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Comparison of Water Dynamics in Aspen and Conifer: Implications for Ecology Water Yield Augmentation

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COMPARISON OF WATER DYNAMICS IN ASPEN AND CONIFER:

IMPLICATIONS FOR ECOLOGY AND WATER YIELD AUGMENTATION

by

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ABSTRACT

Comparison of Water Dynamics

in Aspen and Conifer:

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by

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Differences in water dynamics between deciduous aspen (*Populus tremuloides*) and co-occurring evergreen conifer species in the Northern Rocky Mountains result from complex physical and biological interactions. A comprehensive evaluation of individual water transfer mechanisms was used to elucidate the relative importance of several components of the hydrologic cycles of aspen and conifer, and determine which water transfer mechanisms have potential to cause differences in net water yield.

Adjacent aspen and conifer stands were monitored to determine snow accumulation and ablation (snow survey), soil moisture recharge (capacitance probes), snowpack sublimation (sublimation pan), transpiration period (thermal dissipation probes), and evapotranspiration (soil water content). Snow accumulation was 34 and 44% higher in aspen during springs of 2005 and 2006, respectively. Ablation rates in aspen (9.58 mm day^{-1}) were nearly double that of conifer (4.9 mm day^{-1}). When changes in soil moisture (due to over winter snowmelt) were combined with snow accumulation in 2006, aspen had greater potential (42-83%) for runoff and groundwater recharge. Snowpack sublimation during the ablation period was not different between open, aspen, and conifer sites and comprised <5% of snowpack losses. Extended conifer transpiration in spring did not contribute to large differences in snowmelt water yield (<2.8 mm yr^{-1}). Summertime ET rate was higher in an aspen stand (3.6 mm day^{-1}) than in an adjacent conifer stand (2.7mm day^{-1}) amounting to ~126 mm more water lost over the growing season, but largely reflected post-ablation differences in stored soil water.

The net effects of these water transfer processes could result in more watershed water yield from aspen than conifer forests. However, the difference in water yield between these two forests will largely depend on the fate of snow lost from the conifer canopy. Snow intercepted by conifer branches can be removed by the processes of sublimation (reduces water yield) and redistribution (does not affect water yield). Future studies should focus on partitioning the ratio of sublimation to redistribution to predict hydrologic response of vegetation conversions for water yield augmentation in snow-dominated watersheds.

(156 pages)

DEDICATION

This work was inspired by the strength and tenacity of my untraditional family. It would not have been possible without the love and support of my beautiful wife, Mellisa.

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Eric LaMalfa

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CHAPTER 1

INTRODUCTION

Overview

Quaking aspen and various conifer tree species occur in mixed and adjacent communities throughout the Intermountain West. The absence of fire in these landscapes, coupled with excessive browsing of young aspen ramets (trees) by livestock and wildlife, has contributed to the displacement of aspen communities by conifer forests throughout the west (Kay, 1997; Bartos and Campbell, 1998; White et al., 1998; Brown et al., 2006). It has been hypothesized that the increase in conifer dominated lands has led to a significant decrease in net watershed water yield throughout the Intermountain West and the Colorado River Basin (Hibbert, 1979). Anecdotal accounts of springs drying up as conifers succeed aspen dominated watersheds are common amongst livestock operators and other land managers in Utah.

In Eastern forests there are indications that conifer forests do not yield as much stream runoff as deciduous systems given the same set of climatic and physical hydrologic variables. In the southern Appalachians, reductions in stream flow after conversion from deciduous to coniferous forest primarily occurred during the dormant and early growing season (Swank and Douglass, 1974). In a meta-analysis of water augmentation experiments throughout the world, Bosch and Hewlett (1982), inferred there would be greater water yield responses from removal of coniferous (~ 40 mm increase per 10% decrease in cover) compared to removal of deciduous hardwood communities (~ 25 mm increase per10% decrease in cover). However, to make accurate quantitative generalizations about the impacts of vegetation change between evergreen and deciduous forests, consistent methods and analyses need to be established and applied to a large number of catchments (Brown et al., 2005). Watershed studies in the western snow-dominated systems are limited. Variables which will most accurately predict hydrologic response to vegetation conversions in the west have not been defined.

Researchers in the west have speculated that water yield is higher in aspen relative to conifer. Several authors have suggested water yield augmentation could be achieved by converting conifer stands to aspen in snow-dominated western watersheds (Dunford and Niederhof, 1944; Jaynes, 1978; Gifford et al., 1984). However, because forest cover type conversion from conifer to aspen has not been adequately tested, and the physiographic constraints affecting the magnitude of water yield augmentation are ill defined, this type of vegetation treatment has not become an accepted practice (DeByle and Winokur, 1985). The hypothesized water yield losses resulting from aspen to conifer succession have not yet been tested with direct experimentation.

Watersheds in Utah and throughout the west experience high variation in annual climate regimes, however, they are typically marked by cold wet winters and hot dry summers. The majority of precipitation in the Northern Rocky Mountains of Utah comes in the form of snow, with 69% occurring during the period from October to April (Richardson et al., 1989). The water harvested from snow is delivered primarily during the spring melt period when vegetation is simultaneously becoming active. To understand differences in water dynamics that could lead to differences in water yield between aspen and conifer, we investigated physical and biological processes that occur during the annual hydrologic cycle focusing on the spring snow melt period.

We investigated differences in water dynamics on north facing slopes where aspen and conifer occur in a mosaic of mixed and pure stands. Insolation (incoming solar radiation) is higher on south facing slopes relative to north facing slopes during the dormant season. In eastern forest clear cuts, slopes with low insolation (north facing) yielded more water than slopes with high insolation (Swank et al.; 1987). North facing slopes are expected to have the greatest potential for increasing water yield by conversion from aspen to conifer forest in snow-dominated western watersheds.

The monitoring of dominant water pools and water fluxes was used to evaluate the maximum expected differences in hydrology between an evergreen and a deciduous forest. Simultaneous measurements of physical and biological water transfer mechanisms in aspen and conifer were used to determine differences in water yield at the stand level.

Goals and Objectives

The primary goal of this study was to determine the extent to which physical and biological variables affecting water yield differ in adjacent aspen and conifer stands. To achieve this goal, our objectives were to quantify the primary hydrologic mechanisms which result in water yield differences at the stand level. With a better understanding of these differences in water dynamics, we explore the ecological implications associated with the management of aspen vs. conifer forests. This includes a discussion of how water dynamics in aspen and conifer forest may affect biogeochemical processes, wildlife, soil genesis, susceptibility to disturbance, and potential differences in water yield that could arise under projected climate change scenarios in the West.

Hypotheses

Seven hypotheses were tested to determine how hydrologic mechanisms differ between aspen and conifer stands. Research was focused on those mechanisms expected to significantly affect differences in net annual water yield.

- H1: Aspen and conifer communities will have accumulated different amounts of snow at the time of peak snow accumulation (approx. April 1st).
- H2: Net sublimation losses from the surface snowpack in open, aspen, and conifer stands are significantly different.
- H3: The ablation period is extended in conifers leading to increased sublimation loss of the snowpack and decreased soil moisture recharge.
- H4: Aspen stands have greater evapotranspiration rates during the growth period resulting in higher net summer water loss.
- H5: Conifer stands have a longer annual transpiration activity period in fall and spring relative to aspen leading to increased net annual water loss.
- H6: Spring soil moisture recharge is different between aspen and conifer stands.
- H7: Conifer transpiration activity in spring is facilitated by accelerated snow melt within conifer tree wells, evidenced by lower shallow soil moisture content within tree wells compared to forest interspaces between trees.

The net effects of these differences (H1 – H7) are expected to result in higher net water yield to groundwater and runoff in aspen stands. By examining these hypotheses simultaneously, we were able to identify which water loss mechanisms could have caused large differences in aspen and conifer water yield. With an understanding of the relative importance of each mechanism, we discuss landscape variables that may affect changes in water yield when conifer stands are converted to aspen stands.

CHAPTER 2

LITERATURE REVIEW

The challenge in understanding differences in water yield between aspen and conifer stands is accounting for all the temporal and spatial interactions of various water pools and fluxes. A literature review across disciplines is used to highlight important variables affecting the measurement of winter, spring, and summer water transfer processes. Considering an annual hydrologic cycle, snow hydrology and plant physiology research is temporally disjunct; traditionally these disciplines focus research during winter and summer, respectively. It is particularity important to consider the extent to which both physical and biological water transfer processes simultaneously occur during the transitional snow melt period.

Tree Canopy Effects on Snow Hydrology

Contrasting observations have been made when comparing snow accumulation and melt patterns beneath aspen *(P. tremuloides)* and conifer stands such as white fir (*Abies concolor*), subalpine fir (*Abies lasiocarpa*), Engelman spruce (*Picea Engelmannii*), lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*), possibly due to variability in topographic position, aspect, fetch (topographically induced snow capture), and climate. Winter snow water equivalent (SWE) beneath lodgepole pine was 75% of that below aspen stands in Colorado (Dunford and Niederhof, 1944). Hardwood stands in Minnesota have been estimated to yield 140 mm more water than conifers. The differences in water yield were attributed to greater snow accumulation in hardwoods and a longer transpiration season in conifers (Urie, 1967). Areas with tree cover (leafless or not) were more effective at trapping snow than open areas in windswept Southern Alberta (Swanson and Stevenson, 1971).

Snow accumulation and melt has been observed to differ by aspect. Southerly exposures tend to accumulate less snow relative to the adjacent northern aspects, thus, the hydrologic response of vegetation change is also highly dependent upon aspect (Troendle et al., 1993). Snow water equivalent under Douglas-fir and aspen stands was similar on south facing slopes in New Mexico, however, on north facing slopes Douglas-fir had 72% of the SWE found in aspen (Gary and Coltharp, 1967).

Differences in peak snow accumulation have been attributed to high canopy interception by conifers, which can increase susceptibility to sublimation and redistribution (Miller, 1962; Troendle et al., 1993). In aspen stands there is low interception by the leafless canopy during winter precipitation events. Once intercepted by the canopy, snow can take several mass transport pathways including mechanical transport (wind and gravity), melt (drip), and sublimation (evaporation). The intercepted water will ultimately be lost to the atmosphere via sublimation or retained in the watershed by melting and mechanical transport processes.

Sublimation of snow from ice to water vapor occurs when there is a vapor pressure gradient between the snow and atmosphere. As with transpiration, the vapor pressure at the boundary layer between the snow surface and atmosphere is quickly saturated in the absence of air movement. Conversely, sublimation increases with increasing wind as fresh dry air replaces saturated air maintaining the vapor pressure gradient (Miller, 1962).

The atmospheric conditions of temperature, insolation, relative humidity, and wind, as well as snow energy content are driving variables for sublimation process. Snow that is sublimated from the canopy inhibits the sublimation of the surface snowpack by raising the surface boundary layer vapor pressure (Lundberg and Halldin, 1994). Leonard and Eschner (1968) found that albedo (shortwave reflectance by land surfaces) for intercepted snow on a conifer canopy was considerably lower (~0.2) than for the surface snowpack, resulting in more rapid melting and greater sublimation rates of intercepted snow. Dry air (such as that found in Utah) facilitates sublimation processes (Miller, 1962). While general estimates of the relative rate of canopy-sublimation processes are attainable via indirect measurements, it is not possible to predict how intercepted snow after a given snow event will be divided between atmospheric losses and watershed gains.

Several authors have found an inverse relationship between coniferous stand structure and maximum snow accumulation, presumably caused by canopy-sublimation of intercepted snow (Gary and Troendle, 1982; Skidmore et al., 1994; Moore and McCaughey, 1997). Half of the variation in SWE in the coniferous communities of the Tenderfoot Creek Experimental Forest was attributed to canopy cover and density (Moore and McCaughey, 1997). There is an assumption that over the course of a water year, canopy-sublimation losses in conifer are greater than the losses associated with both surface-sublimation and total site transpiration (Dunford and Niederhof, 1944). Alternatively, reductions in SWE with increasing canopy have also been attributed to the redistribution of intercepted canopy snow into openings via wind effects (Chang, 2003).

Sublimation of intercepted canopy snow has been estimated and modeled using a variety of methods. The hanging tree method uses automated measurements of weight lost from a suspended tree in the forest assuming that reductions in mass are equal to sublimation rate. Using a suspended tree method, without corrections for mass transfer to the surface, Lundberg et al. (1997) estimated that canopy-sublimation occurred at maximum rates of 3.3 mm day^{-1} amounting to a total of 200 mm yr^{-1}. Pomeroy et al. (1998) built a physically based sublimation model using hanging tree measurements for calibration and found that total canopy-sublimation was 29-39 mm yr^{-1}. By adding lysimeters below the hanging tree, Stork and Lettenmaier (2002) accounted for mass transfer and drip below the tree and estimated that canopy-sublimation accounted for less than 1 mm day^{-1} and approximately 100 mm yr^{-1} in a maritime climate. The most recent use of the hanging tree method by Montesi et al. (2004) eliminated mass transfer errors by excluding 10 minute intervals that coincided with abnormal losses in mass caused by gravitational loss of large snow conglomerates from the tree canopy. In the Fraser Experimental Forest in southwestern Colorado, total canopy-sublimation varied between 30 and 39 mm yr^{-1} at a low (2700 m) and high (3900 m) elevation lodgepole pine sites, respectively (Montesi et al., 2004).

Redistribution is the relocation of resting snow particles from one area to another independent of the precipitation event. Redistribution is driven by the wind, which re-mobilizes (re-suspends) snow partials that have come to rest after or during a precipitation event. In upper tree-line and alpine landscapes, high wind speeds, topography, and vegetation interact with snow to produce snow deposition patterns. Ultimately, snow is eroded from exposed areas and deposited on the lee sides of hills, trees, rocks, and other obstructions (Hiemstra et al., 2006). Unlike canopy-sublimation, redistributed snow is retained by the terrestrial system in an adjacent locality where partials come to rest. Redistribution was considered to be more important than canopy-sublimation in causing differences in snow accumulation between lodgepole pine forests and clear cut openings on the Fraser Experimental Forest (Hoover and Leaf, 1967). Gary (1974) found that increases in SWE in clear cut patches of lodgepole pine forest were offset by decreases in SWE in the upwind forest. The clearing affected the distribution of snow but did not increase net SWE at the landscape level. Differences in SWE between forest cover types could also be a product of differential deposition caused by the surface structure and topography effects on wind currents and snow deposition patterns.

Sublimation of the surface snowpack has been reported to occur at greater rates in subalpine environments than in subalpine forests. Hood et al. (1999) estimated surface-sublimation using the aerodynamic profile method at Niwot Ridge in the Colorado Front Range. They found that total surface-sublimation for the snow season was 195 mm, or 15% of peak SWE at the study site. The majority of this sublimation occurred during the snow accumulation season. The snowmelt season from May through mid-July showed net condensation to the snowpack ranging from 5 to 16 mm of water equivalent. Sublimation during the snowmelt was sometimes episodic in nature, but often showed a diurnal periodicity with higher rates of sublimation during the day. Surface-sublimation in the Northern Rocky Mountains has been found to be 20% higher in aspen than conifer. However, total annual losses by surface-sublimation accounted for less than 5% of the total snow pack (Doty and Johnston, 1969).

Snow ablation (melt rate) beneath aspen stands and in openings may be faster than in conifer stands. During high spring rains there was no difference in the timing of snow disappearance between thirty three year old aspen and lodgepole pine stands in Colorado. Melt in both aspen and conifer communities was accelerated by the latent heat input accompanied by 99 and 81 mm of rainfall, respectively (Dunford and Niederhof, 1944). Forest snow packs beneath conifer are relatively shallow and melt slowly but ultimately disappear at the same time as open or aspen sites with deep, fast ablating snowpack (Gelfan et al., 2004). Snow is highly reflective of short-wave radiation and absorptive of long-wave radiation. The leafless aspen canopy provides some shelter from advective energy exchange (wind) but is a source for increased long-wave radiation (Swanson and Stevenson, 1971). The conifer tree canopy is thought to reduce radiation via shading, which decreases the rate and delays the timing of ablation (Hardy and Hansen-Bristow, 1990).

Snowpack Energy Balance

To understand how differences in aspen and conifer snow dynamics could lead to differences in water yield we must consider the effects of forest cover on physical snow properties. The period of snow melt begins when the net energy balance of the snowpack becomes more or less continually positive and can be described in three phases: warming, ripening, and output. The warming phase is the period when the average snowpack temperature increases until the snowpack becomes isothermal at 0 °C. Water begins to melt within the snowpack at the onset of the ripening phase. The output phase begins when the snowpack is saturated with liquid water and additional energy inputs produce liquid water output to the snow/ soil interface. The snowpack may fluctuate between these phases due to seasonal and diurnal ambient temperature changes (Dingman, 2002).

Snowmelt energy balance is the net result of energy exchange with the soil and atmosphere and may be mediated by forest vegetation cover. Snowpack energy balance can be thought of as:

$$S = K + L + H + LE + R + G - M$$

where S is the energy content of the snow, K is net shortwave solar radiation input, L is longwave radiation exchange, H is turbulent exchange of sensible heat, LE is the turbulent exchange of latent heat, R is latent heat inputs from rain, and G is conductive heat exchange of sensible heat with the ground. The energy used to melt the snow (M) is considered an energy sink because the resulting water leaves the system (Dingman, 2002). Woo and Steer (1986) speculated that conductive exchange of sensible heat via the tree trunk and roots could also contribute to snowpack energy balance in coniferous forests.

In a comparison of snowpack energy balance between aspen and conifer forest there will be differences in these individual energy fluxes. Assuming the stands are on similar aspect and latitude, net shortwave radiation (K) would be higher in the relatively open stand of leafless aspen. However, the surface-snowpack albedo would be expected to be lower in snow beneath conifer stands due to leaves and tree resins accumulating in the surface-snowpack beneath the trees.

Longwave radiation (L) reaching the surface snowpack would be expected to be higher in aspen. Although the tops of coniferous forests absorb much of the intercepted shortwave radiation and re-emit longwave radiation, this energy may not reach the snowpack surface because of the thick canopy. The leafless aspen structures are source for increased long-wave radiation that reaches the snowpack (Swanson and Stevenson, 1971). Turbulent heat exchange of sensible heat (H) and latent heat (LE) may be reduced in conifer stands due to diminished wind speeds under the dense evergreen tree canopy.

Surface-sublimation primarily occurs after snow intercepted by the canopy has disappeared by canopy-sublimation, melt water drip, or mass transfer (Lundberg and Halldin, 1994). The canopy-sublimation process consumes incoming radiation as latent heat, thus, the atmosphere interacting with the snowpack below the canopy stays cool and moist. If the snow pack is colder than the atmosphere, the air near the surface is cooled, becomes more dense, and resists being lifted away from the snowpack surface, and cannot be replaced by warmer or moister air (Dingman, 2002).

Energy inputs by rain (R) will be reduced in conifer due to interception effects from the canopy unless precipitation events are long enough that the threshold of interception is passed. The parameter R is rarely a large contributor to the snowpack energy balance (Dingman, 2002). Another source of latent heat is condensation from the atmosphere. If water vapor from moist air condenses on a snowpack, 590 calories of heat are released by each gram of condensate. This is enough energy to melt 7.5g of ice (Dune and Leopold, 1978).

Conductive heat exchange with the ground (G) is a constant input of energy to both aspen and conifer systems due to stored thermal and geothermal heat. The thermal conductivity of the soil would be equal if the aspen and conifer soils have the same texture, density, and moisture content. Conifer stands may have lower G if late season transpiration diminishes soil water content and because of reduced net shortwave radiation reaching the soil prior to snow accumulation due to canopy shading. In contrast, aspen soils may have higher soil water content and greater net shortwave radiation after the trees undergo senescence. Conduction of heat from the ground into the snowpack can contribute as much as 20 mm mo^{-1} of base flow runoff in middle latitudes (Dunne and Leopold, 1978). Any difference in G might be negligible because it is usually much smaller than other terms (Dingman, 2002).

Thermal conductivity by the trees might be another snow energy input parameter in conifer stands. Measurements of sap flux have been hampered by inverse temperature gradients in tree trunks (Ping et al., 2004). In the morning, the tops of trees receive solar radiation before the lower parts of the canopy, and although transpiration is occurring, the heat gradient in the sapwood is reversed. If heat is conducted downward through the sapwood it might transfer the energy directly to the snowpack via the roots and soil. Woo and Steer (1986) measured the variations in snow depth around individual trees in a sub-artic forest in Northern Ontario to determine average snow depth for the forest. They found that depth increased non-linearly when moving away from the tree bole. Presumably, this pattern was produced by snow interception and added heat inputs due to long wave radiation from the tree trunk, which can accelerate snow metamorphosis and melt (Dingman, 2002).

Snow Metamorphosis

The snow energy balance ultimately will determine the onset of snowmelt phases. Differences in energy balance could result in different snowmelt and runoff patterns between aspen and conifer. Another way to look at observed differences in snowpack properties is to focus on processes affecting the physical snow properties in the period of time proceeding the output phase.

As soon as snow settles on a surface (branch or ground) it begins metamorphoses (densification). Four mechanisms of metamorphosis can occur simultaneously including: gravitational, destructive, constructive and melt metamorphosis. Gravitational settling is the increase in density due to the weight of the overlying layers and temperature. Destructive metamorphism is the evaporation of fresh snowflake points and projections and condensation onto less convex surfaces, caused by microscopic differences in vapor pressure over convex surfaces. Constructive metamorphism is the dominant densification process where adjacent snow grains bridge together as a result of vapor transfer within the snowpack. In warmer portions of the snowpack sublimation occurs and the resulting water vapor movement along a concentration gradient towards colder portions of the snowpack where condensation occurs (Dingman, 2002).

Melt metamorphism is the introduction of liquid water to the surface of the snowpack by rain or melt. As the introduced water freezes it releases latent heat that warms the snowpack and accelerates vapor transfer. Within the snowpack smaller grains are sublimated and deposited onto larger grains resulting in larger net grain size and snowpack densification. There is high temporal and spatial variability in snowpack characteristics over short distances due to the effects of vegetation (drip lines), slope, and aspect. In general, the variability will be greatest where periods of melting occur during the winter and where much of the heat input to the snow is from solar radiation (Dingman, 2002).

Interception of snow by the conifer canopy affects surface snowpack density. The density of freshly fallen snow often ranges from 0.004-0.34% (Mckay, 1970), with lower values occurring under calm, very cold conditions and higher values accompanying higher winds and higher temperatures. Schmidt and Gluns (1991) found that (1) individual conifer branches intercepted 11-80% of SWE in 22 storms, (2) the fraction of intercepted snow was inversely related to the snow density and total storm precipitation, and (3) the maximum SWE intercepted was ~7 mm. The high variability in SWE and density beneath conifers could be a result of the random patches of mechanical snow returns from the canopy and their continued effects on the basal snowpack. In conifer stands the heterogeneity in snow energy content may affect sublimation rates. The density of fresh fallen snow beneath conifers might be lower than in the open because lighter snow has a higher probability of being intercepted by the conifer canopy. Even when snow is returned to the conifer snowpack via melt water drip and mass transfer it will have undergone metamorphosis due to high net radiation exposure on the branch.

In cold regions with shallow snowpack and thin vegetation cover, the top soil may be covered by a dense layer of ice lenses referred to as "concrete frost". The infiltration capacity of the soil may be lowered to 0.2 mm hr^{-1} or less by this ice and it may result in rapid surface runoff during melt events. However, under thick snow packs or dense vegetation in temperate regions, the soil may remain unfrozen, or may be occupied by "porous frost" or needle ice, which does not inhibit soil infiltration capacity (Dunne and Leopold, 1978).

Snow metamorphosis and melt dynamics are expected to differ between aspen and conifer. Snowpack properties in conifer stands are more heterogeneous due to canopy effects on snowpack metamorphosis. It is important to consider the processes that affect the observed differences in snowpack morphology in aspen and conifer stands.

Plant Physiology

Transpiration can have two effects on the fate of spring snowmelt. The first is the direct loss of water from the soil column during the snow melt season. The second is the effect on soil moisture content in fall prior to the snow accumulation period. If a soil is relatively dry in the fall prior to the snow accumulation period, the soil will have an additional capacity to absorb and retain a greater amount of water during the spring snow melt. Conversely, if a soil is relatively wet in the fall prior to the snow accumulation period, the soil will have decreased capacity for infiltration leading to increased runoff. Thus, the relative contribution to soil moisture recharge can be a significant loss to stream water inputs (Julander and Perkins, 2005). It is important to define the amount and timing of transpiration in aspen and conifer forest communities (Gifford et al., 1984).

Several physiological processes confound the measurement and comparison of net annual transpiration in aspen and conifer species. Conifers can transpire water during warm periods in winter while hardwoods are leafless or only leafing out (Douglass, 1983). Conifers may begin transpiring as much as two months before aspen (Gifford et al., 1984). However, aspen has consistently higher sap flux than conifers in the early season possibly due to leaf expansion. Mean estimates of daily sap flux in aspen and conifer communities were not different when averaged over the course of the summer growing season (2.6 and 2.7 mm day^{-1}, respectively) in Wyoming (Pataki et al., 2000). However, these estimates were made between day of year (DOY) 168-238 (6/17 and 8/25) which did not account for fall and spring periods when conifer may be active while aspen remains dormant.

A brief summary of transpiration monitoring techniques and parameters affecting transpiration is necessary to understand the complexity of comparing species differences. Plant stomata are the terminal regulator for plant uptake of CO_2 and release of H_2O. During the gas exchange process, water vapor within the leaf moves along the concentration gradient from the leaf to the atmosphere.

