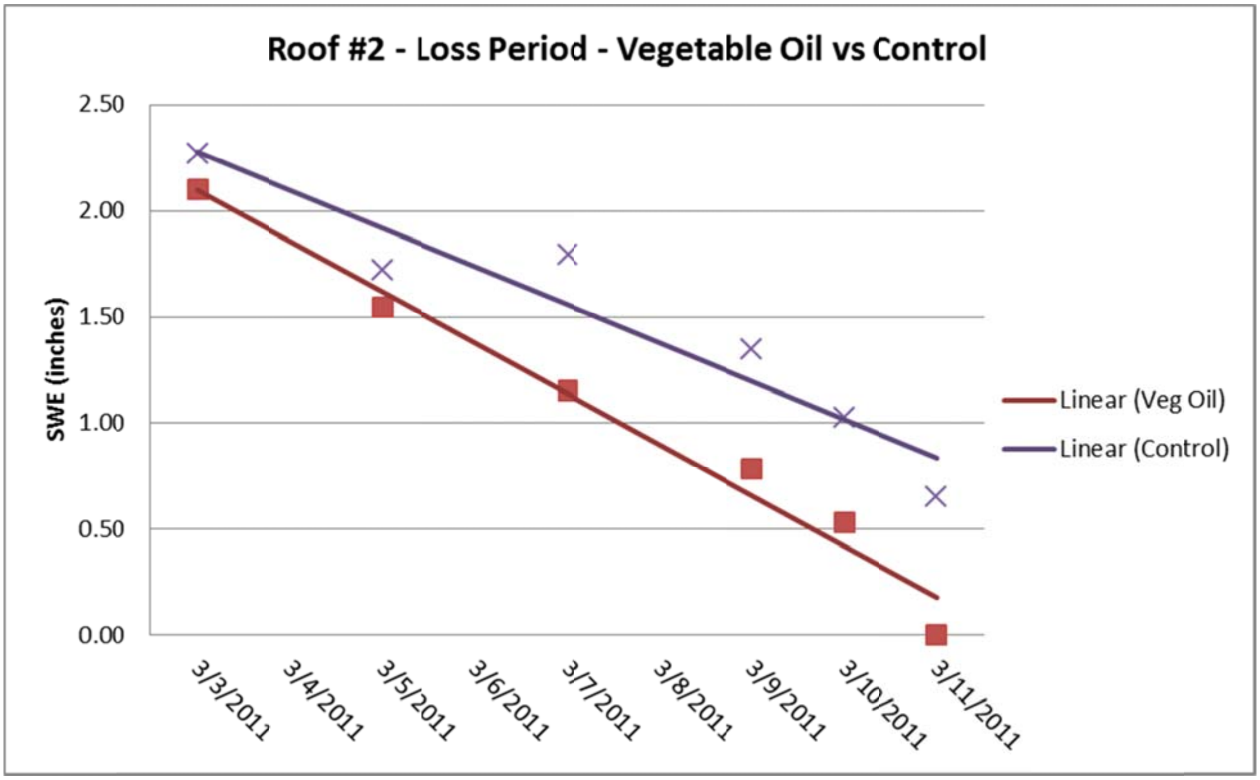


Figure 26: SWE linear regression line for vegetable oil treatment versus the control

Table 10 below shows the slope and R^2 value of the regression lines for the control and vegetable oil subplots.

Table 10: Slope and R^2 values for control and vegetable oil subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.18	0.91
Vegetable Oil	-0.24	0.98

As seen in Table 10, the vegetable oil subplot saw an average SWE loss of 0.24 inches per day. The R^2 value of the vegetable oil subplot was 0.98, showing a strong correlation between the linear regression line and the actual data.

Figure 27 on the next page shows the linear regression line from the subplot treated by thick biomass blanketing compared to the linear regression line from the control subplot.

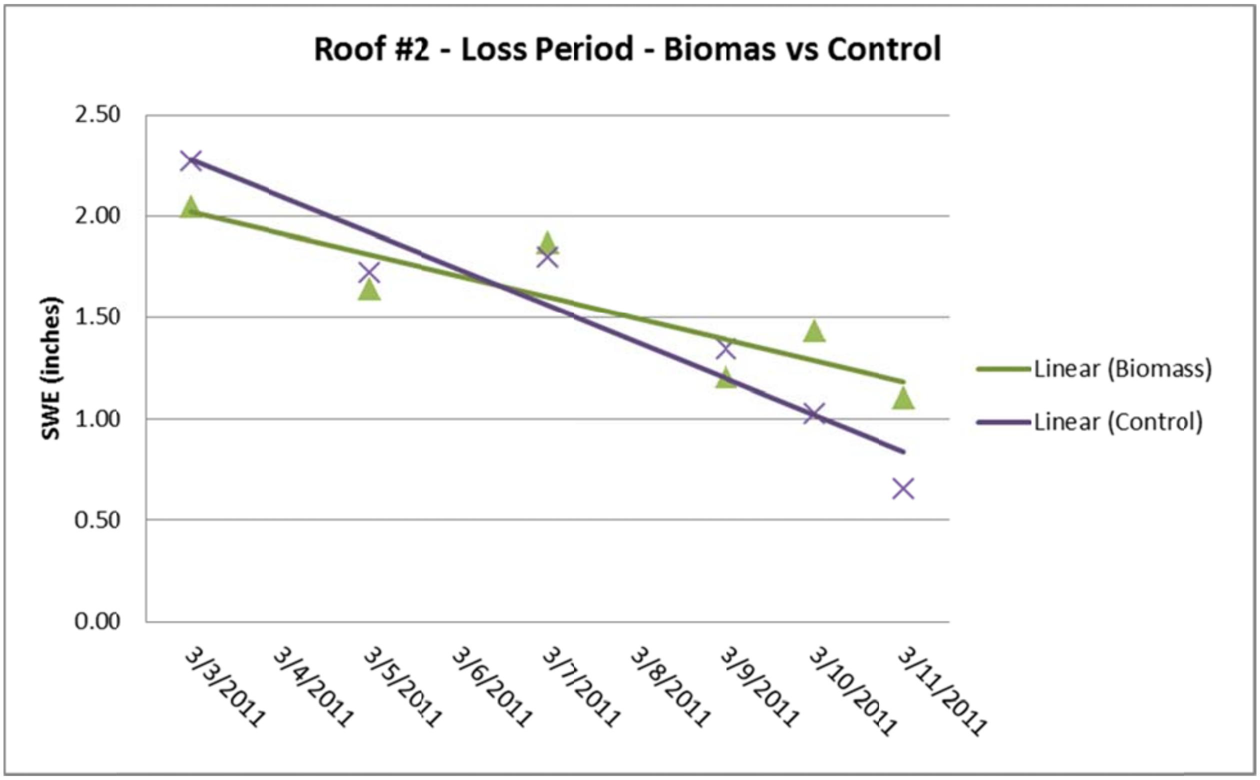


Figure 27: SWE linear regression line for biomass treatment versus the control

Table 11 below shows the slope and R^2 value of the regression lines for the control and thick biomass subplots.

Table 11: Slope and R^2 values for control and thick biomass subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.18	0.91
Thick Biomass	-0.10	0.76

As seen in Table 11, the thick biomass subplot saw an average SWE loss of 0.10 inches per day. The R^2 value of the thick biomass regression line was 0.76, showing a fairly strong correlation between the linear regression line and the actual data.

As was documented in the Roof 1 study plot, there was an observed difference between the rate of SWE loss in the subplots located under the southern portion of the roof structures and those located under the northern portion of the roof structures. To further document if there was a correlation between the location of the subplots and the rate at which the snowpack ablated, the average SWE for the northern plots versus time was graphed against the average SWE for the southern plots versus time. The results of this comparison are shown in Figure 28 and Table 12 on the following page.