At the leaf level stomatal control is a feed forward response that balances the tradeoff between CO_2 assimilation and H_2O loss to maximize water supplies. To scale single leaf transpiration estimates to the whole tree level, measured flux rates must be corrected for boundary layer and leaf area such that the leaves measured represent the range of conductance values throughout the plant canopy (Meinzer, 2002). A complete model of stomatal behavior might include: photosynthetic photon flux density (PPFD); vapor pressure deficit (VPD); CO_2 concentration; temperature; water stress; and a host of tissue, cellular, and sub-cellular processes involving solutes, membrane characteristics, and hormones (Kaufmann, 1982). In a survey of five different models for predicting stomatal aperture in Rocky Mountain subalpine tree leaves, Massman and Kaufmann (1991) found that regardless of the model, variables decreased in importance: PPFD > VPD > temperature.

Scaling stomatal conductance models to whole tree transpiration is difficult because of the heterogeneous microclimate within a single tree canopy. Thus, sap flux (J_s) measurements developed by Granier (1985) can be used to determine whole tree transpiration. The velocity of water movement in the xylem is determined by measuring the difference in temperature between a heated and non-heated needle inserted into the sap wood and calculating the cross sectional sap wood area of the tree. One advantage of J_s measurements is their ability to take continuous measurements throughout the entire growing season. In a J_s, based transpiration study of Rocky Mountain subalpine trees, Pataki et al. (2000) reported J_s values were parabolically related to daytime average VPD regardless of species (R^2 = 0.79-0.91). Compared to all coniferous species investigated, aspen had the greatest increases in J_s with increasing VPD and the least decline in J_s in response to declining soil moisture.

Sap flow measurements can be scaled up to the forest canopy level by estimating the sapwood to area ratio in a given area and multiplying by the measured sap velocity. Using this scaling method, Pataki et al. (2000) observed that two conifer species (lodgepole pine and subalpine fir) had similar whole canopy transpiration when compared to aspen during a summer drought, despite a four fold difference in leaf area index (LAI) for conifers. Thus, LAI and other stand characteristics such as basal area cannot be used to compare transpiration potential between aspen and conifer. Differences in LAI are offset by differences in stomatal regulation and leaf physiology.

Whole ecosystem evapotranspiration (ET) can be monitored directly by eddy-covariance method that uses vapor flux density between the forest and atmosphere to determine energy and mass exchanges. Modeling ET in forests is based solely on physical information gathered from meteorological stations that are erected upon a tower above the tree canopy. The stations can determine energy balance by measuring net radiation, photosynthetically active radiation, and incoming solar radiation. Mass exchange is determined by measuring turbulent velocities with a three-dimensional sonic anemometer as well as measuring water vapor and CO_2 concentrations with a open-path Infra Red Gas Analyzer (IRGA). Other parameters measured include relative humidity, air temperature, precipitation, soil temperature, and soil moisture at rooting depth.

Evapotranspiration estimates based on eddy covariance should always yield lower values than potential evapotranspiration (PET). In a comparison study of several transpiration estimation techniques, Granier et al. (1990) found that in homogeneous maritime pine (*Pinus pinaster*) stands, the average ratio for sap flux to potential evapotranspiration (PET) measurements was 0.55. Estimation of ET should also yield higher values than canopy transpiration estimates based on sap flux. This is because eddy covariance approximates whole ecosystem vapor movement. Granier et al. (1990) reported an $R^2 = 0.66$ comparing the two methods in maritime pine and also noted a lag time between maximum sap flux rate and maximum vapor flux. This observation has since been referred to as the lag time effect and could be a result of transient removal of water stored above the point of sap flow measurement at the base of the tree (Goldstein et al. 1998). Others have recently attributed the lag time effect to quantifiable hydraulic resistance and capacitance properties of the wood (Unsworth et al. 2004). Differences in the hydraulic properties of aspen and conifer wood could lead to temporal difference in the relationship between sap flux rate and actual transpiration. This could systematically bias models based on the relationship between sap flux and physical parameters such as

PPFD, VPD, and temperature. Accurate quantification and comparison of sap flux between aspen and conifer may require calibration with other methods.

Net annual transpiration may not be different between aspen and conifer. At the ecosystem scale, Roberts (1983) suggested that there is no variability observed in forest transpiration between various forest vegetation types under a given climate regime. He suggested that a combination of effects including transpiration from the forest understory, negative wind feedbacks from surface resistance, and insensitivity to soil moisture ultimately buffer against potential differences in water yield.

There is physiological evidence that trees in tropical systems use the same amount of water regardless of species and tree architecture. Functional convergence is an evolutionary response to a given situation where diverse plant taxa may converge on a limited number of solutions to a given problem such as water use. Recent empirical and theoretical scaling models emphasize the strong role of plant size, architecture, allometry and chemistry in constraining functional traits related to water and carbon economy and growth (Meinzer, 2002). It has been suggested by several authors that allometric scaling of plant vascular systems, and therefore water use is universal (Enquist et al., 1998). In tropical trees allometric relationships may exist between J_s and stem diameter and also between water use and aboveground biomass. Meinzer (2002) reported that sap flux and stem diameter for five tropical tree species had a bi-phasic relationship of mean J_s (20 days) vs. stem diameter. From these observations he concluded that three contributing factors drive the biphasic relationship. First, stomatal conductance must increase to compensate for gravity up to a threshold where the risk of cavitations limits J_s. Second, increasing the basal sapwood to leaf area ratio decreases the sap velocity. Finally, as stem water storage increases with tree size the max J_s rate decreases. These J_s convergence observations were made with sap flux probes placed at a single sap wood depth (20 mm) which has raised questions about the observed results. Wullschleger and King (2000) measured radial differences in sap velocities at four depths in yellow-poplar trees (*Liriodendron tulipifera*). They divided each velocity by the maximum sap velocity measured to determine the fraction of sapwood that was functional in water transport (*f*S). The *f*S value varied between 0.49 and 0.96 and there was no relationship between *f*S and sapwood thickness, or between *f*S and stem diameter. They cautioned that not all sapwood is functional in water transport and the magnitude of this variation in a range of non-porous, diffuse-porous, and ring-porous trees could introduce systematic bias into estimates of both tree and stand water use. This implies there may be fallacies in J_s vs. stem diameter and other convergence relationships.

The difference in water use between evergreen and deciduous species has been attributed to a variety of other environmental and biological factors. Leaf morphology affects transpiration in several ways. Common leaf traits for species in dry habitats include thick, hard leaves with thick cuticles and small, thick walled cells. These traits have been interpreted as water conserving traits, which increase resistance to wilting. However, the general occurrence of the same leaf traits in species growing on nutrient-poor soils has led others to propose that these traits are an adaptation to increase leaf life span in habitats where rapid growth is not possible and slow tissue turnover is therefore favored. Stomatal conductance of shade-tolerant species may be more strongly coupled to VPD and less coupled to PPFD than that of shade intolerant species (Massman and Kaufmann, 1991). Many environmental factors confound the comparison of leaf morphology between widely divergent habitats; the effect of a given set of leaf morphological characteristics on water use may not be universal under various climate regimes (Wright et al., 2002).

Insights into the tradeoff between deciduous and evergreen life forms could be derived from geographic differences in morphology within species. Regional foliage retention patterns (leaf life span) of coniferous stands could be an acclimation to winter temperatures, while local variation may be the result of adaptation to patchy microsite environments. In China, coniferous forest climate variables, annual precipitation, evaporation, and solar radiation all had significant relationships with needle longevity, indicating that variation across regions is most likely a result of adaptation to the ambient environment (Xiao, 2003). For 75 perennial species from eastern Australia, individuals on poorer soils had higher leaf mass per unit area and longer leaf lifespan, but significantly so only in areas with high rainfall (Wright et al., 2002). Although these studies suggest that phenological traits within species can show adaptation for conservative water use, it remains unclear if deciduous vs. evergreen morphology is better adapted to conserve water under various climate regimes.

Distribution of Evergreen and Deciduous Species

On a global scale the distribution of evergreen and deciduous forests may reflect adaptations to climate. Temperate deciduous trees in North America tend to dominate forests characterized by cold winters with frozen soils and short day lengths (effective dry season) and high precipitation in the spring, fall, and winter (warm season). Evergreen forests in western North America are associated with mild winters and longer growing seasons (Givnish, 2002). The increase in leaf longevity of evergreens with latitude may buffer against more harsh and windy ambient environments (Xaio, 2003). Simulations of two tree species with contrasting leaf habits in New Zealand suggests there is no clear advantage in terms of annual carbon balance for a deciduous vs. evergreen phenology at sites with relatively mild winters (Dungen et al., 2004). In contrast, at sites where frost-induced photo-inhibition [cavitation] limits photosynthesis for over-wintering leaves, a deciduous phenology results in a higher value of carbon uptake for species with leaves that are very active photosynthetically during spring and summer (Dungan et al., 2004). Sandquist and Ehleringer (1998) suggested that the trade-off among water consumption, photosynthesis, and leaf longevity maximized carbon gain for the Chilean brittle bush (*Encelia farinosa*) along a precipitation gradient.

The distribution of aspen and conifer may influence climate thus complicating biogeographical inferences. Feedbacks between vegetation and the atmosphere can be inferred from the analysis of eddy flux measurements. Rocha et al. (2004) used three years of eddy-covariance and meteorological data from an aspen-dominated northern hardwood forest in Michigan to investigate the effect of cloud cover on ET and water use efficiency (WUE). They found that increasing the proportion of diffuse light (cloud cover) to total PAR decreased midday canopy ET but increased midday canopy WUE. The latent heat absorbed by transpiring forests could have strong implications for atmospheric temperature regulation. It has been postulated by Hogg et al. (2000) that transpiration feedbacks between aspen forests and the atmosphere in the Western Canadian interior may explain anomalously warmer than expected conditions in spring and autumn. Observations using eddy correlation and J_s measurements revealed that latent heat (water vapor) flux reaches a maximum during the summer period when leaves are present, while sensible heat flux is highest in early spring when the forest is leafless. These findings would support the hypothesis that forest cover type can contribute significantly to the distinctive seasonal patterns of mean temperature and precipitation in a region.

Little is known about the trade-offs among water consumption, photosynthesis, and leaf longevity where evergreen and deciduous species co-dominate. However, if leaf life traits are the drivers for xylem vessel size, these traits combined with convergence in hydraulic conductance and resistance might lead to differences in net annual transpiration between evergreen and deciduous trees. Superimposed on temperate bio-geographical water use relationships are complicating factors such fire disturbances, herbivore dynamics, and the physical differences in tree structure leading to differentiation in abiotic interception of precipitation and subsequent evaporation. It is important to consider how these variables have affected the evolution of evergreen and deciduous tree physiology in water limited ecosystems.

Summary

Various scientific disciplines have added insight into the determination of differences in water yield between aspen and conifer forests. To understand the net differences in water yield, one must consider all variables contributing to water transfer over the course of a water-year. In Northern Utah a water-year is considered to begin and end in October. This convention is used because generally the plants have used most of the available soil water and the dry fall precipitation regime often results in the lowest observed water storage and stream flow. Most of the precipitation in Utah comes during the winter in the form of snow. Throughout the winter snow accumulation and melt patterns are affected by the physical structure of forest vegetation. As the melt progresses the biological activity of the trees begins to influence the transfer of water to the atmosphere via transpiration. During summer, precipitation changes to rain which is affected by the physical interception of tree structures and biological transpiration. Finally, the late summer drought and dry fall precipitation regime result in eventual drying of the system.

We expect that differences in physical and biological variables between evergreen conifer species and deciduous aspen species cause differences in annual water yield. While the difference in timing and rates of water transfer in adjacent end point (mature) evergreen and deciduous forest communities is most likely site specific, we expect the relative importance of hydrologic transfer mechanisms to be similar in snow dominated watersheds. Determination of the water "pool sizes" and flux rates within the snow, soil, vegetation and atmosphere will help determine which hydrologic transfer mechanisms could cause large differences in water yield.

CHAPTER 3

FIELD SITE AND RESEARCH METHODS

Water dynamics in mature aspen (deciduous) and conifer (evergreen) stands were compared on north facing slopes in Northern Utah. North facing slopes were expected to have the greatest potential for increasing water yield by conversion from aspen to conifer forest in snow-dominated watersheds. Simultaneous measurement of physical and biological mechanisms of water transfer was used to determine why differences in water yield occur at the stand level.

Study Site

General location

The study was located in the Northern Wasatch Mountains of Utah, USA. Research was conducted primarily within Weber County near the intersection with Cache and Rich Counties on private land owned by Deseret Land and Livestock (Fig.. 3.1). The conifer stands were heavily logged at the turn of the 20th century, however, some stands were not harvested at this time presumably due to difficult road access on steep ridges and in deep gullies. Mature aspen and conifer stands occur adjacent to one another on North facing slopes in the study area. Abrupt edges between pure aspen and conifer stands may have been caused by fire or logging disturbances, or soil characteristics that favor each community.

Block locations and plot descriptions

The comparative study was primarily undertaken in the Frost creek drainage of the Ogden River, which is part of the upper Weber River basin (Fig.. 3.2). Research blocks containing aspen and conifer stands were selected on north, north-west, and north-east facing aspects due to the limited range of conifers, which primarily occur on these aspects within the catchments. Within each block, a single aspen and conifer plot were selected approximately 200 meters apart, based on the criteria that they shared similar slope, aspect, and slope position. In Blocks 2, 7, and 8, open plots devoid of tree cover were also identified using the same selection criteria. Two of the blocks (Blocks 1 and 2, Table 3.1) were sampled and instrumented to monitor SWE, snowpack sublimation, soil moisture content, and sap flux (Fig. 3.2). All remaining blocks within the Frost Creek watershed and adjoining watersheds were only used to measure SWE (Blocks 3-8, Table 3.1). Detailed location maps of plots within each block can be viewed in appendix A.

Automated measurements of atmospheric variables were recorded at a meteorological station and snow telemetry station (MET and SNOTEL, Table 3.1).

Table 3.1 Locations of research blocks, SNOTEL, and meteorological station.

ID	UTM (12 T, NAD 83)	Elevation (m)	Aspect	Slope (%)
1	4580516, 459990	2515	NW	35
2	4579687, 461670	2626	N	40
3	4580593, 460064	2556	NW	30
4	4580800, 460560	2558	N	35
5	4575735, 462320	2531	Flat	0
6	4575735, 462320	2520	N	30
7	4578655, 459227	2635	NE	10
8	4582168, 461319	2641	NE	30
SNOTEL	4578696, 459244	2507	NE	10
MET	4577109, 464359	2572	NW	5

Fig. 3.1 Study site location.

The MET station was located approximately 3 km to the south-east of Block 2 (Fig. 3.2). The SNOTEL station was located approximately 3 km (2.1 mi) West of Block 2 (Fig. 3.2).

Aspen plots consisted of ramets (trees) of varying age class including regenerating young ramets in the understory. The understory in aspen plots was

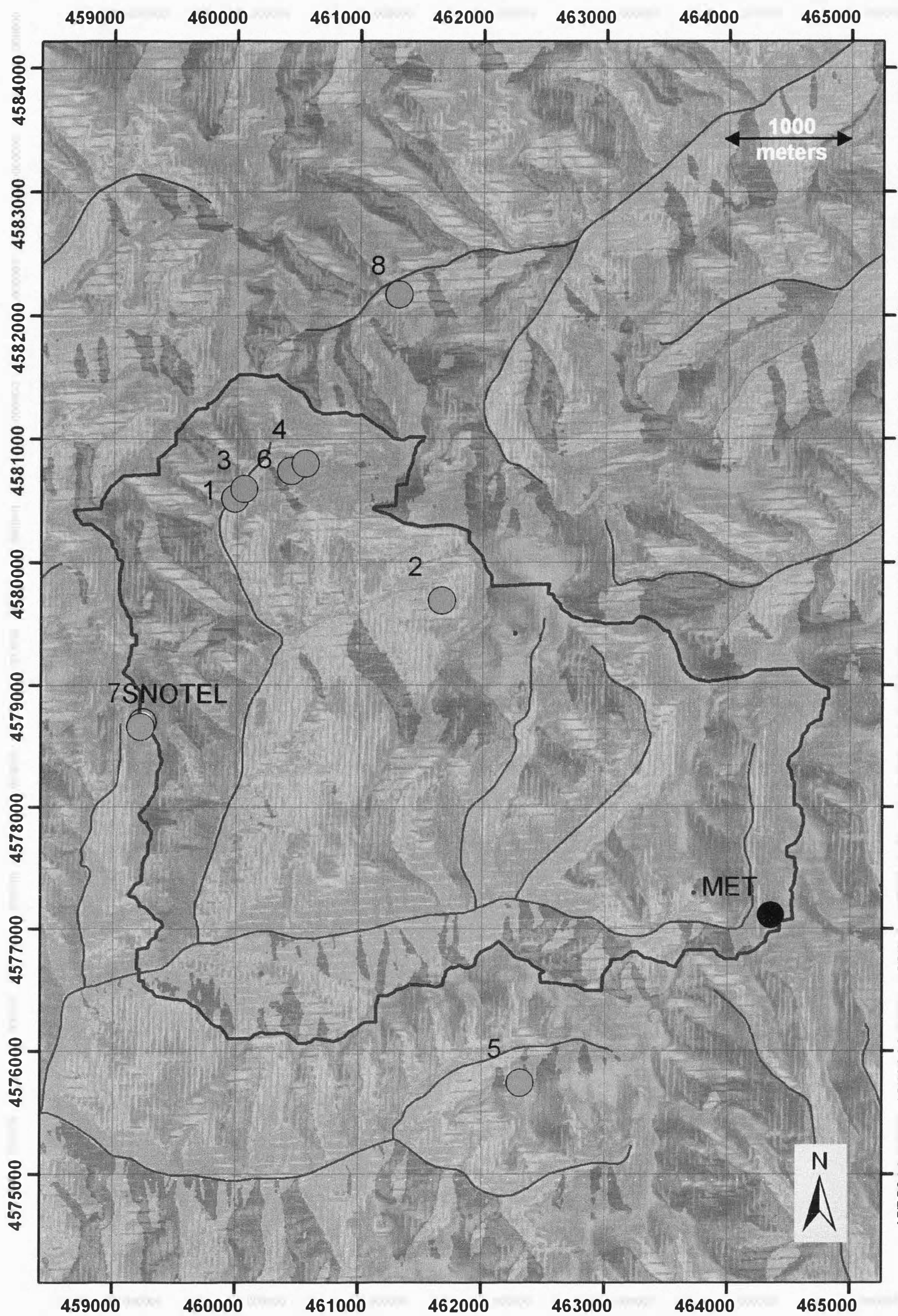


Fig. 3.2 Locations of weather stations and research blocks.

primarily dominated by shrubs (*Symphoricarpos albus*, and *Amelanchier alnifolia*) and forbs (*Conium maculatum, Senecio serra, Geranium richardsonii, Epilobium angustifolium, Mertensia ciliata,* and *Agastache urticifolia*). Overstory trees in conifer plots consisted primarily of white fir (*Abies concolor*) and Douglas fir (*Pseudotsuga menziesii*), although Block 8 was predominantly Engelman spruce (*Picea Engelmannii*). The conifer understory was predominantly bare ground with limited herbaceous vegetation and shrub cover (primarily *Ribes montigenum*).

Methods

Snow Telemetry Station (SNOTEL)

Automated measurements of snow parameters were obtained from the Natural Resource Conservation Service (NRCS) Lightning Ridge SNOw-TELemetry (SNOTEL) station, in operation since 2004. The station was located on the edge between an open meadow and an aspen stand, it was adjacent to Block 7. The station monitored a vertical profile of soil moisture using capacitance probes (Hydra probe, Stevens Water Monitoring Systems, Inc., Beaverton, OR, USA) placed at 5, 10, 20, 51, and 102 cm soil depths; measured and recorded snow depth with a sonic depth sensor; SWE with a snow pillow; total precipitation; and air temperature (see, www.wcc.nrcs.usda.gov/snotel/). Variables were recorded once per hour.

Meteorological station

The Bear Canyon meteorological station monitored physical variables including relative humidity, temperature, wind speed and direction, precipitation, and incoming solar radiation. Variables were recorded at 15-minute intervals.

Peak snow accumulation

Snow accumulation was measured within aspen, conifer and treeless openings at various times during the winters of 2005 and 2006. Peak snow water equivalent (SWE) was determined by conducting snow surveys at or near maximum snow accumulation

Fig. 3.3 Measurement of snow water equivalent with standard snow tube.

(~April 1st) as approximated by the Lightning Ridge SNOTEL station. The decision to measure peak snow accumulation was made with consideration of predicted snow melt forecasts from the National Oceanic and Atmospheric Administration (NOAA). Within each plot several 8 m X 20 m grids were surveyed for SWE. Snow Water Equivalent

(SWE) and snow depth were measured using a standard snow tube (Carpenter Machine and Supply, Seattle, WA, USA). Each snow survey consisted of four line transects oriented up-slope and two meters apart. At each sample point the tube was vertically inserted into the snowpack and depth was recorded (Fig.. 3.3). The tube was gently pushed into the soil, and then removed with a small soil plug at the end. The soil plug was removed and the tube and snow core weighed. During spring 2005, SWE and depth were measured every four meters in aspen and conifer plots (n=16). During spring 2006, SWE and depth were measured every four meters in aspen plots (n=16) and every 2 meters in conifer (n=32). The greater sample size in conifer was used to account for greater heterogeneity in the conifer stand snowpack as indicated by data from 2005. To determine if sampling was missing small scale heterogeneity in conifer stands (e.g. due to sloughing of snow along the drip line) a single conifer tree was sampled in 2006 along each cardinal aspect every 0.1 m in a 4 m X 4 m plot. A complete schedule of data collection is provided in Appendix B.

Snow ablation

Several additional surveys for SWE and snow depth were conducted after the peak snow accumulation period to determine the ablation (melt) rate. Surveys were conducted within Blocks 2 and 4 in 2005 near the end of the melt period DOY 139 (5/19/05), and in Blocks 1, 2, 7, and 8 in 2006 at two week intervals following peak snow accumulation until DOY 139 (5/19/06). Successive snow surveys were conducted in parallel transects adjacent to the original transects where possible, but in the Block 2 conifer plot, repeated measurements along the same transects were used due to spatial limitations. The SNOTEL station recorded daily SWE during the entire snow accumulation and melt periods in 2005 and 2006.

Snow density

Snow density was calculated by dividing SWE by snow depth for each point observation in each snow survey. Daily snow density at the SNOTEL station was also determined by dividing the snow depth (determined by a sonic depth sensor) by the SWE (determined by a snow pillow).

Snow pack sublimation and condensation

Spring surface snowpack sublimation and condensation estimates were determined using sublimation pans (clear plastic Tupperware containers). Bricks of snow were cut from a representative snow surface in each plot and placed into sublimation pans (approx. 60 cm X 20 cm X 10 cm). The containers were weighed in grams using an electronic scale and then installed into snow pits cut to fit the dimensions of the pan. The pans fit inside the pits such that the top of the container was flush with the snow surface (Fig. 3.4). In each plot, sublimation pans (n=5) were placed along a ~25 m transect once every ~5m. Installation occurred around 8 am, and the pans were left for approximately 24 hours before being weighed again. The measured difference in start weight – end weight of the pan and snow was converted from weight to mass of water (1 g H_20 = 1 cm^3 H_20) and divided by the surface area of the pan (520 cm^2) to determine the change in total water content (equivalent depth cm). Weight losses were assumed to be due to sublimation and gains due to condensation.

Sublimation pan measurements were taken approximately once every two weeks throughout the melt period in the springs of 2005 and 2006. During spring 2005, six replicated sublimation pans were installed in open (where available), aspen, and conifer plots in Blocks 1, 2, and 5. During spring 2006 six sublimation pans were installed in each of the aspen, conifer, and open plots in Block 2.

In 2006 snow temperature was monitored in two of the sublimation pans within each plot and in the snow adjacent to each pan to determine if heating effects from the plastic pans were affecting sublimation rates. The first two pans in each transect were instrumented with temperature micro-loggers (iButton DS1922L, Maxim Integrated Products, Inc. Sunnyvale, CA, USA). Within each instrumented sublimation pan the temperature probe was inserted horizontally into the snow brick so as not to disrupt the snow surface. Before placing the brick into the pan, a temperature logger, sewn into a

Fig. 3.4 Sublimation pan methodology.

small white pouch, was pushed into the center of the snow brick using a knife. A 0.32 m section of fishing line connected the pouch to a second pouch with logger. The second temperature micro-logger was then installed 5 cm beneath an undisturbed section of snow approximately 20 cm to the side of the pan for comparison. Temperature was logged once per hour inside the pan and in the adjacent snowpack.

Transpiration

Transpiration activity was estimated by measuring hourly sap flux velocity. Measurements were logged using four sap flux systems (Probe 12, Dynamax inc., TX, USA). The system measured sap flux using a thermal dissipation probe (TDP) similar to that described by Granier (1985). Thirty-two TDP sensors were deployed, eight in each of the aspen and conifer plots in Blocks 1 and 2. In Block 1, one tree in each plot was selected to measure sap flux on all four cardinal aspects; the four remaining probes were installed on the south side of four trees in a ~ 100 m transect perpendicular to the slope. In Block 2, all eight probes in each plot were installed on the south side of eight trees in a ~200 m transect perpendicular to the slope. All probes were installed one meter above the ground and insulated with Styrofoam and reflective bubble wrap (Fig. 3.5). All exposed cables and insulation were protected from ungulate and rodent damage using schedule 40 PVC pipe and chicken wire. Sap flux was measured once every hour beginning in fall and continued until transpiration ceased. Sap flux measurements resumed the following spring during snowmelt period.

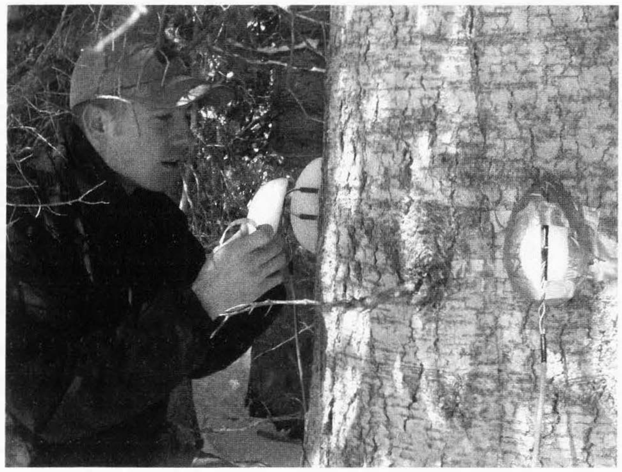


Fig. 3.5. Sap flux probe installation.

Problems with the sap flux system were identified while collecting and interpreting the sap flux data. The clock in the Dynamax system often skipped an hour at midnight which offset the reference temperature (ΔdT) and caused incorrect values to be calculated by the logger. Another problem occurred when the power supply dropped below 11.5 volts causing the system hardware to crash. These problems ultimately lead to large gaps in the data.

Two methods were used to analyze the data. The first method relied on the sap flux reported in grams per hour. In Block 1, reported sap flux values were plotted for single trees monitored on all cardinal aspects. Data were plotted only for days when both aspen and conifer data loggers were functioning for a full 24-hr period. All data points for each probe were scaled (0-1) to the maximum sap flow value calculated by the probe during the study. The daily sap velocity was plotted for individual days.

The second method used the difference in voltage between the heated and unheated probes to determine the seasonality of transpiration activity. This analysis was applied to the four remaining probes in Block 1 and all eight probes in Block 2. In order to approximate the transpiration activity period, the maximum K value for each day was calculated using the daily maximum and daily minimum difference in voltage (ΔV) between the heated and unheated thermocouples where

$$K = \frac{(\Delta V max - \Delta V min)}{\Delta V min}$$

The data were filtered to exclude days when ΔVmin was abnormally high or low based on the assumption that baseline tree temperature (temperature of the trunk) at zero sap velocity should change gradually throughout the season (Ping et al., 2004).

The difference in voltage for each day was used to calculate the daily maximum dimensionless K parameter. In the original Granier equation sap flow density (J_s) is directly related to the scaling parameter K where

$$J_s = 118.99 \times 10^{-6} [K]^{1.231}$$

As K increases J_s increases. In many sap flux studies J_s is multiplied by the sap wood area of each tree to calculate sap flow rate (volume hr^{-1}). The analysis of K alone was used to scale the relative transpiration index at daily intervals rather than quantify the volume $hr^{-1}$of water transpired by the trees.

Soil moisture

Volumetric soil water content was monitored at shallow depths beneath trees and in the interspaces and in vertical profiles of the soil column. Calibrated measurements of soil volumetric water content were made with capacitance probes (Hydra Probe, Stevens Water Monitoring Systems, Inc., Beaverton, OR, USA). The hydra probe measures soil dielectric content and temperature which are then entered into the manufacturers proprietary software (Hyd_file.exe, Stevens Water Monitoring Systems, Inc., Beaverton, OR, USA) to determine volumetric water content.

Spatial differences in soil moisture within the aspen and conifer stands were measured inside and outside of tree wells to determine if transpiring trees had a negative effect on shallow soil water content during the spring snow melt period. A tree well was defined as the area beneath the conifer tree canopy where snow accumulation is diminished due to interception (0-2 m from the trunk). In deciduous aspen there are no tree wells (because winter canopy is absent) so probes were placed in small clearings approximately 2 m from the nearest aspen ramet (tree) for comparison. Twenty probes were deployed in 10 pairs inside and outside of the tree wells at 10 cm soil depth and monitored at 1-hour intervals using data loggers (CR21X and CR23X, Campbell Scientific Inc., Logan, UT, USA) throughout the spring snow melt. Twelve probes were deployed evenly between the aspen (3 pairs) and conifer plots (3 pairs) in Block 1 and eight probes were deployed evenly between the aspen (2 pairs) and conifer plots (2 pairs) in Block 2.

Vertical distribution of water in the soil profile and soil column water content were measured using four stacks of five probes each. Two stacks were placed in each block, one per plot. The probes were placed at 5, 10, 20, 51, and 102 cm soil depths. Probes were monitored at 1-hour intervals using data loggers (RS 205, and CR23X , Campbell Scientific Inc., Logan, UT, USA).

Soil moisture probe calibration

Two shallow soil cores were extracted from each plot in Blocks 1 and 2 for the calibration of Hydra probes. One core was taken near the bole of a tree (< 1 m from trunk), and a second core was taken in the interspaces between two trees (> 3 m from trunk). The containers used to hold the soil cores were constructed of ~10 cm (diameter) PVC pipe cut to 10.5 cm height and caped at one end (697 cm^3). Holes were drilled in the cap at the bottom of the container to provide for drainage. To extract the soil cores, the topsoil at each site was excavated and leveled to 5 cm depth using a hand trowel. The PVC containers were then pounded into the ground until soil was visible through the drainage holes in the cap. The soil surrounding the container was then excavated and the trowel used to turn the container upright and keep the soil from falling out the container.

Soil cores were taken to the Utah State University ecophysiology lab for calibration experiments. Each container was saturated with water for 12 hours and then a Hydra probe was inserted into the open top containers (Fig. 3.6). The entire apparatus was placed into a Tupperware container and weighed. Then each probe was connected to data logger and the analog voltages were read. Soils were then allowed to dry for 24 hours and the measurement of weights and voltages repeated. This process was repeated three times. The soils were then allowed to air dry for two weeks until all soil cores had low water content measured by weight (0.08-0.15 m^3 m^{-3}) and then final voltages and weights were recorded. Soils cores were then oven dried at 110 $^{\circ}C$ for 24 hours. The weight of the water contained in the cores during each of the measurements was determined by subtracting the weights of the Tupperware container, hydra probe, PVC container, and oven dry soil core weight from the total weight. The volumetric water content was then compared to volumetric water content given by the capacitance probes (after processing raw voltages with Hyd_file.exe software). Water content estimated by

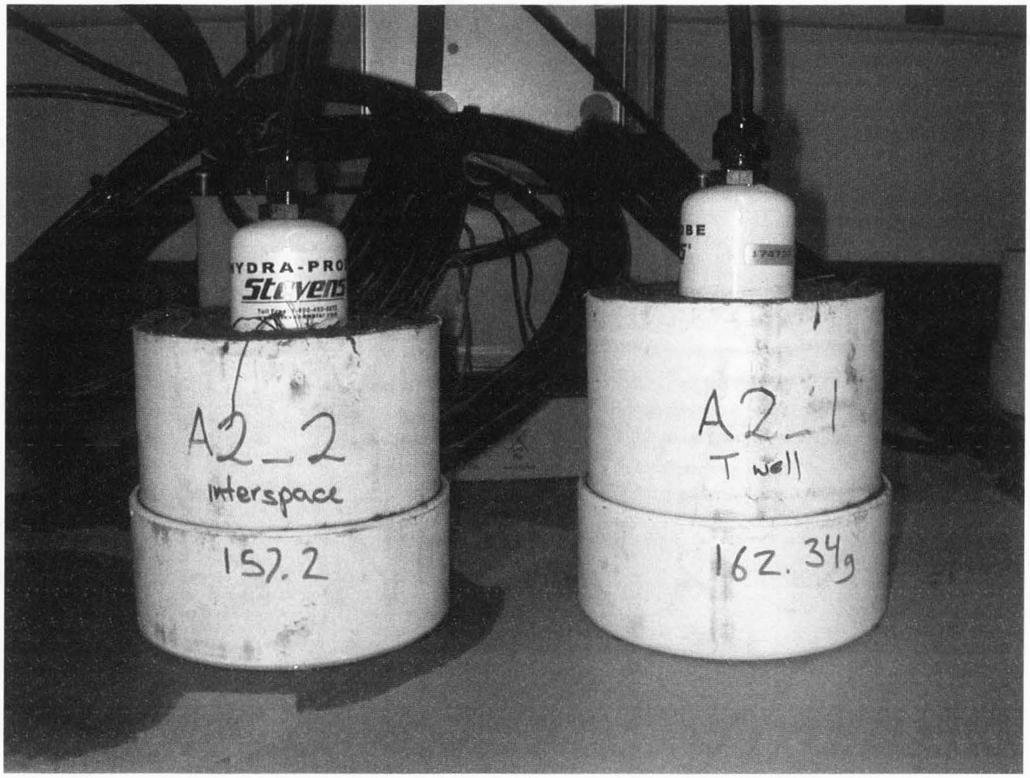


Fig. 3.6. Soil moisture calibration.

capacitance probes in aspen had a slightly stronger relationship to water content determined by weight ($P < 0.05$, $R^2 = 0.96$), than conifer soils ($P < 0.05$, $R^2 = 0.90$). Calibration equations were applied to the soil moisture data collected by the all of the capacitance probes installed in aspen and conifer soils (Fig. 3.7).

Soil column equivalent depth water content calibration

The total soil moisture content was determined by interpolating vertical soil moisture values (calibrated) from Blocks 1 and 2, and then applying a second calibration to account for soil column characteristics. The second calibration was determined using Block 2 peak spring water content values and soil column porosity calculated from soil survey information (Table 3.2).

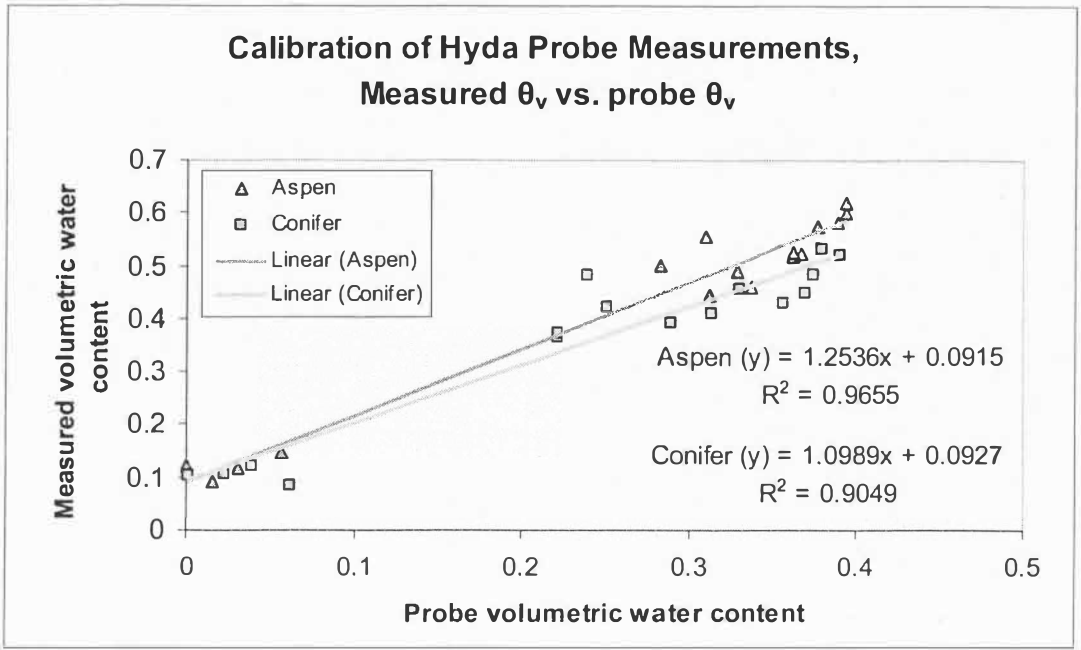


Fig. 3.7 Calibration equations for the correction of capacitance probe readings.

In Block 2, the NRCS completed pedon descriptions of the pits where vertical stacks of aspen and conifer soil moisture probes were installed (Appendix C). The bulk density for each soil horizon was used to calculate the porosity assuming a particle density of 2,650 kg m^{-3}, the approximate density of quartz and most mineral soils. The total porosity of the soil column was compared to the calculated water content of the column during the spring saturation to further calibrate water content values.

The NRCS determined the bulk density of each horizon in an excavated soil pit using a re-wetted soil sample method (Burt, 2004). Naturally occurring soil clods were collected from the face of the soil pit. One coat of plastic lacquer was applied in the field. Additional coats of plastic lacquer were applied in the laboratory. The clod was weighed in air to measure its mass and placed in water to measure its volume. After the clod was

Table 3.2 Soil column water content calibration (Block 2).

Cover	Horizon depth [cm]	Horizon thickness [cm]	Bulk density [Mg m^{-3}]	Soil porosity [m^3 m^{-3}]	Horizon $D_{e\ max}$ [mm]	Column $D_{e\ max}$ [mm]	Hydra peak content [mm]	Difference In water depth [mm]
Aspen	0-10	10	1.21	0.54	54			
Aspen	10-38	28	1.28	0.52	144			
Aspen	38-76	38	1.29	0.51	195			
Aspen	76-89	13	1.32	0.50	65			
Aspen	89-127	38	1.23	0.54	203	663	706	43
Conifer	0-18	18	1.06	0.6	108			
Conifer	18-36	18	1.13	0.57	103			
Conifer	36-58	22	1.44	0.46	100			
Conifer	58-114	56	1.77	0.33	185	498	555	57

dried in the oven at 110°C, its mass and volume were determined again. Corrections were made for the mass and volume of rock fragments > 2 mm and for plastic coatings. Table 3.2 Soil column water content calibration (Block 2). The maximum equivalent depth of soil water ($D_{e\ max}$) for the soil column was calculated as the sum of soil horizon thickness multiplied by the calculated porosity of the individual horizons (Table 3.2). When estimates of soil column porosity were compared, Hydra probe soil water content measured at peak saturation in aspen on DOY 137 (5/17/06) and conifer on DOY 144 (5/24/06) plots in Block 2 overestimated water content by 43 mm and 57 mm, respectively. The overestimation of water content was used as an offset to correct the total soil column water content values in Blocks 1 and 2. 137 (5/17/06) and conifer on DOY 144 (5/24/06) plots in Block 2 overestimated water content by 43 mm and 57 mm, respectively. The overestimation of water content was used as an offset to correct the total soil column water content values in Blocks 1 and 2.

Soil moisture calibrations determined using upper soil layers were used to calibrate all probe values including deeper probes. Appling calibration equations derived from upper soil horizons to the probes in lower soil horizons resulted in a slight overestimation of volumetric water content in the soil profile. However, the mean error across all five probes in the soil profile (+/- 0.03-0.05 $m^3 m^{-3}$) was close to the manufacturers reported probe error (+/- 0.03 $m^3 m^{-3}$).

Summary

Many variables were monitored to directly test our hypotheses. Data were also used for descriptive analysis of water transfer processes. Paired measurements of SWE, sublimation, ablation rate, sap flux, and soil moisture were used to directly test hypotheses dealing with differences in individual water pool sizes and fluxes. All data were then used to predict the equivalent depth of water lost or gained from each component. Data were then combined to calculate the magnitude of influence that each has in determining water yield from each stand type and determine the potential for water yield differences between aspen and conifer stands.

CHAPTER 4

RESULTS

Peak Snow Accumulation

SWE comparisons among and within survey blocks

Differences in April 1st peak snow accumulation (PSWE) between aspen and conifer stands were monitored during the 2004-2005 and 2005-2006 water years (WY). During spring 2005 PSWE was measured in six blocks (Blocks 1-6) over a 2-week period from DOY 101 (4/11/05) to 116 (4/26/05). Peak snow accumulation of 513 mm was observed at the Lightning Ridge SNOTEL station on DOY 92 (4/2/2005). Blocks 1-5 were monitored within a week of the SNOTEL peak before significant melting had begun (Fig. 4.1), while Block 6 was monitored DOY 116 (4/26/2005) after the SNOTEL peak had passed and 97 mm had ablated from the snow pillow.

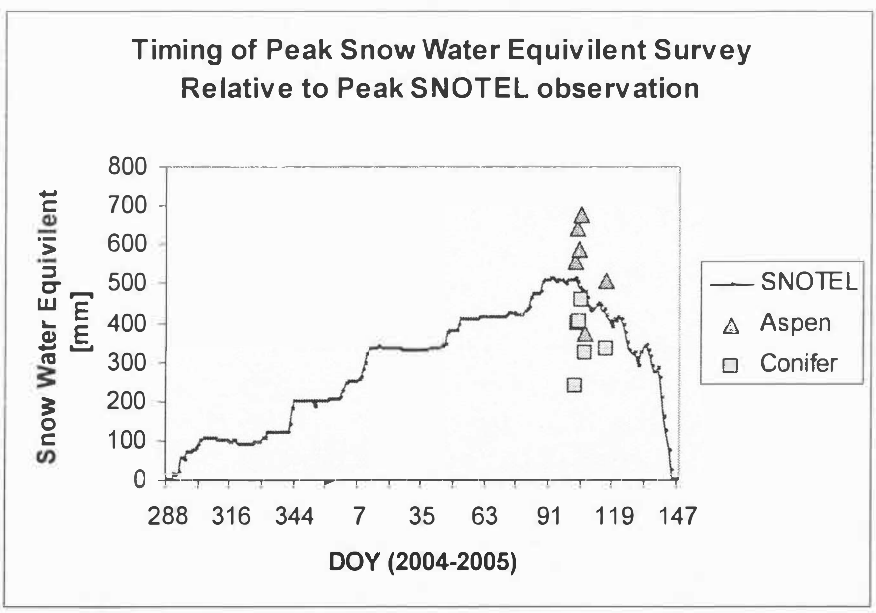


Fig. 4.1. Timing of peak snow accumulation at the SNOTEL station relative to timing of peak snow water equivalent surveys 2005.

Peak SWE observations in spring 2005 were compared between adjacent aspen and conifer plots using a one-way ANOVA in a randomized block design. Aspen plots had significantly higher PSWE than the adjacent conifer plots ($F_{1, 5} = 52.21$, $p<0.0001$). Within block differences in PSWE ranged from 48 – 322 mm (12% to 57% less in conifer). The mean difference between aspen and conifer plots across all blocks was 197 mm (34% less in conifer). Aspen plots in all blocks, with the exception of Block 5, had greater PSWE than the SNOTEL station (Fig.. 4.1); in contrast the conifer plots all had less PSWE than the Lightning Ridge SNOTEL snow pillow. Block 5 had the least difference in PSWE between aspen and conifer plots, possibly due to its exposed position along the crest of a windswept ridge (Fig.. 4.2).

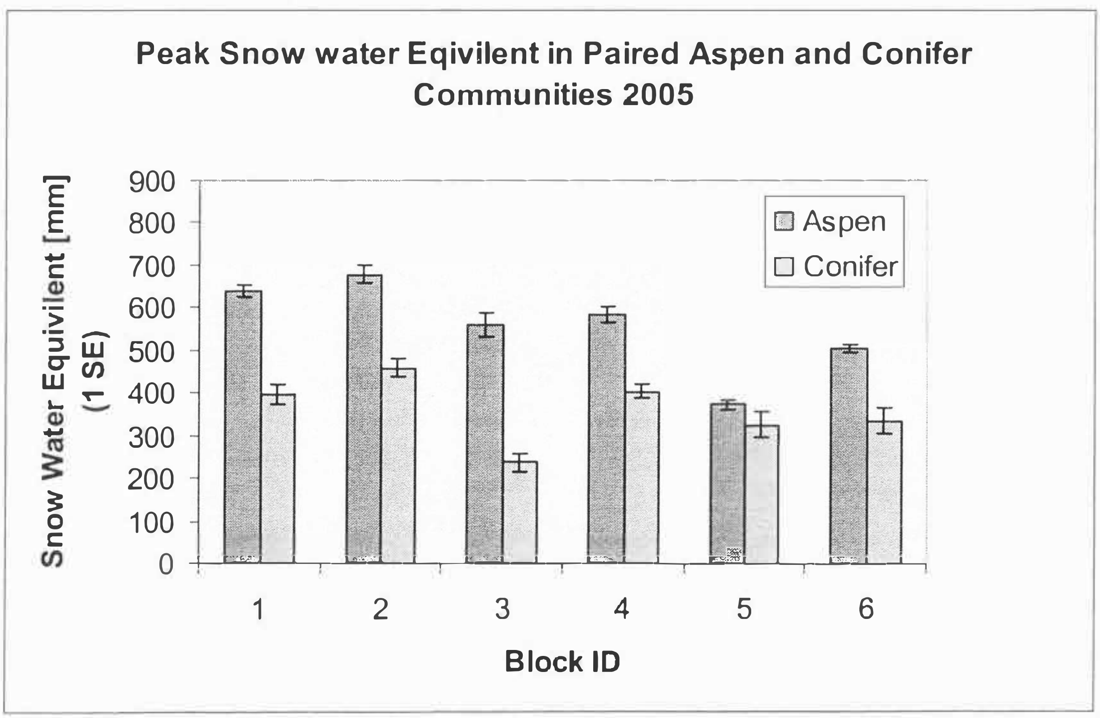


Fig. 4.2. Peak snow water equivalent for paired aspen and conifer plots in six study blocks in 2005.

During the spring of 2006 peak snow observations were made in four blocks, including Blocks 1 and 2 from the previous year as well as two new Blocks, 7 and 8. In addition to aspen and conifer plots, snow surveys were also conducted in an adjacent open meadow plot in Blocks 2, 7, and 8. Block 7 was located adjacent to the Lightning Ridge SNOTEL site in order to compare snow survey and snow pillow observations. Corresponding open and conifer plots were not available in Blocks 1 and 7, respectively.

Peak SWE observations were measured over a 2-week period from DOY 99 (4/9/06) to DOY 113 (4/23/06). Peak snow accumulation observed at the SNOTEL station was 655 mm on DOY 97 (4/7/2006). Blocks 1, 2, and 7 were monitored within a week of the SNOTEL peak after 10 mm of SWE had ablated at the snow pillow. Block 8 was monitored DOY 113 (4/26/2005) after the SNOTEL peak had passed and 81 mm had ablated from the snow pillow (Fig. 4.3).

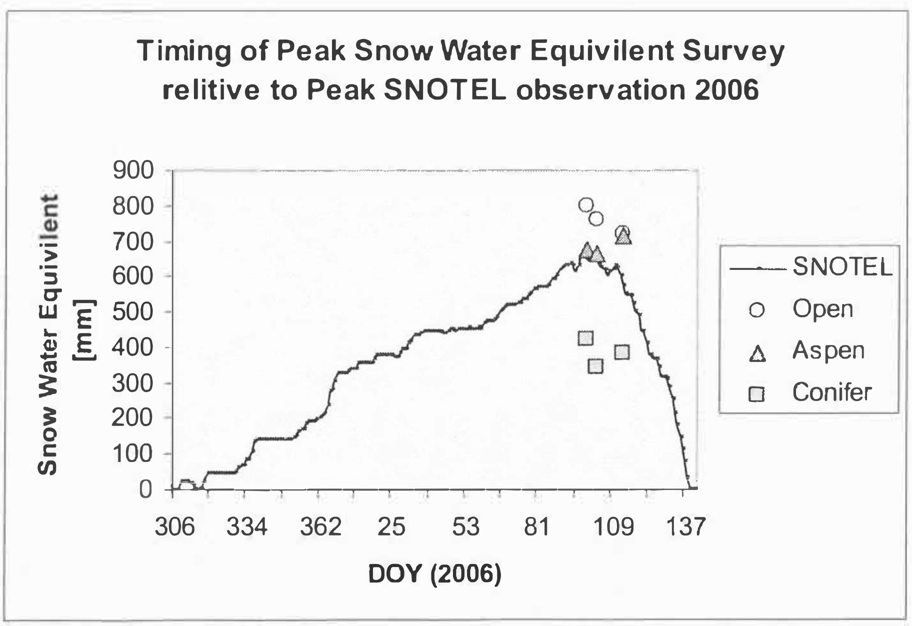


Fig. 4.3. Timing of peak snow accumulation at the SNOTEL station relative to timing of peak snow water equivalent surveys 2006.

As in the previous year, aspen plots had significantly higher PSWE than the adjacent paired conifer plots during the spring of 2006 ($F_{2,3} = 139.13$, $p<0.0001$). Differences in PSWE ranged from 250 – 334 mm (37% – 49% less in conifer). The mean difference between aspen and conifer plots across all blocks was 305 mm (44% less in conifer).

A one-way ANOVA with a Tukey-Kramer adjustment for multiple comparisons was used to test for differences between open, aspen, and conifer plots (Fig.. 4.4). The open plots had significantly higher PSWE than the adjacent aspen plots (P = 0.0007). Aspen plots had 10% lower PSWE relative to the open plots.