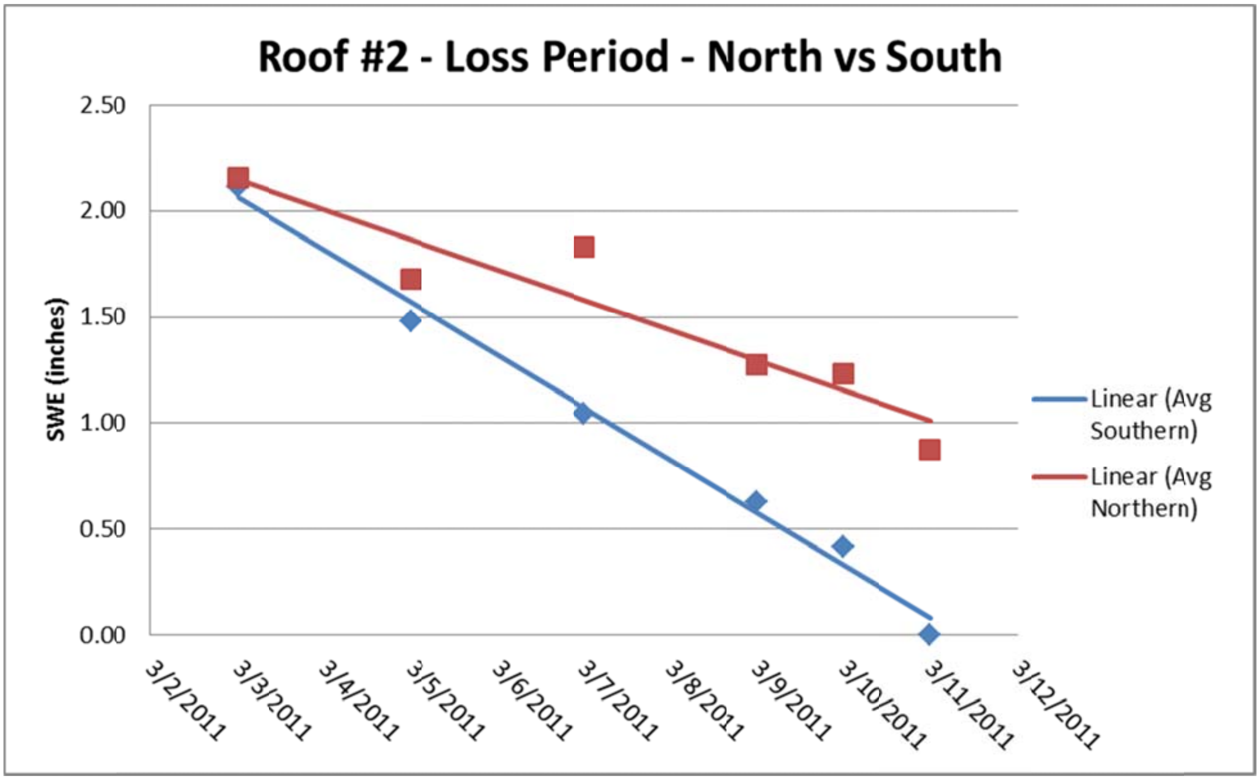


Figure 28: SWE for the northern and southern subplots

Table 12 below shows the slope and R^2 value of the regression lines for the southern and northern subplots.

Table 12: Slope and R^2 values for the southern and northern subplots

	Slope (inches SWE/day)	**R^2 Value**
Southern	-0.25	0.99
Northern	-0.14	0.89

The average loss of SWE per day for subplots in the northern portion of the Roof 2 study plot was 0.14 inches, while the average loss of SWE per day for subplots in the southern portion of the Roof 2 study plot was 0.25 inches of water. The R^2 values for the northern and southern plots were 0.89 and 0.99, respectively. As was done with the Roof 1 study plot, this data was ignored when determining the effectiveness of the treatments because the ablation was more strongly correlated to the location of the subplots.

4.3 Canopy

The following three sections present analyses performed on the data as collected at the Canopy study plot. Section 4.3.1 presents the data over the entire duration of the data collection period, while

Sections 4.3.2 and 4.3.3 present the data for the *Accumulation Period* and the *Loss Period* of the snowpack, respectively.

4.3.1 Canopy Entire Duration of Data Collection

Data collection took place at the Canopy study plot from February 21st, 2011 to March 7th, 2011. This data collection period encompassed two significant storm events. The first storm event took place February 19th and 20th, and the second storm event took place February 26th and 27th. Thus, as can be seen from Figure 34 below, there were two sample days after the first storm event, and four after the second storm event.

Figure 29 below is a graphical representation of the snow water equivalent (SWE) versus time for each of the four subplots in the Canopy study plot.

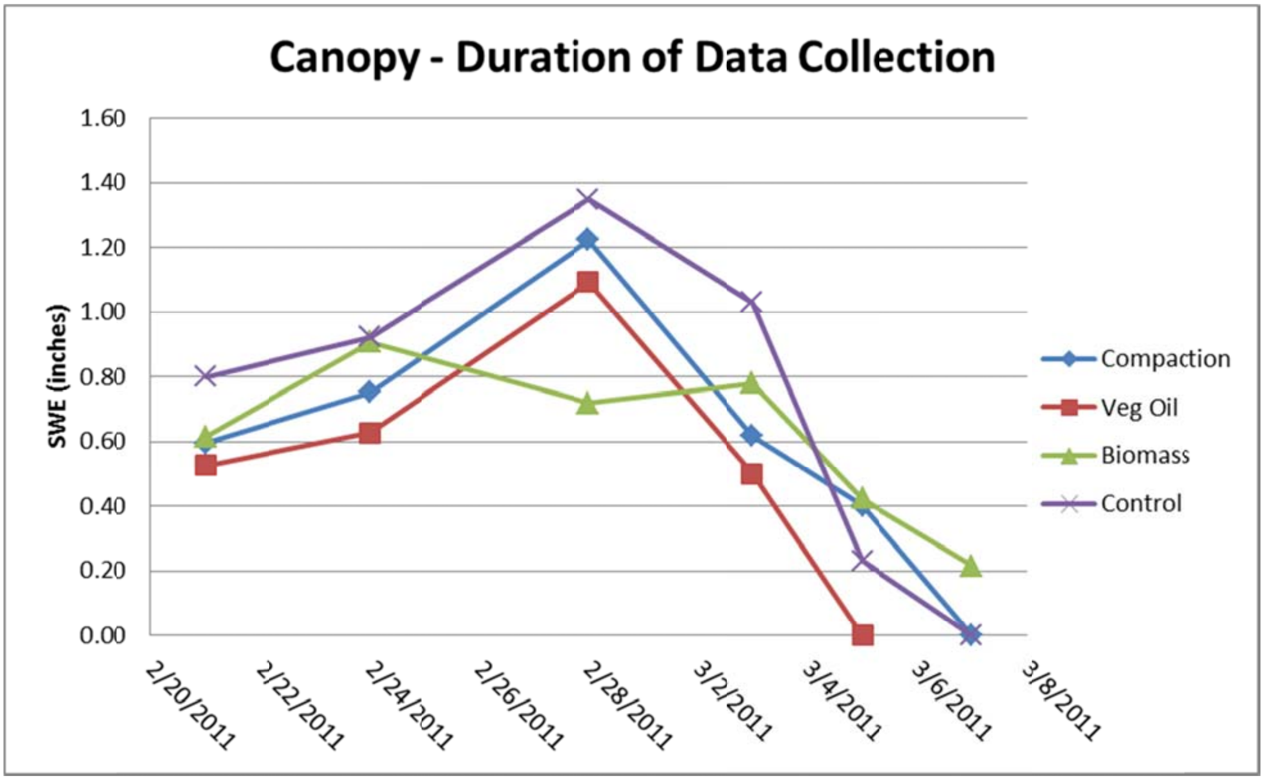


Figure 29: SWE versus time for the Canopy study plot

The snow on the vegetable oil subplot was completely eliminated by March 5th, while the snow on the compaction and control subplots was not completely ablated until March 7th. However, on March 7th, the thick biomass subplot still had an average SWE of 0.22 inches.

Furthermore, the graph shows two distinct trends in the data. The first trend was from February 21st to February 28th, and can be categorized by each of the snow water equivalents increasing. This period will be referred to as the *Accumulation Period*. The second trend in the data took place from February 28th to March 7th, when there were consistent losses in each of the subplots until they had been completely ablated. This period will be referred to as the *Loss Period*.

As was done with the two roofed study plots, the analyses were performed separately for both the *Accumulation* and *Loss* periods. The emphasis of the data analysis is focused on the *Loss Period* because the treatments were designed to limit sublimation losses of snowpack, and the *Accumulation Period* does not illustrate much loss in snow water equivalent. It should also be noted that during the *Accumulation Period*, the biomass was applied in a very thin layer, and during the *Loss Period*, the biomass was reapplied in a thick layer of about three to four inches.

4.3.2 Canopy Accumulation Period

The *Accumulation Period* of the Canopy site encompasses the time between the two major storm events, from February 21st through the 28th. The snow water equivalent increased during this time period in each of the four subplots. As can be seen in Figure 30, the SWE increased 0.16 inches in the compaction subplot, 0.10 inches in the vegetable oil subplot, 0.29 inches in the thin biomass subplot and 0.12 inches in the control subplot. The average increase in snow water equivalent for each of the four subplots was 0.17 inches over the course of the three days.

Figure 30, shown below, is a graphical representation of the increase of the snow water equivalent for each of the four subplots in the Canopy study plot.

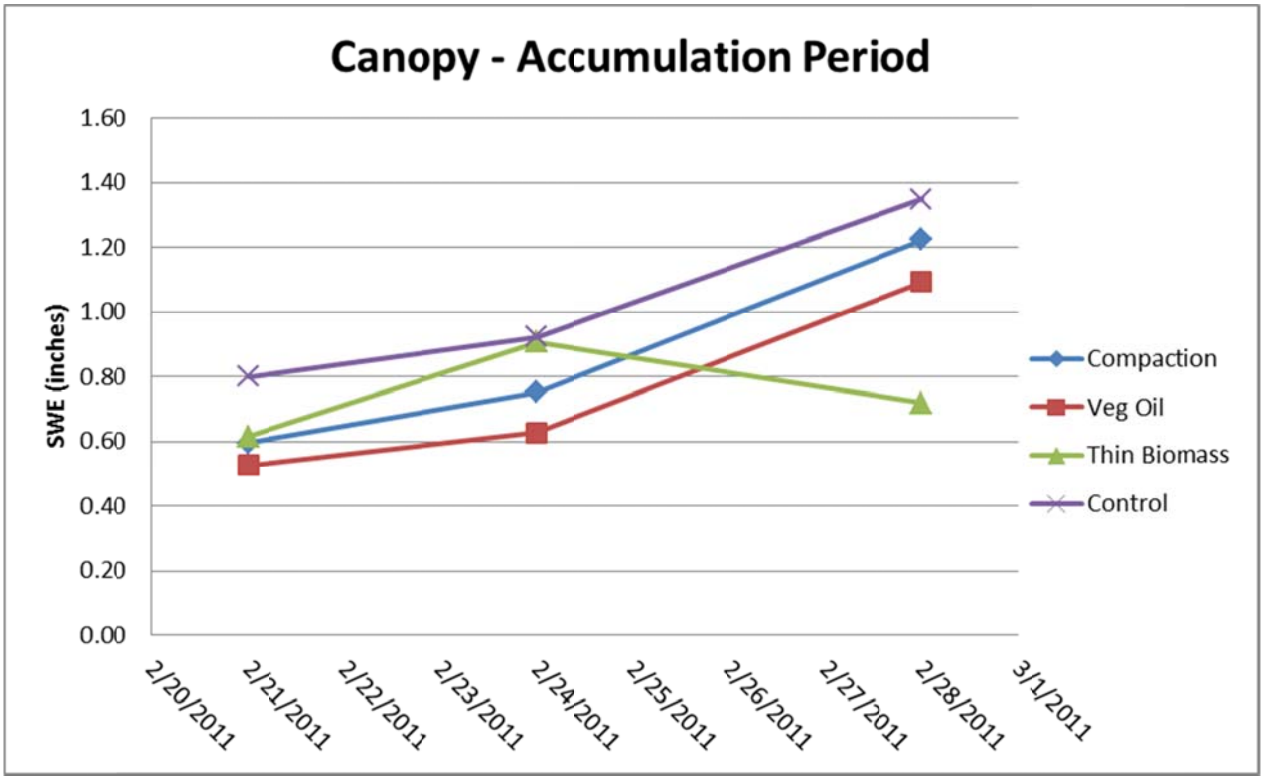


Figure 30: SWE versus time for the Canopy study plot

Each of the snow water equivalents increased during the *Accumulation Period* in the subplots. The thin biomass did show a local decrease in SWE from February 24th to the 28th, but the overall snow water equivalent increased in the biomass plot from February 21st to February 28th. The increase in SWE for the subplots makes it nearly impossible to quantify the sublimation losses during this time period. For this reason, the majority of the in-depth data analysis was done on the *Loss Period* of the Canopy plot.

4.3.3 Canopy Loss Period

The *Loss Period* of the canopy site encompasses the time after the second major storm event until the completion of snowpack ablation, from February 28th through March 7th. As can be seen in Figure 31 each of the treatments' snow water equivalents declined during this period. The subplot treated with vegetable oil lost all of its snow by March 5th and sampling ceased altogether on March 7th when the compaction and control had also reached negligible amounts of snow. Although sampling stopped at this point, the plot with a thick biomass treatment still retained approximately 0.22 inches of SWE.

Figure 31 below shows the plot of snow water equivalents versus time for each of the subplots during the *Loss Period* in the Canopy study plot.

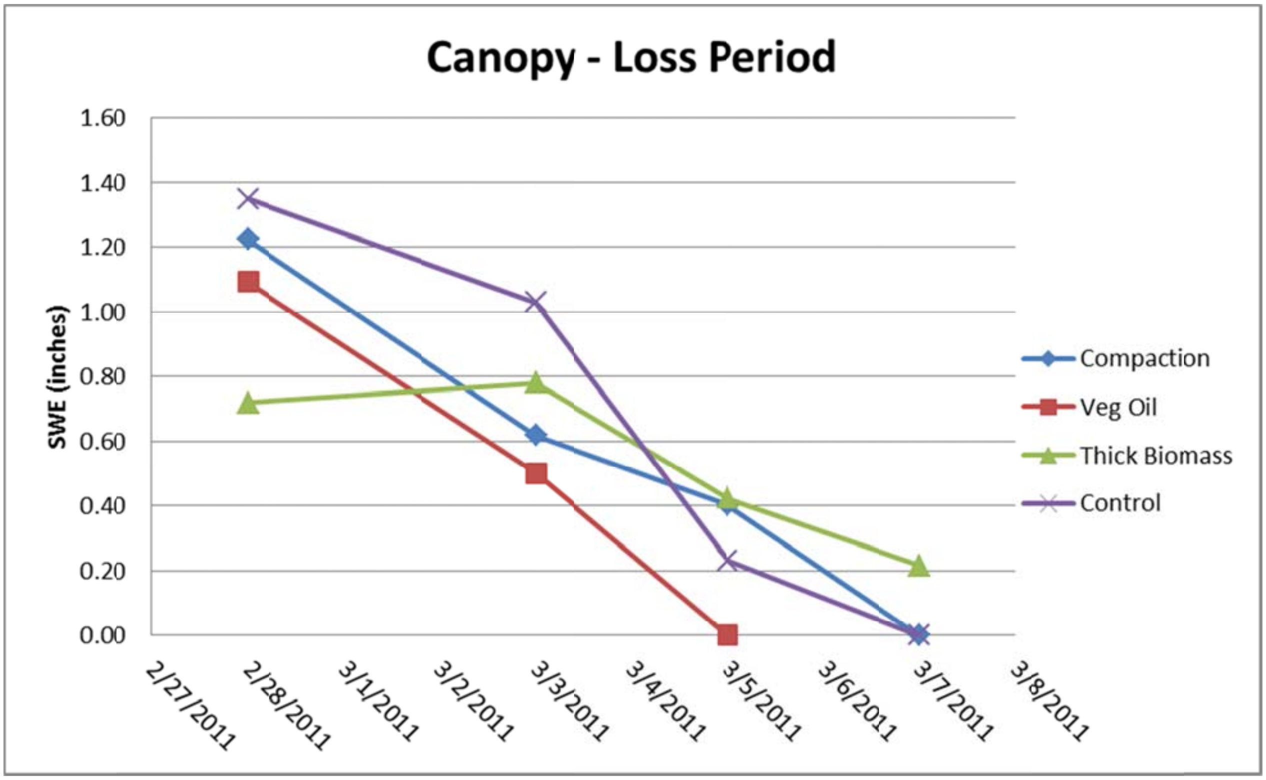


Figure 31: SWE versus time for the Canopy study plot

Each of the treatment's data was fit with a linear regression line in Microsoft Excel. As was done for the roofed study plots, the slope from each of the linear regression lines will represent the average SWE loss per day for a specific treatment. Also performed in Excel was a calculation of the coefficient of determination (R^2).

Figure 32 shows the linear regression lines for the thick biomass and control subplots. A linear regression of the vegetable oil and compaction subplots were not performed because it is apparant from Figure 31 that they did not work better than the control.

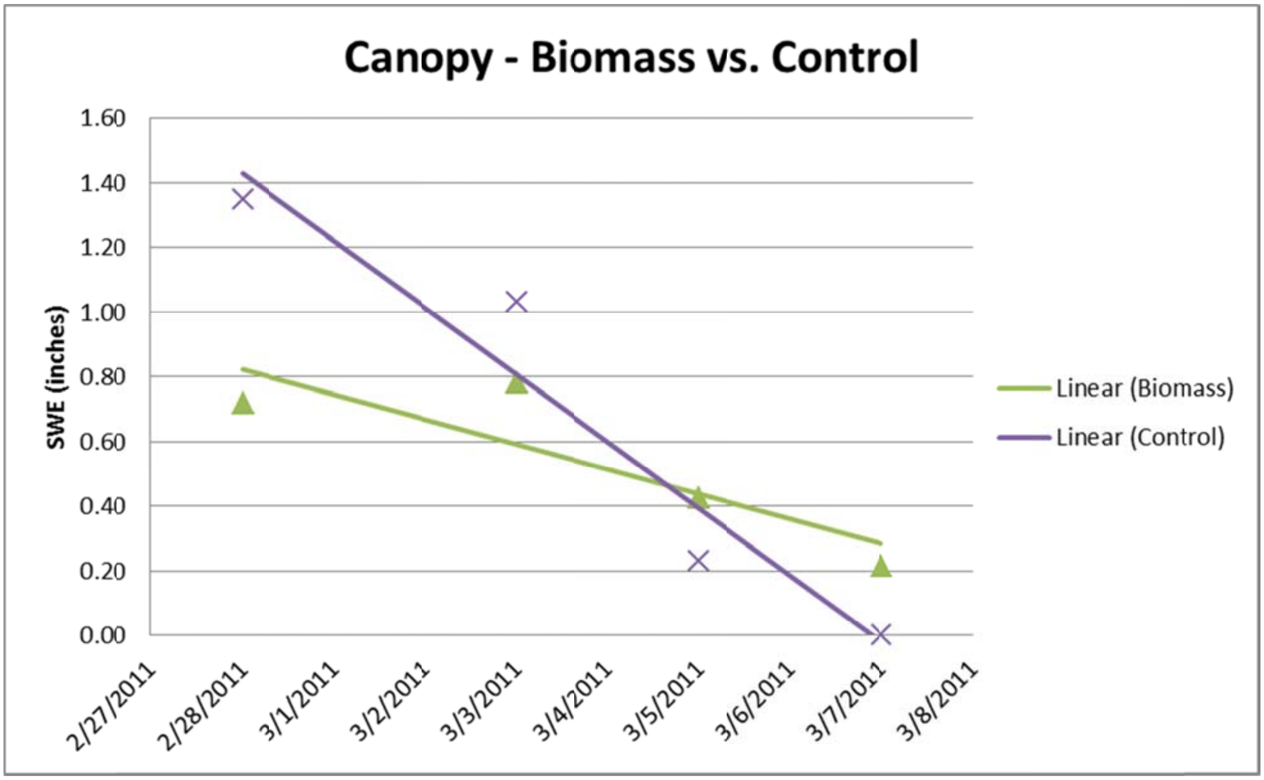


Figure 32: SWE linear regression line for biomass versus control

Table 13 shows the slope and the R^2 value for the regression lines of the control and thick biomass subplots.