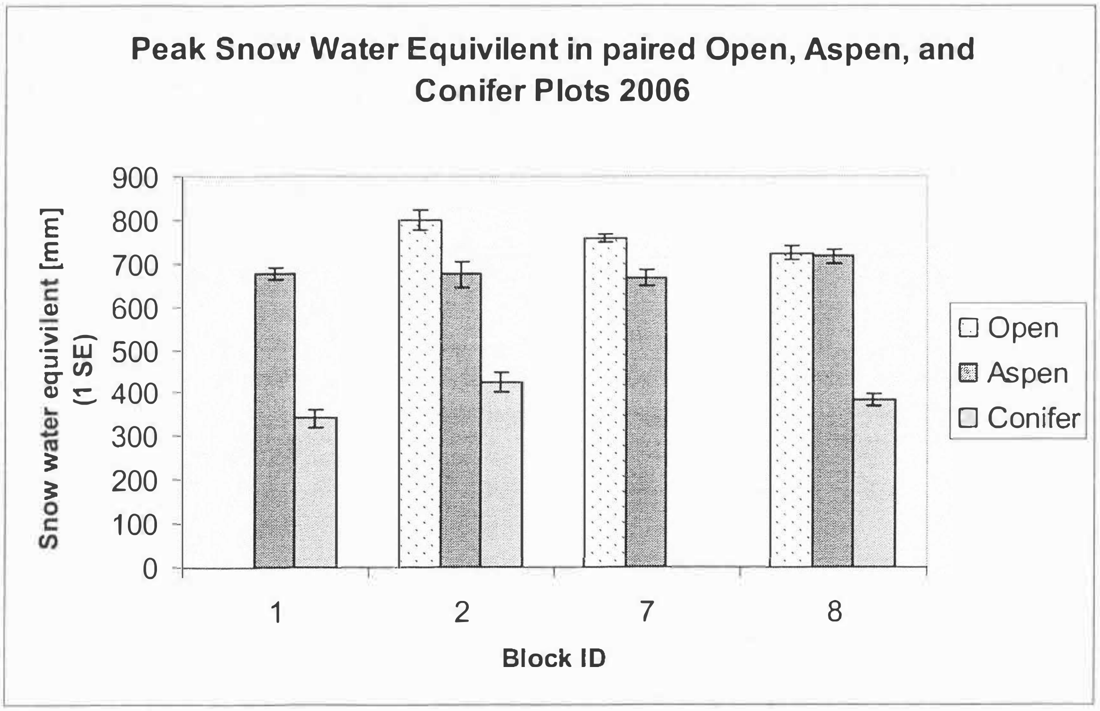


Fig. 4.4 Peak snow water equivalent for paired open, aspen, and conifer plots in four blocks in 2005.

Micro-plot SWE

During spring 2006 the snow around a single conifer tree in Block 2 was surveyed for SWE to determine if micro-site differences beneath a single conifer tree canopy could bias snow survey results. The tree bole survey was conducted DOY 112 (4/22/06), fifteen days after the initial Block 2 standard snow survey and 5 days prior to the second ablation snow survey (DOY 120). No relationship between SWE and distance from the tree bole or drip line was apparent (Fig. 4.5). The PSWE determined from the single conifer tree survey was 451 mm (SE =13.8). The PSWE determined from a conventional snow survey in block 2 was 400 mm (SE = 27.2).

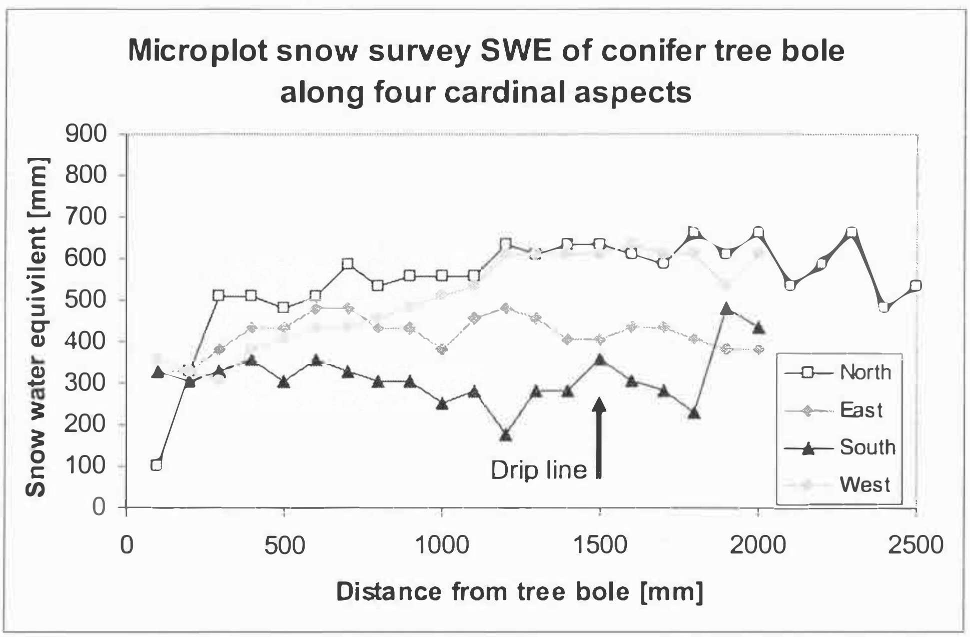


Fig. 4.5 Snow survey micro-plot extending in four cardinal directions away from a single conifer tree bole in Block 2.

Snow Ablation

The ablation (melt) rate was observed for consecutive sets of snow survey observations during spring 2005 and spring 2006. During the 2005 melt period, Blocks 2 and 3 were surveyed during the ablation period. In Block 2, observations were made on DOY 101 (4/11/05) and 144 (5/24/05). Over the 43-day period the aspen and adjacent conifer stands lost 420 mm and 297 mm of SWE at rates of 9.8 mm day^{-1} and 6.9 mm day^{-1}, respectively. In Block 3, observations were made four times throughout the melt period on DOY 101, 123, 139, and 143 (4/11/2005, 5/3/2005, 5/19/2005, and 5/23/2005). Over the 42-day period from observation 1 (DOY 101) to observation 4 (DOY 143) the aspen and adjacent conifer stands in Block 3 lost 316 mm and 17 mm SWE at rates of 7.5 mm day^{-1} and 0.42 mm day^{-1}, respectively (Fig. 4.6). The initial conifer observation in Block 3 appears abnormally low and could have been caused by within stand variability in SWE. From the second to fourth observations over a 20-day period, aspen lost 278 mm and conifer lost 122 mm at rates of 13.9 mm day^{-1} and 6.1 mm day^{-1}. The most rapid

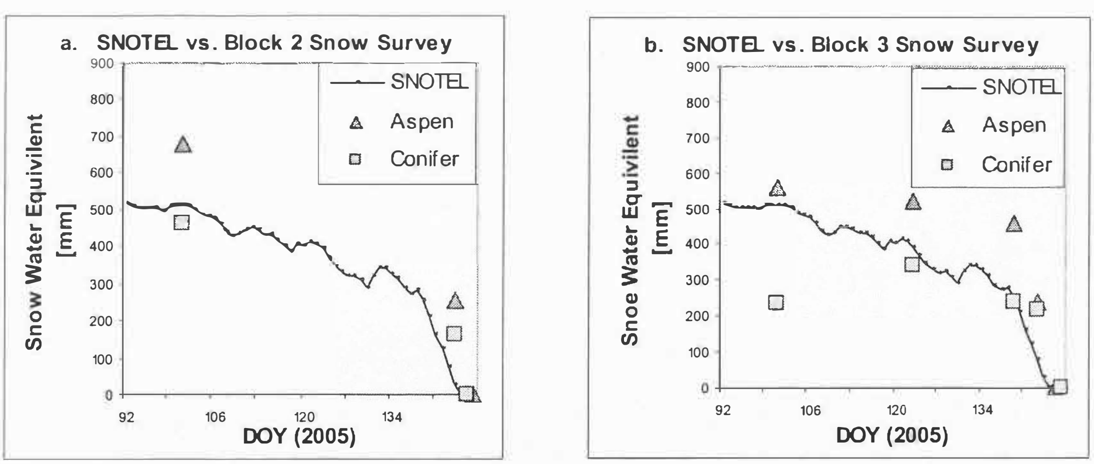


Fig. 4.6 Snow ablation patterns at the Lightning Ridge SNOTEL station and in snow surveys in Blocks 2 and 3 for spring 2005.

rate of ablation occurred in Block 3 between the third and fourth observations. Over a 4- day period aspen lost 241mm (60 mm day^{-1}) while the adjacent conifer stand lost 22 mm (5.5 mm day^{-1}).

During the spring 2006 melt, three additional snow surveys were conducted after the PSWE survey. In Block 1, surveys were conducted on DOY 103, 120, and 130 (4/13/06, 4/30/06, and 5/10/06). During the 27-day period the aspen and conifer plots lost 271 mm (10.3 mm day^{-1}) and 101 mm (3.7 mm day^{-1}) of SWE, respectively

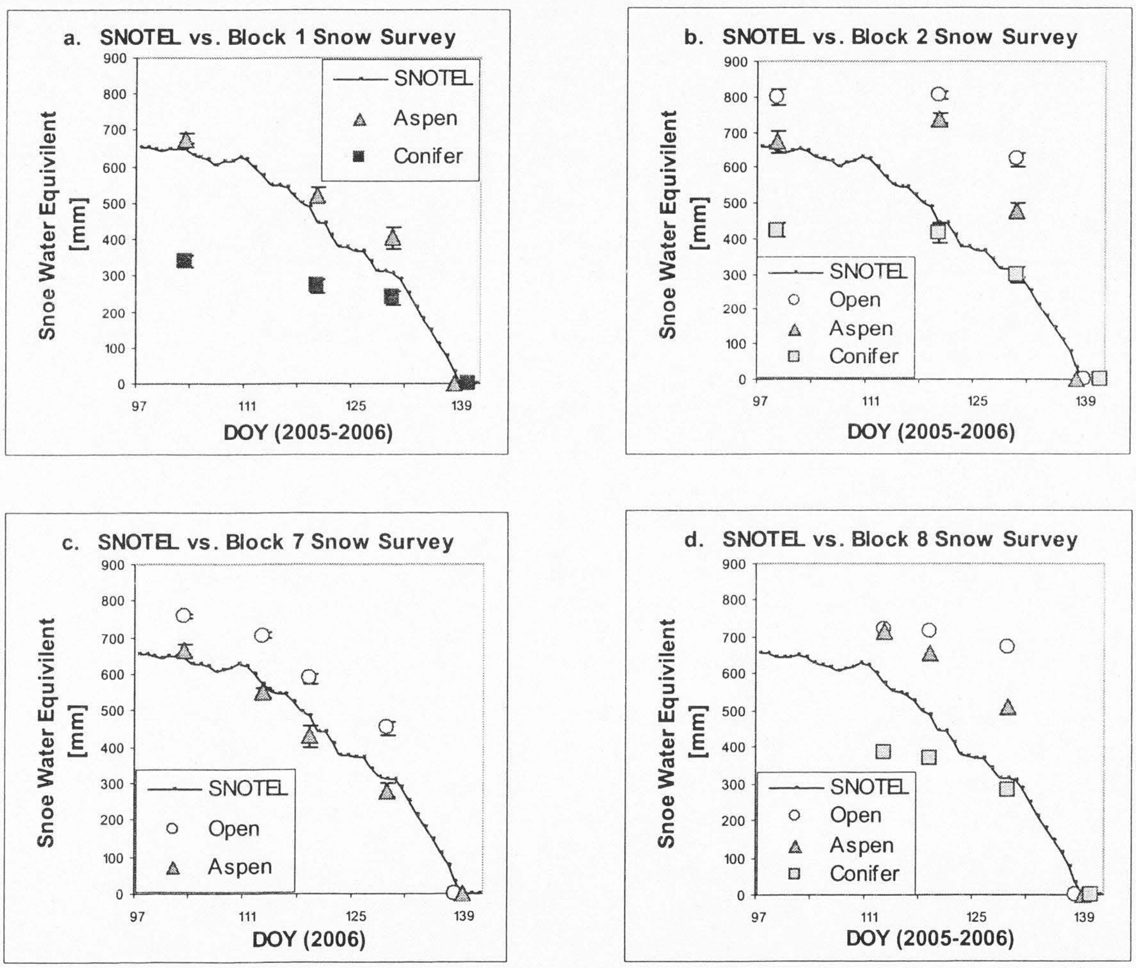


Fig. 4.7 Snow ablation patterns at the Lightning Ridge SNOTEL station and in snow surveys in Blocks 1, 2, 7 and 8 for spring 2006.

4.7a.). In Block 2, observations were made on DOY 99, 120, and 130 (4/9/06, 4/30/06, and 5/10/06). Over this 31-day period the open, aspen and conifer plots lost 177 mm (5.7 mm day^{-1}), 195 mm (6 mm day^{-1}), and 128 mm (4.2 mm day^{-1}) of SWE, respectively (Fig. 4.7b.). In Block 7, measurements were made on DOY 103, 113, 119, and 129 (4/13/06, 4/23/06, 4/29/06, and 5/9/06). During this 36-day period the open and aspen plots lost 307 mm (8.5 mm day^{-1}) and 386 mm (10.7 mm day^{-1}) of SWE, respectively (Fig. 4.7c.). In Block 8, observations were made on DOY 113, 119, and 129 (4/23/06, 4/29/06, and 5/9/06). Over this 27-day period the open, aspen, and conifer plots lost 48 mm (1.7 mm day^{-1}), 204 mm (7.6 mm day^{-1}), and 99 mm (3.7 mm day^{-1}) of SWE, respectively (Fig. 4.7d.).

Within each block, aspen had the highest average ablation rate over the entire melt period. Comparison of blocks containing both aspen and conifer (Blocks 1, 2, 3, 4, 5, 6, and 8) revealed that average melt rates were 49% faster in aspen (9.58 mm day^{-1}) compared to the conifer (4.9 mm day^{-1}). Comparison of blocks containing both open and aspen plots (Blocks 2, 7, and 8) revealed that average melt rates were 35% faster in aspen (8.2 mm day^{-1}) compared to the open (5.3 mm day^{-1}). The completion of snow melt as signified by a snow free surface was very similar in aspen and conifer plots. In 2006 the majority of snowpack (with the exception of snow drifts) had disappeared in all plots around DOY 140 (5/20/06).

Snow Density

Comparisons among and within blocks

At peak snow accumulation at the Lightning Ridge SNOTEL station on DOY 97 (4/7/05), the snow density was 35%. The snow density reached 41% by DOY 105

(4/25/05) and oscillated between 39% and 42% until snowpack ablation was complete on DOY 137 (5/17/05, Fig. 4.8).

In all blocks aspen had higher snow density than adjacent conifers throughout the ablation period (Fig. 4.9). In Block 2 the density of the open plot was higher than aspen plot; however, open and aspen plots were more similar in Blocks 7 and 8 (Figs. 4.9b – 4.9d). The snow density in Block 7 (adjacent to SNOTEL) approximated by the snow survey observations, was slightly higher than SWE approximated by the SNOTEL snow pillow and sonic depth sensor measurements (Fig. 4.9c). In general the snowpack matured and began to melt earlier in aspen and open plots relative to the conifer plots.

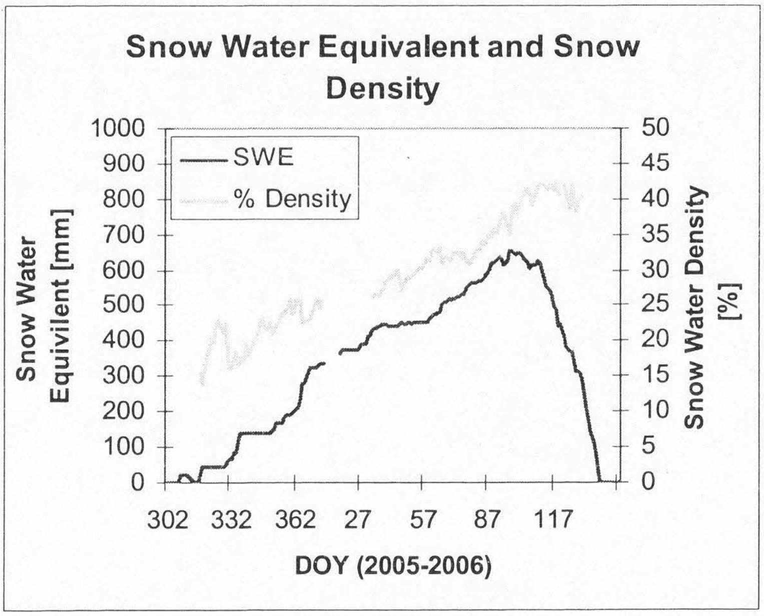


Fig. 4.8 Snow density and SWE at the Lightning Ridge SNOTEL station 2005-2006 WY.

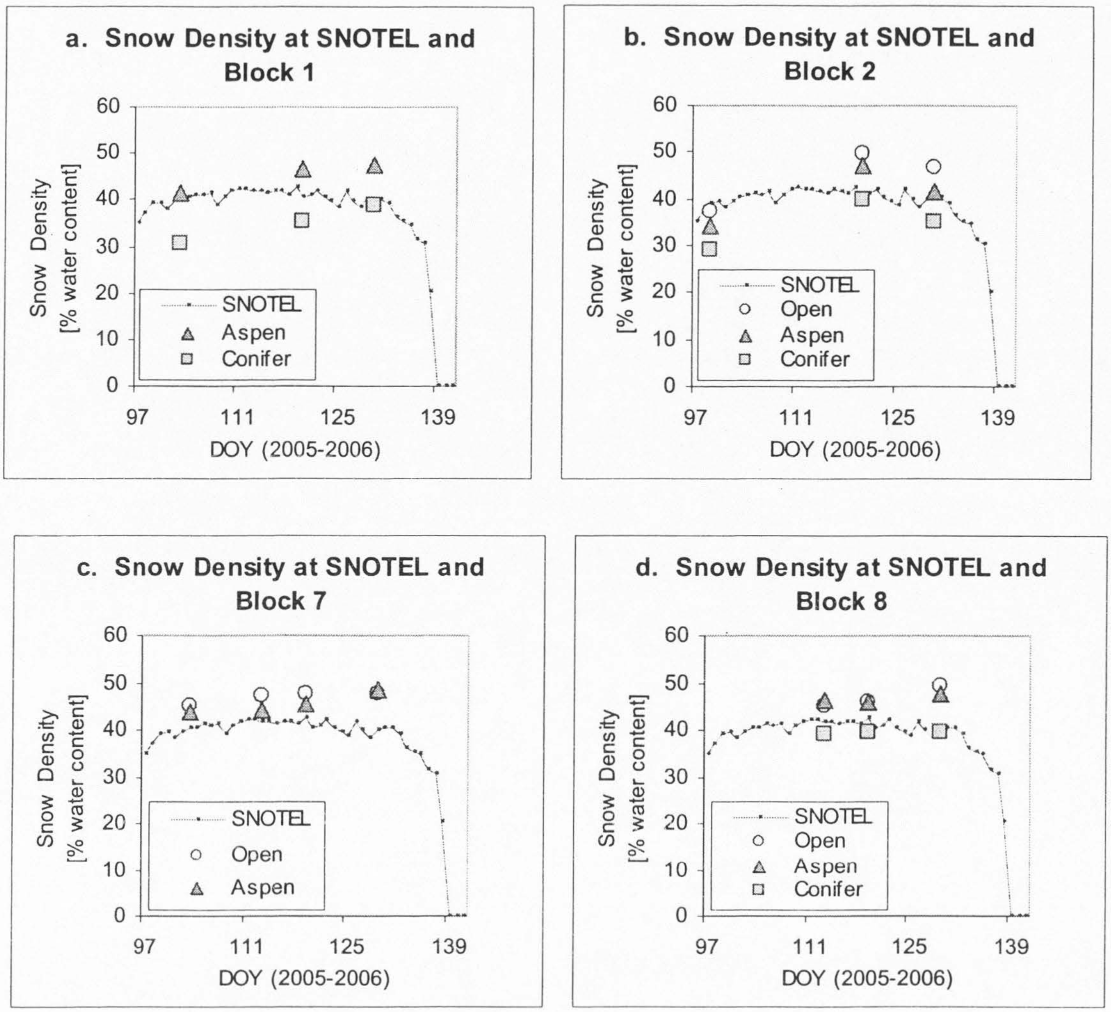


Fig. 4.9 Snow density at the SNOTEL station and in snow surveys 2006.

Micro-plot snow survey density

The density of snow in spring 2006 was also determined for snow around a single conifer tree in Block 2 in order to determine if micro-site differences beneath a single conifer tree conifer canopy could systematically bias snow survey results. There did not appear to be a consistent pattern that could be related to the drip-line of the conifer tree canopy (Fig. 4.10).

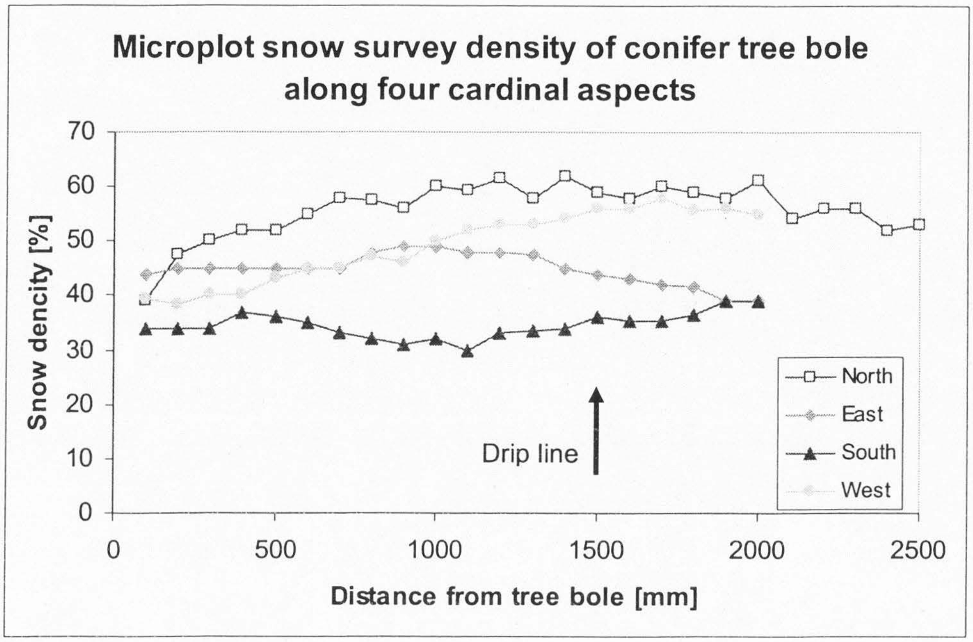


Fig. 4.10 Snow survey micro-plot density extending in four cardinal directions away from a single conifer tree bole in Block 2.

Snow Pack Sublimation/ Condensation

Rates of sublimation/ condensation

During the winter and spring of 2005 and the spring of 2006, sublimation and condensation of the surface snowpack beneath aspen and conifer stands were measured using sublimation pans. During the 2005 accumulation and ablation period, eight attempts were made to measure sublimation and condensation in Block 1. Due to consistent precipitation events and subsequent transfer of intercepted snow from the canopy to the pans in conifer stands, six of the eight observations were compromised. Two successful observations were made on DOY 53 (2/22/2005) and DOY 143

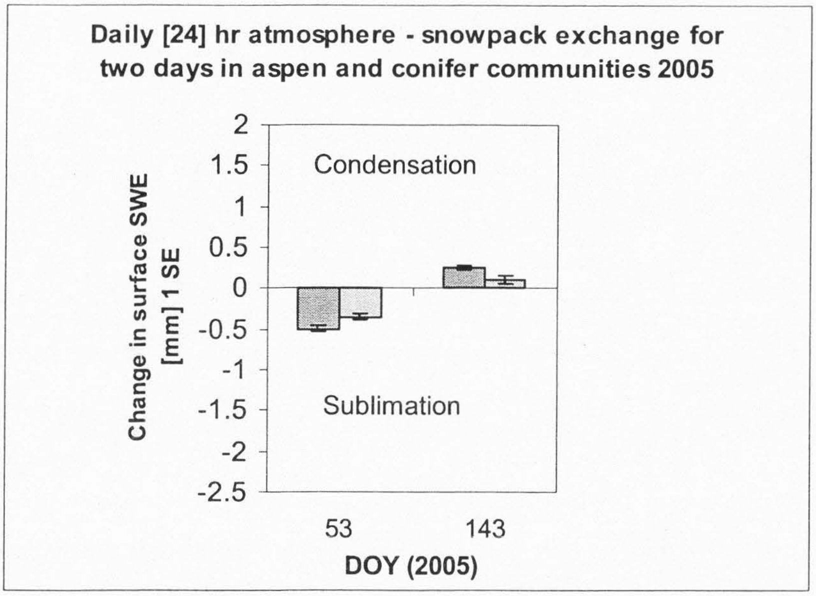


Fig.. 4.11 Sublimation and condensation of snowpack during two 24-hour events in 2005.

(5/23/2005). During the first observation, the aspen and conifer snowpack sublimated 0.5 mm day^{-1} and 0.4 mm day^{-1} of SWE, respectively. During that 24-hour observation period the average ambient temperature was -4 °C and average relative humidity (RH) was 81%. During the second observation, there was a net condensation of water into the aspen and conifer snowpack of 0.3 mm day^{-1} and 0.1 mm day^{-1}, respectively (Fig. 4.11). Average ambient temperature was 12 °C and average RH was 44%.

During the 2006 ablation period five observations were made in open, aspen, and conifer plots located within Block 2. Observations were made on DOY 102, 103, 113, 120, and 131 (4/12/2006, 4/13/2006, 4/23/2006, 4/30/2006, and 5/11/2006). Sublimation rates ranged from 1.84 mm day^{-1} to 0.4 mm day^{-1} across all plots (open 1.36 to 0.5, aspen 1.46 to 0.4, and conifer 1.84 to 0.48 mm day^{-1}). The condensation event that occurred in open and aspen plots on DOY 113 was marked by significant differences in flux between plots which ranged from 1.17 mm day^{-1} sublimation in the open to 0.03 mm day^{-1} condensation in the conifer plot (Fig. 4.12).

During the condensation event the Bear Canyon meteorological station recorded an average temperature of 3.7 °C and 58% RH. The meteorological station data was unavailable during sublimation events on DOY 102, 103, and 120 but temperature and humidity averages on DOY 131 were 9 °C and 27% RH. The mean daily temperatures at the Lightning Ridge SNOTEL station on DOY 102, 103, 120 were 2.5, 6.7, and 8°C, respectively. Fluxes were not significantly different between open, aspen and conifer plots during the five observed periods. The average snowpack sublimation rate for all plots and days in spring 2006 was 0.8mm day^{-1}.