Table 13: Slope and R^2 values for the control and thick biomass subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.21	0.93
Thick Biomass	-0.08	0.75

The slopes of the regression lines indicate that the average rate of SWE loss was 0.21 inches on the control subplot and 0.08 inches on the thick biomass subplot. The R^2 values for the thick biomass and control subplots were 0.75 and 0.93. Each of these values shows a fairly strong correlation between the regression line and the data the line represents.

The regression lines in Figure 32 suggest that the thick biomass treatment was most effective at reducing losses of the snowpack. Because the subplots each started out with different levels of snow, the data was alternatively graphed as a percent loss of SWE over time as seen in Figure 33.

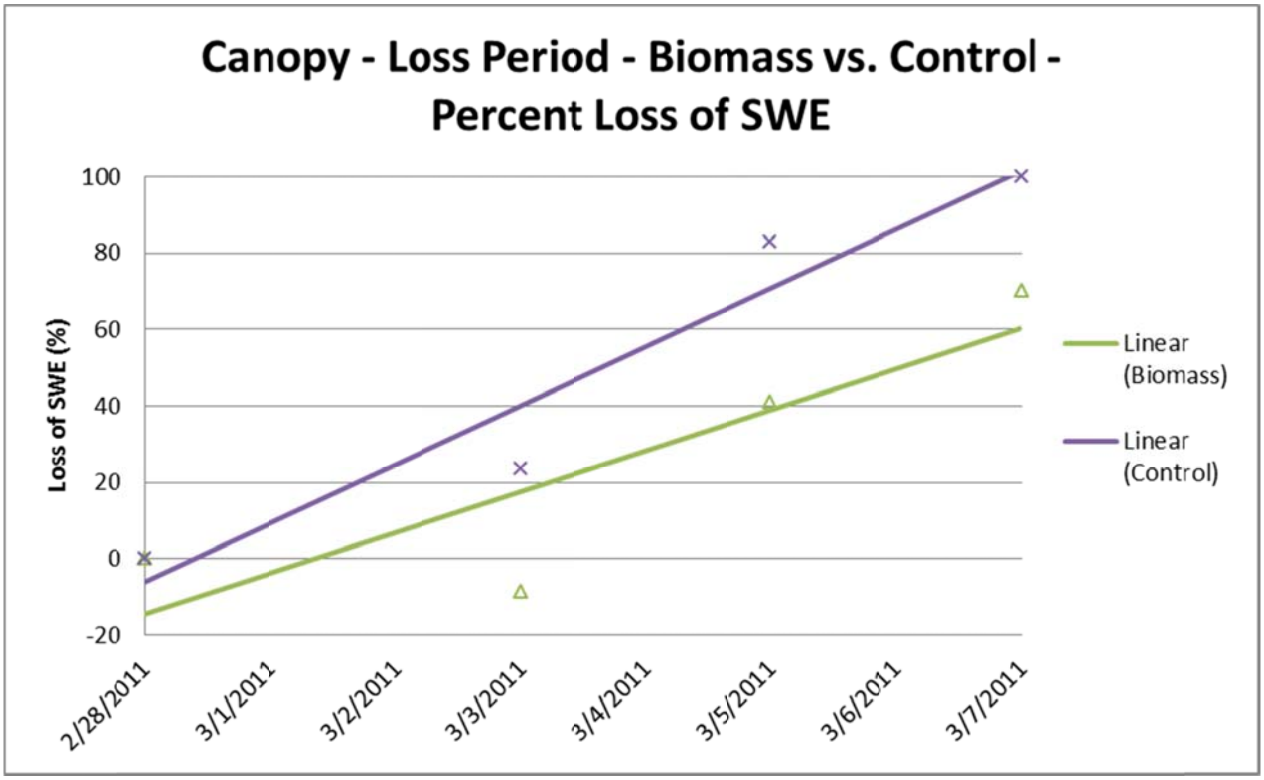


Figure 33: SWE linear regression as a percent loss for the biomass versus control

Table 14 shows the slope and the R^2 value for the regression lines of the control and the thick biomass subplots.

Table 14: Slope and R^2 values for the control and thick biomass subplots

	Slope (% SWE/day)	**R^2 Value**
Control	-15.35	0.93
Biomass	-10.67	0.75

The control subplot lost an average of about 15.35% of its SWE per day, while the thick biomass plot only lost about 10.67% of its SWE per day. Further, at the end of the data collection period, the control had lost 100% of its original SWE, while the thick biomass subplot had only lost about 70% of its original SWE. The R^2 value for the control subplot and biomass subplots were again 0.93 and 0.75.

4.4 Open Meadow Plot

The following three sections present analyses performed on the data collected at the Open Meadow study plot. Section 4.4.1 presents data over the entire duration of the data collection period, while Sections 4.4.2 and 4.4.3 present data for the *Accumulation Period* and the *Loss Period* of the snowpack.

4.4.1 Open Meadow Duration of Data Collection

Data collection took place at the Open Meadow study plot from February 21st, 2011 to March 9th, 2011. This period encompassed the same two storm events as the Canopy plot, with storm one occurring on February 19th and 20th, and storm two occurring on February 26th and 27th. Thus, as can be seen from Figure 34 below, there were two sample days after the first storm event, and six sample days after the second storm event.

Figure 34 below is a graphical representation of the snow water equivalent versus time for each of the four subplots in the Open Meadow study plot.

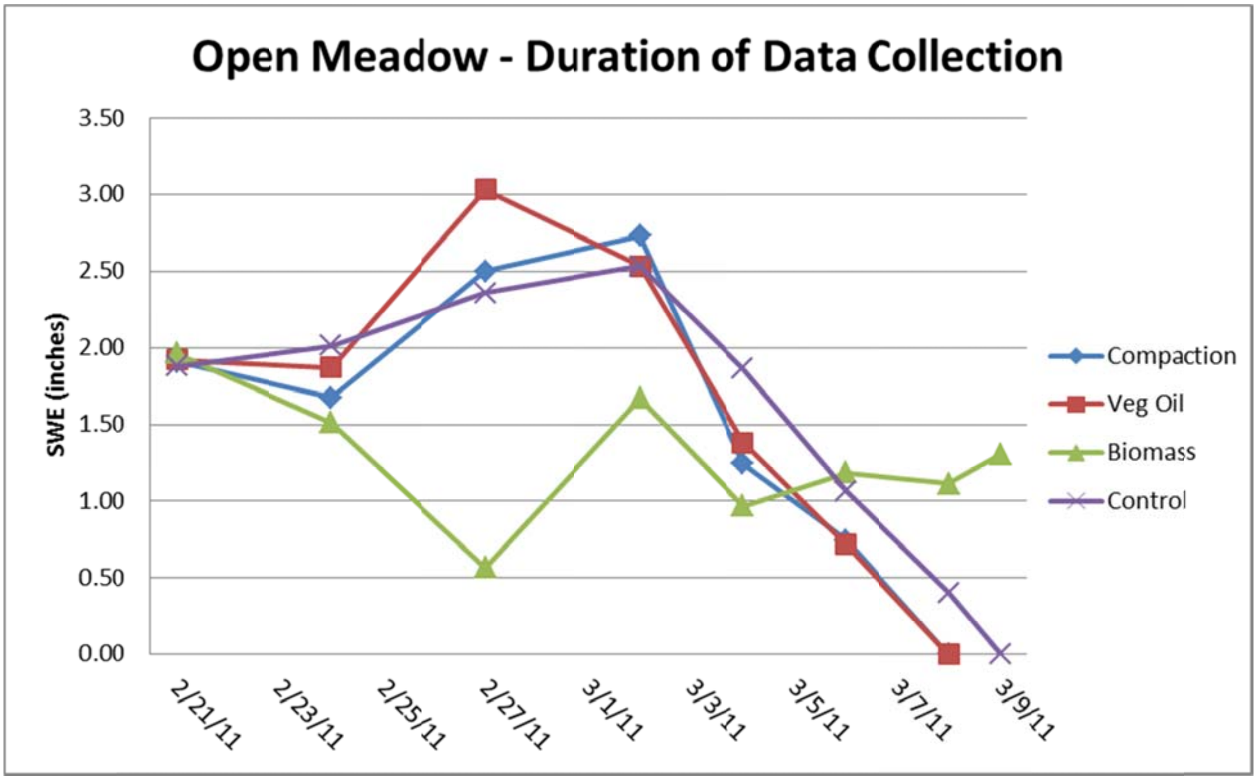


Figure 34: SWE versus time for the Open Meadow study plot

The snowpack on the vegetable oil and compaction subplots were completely eliminated by March 8th, while the snow on the control subplot was not completely ablated until March 9th. However, on March 9th, the thick biomass subplot still had an average SWE of 1.31 inches.

Furthermore, the graph shows two distinct trends in the data for most of the treatments. The first trend was from February 21st to February 27th, and can be categorized by increasing SWE on all subplots except for the thin biomass subplot. This period will be referred to as the *Accumulation Period*. The second trend in the data took place from February 27th to March 9th, when there were consistent losses in each of the subplots until they had been completely ablated. This period will be referred to as the *Loss Period*.

It should also be noted that during the *Accumulation Period*, the biomass was applied in a very thin layer, and during the *Loss Period*, the biomass was reapplied in a thick layer of about three to four inches. The reason for the decline of SWE in the thin biomass subplot during the *Loss Period* was because it was believed that the thin layer of biomass was actually increasing the melt potential of the snow. When this was realized, a thicker layer was applied.