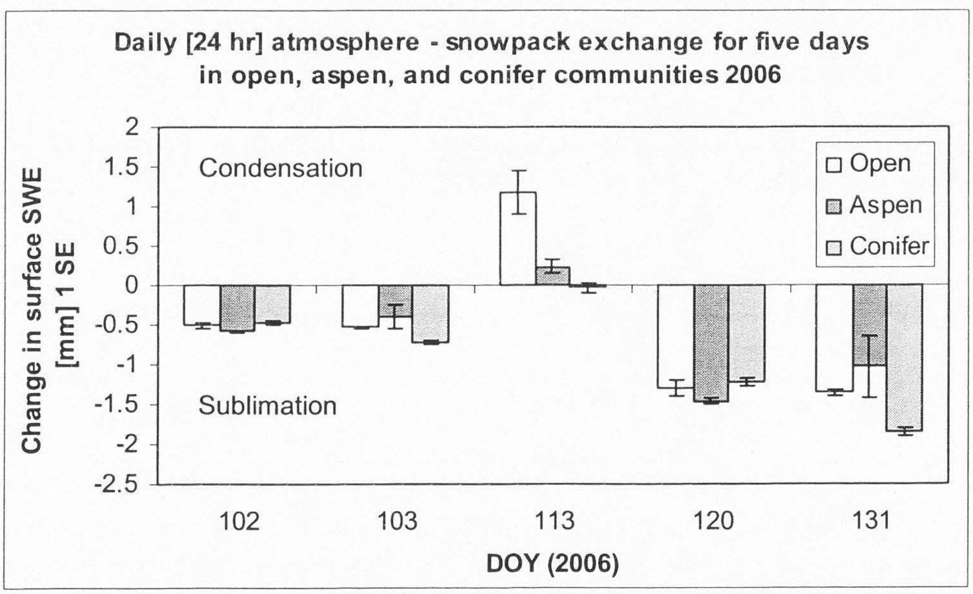


Fig.. 4.12 Sublimation and condensation of snowpack during two 24-hour events in 2006.

Sublimation pan temperature

During four of the sublimation and condensation events in 2006, probes recorded the temperature within the sublimation pan and in the adjacent snowpack near the pan (Appendix D). In general, the snowpack temperature was highest in the open and the aspen snowpack. Pans in the conifer stand remained at or near 0°C during the day and night, except for periods when shortwave radiation reaching the pans was not obstructed by foliage (~ solar noon). The range of temperature differences observed between all pans and the adjacent snowpack was 0 – 2.4 °C. The greatest differences occurred in the open plot (2.4 °C) when the pan was cooler than the adjacent snowpack. In the aspen plot the largest difference (1.5 °C) occurred in the daytime when the pan was relatively warmer. In conifer there was little difference (0.5 °C) mostly during the day. The average difference across all plots and times was 0.7 °C (Fig. 4.13). The difference in temperature could have caused a slight bias in the sublimation rate estimates. It is unclear if differences in pan temperature would cause an increase net condensation or sublimation during a 24-hour period.

During the sublimation observations on DOY 102 and 103, the snow was not replaced between observations. It was noted that melting snow had produced liquid water (~15 mm) which had subsequently frozen at the bottom of the pan during the first observation (DOY 102). The frozen water could have prevented the pan temperature from dropping below freezing at night due to the increased ice density (less air). On the second day (DOY 103) the temperature of the snowpack was raised several degrees above the temperature of the pan. All other observations the snow was replaced at the start of each 24-hour period.

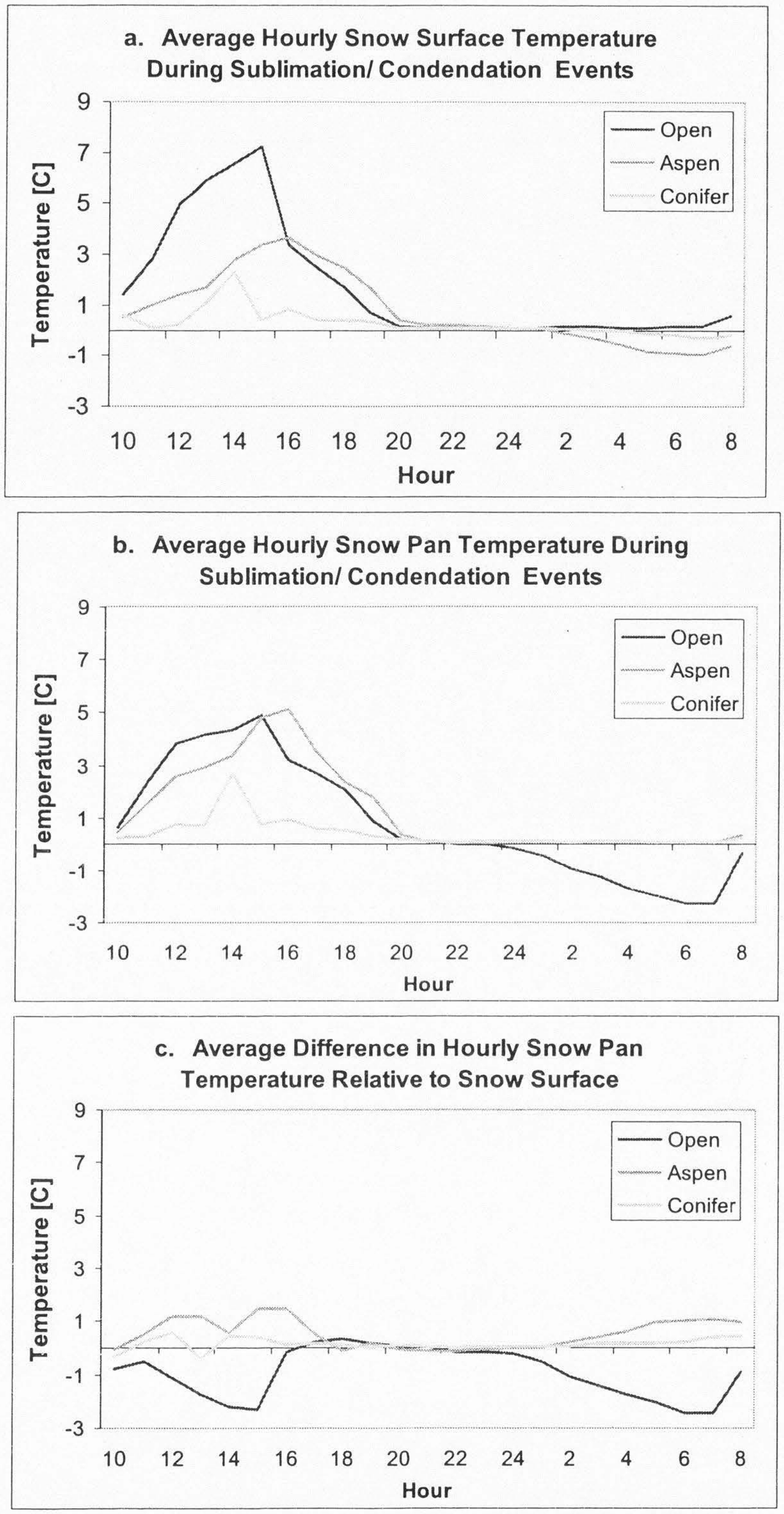


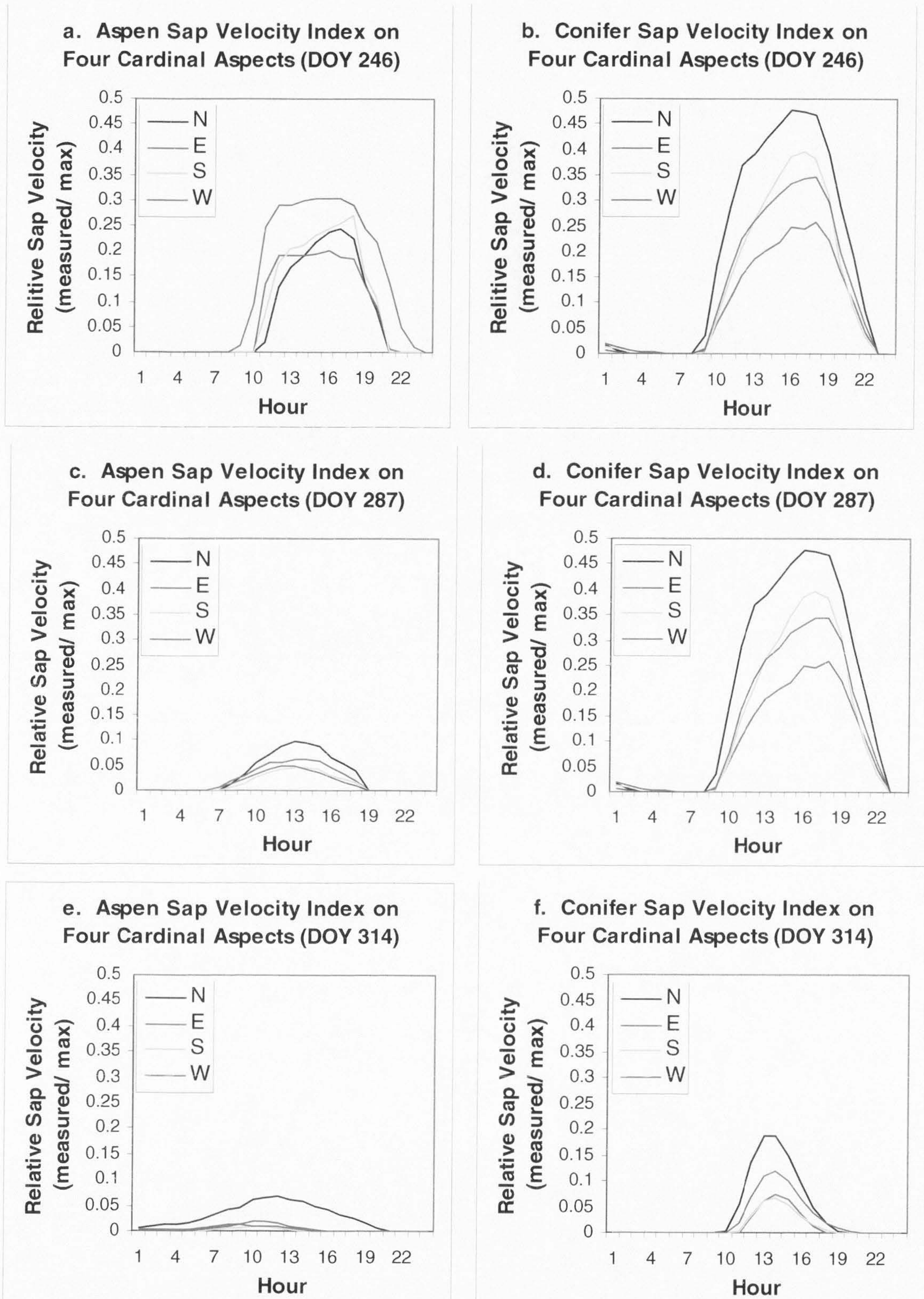
Fig. 4.13 Hourly snow temperature during sublimation and condensation events in the snowpack (a), inside the adjacent evaporation pan (b), and the difference between them (c.) in Block 2 in spring 2006.

Transpiration Period

Aspect effects on relative sap velocity

Differences between the period of transpiration for aspen and conifer trees were evaluated by indexing sap velocity for aspen and conifer based the on peak daily sap velocity parameter K. Sap velocity was assessed for the four cardinal aspects of a single aspen and a single conifer tree and were plotted for within tree comparison. The dates chosen for comparison were selected at approximately one month intervals when both aspen and conifer data loggers were working, DOY 246, 287, and 314 (9/3/06, 10/13/06, and 11/10/06). Several differences between the cardinal distributions of sap velocity can be observed between the aspen and conifer trees (Fig. 4.14). The highest sap velocities for the conifer tree occurred on the north side of the tree on all days. The next highest velocities were observed in descending order: south, west, and east, although this pattern changed by the last observation on DOY 314 (Fig. 4.14f), when the west aspect flux exceeded the south.

In the aspen tree the sap velocity was initially highest on the west side of the tree followed closely by the south, north, and east aspects (Fig. 4.14a). The aspen were observed to senesce their leaves during the first 2 weeks of October (~DOY 274-288). The observed sap velocities on DOY 287 and 314 (10/13/06 and 11/10/06) are considered signal noise possibly associated with the extreme changes in diurnal temperature. In the second and third observations the differences in measured sap velocity could be due to differences in daytime stem temperature by aspect, under no flow conditions. Although sap velocity differed by aspect, the south side of the tree appears to be a reasonable
differences in daytime stem temperature by aspect, under no flow conditions. Although



4.14 Daily sap velocity index in aspen and conifer on four cardinal aspects (n=1).

Although sap velocity differed by aspect, the south side of the tree appears to be a reasonable approximation of seasonal transpiration activity for both species. In both species the south side of the tree reported moderate values relative to the other aspects.

Seasonal sap flow

Transpiration activity period differed between aspen and conifer plots in fall 2005 and spring 2006 (Fig. 4.15). Transpiration activity scaling (K) values less than 0.1 were considered signal noise, based on the observation that values < 0.1 K continued to be recorded in aspen plots after leaf senesce occurred on DOY 280 (10/7/06) and DOY 288 (10/15/06) in Bocks 1 and 2, respectively. In the fall, conifer had K values greater than 0.1 K until DOY 304 (10/31/06) and DOY 305 (11/1/06) in Bocks 1 and 2, respectively. This extended the transpiration activity period in conifer for 24 days in Bock 1 and 31days in Bock 2. However, the conifer transpiration rate in fall (~0.2 K) was less than peak summertime transpiration rate (~0.5 K).

In spring, both of the aspen data loggers failed, however, aspen leaf flush did not occur until after snow ablation period ended on ~DOY 139 (5/19/05, Fig. 4.15b and d). Conifer K values greater than 0.1 were recorded in Blocks 1 and 2 beginning on DOY 120 and 135 (5/1/05 and 5/15/06), respectively. Conifers were active for 13 and 4 days during the snowmelt period in Blocks 1 and 2, respectively. The peak daily transpiration values during this time were 0-0.2 K. Conifer transpiration rates may have been diminished during these extended fall and spring periods in response to low VPD, daytime temperature, and soil moisture (Fig. 5).

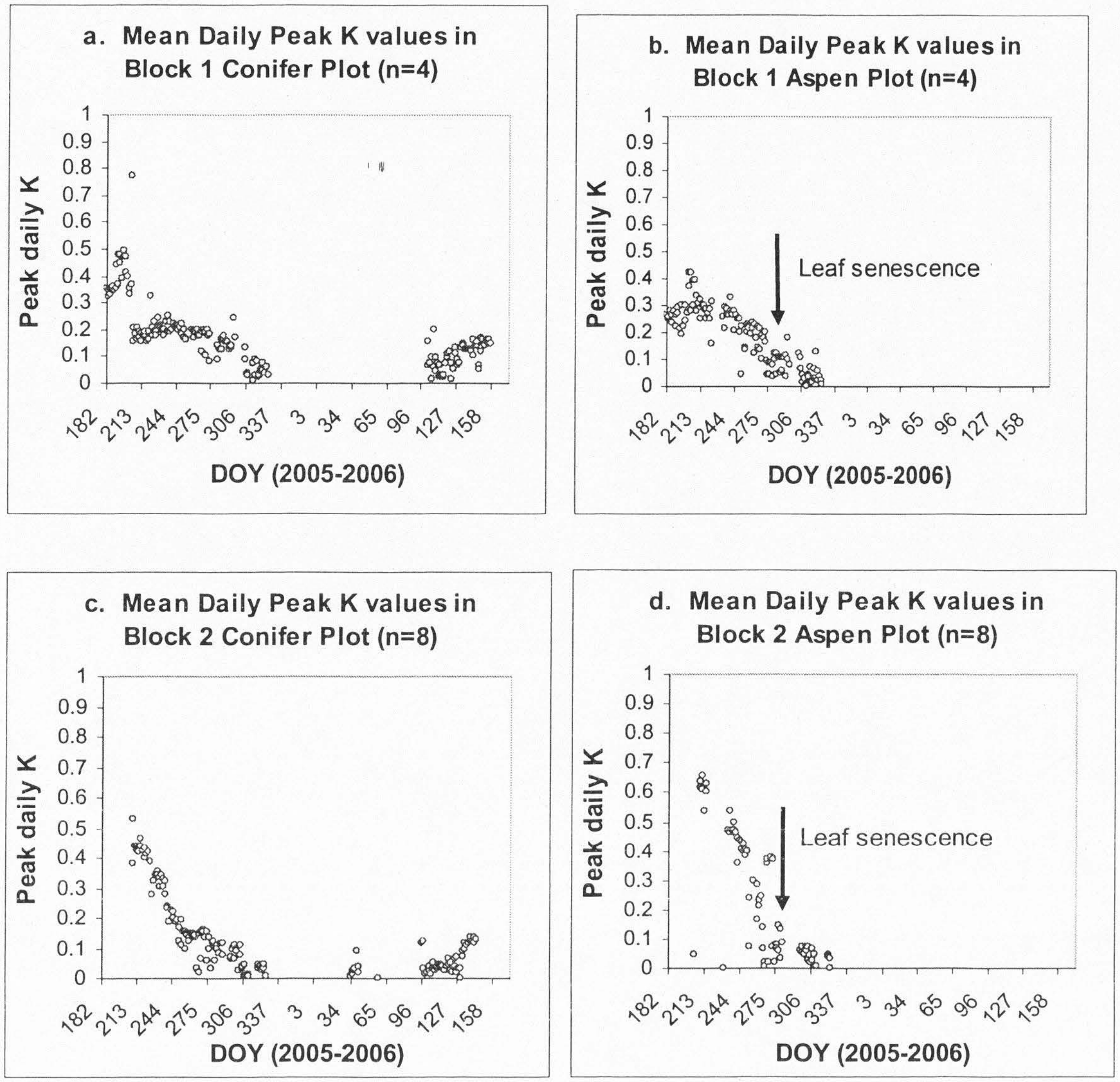


Fig. 4.15 Peak daily K values in aspen and conifer plots 2005-2006.

We estimated net transpiration in conifer during the fall and spring periods when aspen were dormant. The available K data from Block 2 was combined ET estimates (discussed in next section) which were within the range of transpiration rates reported in the literature. Transpiration rates reported for *Pinus contorta* stands (Knight et al., 1981) were 3.3 mm day^{-1}, while Pataki et al. (2000) reported 2.6 +/- 0.6 mm day^{-1} in *P. contorta* and *Abies lasiocarpa* stands in Wyoming. We scaled our estimate of average daily summertime ET rate in conifer (2.8 mm day $^{-1}$) using daily K values during the fall and spring period.

We assumed that maximum transpiration rates in conifer (2.8 mm day $^{-1}$) occur at a K value of 0.5 or greater. For each day that K > 0.1 the stand level transpiration was calculated as

$$\text{Transpiration [mm day}^{-1}] = \frac{\text{K*2.8 mm day}^{-1}}{0.5}$$

The total transpiration during the extended fall transpiration period after aspen leaf senescence, conifer transpired approximately 14 mm and 5 mm in Blocks 1 and 2, respectively. During spring snow melt in Blocks 1 and 2 conifer plots was estimated to be 14 mm and 3 mm during the spring snowmelt period.

Transpiration activity related to meteorological variables

A linear regression model was used to test the seasonal trend in conifer transpiration activity and to determine atmospheric variables related to spring and fall transpiration activity period. The fall season K values over the period of DOY 213 to 304 (8/1/06 to 10/31/06) were used to test for relationships with physical atmospheric variables. Peak daily K values were plotted separately for each block against: mean daytime VPD, peak daytime VPD, and mean daytime temperature. Of all variables tested, mean daytime temperature (7am – 6pm) had the best relationship to peak K (Fig. 4.16), in Block 1 ($R^2 = 0.33$, $P < 0.05$) and Bock 2 ($R^2 = 0.53$, $P < 0.05$). Vapor pressure deficit was low during the fall, winter and spring periods when aspen were dormant and

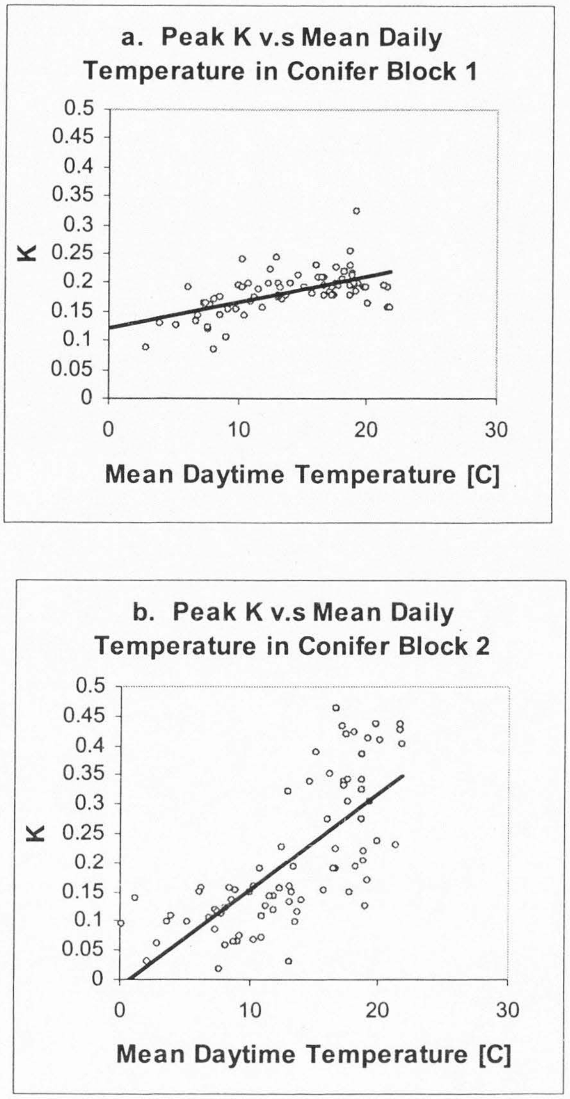


Fig. 4.16. Regression of mean daytime temperature (7am – 6pm) and peak K values in aspen and conifer fall 2005.

conifer continued to transpire (Fig. 4.17). For these reasons, transpiration activity period had little effect on net annual transpiration differences between aspen and conifer.

Soil Moisture

Shallow soil water recharge

Shallow soil moisture in Blocks 1 and 2 was monitored from fall 2005 through spring 2006. The volumetric water content of shallow probes placed outside the tree

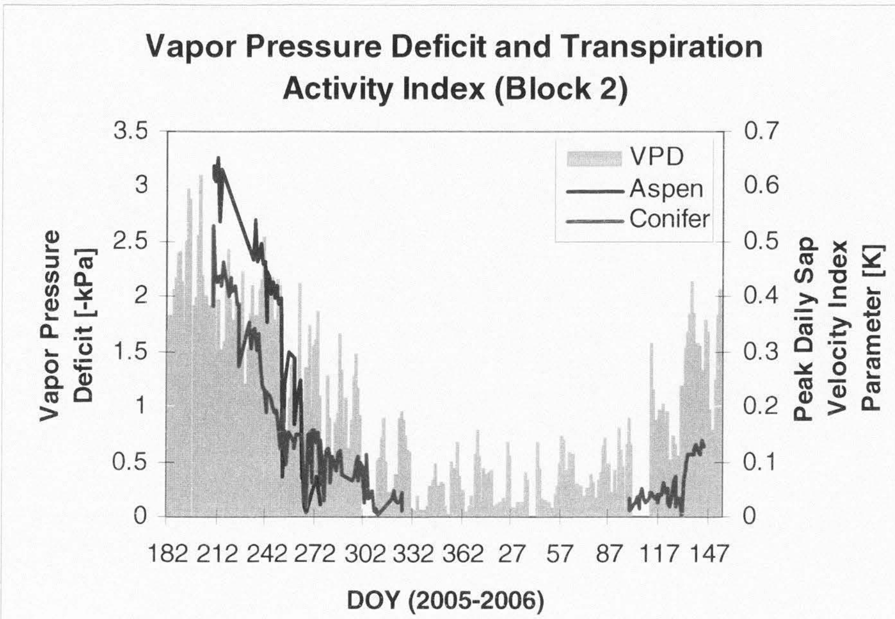


Fig. 4.17 Vapor pressure deficit and transpiration activity in aspen and conifer.

numbered wells (odd probes) and within the tree wells (even numbered probes) were not consistently higher or lower in either aspen or conifer plots (Fig. 4.18). Thus, there was no evidence that shallow soil moisture depletion near the tree wells was greater than soil moisture depletion in the interspaces.