As was done with the data analysis on the other study plots, the analyses were performed separately for the *Accumulation* and *Loss* periods. The emphasis of the data analysis is focused on the *Loss Period* because the treatments were designed to limit sublimation losses of snowpack, and the *Accumulation Period* does not illustrate much loss in snow water equivalent.

4.4.2 Open Meadow Accumulation Period

The *Accumulation Period* of the Open Meadow site encompasses the time between the two major storm events, from February 21st through the 27th. The snow water equivalent increased during this time period in each of the four subplots. The snow water equivalent increased 0.59 inches in the compaction subplot, 1.11 inches in the vegetable oil subplot, and 0.48 inches in the control subplot. The snow water equivalent for the thin biomass subplot actually decreased 1.39 inches. As was stated above, this was probably due to the application of the biomass blanket in a thin layer.

Figure 35, on the next page, is a graphical representation of the change in the snow water equivalent for each of the four subplots in the Open Meadow study plot.

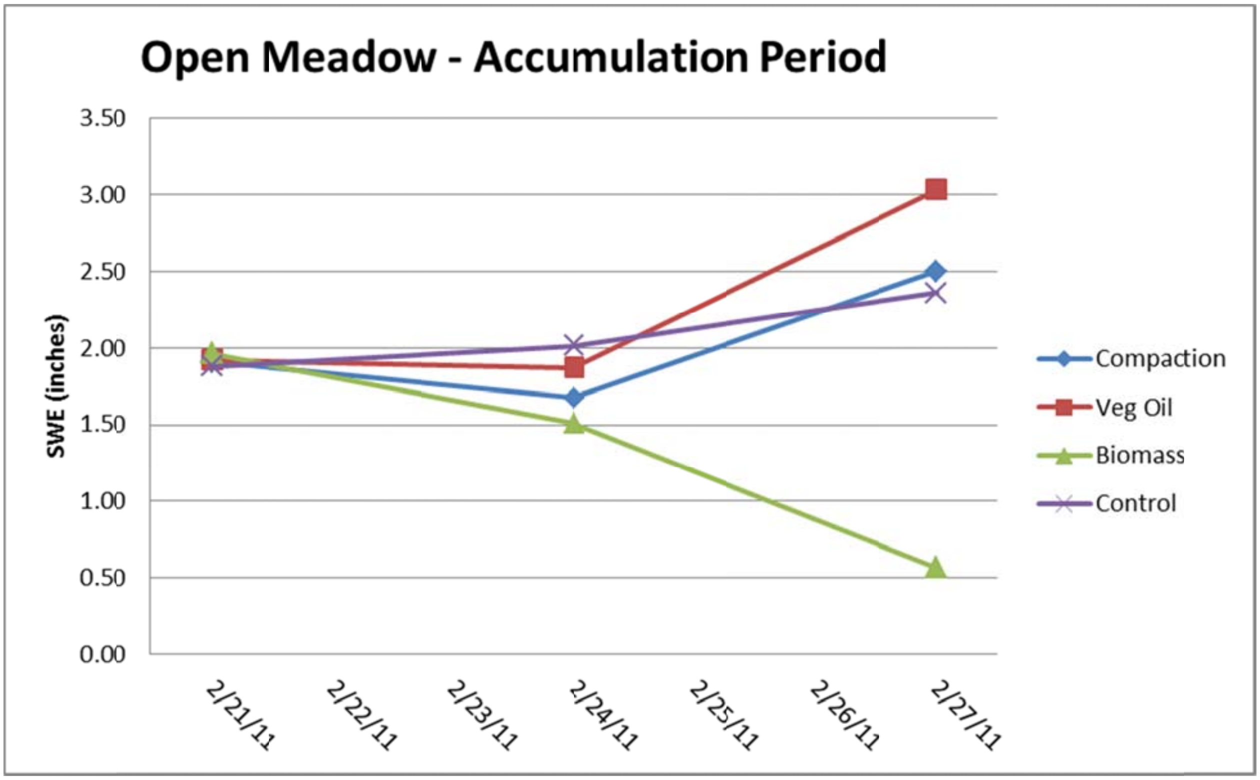


Figure 35: SWE versus time for the Open Meadow study plot

Each of the snow water equivalents, with the exception of the thin biomass subplot, increased during the *Accumulation Period*. The overall increase in SWE for the subplots makes it nearly impossible to quantify the sublimation losses during this time period. For this reason, the in-depth data analysis was done on the *Loss Period* of the Open Meadow plot.

4.4.3 Open Meadow Loss Period

The *Loss Period* of the Open Meadow site encompassed the time after the second major storm event until the completion of snowpack ablation, from February 27th through March 9th. As can be seen in Figure 36, each of the treatments' snow water equivalents declined during this period. The vegetable oil and compaction treated subplots lost all of their snow by March 8th, while the control had lost all of its snow by March 9th. However, on March 9th, the thick biomass treatment still retained 1.31 inches of SWE.

Figure 36 on the following page shows the plot of snow water equivalents versus time for each of the subplots during the *Loss Period* in the Open Meadow study plot.

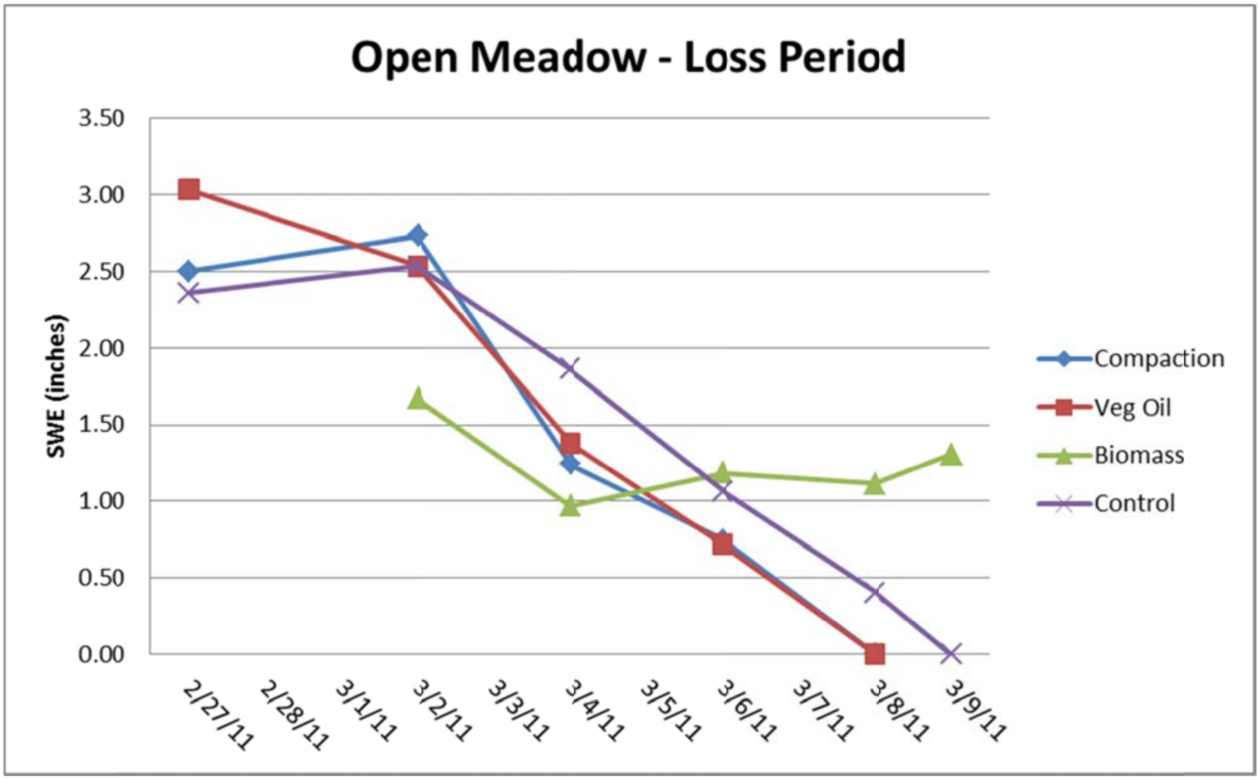


Figure 36: SWE versus time for the Open Meadow study plot

As was done with the previous data sets, each of the treatment's data was fit with a linear regression line in Microsoft Excel.

Figure 37 shows the linear regression line for the thick biomass and control subplots. A linear regression of the vegetable oil and compaction subplots were not performed because they did not seem to work as well against the control as the thick biomass treatment.

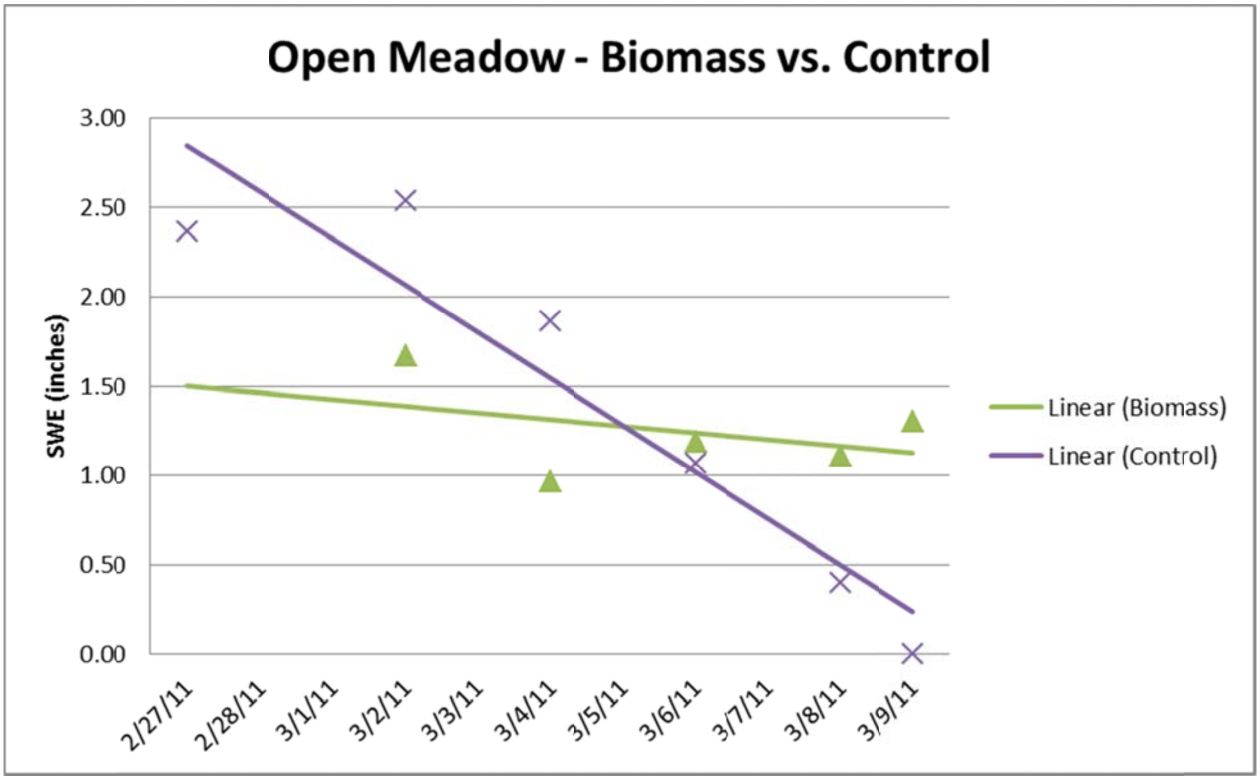


Figure 37: SWE linear regression line for biomass versus the control

Table 15 shows the slope and the R^2 value for the regression lines of the control and the thick biomass subplots.

Table 15: Slope and R^2 values for the control and thick biomass subplots

	Slope (inches SWE/day)	**R^2 Value**
Control	-0.26	0.89
Biomass	-0.04	0.16

As can be seen in the above table, the snow in the thick biomass subplot ablated at a rate of 0.04 inches of SWE per day, while the control shows an average loss of 0.26 inches of SWE per day. The R^2 values for the thick biomass and control subplots were 0.16 and 0.89, respectively. The R^2 value for the control shows a strong correlation in the data, while the R^2 for the thick biomass subplot shows a fairly weak correlation.

The weak correlation is believed to be due to the “mounding” of the snow under the thick biomass layer. The snow had high points and low points under the biomass layer as shown in Figure 38 below. This made it very difficult to sample at an average location representing the entire subplot, which is why the data seems to vary a bit, causing a low correlation between the regression line and the actual data.

However, it is fairly obvious by looking at the raw data, that the biomass limited the losses of the snowpack simply because a significant amount of SWE was still under the biomass on the last day of data collection.

Figure 38: Mounding of biomass

The regression lines in Figure 37 suggest that the thick biomass treatment was most effective at reducing losses of the snowpack. To further illustrate this, the thick biomass data was alternatively graphed as a percent loss of SWE over time in Figure 39 below.

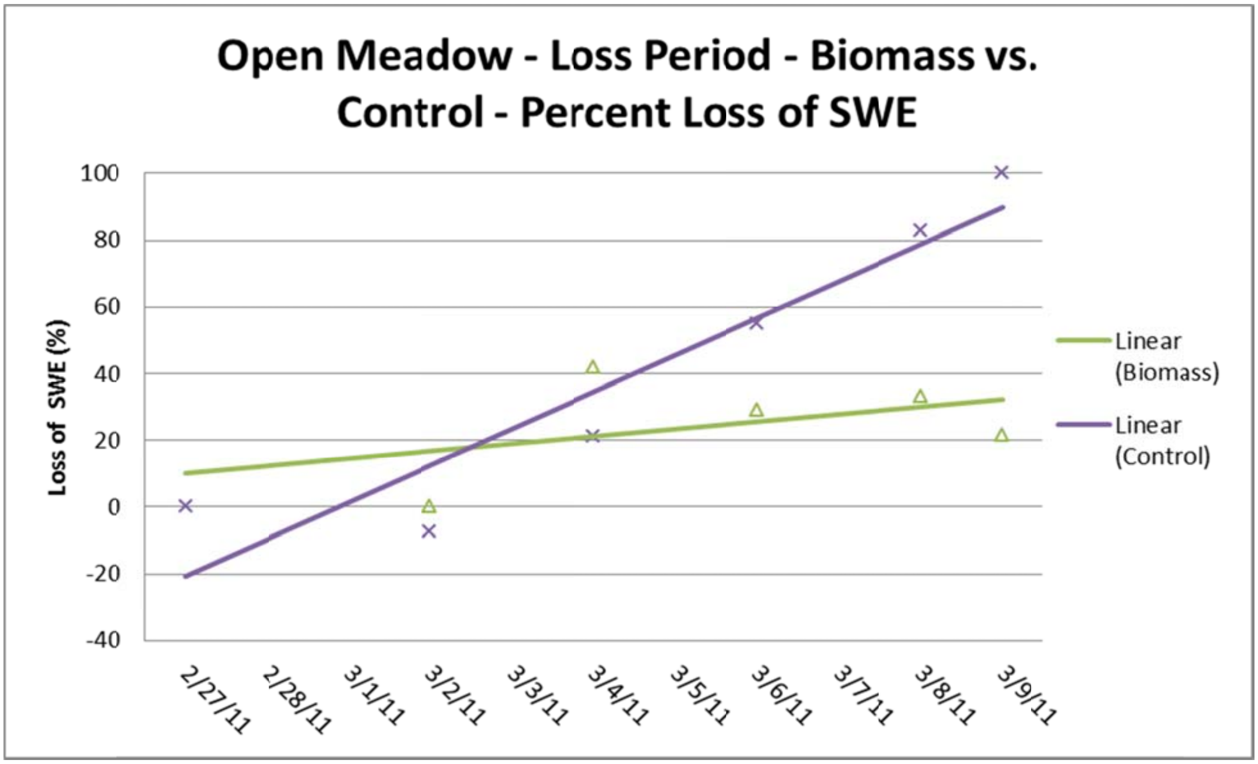


Figure 39: SWE linear regression as a percent loss for the biomass versus control

Table 16 shows the slope and the R^2 value for the regression lines of the control and the thick biomass subplots.

Table 16: Slope and R^2 values for the control and thick biomass subplots

	Slope (% SWE/day)	**R^2 Value**
Control	-11.05	0.88
Biomass	-2.22	0.16

The control lost an average of about 11.05% of its SWE per day, while the thick biomass subplot only lost about 2.2% of its SWE per day. Further, at the end of the data collection period, the control had lost 100% of its original SWE, while the thick biomass subplot had only lost about 22% of its original SWE.

5.0 Cost Analysis

This section of the report is a cost estimate for the application of a four inch biomass blanket on a landscape scale. The following cost analysis will be based on one treatment application over one acre of snowpack, which will require approximately 14,500 cubic feet of woodchips as the biomass blanket.

5.1 Introduction

The standards of forest health and fire prevention are leading forest managers to thin natural stands of forest[28]. Specifically in Arizona, dense stands of Ponderosa Pine pose a great risk of contributing to catastrophic forest fire events. The current practice of thinning forests is typically contracted out by the Forest Service to a lumber company [28]. Generally, the lumber company thins the forest and is allowed to take parts of the tree that they consider useable as lumber, this consists of the main trunk of the Ponderosa tree. The branches and limbs, called slash, are left behind, gathered into piles by fire management crews, and burned[29]. It is proposed by Snowpack Engineering that instead of the limbs and branches being left behind as fire fuel, they could be chipped and used as the main component of the biomass blanket applied to snowpack. Snowpack Engineering believes this would be a better use of the slash than the current burn practice.

5.2 Assumptions

To perform this cost analysis it was assumed that a fuels crew, which typically piles up and burns the limbs and branches, would not be incurring any additional work hours by chipping them. Inter-agency cooperation from Forest Service fuels crews or Bureau of Land Management fuels crews will be necessary in order to chip the limbs and branches without additional hired labor. Based on the skill set typical of a fuels crew, they would be an excellent labor force to operate a wood chipper. It was also assumed that the limbs and branches will be chipped in an area of the forest which will minimize the transport distance to the site of application. Given these two assumptions, wood chipping labor costs and transportation costs will be excluded from the cost analysis.

5.3 Heavy Equipment

The heavy equipment which Snowpack Engineering recommends as necessary includes a wood chipper, a pull-type hydraulic woodchip spreader, and a tractor for loading and pulling the spreader. The purchase price of the heavy equipment will be the bulk of the calculated cost for the application of woodchips. The following sections will provide cost estimates for purchase of the heavy equipment. However, the cost analysis provided will focus on the costs to apply four inches of biomass blanket to one acre of snowpack. The costs associated with the application of woodchips will be generated by the cost of operating the equipment and the associated maintenance costs.