Over the entire fall through spring period average shallow soil moisture within both Blocks 1 and 2, was higher in the aspen plots relative to the adjacent conifer plots (Fig. 4.19). Shallow soil moisture content was very low for several weeks in fall 2005, prior to DOY 270 (9/27/05). A series of precipitation events that occurred over the period from DOY 270 to 281 (10/8/05 to 9/27/05) recharged a portion of the shallow layers in both aspen and conifer stands. The effect of precipitation on shallow soil moisture recharge was higher in Block 2, suggesting either greater precipitation or greater

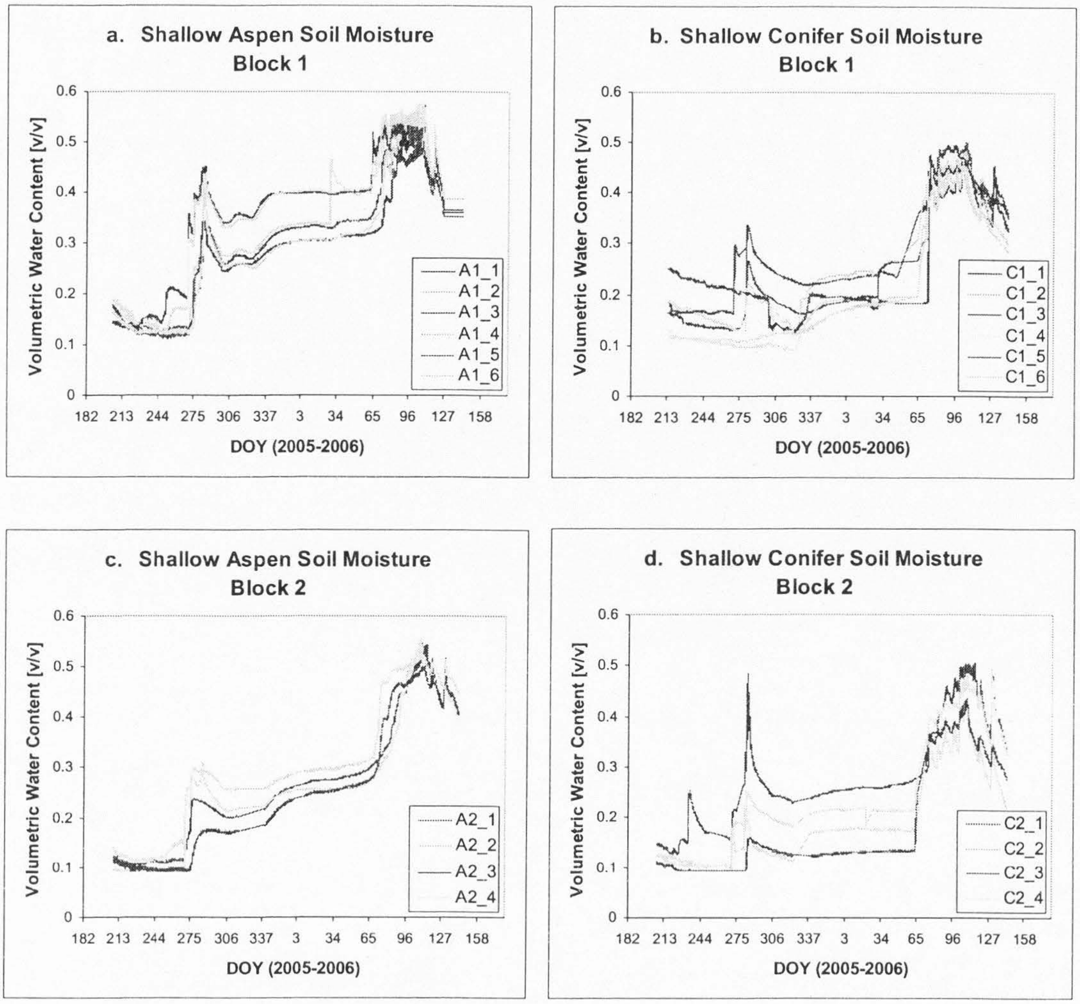


Fig. 4.18 Soil moisture (10 cm) near tree boles (even number probes) and in the interspaces (odd number probes) during winter 2005-2006.

melting of intercepted snow. In both Blocks 1 and 2 shallow soil layers in aspen recharged more than the adjacent conifer following these precipitation events.

Shallow soil moisture recharge occurred differently during the snow accumulation and the snowmelt periods. Only a small amount of recharge occurred during snow accumulation period from DOY 323 to DOY 64 (11/13/05 to 3/5/06). During this period shallow water content in aspen increased by 0.09 and 0.08 m^3 m^{-3} in Blocks 1 and 2, respectively, while shallow soils in conifer increased shallow water content by 0.11 and 0.04 m^3 m^{-3} in Blocks 1 and 2, respectively.

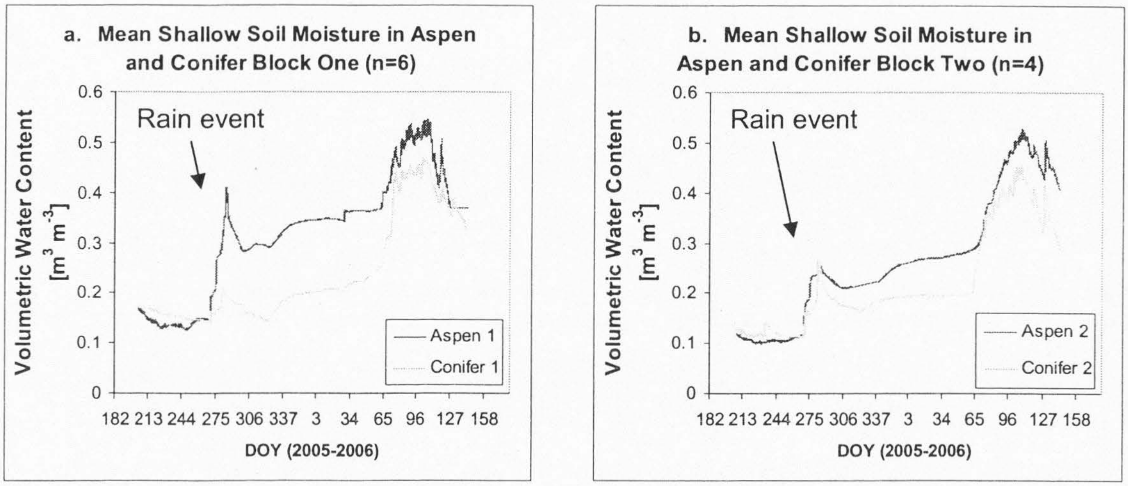


Fig. 4.19 Mean shallow soil moisture (10 cm) content in Blocks 1 and 2 during fall, winter, and spring 2005-2006.

Infiltration of water from snowmelt rapidly increased shallow soil water content over the period from DOY 64 to DOY 77 (3/5/06 to 3/18/06). This period was preceded by a week of above freezing temperatures which continued during the following week. Although the water content in shallow soils continued to increase in aspen and conifer recharge rates slightly declined around DOY 77 (3/18/06). The rate of increase in shallow soil moisture content was slightly higher in aspen plots in both Blocks 1 and 2. Shallow soil moisture content was greater in aspen at all times during the late fall, winter, and spring.

Vertical soil water recharge

Vertical profiles of soil moisture were monitored in Blocks 1 and 2 during fall 2005 and spring 2006. The soil moisture profile was also monitored at the Lightning Ridge SNOTEL station in an aspen stand. The moisture profile in Block 1 was monitored beginning DOY 274 (10/1/05, while the SNOTEL and Block 2 data became available DOY 31 (1/31/06). Data from the deepest probe (102 cm) in the aspen plot of Block 1 was not collected until late summer 2006, due to a bad wire connection.

The recharge of deep soil layers began earlier in aspen than in conifer. The initial fall precipitation events that occurred from DOY 270 (9/27/05) to DOY 281 (10/8/05) infiltrated into the 51 cm depth in Block 1 aspen. All soil layers in aspen continued to recharge through the winter (Fig. 4.20a).

The conifer soil profile in Block 1 was not affected by the initial fall precipitation events. Shallow probes in conifer (5 cm and 10 cm) rapidly began to recharge in the middle of winter DOY 342 to DOY 7 (12/8/05 to 1/7/06, Fig. 4.20b). This relatively rapid rate of infiltration was also observed in some of the other shallow conifer probes (Fig. 4.19b). Deeper areas of the conifer soil profile in Block 1 did not begin to recharge until DOY 74 (3/15/06).

The vertical profile of soil moisture recharge patterns in Block 2 were similar to those in Block 1 aspen and conifer. The aspen profile began to recharge the deepest layers of the profile while the deepest conifers layers remained relatively dry (Fig. 4.20 c and d). The deepest layer (102 cm) in aspen was consistently wetter than the overhead layer prior to saturation. Both aspen and conifer profiles rapidly increased the rate of recharge later in Block 2 than in Block 1.

The vertical profile of soil moisture content in the Lightning Ridge SNOTEL station was different from aspen and conifer plots in Blocks 1 and 2. The soil profile had begun to recharge to 20 cm depth by DOY 31 (1/31/06). The deepest layers in the soil profile rapidly increased water content beginning DOY 98 (8/4/06) (Fig. 4.21). The deepest probes in the SNOTEL and Block 2 aspen profile (51 cm and 102 cm) were

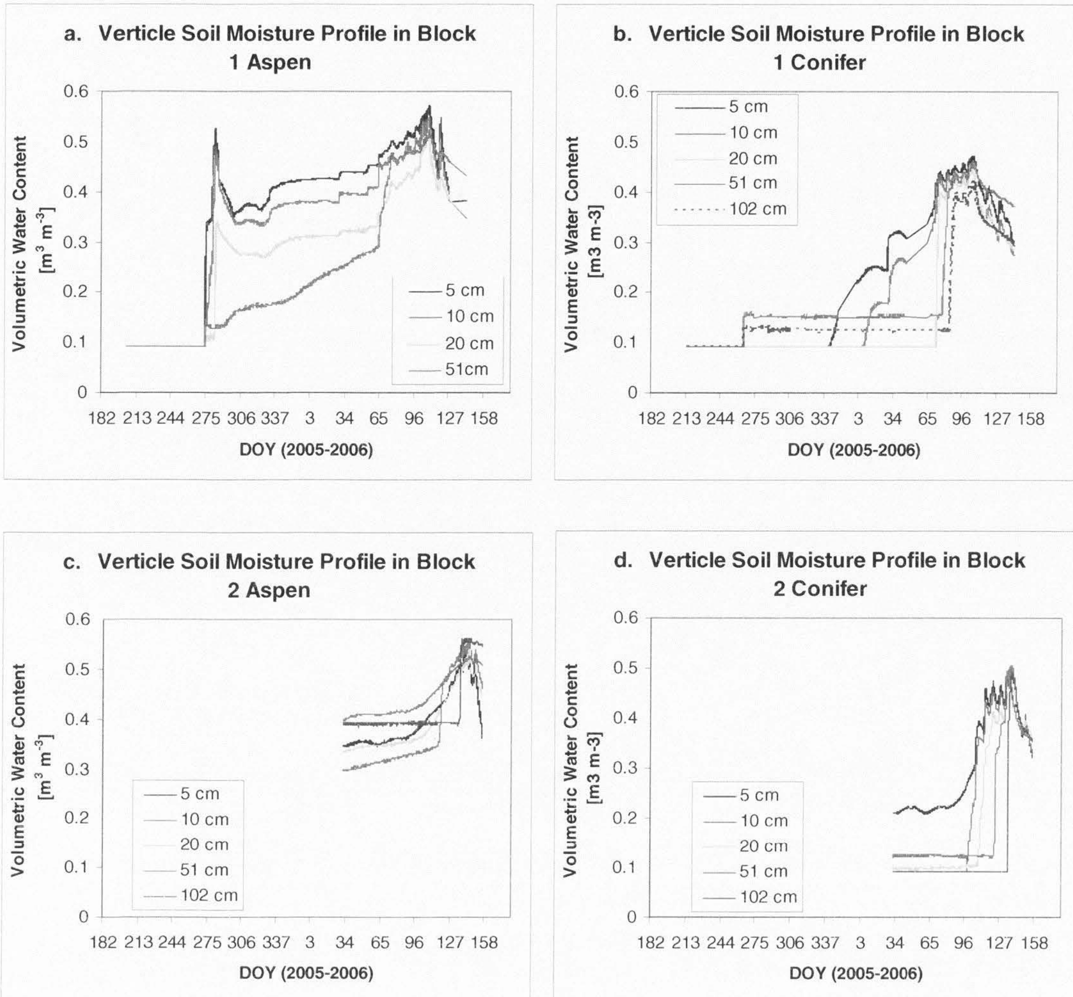


Fig. 4.20 Vertical profiles of soil moisture content in Blocks 1 and 2 during fall winter and spring 2005-2006.

similar to each other. Thus, missing values in aspen Block 1 profile (102 cm) were expected to be similar to the overhead probe (51 cm).

Soil temperature

Winter-time soil temperatures were measured for the vertical soil columns instrumented in Block 1 aspen and conifer. In both aspen and conifer soil temperature increased with depth. Aspen soils remained slightly warmer thought the winter, possibly due to greater shortwave radiation inputs prior to snow accumulation and a deeper

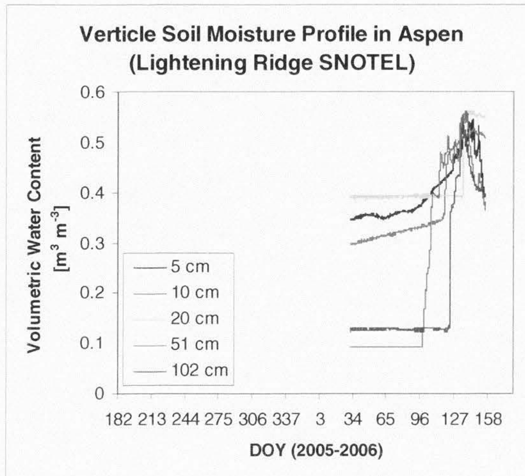


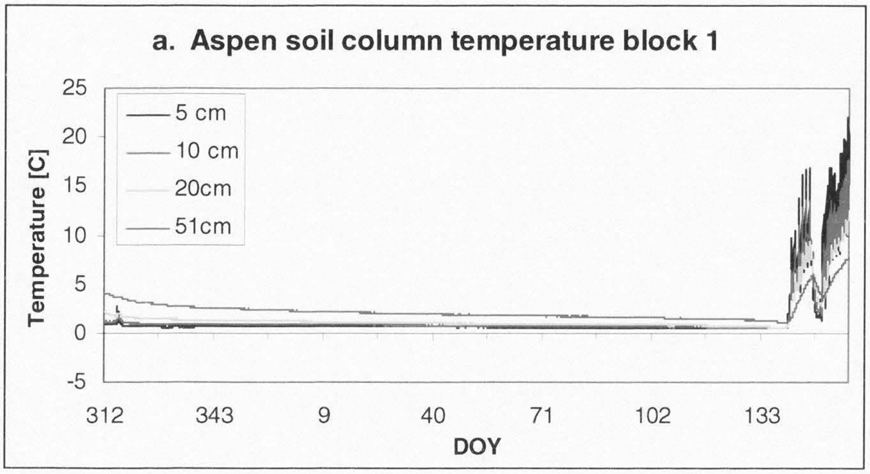
Fig. 4.21 Vertical profile of soil moisture content at the SNOTEL station.

insulating snowpack throughout the winter. Shallow soil layers under conifer (10 cm) were frozen during the first months of winter (Fig. 4.22).

Soil column water content

The equivalent depth soil column water content during the melt period was calculated for Blocks 1 and 2. The missing values for the Block 1 aspen plot (102 cm) were estimated to be equal to the soil moisture content of the overhead probe (51 cm). The lowest probes (51 cm and 102 cm) at the SNOTEL station and in Block 2 were similar.

Total soil water content in fall DOY 270 (9/27/05) was similar between aspen and conifer in Block 1. Total soil water content peaked at different times between blocks but was similar within blocks probably due to differences in snow energy balance caused by aspect. In both Blocks 1 and 2, soils under aspen had a greater water content at peak saturation due to soil column characteristics including depth, and porosity (Appendix C).



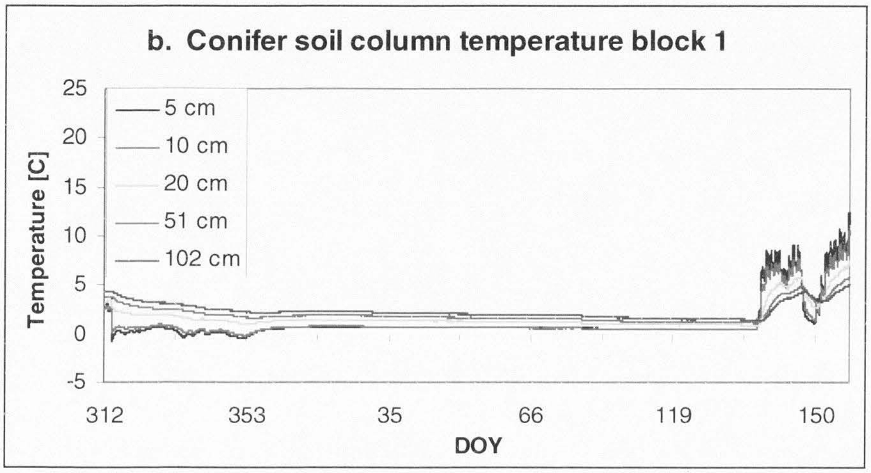


Fig. 4.22 winter soil temperature profiles in aspen and conifer Block 1.

Soil column water content was monitored throughout the remainder of the 2005-2006 WY in Block 1 (Fig. 4.24a). The soil water content declined during the summer growth period. The water content on the last day of observation DOY 250 (9/7/05) was 132 mm in aspen and 141 mm in conifer.

Patterns of soil water depletion during the summer growth period were similar in Block 1 aspen and conifer. In aspen and conifer, shallow soil layers were depleted faster than deep layers (51 and 102 cm), due to higher plant root density. In both aspen and

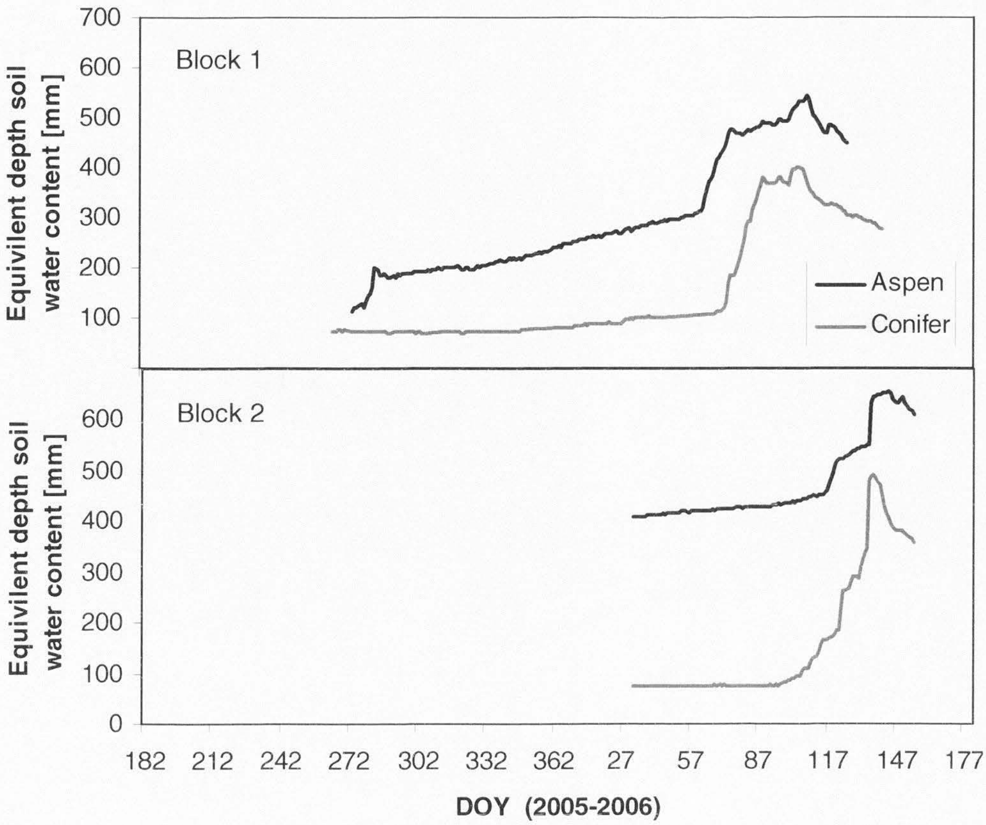


Fig. 4.23 Total soil column water content in Blocks 1 and 2 during fall, winter, and spring 2005-2006.

conifer profiles, three distinct precipitation periods recharged the shallow soil layers to 10 cm depth. By the end of the summer, both profiles indicated the majority of water was contained in the lower half of the soil column (Fig. 4.24b and c). Over the course of the 2005-2006 water year aspen soils usually contained more water in the column; soil moisture content converged in the fall dry season. Shallow soil layers in the aspen plot had higher volumetric water content for the majority of the year.

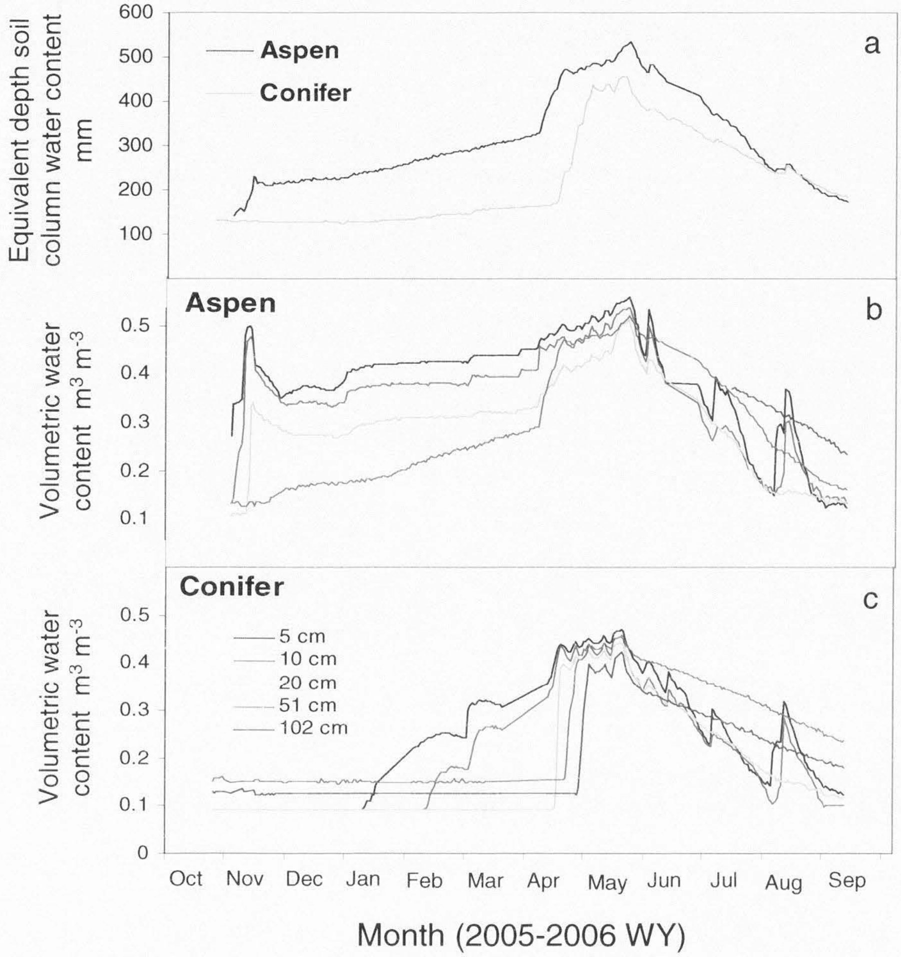


Fig.. 4.24 Annual soil column water content and vertical distribution of water in Block 1 aspen and conifer soils.

Spring Snowmelt Potential for Groundwater Recharge and Runoff

A mass balance model for water based on measured water pools and estimated daily fluxes was used to determine the potential for differences in groundwater and runoff yield in aspen and conifer stands. Water contained in the snow, soil, net snowpack sublimation, and net potential for groundwater recharge and runoff were estimated for 5 days, one at the beginning of the water year and 4 days at 2-week intervals during spring snowmelt (Fig. 4.25). On the first day of observation DOY 270 (9/27/05) the soil columns in Block 1 were relatively dry in aspen (99 mm) and conifer (97 mm). Data for Block 2 soil profile were not available for this day, but, were assumed to be to similar to Block 1. This assumption was, in part, supported by similar water content in shallow soil probes in Blocks 1 and 2 during in fall 2006 (Fig. 4.19). Assuming that Block 2 soil profile and shallow probes would be similar as in Block 1, shallow probe measurements were used to determine soil column water storage for the DOY 270 (9/27/05) observation, estimated at 69 mm in aspen and 67 mm in conifer.

The second date corresponds to the peak SWE in spring, and estimates of water contained in the snow and soil profile were used to determine total moisture storage in the aspen and conifer stands (Fig. 4.25). For Blocks 1 and 2, the second observation occurred on DOY 103 (4/13/06) and DOY 99 (4/9/06), respectively, corresponding to the dates on which snow surveys were conducted. The total water stored in snow and soil pools on these dates were used to estimate potential runoff or groundwater recharge for three subsequent dates. Estimated water pools for the last three dates, DOY 120, DOY 130, and DOY 138 (4/30/06, 5/10/06, and 5/18/06) included snow, soil, net sublimation, net transpiration, and net potential for groundwater recharge and runoff.