5.3.1 Wood Chipper

There are several types of wood chippers available to accomplish the task of chipping limbs and branches. The necessary characteristics for a wood chipper require that it be portable and that it have the necessary torque to chip the diameter of branches which are typical of a slash pile. The average cost associated with a used chipper is between $20,000 and $30,000. New models are in the range of

\$60,000 to \$80,000[30]. The recommended wood chipper costs \$70,000. In addition to purchasing a wood chipper, costs associated with maintenance will be considered.

Typical maintenance for any of the heavy equipment will be divided into two distinct categories; parts and labor. The replacement costs for small parts; including items such as lube, oil, and filter, is in the range of \$30 per 100 hours of use[31]. Major parts, such as replacement teeth, can be as high as \$200 per year of use. A skilled maintenance worker will typically charge \$25 per hour of labor[31]. It is estimated, in order to chip the necessary quantity of slash to produce 14,500 cubic feet of woodchips, a chipper will need to operate for 90 hours. Fuel costs are \$4 per gallon, based on the average price of diesel in the state of Arizona as of April, 2011[32], and the recommended wood chipper will run for 2 hours on one gallon of fuel. The costs associated with the assessed hours are presented in Table 17.

Table 17 Wood Chipper Costs

4 inches/1 acre-90 hours operation	Cost
Maintenance-Parts and Labor	\$49.50
Fuel-Arizona Average	\$180.00
Total	\$229.50

5.3.2 Hydraulic Woodchip Spreader

Many wood chippers chip and deposit the woodchips where they need to go. However, for the recommended application, it is necessary to use a woodchip spreader for the application of a woodchip biomass blanket. This is due to the fact that the wood chipping would need to take place prior to snowfall and the application of woodchips would take place after snowfall. The average cost for a new spreader is around \$30,000. Maintenance is minimal on the spreader compared to the chipper and the tractor. Using the same skilled maintenance worker at \$25 per hour, an estimated one hour of labor will be necessary per 100 hours of woodchip application[31]. Costs for materials such as tires, lube, oil, and hydraulic fluid will be in the range of \$20 per 100 hours of operation[31]. The recommended spreader carries approximately 900 cubic feet of woodchips and will require 16 loads to cover one acre to the recommended depth. Operating time to cover one acre is estimated to be less than eight hours.

Table 18 Woodchip Spreader Costs

4 inches/1 acre-8 hours operation	Cost
Maintenance-Parts and Labor	\$3.60
Total	\$3.60

5.3.3 Tractor

There are several name brand tractors on the market. The average cost of the tractor recommended by Snowpack Engineering, which will need to be able to operate in deep snow, pull a 16 ton trailer, and have a power take off (PTO) geared to operate the hydraulic spreader, is approximately \$50,000.

Maintenance on this tractor is less than one hour labor per 100 hours of use. The necessary parts for the 100 hour maintenance are lube, oil, and filter and can be supplied for around $30[31]. In order to apply woodchips to an acre of snow, the tractor will be in operation for less than eight hours and will use around eight gallons of fuel. Assuming an average wage of $12 per hour, the cost of an operator will be an additional $96 per acre.

Table 19 Tractor Costs

4 inches/1 acre-8 hours operation	Cost
Maintenance- Parts and Labor	$4.40
Operating Cost- Fuel and Operator	$128.00
Total	$132.40

5.4 Summary

There are several buying options for the recommended heavy equipment. Depending on whether the client chooses to purchase new or used, the price will vary dramatically. The cost of application per acre excludes any up front purchase prices. The bulk of the cost comes from operating the wood chipper. The volume of woodchips, 14,500 cubic feet, will take nearly 100 hours to chip. The fuel costs for the wood chipper operation is where the bulk of the expenses will come from. The total expenses for operating and maintaining the necessary equipment are summed in Table 20 below as the cost to apply biomass per acre.

Table 20 Operation Costs per Acre

Operation Cost	
Wood Chipper	$229.50
Woodchip Spreader	$3.60
Tractor Operation	$132.40
Total for 4 inches over 1 acre	$365.50

6.0 Conclusions

This section of the report presents the conclusions reached by Snowpack Engineering. The conclusions drawn from the results are summarized and recommendations for the application of a treatment on the landscape scale are given along with recommendations for future work on this subject.

6.1 Isolating Sublimation

The treatments applied to the snowpack were aimed at targeting sublimation losses; consequently, an important priority in the design of the experiment was to isolate the losses incurred by sublimation from other losses, such as melting. Based on research by Snowpack Engineering, the primary driving forces behind sublimation are wind and low humidity. When these two phenomena are coupled with temperatures below freezing, an ideal environment for monitoring only sublimation losses is obtained. If temperatures are above freezing, sublimation still occurs, but it becomes difficult to differentiate between sublimation losses and melt losses.

During much of the data collection period, the weather conditions did not allow Snowpack Engineering to differentiate melt losses from sublimation losses. Daytime highs during the data collection period were always above freezing, and often near 55 or 60 degrees Fahrenheit. Thus, the snow which was treated and sampled, while still undergoing loss to sublimation, was also losing SWE to melt. This was verified throughout the data collection period by the observation of overland flow of snowmelt, and further supported with temperatures consistently above freezing. With this in mind, the conclusions are based on a treatment's ability to delay snowpack ablation. The key assumption made by Snowpack Engineering is that the snow kept on the ground for a longer period of time is a result of the applied treatment restricting snow losses. These losses include both sublimation and melting.

6.2 Summarized Conclusions

The following two sections address the data that was collected and analyzed by Snowpack Engineering. Section 6.2.1 addresses data that was deemed invalid pertaining to the purpose of this project, while Section 6.2.2 addresses the valid data collected during this project. Conclusions and recommendations were generated from both sets of data.

6.2.1 Invalid Data

Based on the strong correlation between the location of the plots underneath the roofs (southern vs. northern), this data was unusable for determining the most effective treatment of snowpack. In both roofed structures, the control subplot was on the northern end and thus performed better than the two southern subplots because of its location. The southern subplots received a large amount of sun contamination and ablation occurred much faster than in the northern subplots.

When looking at data from the Roof 1 and Roof 2 study plots, the snowpack in the southern subplots ablated about 60% faster than the snowpack in the northern subplots. Snowpack Engineering determined that the faster rate of ablation in the southern subplots was a direct function of these plots receiving more sunlight than the northern subplots. Because the sun was such a large influencing factor in the loss rates observed in these study plots, data from the Roof 1 and Roof 2 were not used to draw conclusions about which treatment may have worked at limiting sublimation losses.

It was determined from these subplots that shading and southerly or northerly aspect does have an influence on snowpack ablation. The southern subplots under the two roofed structures ablated at rates of 0.19 and 0.25 inches of SWE per day, while the northern subplots under the two roofed structures ablated at rates of 0.12 and 0.14 inches of SWE per day. These trends were shown with very low levels of variance (R^2 values of 0.96 and higher), and it can be concluded that snowpack on a southern aspect ablates at a much higher rate than snowpack on a northern aspect. Said differently, shaded snowpack ablates much slower than snowpack that is not shaded and receives direct sunlight.

6.2.2 Valid Data

The canopy and meadow results both clearly showed that a thick layer of biomass (about three to four inches in thickness) delayed the ablation of snowpack when compared to the control and the other two treatments. It is assumed that at least part of the reason why a thick biomass blanket is effective at retaining snowpack is because of its ability to reduce the sublimation losses.

In the canopy setting, biomass retained 30% of the snow water equivalent by the time that all other treatments and the control had seen complete ablation of the snowpack. The loss rate of snowpack treated with a thick blanket of biomass was 0.08 inches of SWE per day, while the loss rate of the untreated snowpack was 0.21 inches of SWE per day. The snowpack under the thick biomass blanket dissipated about 38% slower than the untreated snowpack; the open meadow setting had similar results.

In the open meadow setting, biomass retained 78% of the snowpack by the time the snow under all the other treatments and control had been completely eliminated. The loss rate of the snowpack treated with a thick blanket of biomass was 0.04 inches of SWE per day, while the loss rate of the untreated snowpack was 0.26 inches of SWE per day. The snowpack treated with a thick biomass blanket ablated at a rate that was 15% slower than the control. Vegetable oil and compaction both consistently performed worse than the control with little difference between each other in the open meadow setting.

6.3 Other Data

Snowpack Engineering’s first application of the biomass blanket was initially considered a failure because it melted the snowpack at a fast rate. This occurred because the biomass blanket was originally applied in a thin layer. The thin layer heated up quickly as a result of direct solar radiation, and consequently, melted the snowpack at an increased rate. As was mentioned previously, as soon as this was documented, the next application of biomass was applied in a thicker layer.

However, when Snowpack Engineering changed the treatment from a thin layer to a thicker layer, an interesting advantage in the data was initially overlooked. If snowpack is melted very quickly, it may not have a chance to sublimate. Thus, a reasonable approach to increasing the amount of surface runoff would be to melt the snowpack before it has a chance to sublimate. Intentionally melting the snowpack could also help in other veins such as decreasing snow mold on crops, or melting snow on dirt roads.

6.4 Recommendations for Treatment

The application of four inches of biomass would be a very expensive treatment. The cost analysis, ignoring the initial costs of purchasing equipment, showed that the cost of application of the biomass blanket would be about $365.50 per acre. Additionally, the price of a new tractor, wood chipper and woodchip spreader could run as high as $150,000. These estimates could increase even more if the cost of wood chipping labor or transportation is included. Based on the initial estimates, it seems unlikely that this treatment would be cost effective to implement at a landscape scale.