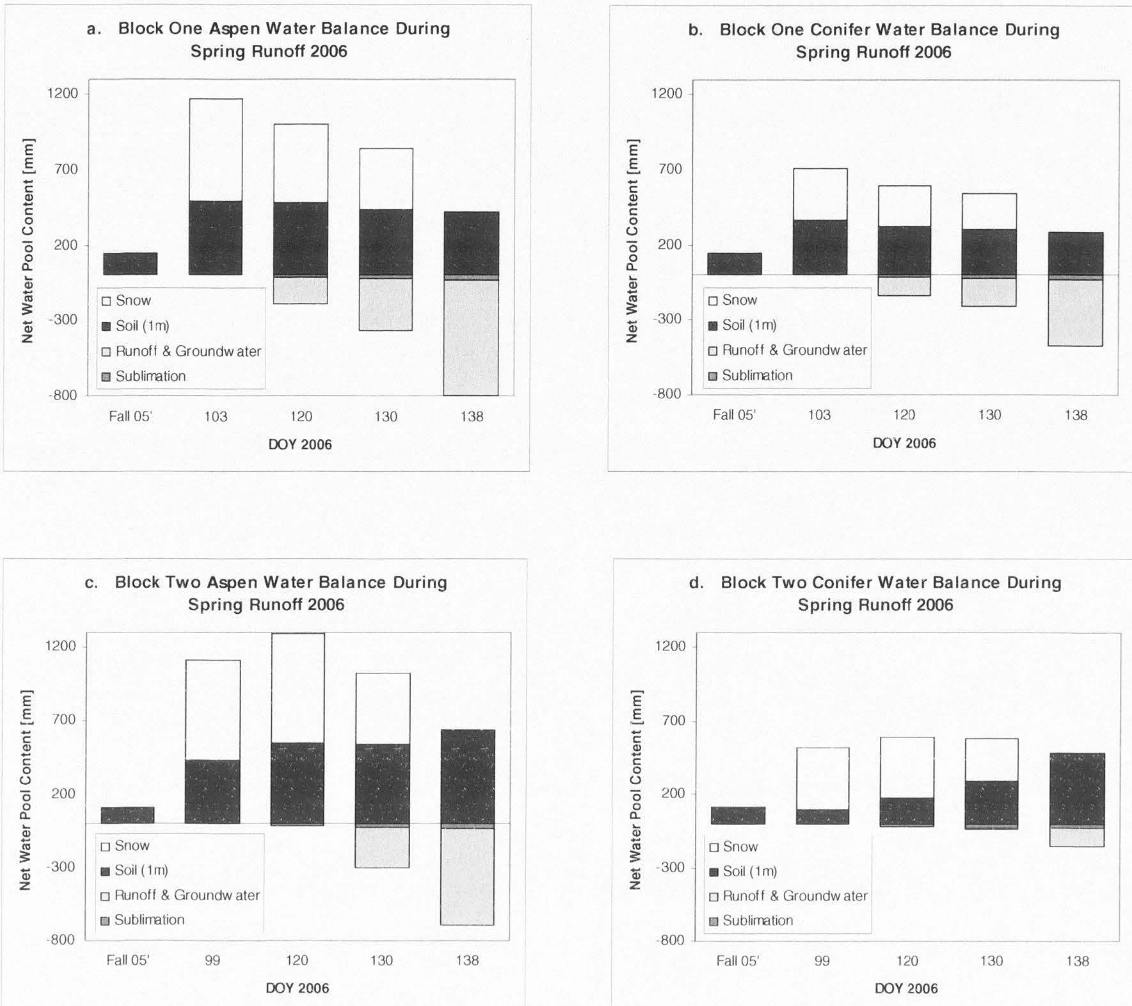


Fig. 4.25 Water pools for aspen and conifer in Blocks 1 and 2 for 5 days in fall 2005 and spring 2006.

Sublimation losses between observation dates were estimated as the average of the 2006 sublimation / condensation observations (0.8 mm day^{-1}) multiplied by the number of days since the last observation date. Transpiration was calculated for the conifer only (aspen had no leaves), but was relatively minor during the ablation period. The amount of water potentially available for runoff and groundwater recharge for a given date was calculated as the difference between the total water in the preceding observation date and amount of water remaining in the snow and soil on that date minus net sublimation and transpiration losses since the first observation date. It was assumed that modeled groundwater recharge and runoff was not available for transpiration later in the growing season.

The predicted potential for runoff and groundwater recharge was greater in aspen than conifer stands in both Blocks 1 and 2. In Block 1 the greatest water storage (snow and soil) was measured on DOY 103 (5/10/06) in aspen (1160 mm) and conifer (706 mm). The potential for runoff and groundwater recharge in Block 1 on DOY 138 was predicted to be 42% greater in aspen (773 mm) than conifer (447 mm). In Block 2, peak water storage in snow and soil was observed on DOY 120 (4/30/06) in aspen (1274 mm) and conifer (573 mm). Potential for runoff and groundwater recharge in Block 2 on DOY 138 was predicted to be 83% greater in aspen (662 mm) than conifer (118 mm). Most of the snow water in the Block 2 conifer plot recharged the soil column during the melt period.

Potential for Canopy Snow Redistribution

Total precipitation (measured) was compared to the calculated net precipitation in Blocks 1 and 2 to indirectly determine if canopy redistribution caused snow accumulation differences between aspen and conifer. In the winter net precipitation = precipitation – redistribution – sublimation. The net precipitation was calculated from water storage in snow and soil at PSWE in aspen and conifer plots in Blocks 1 and 2, and the Lightning Ridge SNOTEL station. The water storage of the Lightning Ridge SNOTEL station was calculated (SNOTEL*) as the sum of measured soil and snow water pools minus soil water storage measured at the beginning of the water year DOY 270 (9/27/05). When

SNOTEL* was compared to measured net precipitation (SNOTEL) the estimate was similar, SNOTEL* underestimated net precipitation by 29 mm (Table 4.1).

Because a direct measurement of total precipitation was not available in Blocks 1 and 2 net precipitation was calculated for each plot as described above (Table 4.1). In Blocks 1 and 2, aspen had higher net precipitation in snow and soil than the measured net precipitation at the SNOTEL station. In Blocks 1 and 2, conifer had less net water stored compared to the SNOTEL station. The within block mean net precipitation of aspen and conifer plots was slightly greater than the measured net precipitation at the SNOTEL site. While net precipitation between individual plots and the Lightning Ridge SNOTEL station were different, net precipitation between Blocks 1 and 2 and the Lightning Ridge SNOTEL station were similar (Fig. 4.26). This indicates that net precipitation in Blocks 1 and 2 may be slightly higher than at the Lightning Ridge SNOTEL station. Redistribution processes may have caused differences in peak SWE that were observed between aspen and conifer. The net precipitation at the block level might have been lower than the SNOTEL total precipitation if significant canopy sublimation had occurred in the conifer plots, rather than redistribution of intercepted canopy snow.

Summertime Ecosystem Evapotranspiration

Total soil moisture content was monitored throughout the summer of the 2005-2006 WY in Block 1. Summer precipitation events did not add large amounts of water to the soil column. In the course of the 2005-2006 WY, 1006 mm of precipitation fell as snow. During the summer growth period 91mm of precipitation fell in the form of rain.

Table 4.1 Net precipitation measured at the Lightning Ridge SNOTEL station (SNOTEL), and calculated net precipitation for the Lightning Ridge SNOTEL (SNOTEL*), aspen and conifer plots, average of aspen and conifer in Blocks 1 and 2 ((A+C)/ 2), and difference between average and SNOTEL (Difference).

	DOY	SNOTEL mm	SNOTEL* mm	Aspen mm	Conifer mm	(A+C)/2 mm	Difference mm
Block 1	103	765		985	653	819	54
Block 2	120	789		1083	532	808	19
SNOTEL	98	752	723				29

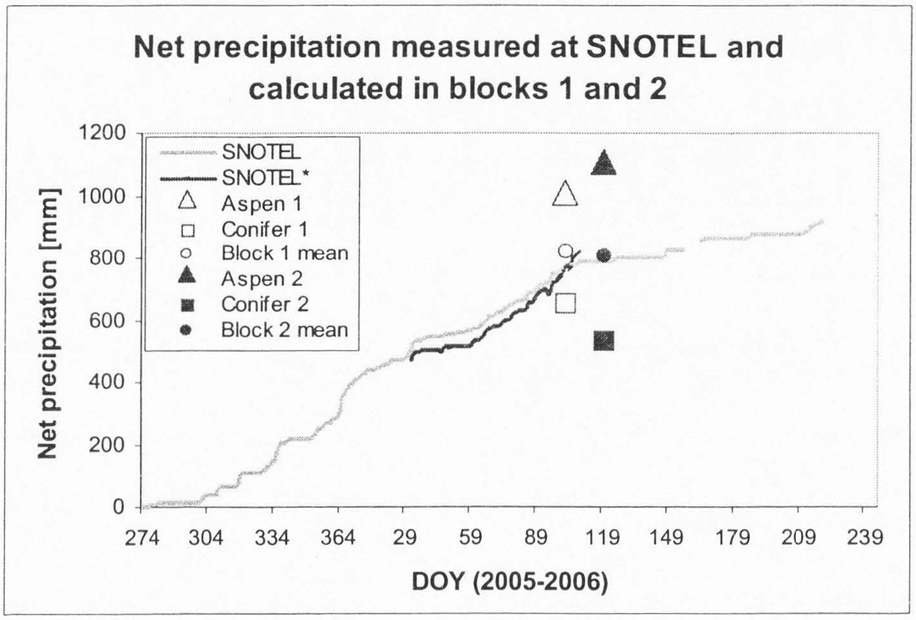


Fig. 4.26 Net precipitation measured at the SNOTEL station and calculated from water stored in Blocks 1 and 2.

Both aspen and conifer soils experienced depletion of nearly all available soil water during the summer growing period (Fig. 4.27).

Ecosystem evapotranspiration (ET) rate for Block 1 aspen and conifer was estimated based on the initial spring soil water storage on DOY 144 (5/24/06),

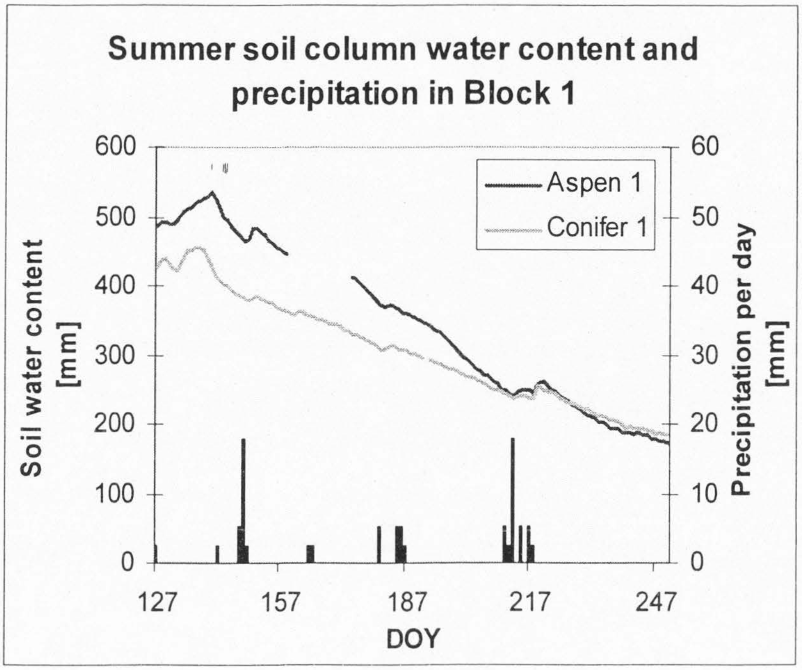


Fig. 4.27 Soil water column depletion during summer of 2006.

summertime precipitation inputs, and the final fall water storage on DOY 250 (9/7/06). It was assumed that after spring snow melt there was minimal percolation of soil water to bedrock fissures below the soil column, and that summertime precipitation events were not of sufficient intensity and duration to exit the system via overland flow. Given these assumptions, average daily ET was 3.6 mm day^{-1} in aspen (451 mm) and 2.7 mm day^{-1} in conifer (343 mm) during the period from DOY 144 – 250. The higher soil water storage in aspen at the beginning of the growth period was offset by a greater ET rate per day during the growth period. The ET rates converged around DOY 210 (7/29/06). This was likely the result of decreased soil matric potential which at ~ 0.22 m^3 m^{-3} water content is approximately -600 kPa for silt loam soils (van Genuchten, 1980). Under these conditions, transpiration rate could be primarily regulated by soil water movement to the plant rather than VPD and temperature of the atmosphere. Near the end of the water year, on DOY 224 (12/8/06) both aspen and conifer ecosystems had equally depleted nearly all plant available water.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

Mechanisms Related to Water Yield

This study examined several hydraulic parameters and water transfer mechanisms to determine how differences in water yield could differ between stands of aspen and conifer. Seven hypotheses related to water dynamics were addressed to determine which hydrologic processes might affect water yield. This study is unique in that we measured many hydrologic variables simultaneously to asses the relative importance of each component in contributing to potential annual water yield differences.

The first hypothesis stated that aspen and conifer communities were expected to retain different amounts of snow during peak snow accumulation. This was strongly supported during both years and across all blocks. Aspen stands had significantly higher SWE than paired conifer stands. In the winters of 2005 and 2006, aspen stands had 34-44% greater snow accumulation. These findings are consistent with those of previous researchers that have measured differences between open or deciduous stands and the contrasting winter foliage density of conifers. Relative to open or deciduous stands, peak snow accumulation in conifer has been reported to be 15-40% lower in montane and alpine systems (Dunford and Niederhof, 1944; Miller 1962, Hoover and Leaf, 1967; Gary, 1974; Gary and Troendle, 1982; Troendle et al., 1993; Skidmore et al., 1994; Moore and McCaughey, 1997; Gelfan et al., 2004).

When changes in soil water content are combined with peak snow water equivalent, aspen stands had even greater (42-83 %) winter precipitation accumulation relative to adjacent conifer stands in 2006. Previous studies which have examined only the SWE differences between forest stands have neglected changes in soil water content during the snow accumulation period. Our data illustrate that SWE alone may not be sufficient to accurately compare total winter snow accumulation between forest types. Soils under aspen stands in our study had greater soil column water content at the time of peak snow accumulation.

Aspen had higher soil moisture recharge during the snow accumulation phase, which could have been a result of heat transfer from the aspen soil to the snowpack and greater snowpack energy content. The snowpack temperatures measured during the melt period were higher in aspen stands relative to conifer stands, as previously reported by Swanson and Stevenson (1971). This suggests that the aspen snowpack receives more direct shortwave radiation as well as long-wave radiation reemission from the leafless aspen canopy structures. Increased snow energy content of the aspen snowpack accelerated the snow metamorphosis and densification, indicated by aspen snowpack density which was consistently higher than conifer snowpack density across all blocks and times during the melt period. Earlier soil column saturation in aspen was a result of faster snow ablation rates.

The second hypothesis stated that sublimation and condensation gains and losses from the snowpack beneath aspen and conifer stands were expected to differ throughout the melt period because of differences in energy balance caused by canopy stature. Our data did not indicate significant differences in net sublimation between aspen and conifer for seven observation days. Sublimation rates were estimated at 0.8 mm day^{-1} over a 39-day melt period in open aspen and conifer plots. Aspen tended to exchange more water with the atmosphere via sublimation or condensation during individual observations, suggesting that differences in atmospheric exchange rates between stand types may occur. Higher rates of sublimation and condensation in aspen offset each other to reducing overall mean difference compared to conifer across all observations. The difference in snowpack temperature observed adjacent to the sublimation pans in aspen and conifer also suggests that the surface of the aspen snowpack was warmer which could contribute to greater sublimation rates. The amount of water sublimated from the snowpack surface during the melt period was minor (<5%) relative to snow accumulation and soil water pools, a finding consistent with Doty and Johnson (1969) who also compared sublimation rates in aspen and conifer stands within the Northern Rocky Mountains of Utah.

The third hypothesis stated that the ablation period was expected to be extended in conifers leading to increased evapotranspiration loss within the late season snowpack. In both years, snow disappeared from both aspen and conifer stands within the same week. Given the low measured sublimation rates (0.8 mm day^{-1}), the potential for differences in snowpack sublimation due to greater length of exposure (ablation period) to the atmosphere were minor (6 mm wk^{-1}). This pattern was also observed in boreal forests and other aspen-conifer stands (Dunford and Niederhof, 1944; Gelfan et al., 2004) where forest canopy structure affects both snow accumulation and snow melt rate. Forest snowpacks beneath conifer are shallow and melt slowly but ultimately disappear at the same time as open or aspen sites with deep, fast melting snowpacks.

The fourth hypothesis stated that aspen stands were expected to have greater evapotranspiration rates during the growth period resulting in higher net summer transpiration. Summertime ecosystem ET estimated from soil column water content was 25% higher in aspen (3.6 mm day^{-1}) relative to conifer (2.7 mm day^{-1}). If we assume the growing period is approximately 140-days long this would amount to 126 mm more water lost to ET in aspen than in conifer each year, accounting for approximately 11% of the average annual precipitation.

Increased net summertime ET in aspen was likely related to higher soil column porosity. The aspen soil stored more water during the snowmelt when soils became saturated. Both aspen and conifer utilized most of the soil column water content by the end of the growing season. Because of the higher ET rates in aspen stands, there was no difference in soil water content at the end of the fall 2005.

The evapotranspiration rates we estimated from soil moisture loss in conifer were similar to previously values reported by Pataki et al. in (2000) [2.6mm day^{-1}] and by Knight et al. (1981) [3.4 mm day^{-1}]. Although sap flux was nearly identical between aspen and conifer trees per ground area in Wyoming (Pataki et al., 2000), our data suggests that the presence of understory plants in aspen could increase the whole ecosystem ET rate by at least 0.9mm day^{-1} averaged over the growing period.

The fifth hypothesis stated that aspen and conifer stands were expected to differ in total annual transpiration activity period leading to increased net annual transpiration. Sap flux measurements suggested that conifer were active for a longer total transpiration period beginning five day earlier in the spring, and continuing 24 to 31 days longer into the fall. Contrary to the modeling results of Gifford et al. (1984), net transpiration during periods of extended activity in conifer is a minimal portion of annual transpiration losses. Late season drought in 2005 equally impacted soil moisture in aspen and conifer. Aspen stands utilized most available soil water before leaf senescence. The extended transpiration activity in conifer stands resulted in the near equal utilization of most plant available soil water between stand types, as evidenced by the very dry soil column water contents (0.07-0.10 $m^3\ m^{-3}$) in fall 2005.

The sixth hypothesis stated that spring soil moisture recharge was expected to differ between aspen and conifer stands. We observed that aspen soils recharged more during the fall and winter, and became saturated earlier in the spring. This was corresponded to higher snow ablation rates in aspen. In aspen, shallow soil moisture recharge was 5 mm higher in early fall 2005. This soil recharge followed several early season snow events. Aspen could have had increased soil recharge during this period due to higher ground heat storage prior to the snow event and greater long wave radiation inputs to the snow and soil following the event. The aspen had lost their leaves at the time of the snow events, and we speculate that the heated soils transferred energy to the snow following the storm causing more melting to occur. In conifer stands, less soil water recharge may have been due to canopy snow interception. The snow that did reach the surface was relatively shaded, which may have reduced snow melt on warm days following the early fall snow events.

Hypothesis seven stated that conifers transpiration activity in spring is facilitated by accelerated snow melt within conifer tree wells, evidenced by lower shallow soil moisture content within tree wells compared to forest interspaces between trees. The "tree well hypothesis" would have been supported by relationships between transpiration activity and changes in shallow soil moisture during the snow melt period. However, we found that the shallow soil moisture content in the interspaces and beneath tree boles was not different. Sap flux data indicated that the transpiration rate (0.56 mm day $^{-1}$) in conifers was much less than conifer snowmelt infiltration (4.9 mm day^{-1}) rates. These findings do not support the hypothesis that tree wells function as a significant snow melt water loss mechanism in conifer.

We measured large differences in snow accumulation in aspen and conifer stands on north and northwest and northeast facing slopes within the Frost creek and adjacent watersheds in Northern Utah. The estimated snowmelt water yield to runoff and groundwater was higher in aspen relative to conifer, primarily due to higher snow accumulation in aspen forests. The results of this study suggest that contrary to the speculations of several researchers, transpiration does not contribute to large differences in annual water yield between aspen and conifer. The largest discrepancy in water balance we measured resulted from snow water accumulation throughout the winter. When changes in wintertime soil moisture content were taken into account, there was even greater water accumulation in aspen relative to conifer. Although aspen stands had higher ET rates during the growing season, these were not of sufficient magnitude to offset differences in water yield due to snow accumulation. Differences in transpiration and snowpack surface-sublimation during the snow melt period were not large enough to cause aspen and conifer water yield differences.

Quantification of Water Yield in Aspen and Conifer

There is great interest in the question of whether or not aspen forests will yield more water to stream runoff and groundwater recharge when compared to conifer forests. The decline in aspen stands in the Intermountain West may be due to conifer encroachment or wildlife and livestock over-utilization of young aspen ramets (Bartos and Campbell, 1998). Many land managers are now interested in restoring aspen forests to regain a variety of resource values including livestock forage, wildlife habitat, and recreation. The hydrologic benefits of aspen restoration may include increasing the quantity of water delivered for agricultural and municipal use.

Quantifying water yield increases after the restoration of aspen will have broad utility. Restoration treatments could pay for themselves if the initial cost of treatment is exceeded by the economic benefits of long-term water yield increases. While it is tempting to extrapolate our results across all aspen-conifer forests in the Intermountain West, it would be premature, based on the limited spatial inference of this study and our limited understanding of the factors affecting snow accumulation. A complete understanding of the water yield augmentation potential of conifer to aspen conversions requires a better quantification of the sublimation and redistribution processes acting on snow intercepted by the conifer canopy.

Evidence for sublimation

The physical processes of canopy-sublimation and redistribution were not directly investigated in this study. Average PSWE for two years was 197 mm (2005) and 305 mm (2006) more in aspen relative to adjacent conifer stands, amounting to a 34% to 44% difference in snow accumulation. If we account for differences in wintertime soil moisture recharge, there was 42-83% higher net SWE in aspen during 2006. Canopy sublimation rates reported for conifer range from 29 mm yr^{-1} to 200 mm yr^{-1} (Lundberg et al., 1997; Pomeroy et al., 1998; Stork and Lettenmaier, 2002; Montesi et al., 2004). This suggests that sublimation could have accounted for 10 – 100% of the observed difference in snow accumulation.

There is great difficulty in tracing the pathway that snow will take after being remobilized from the tree canopy via the wind. Many authors have quantified canopy sublimation using the hanging tree method which makes the assumption that snow leaving the tree canopy moves in one of two vectors (Lundberg et al., 1997; Pomeroy et al., 1998; Stork and Lettenmaier, 2002; Montesi et al., 2004). The snow is either sublimated into the atmosphere or falls directly below the tree where it can be measured with lysimeters. The problem with measuring sublimation this way is that it does not account for snow particles that move away from the tree of interception to an adjacent snowpack surface. We expect sublimation to be greater in the conifer canopy because the surface area of intercepted canopy snow can be 60 to 1800 times greater than that of snow on the ground (Pomeroy and Schmidt, 1993). The greater surface area provides the opportunity for both accelerated sublimation and redistribution to occur.

Canopy sublimation in the conifer stands is occuring to some extent in our system as evidenced by the sublimation of snowpack beneath the canopy. In addition, snow intercepted by the conifer canopy could be expected to sublimate at rates higher than those observed in the surface snowpack for three reasons. First, the surface area of intercepted snow is much greater than that of the flat snowpack surface. Second, the conifer trees themselves are dark bodies that reemit long-wave radiation that has penetrated the intercepted snow, thus, raising the temperature of the intercepted snow. Finally, sublimation is likely to be greater during the snow accumulation period

(November –March) when the air is cooler and often dryer, compared to during the warm ablation period (April – May) when we conducted snowpack sublimation measurements.

Evidence for redistribution

Evidence for the redistribution of intercepted snow from the conifer canopy to the aspen snowpack may be inferred from calculated net precipitation and snow survey data. Peak snow accumulation in all aspen plots was consistently higher than the SNOTEL snow pillow, while nearly all conifer plots were consistently lower than the snow pillow. The snow pillow placement within the watershed was chosen by experienced NRCS snow hydrologists to approximate average snow conditions across the watershed. If the snow pillow is in fact a neutral position for averaging snow accumulation across the watershed, then the elevated snow accumulation in aspen relative to the snow pillow suggests that redistribution of snow from the conifer canopy to the aspen snowpack is occurring in this watershed.

Redistribution and differential deposition processes are difficult to measure as they depend upon the large spatial scale of redistribution processes. In Blocks 1, 2, 3 conifer stands were up-wind of the adjacent aspen stands, which could have redistributed the intercepted canopy snow to the aspen snowpack during the winter. However, in Blocks 4, 5, 6, and 8 there were no conifer stands in close proximity and upwind of the aspen plots. We calculated net precipitation in Blocks 1 and 2 to determine the net redistribution and sublimation effects of both aspen and conifer stands on the landscape. Net precipitation estimates were similar between Blocks 1 and 2 and the Lightning Ridge SNOTEL station when mean aspen and conifer values were averaged across blocks at peak accumulation. This suggests that redistribution could account for a portion of the difference in SWE between aspen and conifer. This agrees with the findings of landscape-level inventories of SWE, which have suggested that alterations to forest canopy structure (e.g. clear cuts) change snow distribution, however, net accumulation in the catchment remains unchanged (Hoover and Leaf, 1967; Gary, 1974; Stegman, 1996).

Prospectives

The ratio of sublimation to redistribution will largely determine the extent to which conifer to aspen conversion will augment water yield. It is likely that the sublimation to redistribution ratio changes across geographic regions and within topographically heterogeneous landscapes, due to canopy structures and physical climatic variables. In the present condition at Frost Creek watershed, aspen on North facing slopes are a likely a greater source of stream and groundwater yield than adjacent conifer stands due to greater snowpack. Conversion from conifer to aspen forest could increase annual water yield if canopy sublimation in conifer is the primary process driving differences in snow accumulation.