Snowpack Engineering has provided a treatment scenario, to demonstrate cost, based on the following assumptions. The treatment area will be 100 acres of open meadow. The snowpack will be treated four separate times, following four separate storm events. Each of the four storm events will average 2.5 feet of snow with an assumed 10% SWE. Based on the assumed snow characteristics and a 75% loss of SWE to sublimation, an untreated snowpack would deliver 25 acre-feet of water into surface runoff streams. The same area and snow events, if treated with biomass, with an assumed 100% effectiveness at preventing sublimation, would produce 100 acre-feet of water into surface runoff streams. The cost of the four layers of treatment over the 100 acres would be about $146,200.

If the treatment was considered cost effective, it should be implemented in a meadow area. The first reason for this is that meadows, on average, receive more snowfall than canopied areas at the same elevation. As was seen at Snowpack Engineering's study plots, meadow areas received greater than 50% more snowpack than canopied areas. Thus, the potential amount of runoff generated from the meadow area is much greater than that of a canopied area. The second reason is that the large machinery used to apply the treatment would be nearly impossible to operate in a canopied area.

6.5 Recommendations for Additional Research

Snowpack Engineering recommends that research be conducted to further evaluate the performance of a biomass treatment. Because the weather did not remain cold during the period of snow loss, much of the loss is likely due to melting and cannot be positively attributed to sublimation. Without this information, an increase in water retention cannot be verified, only assumed; however, a delay of the snow ablation can be confirmed. Although delayed snow ablation is valuable for water resource managers because it helps to supply water when demand is higher, it was not the intention of this study to simply delay ablation of snowpack. This study was specifically looking at limiting sublimation losses of the snowpack.

Further research should be conducted to determine an actual increase in runoff that could be obtained for limiting the sublimation losses of snowpack, and specifically, treating the snowpack with a thick biomass layer. This type of hydrologic study could be used by water managers to determine what the return rate on the cost of the treatment would be. If the treatment costs less than what the additional water delivered to the reservoir is sold for, the high cost of implementation could be absorbed by water managers.

References

1 Solomon, S., D. Quin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge University Press: Cambridge, UK and New York, NY, USA.

2 Welker, J. M., J.T. Fahnestock, and M.H. Jones. “Annual CO_2 Flux in Dry and Moist Arctic Tundra: Field Responses to Increases in Summer Temperatures and Winter Snow Depth”. *Climatic Change*. 44: 139-150.

3 U.S. Environmental Protection Agency. “Climate Change – Science”. 25 Mar. 2011. Web. 25 Mar. 2011. <http://www.epa.gov/climatechange/science/index.html#ref#ref>.

4 Ostler, W. Kent, K.T. Harper, Karl B. McKnight, and David C. Anderson. “The Effects of Increasing Snowpack on a Subalpine Meadow in the Uinta Mountains, Utah, U.S.A.”. *Arctic and Alpine Research*. 14.3 (Aug 1982): 203-214.

5 Vernekar, A. D., J. Zhou, and J. Shukla. “The Effect of Eurasian Snow Cover on the Indian Monsoon”. *Journal of Climate*. Vol. 8: 248-266.

6 Vaganov, E. A., M. K. Hughes, A. V. Kirdyanov, F. H. Schweingruber, and P. P. Silkin. “Influence of snowfall and melt timing on tree growth in subarctic Eurasia”. *Nature*. Vol. 400 (1999): 149-151.

7 Knight, D. H., S. W. Weaver, C. R. Starr, and W.H. Romme. “Differential response of subalpine meadow vegetation to snow augmentation”. *Journal of Range Management*. Vol. 32 (1979): 356-359.

8 Grippa, M., L. Kergoat, T. Le Toan, N.M. Mognard, N. Delbart, J. L’Hermitte, and S.M. Vicente-Serrano. “The impact of snow depth and snowmelt on the vegetation variability over central Siberia”. *Geophysical Research Letters*. Vol. 32.

9 Hanley, Thomas A. and Cathy L. Rose. “Influence of Overstory on Snow Depth and Density in Hemlock-Spruce Stands: Implications for Management of Deer Habitat in Southeastern Alaska.” United States Forest Service.

10 Walsh, N.E., T.R. McCabe, J.M. Welker, and A.N. Parsons. “Experimental manipulations of snow-depth: effects on nutrient content of caribou forage”. *Global Change Biology*. Vol. 3 (August 1984): 158-164.

11 Sweeney, James M. and John R. Sweeney. “Snow Depths Influencing Winter Movements of Elk”. *Journal of Mammalogy*. 65.3 (August 1984): 524-526.

12 Hovey, Frederick W., and Alton S. Harestad. “Estimating Effects of Snow on Shrub Availability for Black-Tailed Deer in Southwestern British Columbia”. *Wildlife Society Bulletin*. 20.3 (Autumn 1992): 308-313.

13 Brodie, Jedediah F. and Eric Post. “Nonlinear responses of wolverine populations to declining winter snowpack”. *Population Ecology*. 52.2: 279-287.

14 Nixon, Phil and Raymond A. Cloyd. “Japanese Beetles: Impact of Winter”. *Home, Yard & Garden Pest*. University of Illinois Extension: Issue 15 (2003). <http://hyg.ipm.illinois.edu/pastpest/200315f.html>.

15 USGS. “The Water Cycle: Snowmelt Runoff”. Web. Feb 2011. <http://ga.water.usgs.gov/edu/watercyclesnowmelt.html>.

16 Steinemann, Anne C. and Luiz F. N. Cavalcanti. “Developing Multiple Indicators and Triggers for Drought Plans”. *Journal of the Water Resources Planning & Management.* 132.3 (May 2006): 164-174.

17 Parry, Martin L. “Impacts, adaptation and vulnerability”. Contribution of Working Group II to the Intergovernmental Panel on Climate Change, 2007. Cambridge University Press: Cambridge, UK and New York, NY, USA.

18 Arizona Department of Water Resources. “Arizona's Water Supplies and Water Demands”. 2006. Web. Feb 2011. <www.adwr.state.az.us/azdwr/.../documents/supplydemand.pdf >.

19 Arizona Department of Water Resources. “Statewide Cultural Water Demand in 2001-2005 and 2006”. 2010. Web. 14 Apr 2011. <www.adwr.state.az.us/.../StatewidePlanning/WaterAtlas/.../statewide_demand_ web.pdf

20 Arizona Department of Water Resources. “Salt River Watershed”. 2006. Web. Feb 2011. <www.adwr.state.az.us/azdwr/.../documents/supplydemand.pdf >.

21 U.S. Department of the Interior. “Securing Water in the West, The Salt River Project”. Washington, D.C.: U.S. Department of the Interior, 2009. Web. Feb 2011. <http://www.usbr.gov/projects/Project.jsp?proj_Name=Salt+River+Project>.

22 U.S. Department of Agriculture. “Arizona Snowtel SWE (inches)”. Washington, D.C.: U.S. Department of Agriculture, 2008. Web. Mar 2011. <http://www.wcc.nrcs.usda.gov/cgibin/factpub/ads/ads.pl?state=arizona&report=snt>.

23 Dennis, Arnett S. “Weather Modification by Cloud Seeding”. *International Geophysics Series*. Vol 24 (1980): 2-3.

24 Ffolliott, Peter F. and Malchus B. Baker, Jr. “Snowpack Hydrology in the Southwestern United States: Contributions to Watershed Management.” USDA Forest Service Proceedings RMRS-P-13 (2000).

25 Lopes, Vicente L., Peter F. Ffolliott, and Malchus B. Baker, Jr. “Impacts of Vegetative Practices on Suspended Sediment from Watersheds of Arizona”. *Journal of Water Resources Planning and Management*. January/February 2001: 41-47.

26 Osterhuber, Randall, Michael Hogan, Mark Grismer, and Kevin Drake. “Delaying Snowpack Ablation.” Presented at the 75th Annual Meeting of the Western Snow Conference, Kailua-Kona, Hawaii, April 2007.

2 7 Davis, Hillary. "Second Driest January in Flagstaff Nears." *Arizona Daily Sun.* 29 Jan 2011, local sec. 1. Print.

28 Calvert, Jeffrey. “Thinning for Increased Forest Health and Profit”. Sacramento, CA: California Forest Stewardship Program. 2002. Web. 18 Apr 2011. <http://ceres.ca.gov/foreststeward/html/thinning.html>.

29 Larimer County Sheriff’s Office. “Forest Slash Burning Guidelines”. Fort Collins, Colorado: Larimer County. 2011. Web. 12 Apr 2011. <http://www.larimer.org/burnpermit/slash_burning_guidelines.htm>.

30 Tree and Landscape Equipment Trader. "Brush Chippers". Web. 12 Apr 2011. <http://equipment.treetrader.com/index.php?a=5&b=204>.

31 Wieber, Jeff. Total Grand Rental, Flagstaff, Arizona. Personal Interview by Adam Bringhurst. 16 April 2011. 16 Apr 2011.

32 Arizona Gas Prices.com. "Average Diesel Prices in Arizona." Web. 16 Apr 2011. <http://www.arizonagasprices.com/index.aspx?fuel=D>.

33 Murray, Timothy, Stephen Jones, and Ed Adams. "Snow Mold Diseases of Winter Wheat in Washington." *College of Agriculture and Home Economics.* Pullman, Washington 1.1 (1999): 1-8. Web. 26 Apr 2011. <cru.cahe.wsu.edu/CEPublications/eb1880/eb1880.pdf>.