The distinction between sublimation and redistribution mechanisms leading to differences in observed peak SWE were not investigated in this study. If sublimation is responsible for snow accumulation differences, then removal of the evergreen canopy can be expected to increase net snow accumulation at the watershed scale. Conversely, if redistribution is responsible for differences in snow accumulation, then removal of the evergreen canopy will cause net snow accumulation to stay the same at the watershed scale with moderately decreased snow packs more uniformly distributed in aspen. Snow packs in the restored aspen area would be higher due to decreased canopy interception, but the increase would be offset by decreased snowpacks in the pre-existing open or aspen stands which would not receive snow inputs from the conifer canopy. This could decrease stream water yield in soils beneath aspen if the soils develop higher porosity (discussed in the next section), which could retain more of the snow melt water for summer use. If redistribution is a dominant process leading to snow accumulation differences, then mosaic patterns of aspen and conifer stands might lead to the greatest stream water yield by creating large snow deposits in aspen. As we observed, large snow deposits in the aspen stands melt quickly. Future studies focusing on partitioning the ratio of sublimation to redistribution of intercepted canopy snow will greatly enhance our ability to predict water yield increases that could result from conifer to aspen conversion.

Ecological Implications for Different Water Dynamics

We speculate that ecosystem functions will respond to the differences in water balance observed in aspen and conifer. Differences in snow accumulation, soil moisture recharge, soil porosity, and melt rates in aspen and conifer may have the greatest effects on ecosystem function. Under aspen stands, a deep winter snowpack insulates the soils from freezing, and soil moisture is higher throughout the winter. These attributes would be expected to favor conditions for prolonged soil microbial activity and related food webs. Other wintertime ecological effects arising from aspen and conifer cover include canopy structure influences on energy balance and wintertime litter deposition. Increased peak soil column water content in aspen may lead to increased total primary productivity over the course of the growing season.

Biogeochemistry

Snow cover acts as a dynamic nutrient reservoir, a mediator of soil nutrient cycling and gas emissions, and a source of hydrologic flux which drives nutrient export during snowmelt (Jones, 1999). Given that our snow accumulation and ablation rates were higher in aspen, we expect nutrient export during snowmelt to be elevated in aspen relative to conifer stands. Although nutrients accumulated in the snow may be small relative to nutrient pools in the soil, the nutrients in the snow melt water can increase rates of microbial transformation and root uptake in spring (Tranter, 1991). Elevated snow accumulation in aspen would be expected to have greater snow nutrients and therefore increased microbial transformation and root uptake during spring snowmelt.

Inorganic nitrogen (N) pools are affected by the meteorological conditions driving deposition, as well as the biological activity of snow microbial assimilation. Biological assimilation of NH_4 and NO_3 in snow was reported to exceed the daily rate of dry deposition during periods when the snow is saturated with free water in a northern boreal forest (Jones and Sochanska, 1985). Microbial assimilation of inorganic N was reported to be accelerated by the addition of conifer needles in snow. Over the course of a winter conifer needles could reduce available N in the snow water pool by 62% prior to melt (Gamanche, 1992). The energy balance in aspen and conifer snowpacks were very different as evidenced from snow density and ablation rates. We speculate that the litter quantity within the aspen snowpack will be diminished because leaves undergo senescence prior to snow accumulation. However, aspen will be expected to have much greater surface litter deposition prior to snow accumulation. These differences may be significant enough to moderate the composition of snow and soil microbial populations and affect nutrient cycling pathways in each stand.

Snow cover also affects soil microbial activity and soil respiration by regulating soil temperature, moisture, and gas exchange with the atmosphere. During this study, ice lenses were observed only in the conifer stands during snow surveys. These impermeable layers reduce gas fluxes between the soil and atmosphere (Winston et al., 1995). Soil microbial activity could be higher throughout the winter in aspen due to higher soil oxygen concentrations and available carbon substrate as well.

Nutrient export is highest during snowmelt in evergreen and deciduous forests dominated by snow precipitation (Jones and Roberge, 1992; Williams, 1993). Stream runoff nutrient concentrations could have originated from both snow and soil nutrient pools that have undergone mineralization during the winter. Aspen had higher snow accumulation, ablation rates, and higher porosity (lower bulk density) in our study. Longer periods of saturation and higher infiltration rates through the aspen soil column could increase the leaching of soil nutrients. However, over winter decomposition of aspen litter beneath the snowpack may have immobilize soil nutrients before melting occurs.

Wildlife

We speculate that aspen may serve as refugia for small mammals during the winter snow accumulation period. In this study, higher spring rodent activity in aspen stands was anecdotally observed. To survive in the cold, insectivores possess high metabolic rates and have to feed almost continuously. Subnivian (below snow) fauna active in the winter include: oligochaetes, mollusks, centipedes, pseudoscorpions, phalangids, spiders, mites, springtails, beetles, flies, wasps, and other insects (Aitchison-Benell, 2001). Shrews favor habitats with deep humus or snow cover where they construct nests to conserve heat (Atichison-Benell, 2001). Omnivorous rodents tend to be hibernators or in torpor, while herbivorous microtine rodents are active during the winter (Jones et al., 2001). Small mammals are a key component of the winter food supply for weasels, foxes, birds of prey and other large carnivores. Higher soil water contents and temperatures in aspen soils would be expected to increase subnivian animal activity during winter, and thus, facilitate greater productivity within the higher trophic levels of the animal community.

Soil genesis

During soil genesis, morphological features such as soil column porosity could be affected by feedbacks with forest cover. Aspen and conifer may have occupied these soils with alternating residence during succession cycles at perhaps 200-500 year intervals, or they may be relatively persistent. It is noteworthy that under the current conditions, aspen soils in our study plots had greater porosity which increased soil column water content during the growing season by retaining more snowmelt water. An investigation into whether or not soils mediate vegetation or vice versa is warranted in this system.

Differences in soil porosity beneath aspen and conifer could have resulted from ecological feedbacks including snow accumulation, litter quality and quantity, and small mammal activity which facilitate soil genesis. Dahlgren et al. (1997) found that soil properties including pH, soil color, clay and secondary Fe oxide concentrations showed a pronounced change (threshold-type step) over a 1600 m vertical transect which coincided with the present winter snow-line. Presumably the difference in snow accumulation and differences in spring infiltration rates and duration in aspen and conifer could effect these properties. Yimer et al. (2006) reported that differences in soil textural fractions and bulk density may be attributed to differences in organic matter contents and leaching within the soil profiles mediated by vegetation type. The aspen had greater SWE and snow melt rates that increased potential for leaching and could be a greater source for annual leaf litter inputs relative to conifer.

Aspen soils may have greater rodent activity during the winter due to the deeper snowpacks which insulate soil and maintain higher temperatures and water contents during the winter. Bioturbation (rodent disturbance) can increase soil porosity by the ejection of soil from fossorial mammal burrow systems. Ejected soil is generally of low bulk density, erodes readily, and varies greatly with respect to concentration of nutrients and organic matter (Van Miegroet et al., 2000). While pedogenisis was not investigated during this study we speculate that soil properties will be affected by the presence of aspen vs. conifer forest.

Fire, drought, and pathogen stress

Summer water dynamics in forest vegetation and soils are complimentary variables that may affect fire risk and beetle invasion caused by summer drought. In our study, aspen maintained higher soil water content than conifer during the 2006 summer fire season. This occurred despite higher rates of aspen ET, which were offset by higher soil column porosity and water content at the onset of the growth period. During the 2006 water year, snow accumulation was above average and both aspen and conifer soil columns were saturated during the snowmelt period. In a below average snow year soils in conifer stands may be less likely to saturate the soil column during snowmelt because of less SWE. If summer precipitation is low as well, conifer stands could be more susceptible to drought stress and associated disturbances such as fire and beetle outbreaks.

Evapotranspiration estimates were higher in aspen stands than in conifer stands, suggesting that aspen community has the potential to transpire more when soil water is unlimited. This could mean that aspen stands will be more susceptible to persistent annual drought due to a early utilization of limited soil water. Conversely, reductions in understory biomass in aspen may compensate for water scarcity following dry winters.

Mixed stands containing both aspen and conifer could have the greatest potential for water stress and associated disturbances. If canopy sublimation is the main mechanism lowering SWE, then the presence of conifer in the stand will result in lower snow accumulation available for soil moisture recharge in spring. During the growth period, the presence of aspen may increase evapotranspiration causing an early utilization of soil water. As we observed, aspen had higher ET rates until soil water content was diminished to 0.22 m^3 m^{-3}. This could explain why Pataki et al. (2000) found that mixed aspen and conifer stands had lower transpiration rates than adjacent stands of pure aspen and pure conifer during persistent summer drought.

If mixed aspen and conifer stands have increased susceptibility to disturbance it would explain part of the succession cycle. If disturbance is more likely to occur in drought susceptible climax stand (conifer dominated), it will be followed by the rapid recruitment of young aspen ramets from root reserves that survive the fire. I speculate that by utilizing unlimited soil water early in the growing season, aspen facilitate wildfires in mixed stands thereby competing with conifer.

Climate Change Scenarios

The U.S. Global Change Research Program (USGCRP) has made climate change projections for the Rocky Mountain and Great Basin regions based on various global circulation models (GCM). According to these models, annual temperature could increase by 1.1-2.7 °C (2 to 5 °F) and total precipitation could increase by 50-100% by the end of the 21st century (USGCRP, 2006). We can use this hypothetical climate change scenario to further postulate the impacts that climate change could have on water yield from aspen and conifer forests.

Climate change can affect the availability of water resources by altering the seasonal timing and form of precipitation which are dependent upon atmospheric temperature (USGCRP, 2006). According to the GCM, the largest increase in precipitation is projected to occur during the winter. Warmer temperatures could cause rainfall to change to snow later in the fall, and spring snowmelt may occur earlier. Along with snowpack retreating to increasingly higher elevations, the overall result could be reduced snowpacks, increased winter stream-flow, earlier spring run-off with lower peak discharge, and longer periods of low summer and fall flows. Evapotranspiration would likely increase due to rising temperatures and VPD. This could offset the gain from increased precipitation if water is available during the growing season.

If the GCM predictions are correct, we can further speculate as to the effects on water dynamics in aspen and conifer forests. Increased rainfall during winter could reduce the discrepancy between aspen and conifer snow accumulation and increase winter soil moisture recharge rate in both systems. Conifers might still have diminished winter soil moisture recharge relative to aspen due to the interception of rainfall by the evergreen canopy. If snowpacks alone are diminished, then the flood potential due to fast ablation of deforested or aspen-dominated landscapes could be diminished. However, if soils are saturated prior to snowmelt, then floods could result from the rapid ablation of a smaller snowpack. If high variability in temperature occurs, then we could expect more rapid spring warming and rain on snow events leading to rapid melt rates. Snow melt is able to saturate the soil column by prolonged persistent irrigation which can eventually displace air trapped in the soil pores. Diminished snow packs would be less likely to fully saturate the soil column via prolonged irrigation.

If there is no increase in summer precipitation accompanied by increasing summertime temperatures and ET, drought stress could increase in both aspen and conifer. Conifer respond to high VPD by restricting their stomata, resulting in slower growth rates and the conservation of soil water (Massman and Kaufmann, 1991). Aspen and conifer have similar transpiration rates during annual summer drought (Pataki et al., 2000). Our ET data suggests that once the soil water content passes a threshold where soil matric potential limits water uptake rate in plants. Transpiration rates converged when soil water content was ~22 m^3 m^{-3}. However, above the threshold, aspen use water with little stomatal regulation in response to high VPD. We found that aspen communities had a 25% higher evapotranspiration rate than conifer communities over the entire growth period. If summertime precipitation increases, aspen can be expected to utilize the soil water column faster than conifer during periods when soil moisture is unlimited.

Givnish (2002) reported that temperate deciduous trees in North America tend to dominate forests in areas characterized by cold winters with frozen soils and short day lengths and high precipitation in the spring, fall, and winter; while evergreen forests are associated with mild winters and longer growing seasons. Based on these observations it is difficult to determine weather the USGCRP climate predictions would favor either aspen or conifer.

If, contrary to GCM projections, precipitation actually decreases in the Rocky Mountains and Great Basin regions, competition for already limited water supplies will increase in aspen and conifer stands. Aspen soils had a greater peak water content at saturation due to higher soil column porosity. During an average or below average snow year, peak soil water content differences may be even greater. Conifer soils may not reach saturation in a below average snow year, assuming that snow accumulation ratios stay constant. We might expect greater stress on both species and increasing susceptibility to disease and fire in conifer and perhaps aspen die off both due to drought stress. Causes of aspen decline previously reported include the absence of fire and excessive browsing of young aspen ramets (trees) by livestock and wildlife (Kay, 1997; Bartos and Campbell, 1998; White et al., 1998; Brown et al., 2006). Changes in the seasonality and amount of precipitation and may be additional factors contributing to the decline of some aspen stands.

Conclusions

A comprehensive evaluation of individual water transfer mechanisms was used to elucidate the relative importance of each component in the hydrologic cycle in aspen and conifer. Contrary to the speculations of previous authors transpiration did not contribute to large differences in potential water yield between aspen and conifer in a snow dominated system. Snow accumulation, winter soil moisture recharge, and summertime ET were the dominant mechanisms leading to differences in potential water yield between adjacent aspen and conifer stands. A mass balance water model predicted that potential snowmelt water yield was greater in aspen relative to paired conifer plots in the 2005-2006 water year. Future studies should focus on partitioning the ratio of sublimation to redistribution of intercepted canopy to predict hydrologic response of vegetation conversions at the watershed scale.

Across diverse landscapes the magnitude of difference between aspen and conifer water yield may be highly variable. The influence of individual water transfer mechanisms is likely to change across spatially and temporally. How these individual water transfer mechanisms respond to climate, soils, and topography at a given site, should be considered when manipulating aspen and conifer ecosystems.

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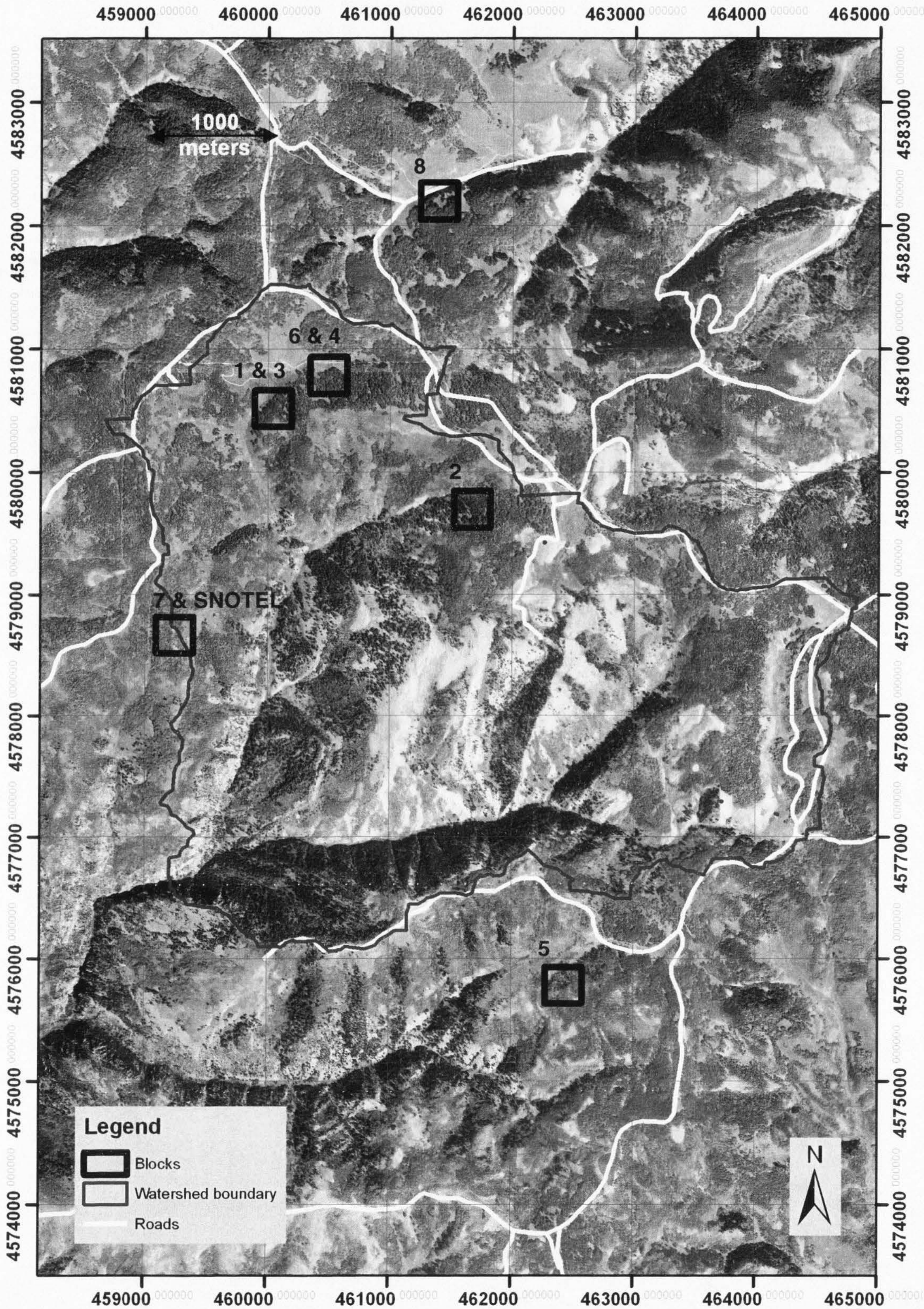
APPENDICES

APPENDIX A

Detailed plot locations


459000
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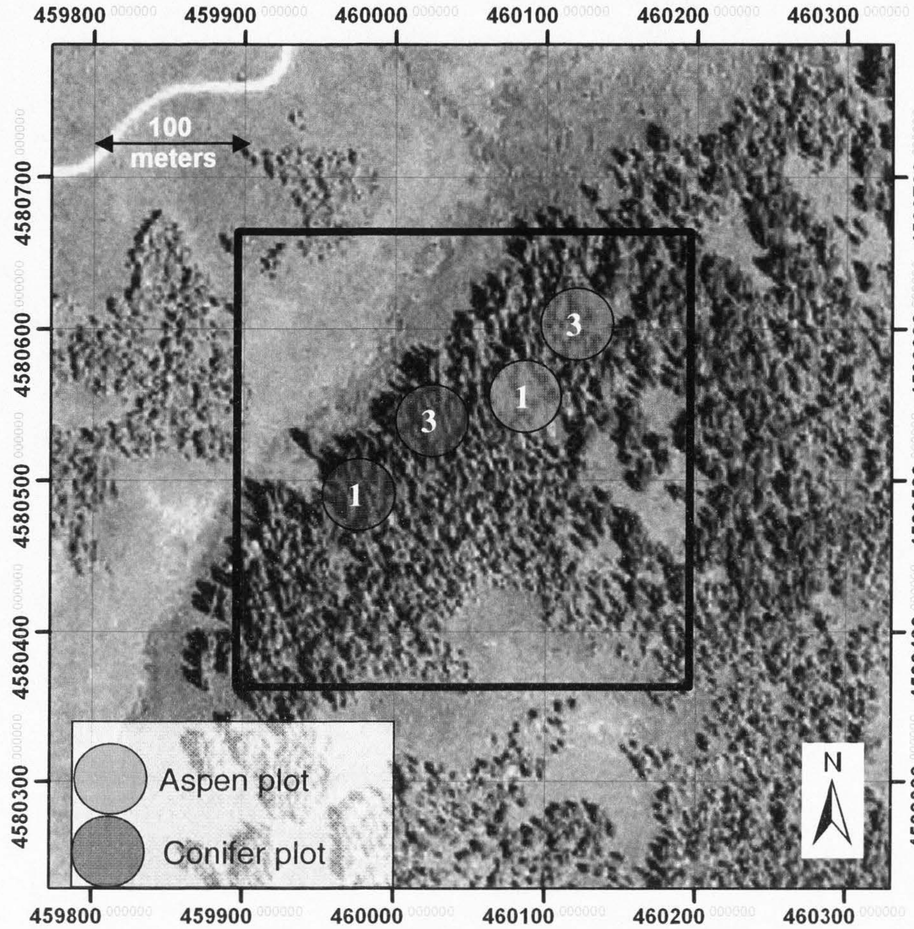
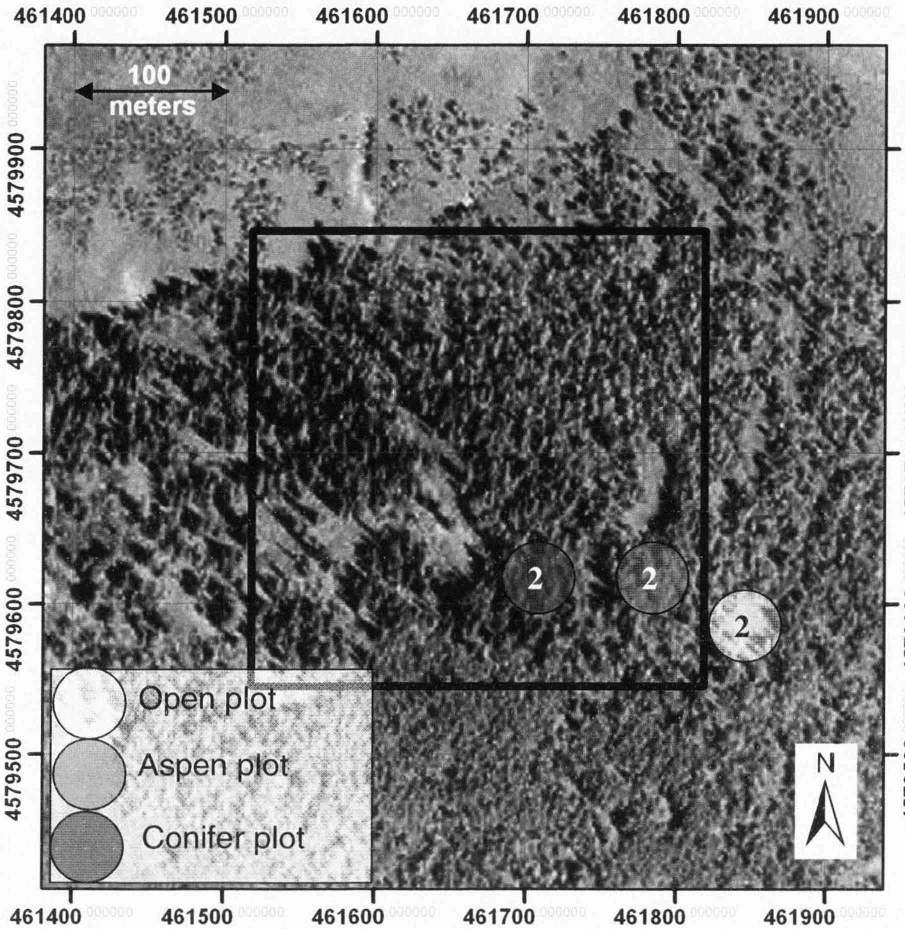
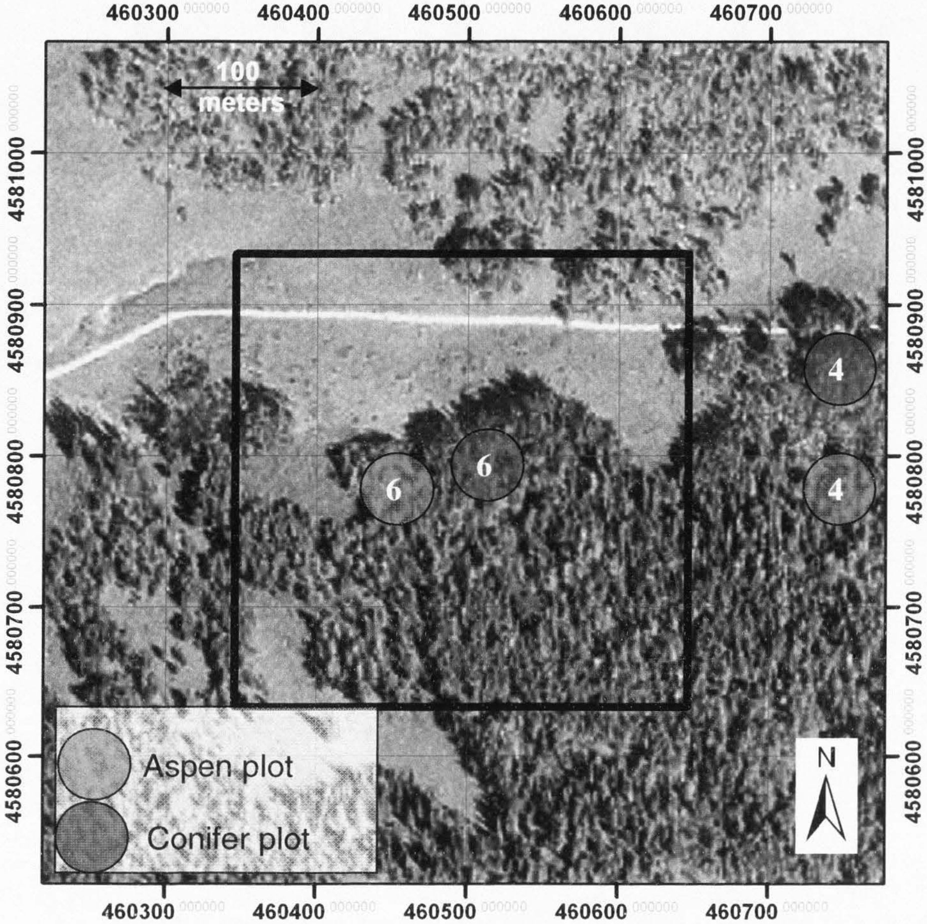
5
Legend
Blocks
Watershed boundary
Roads
N



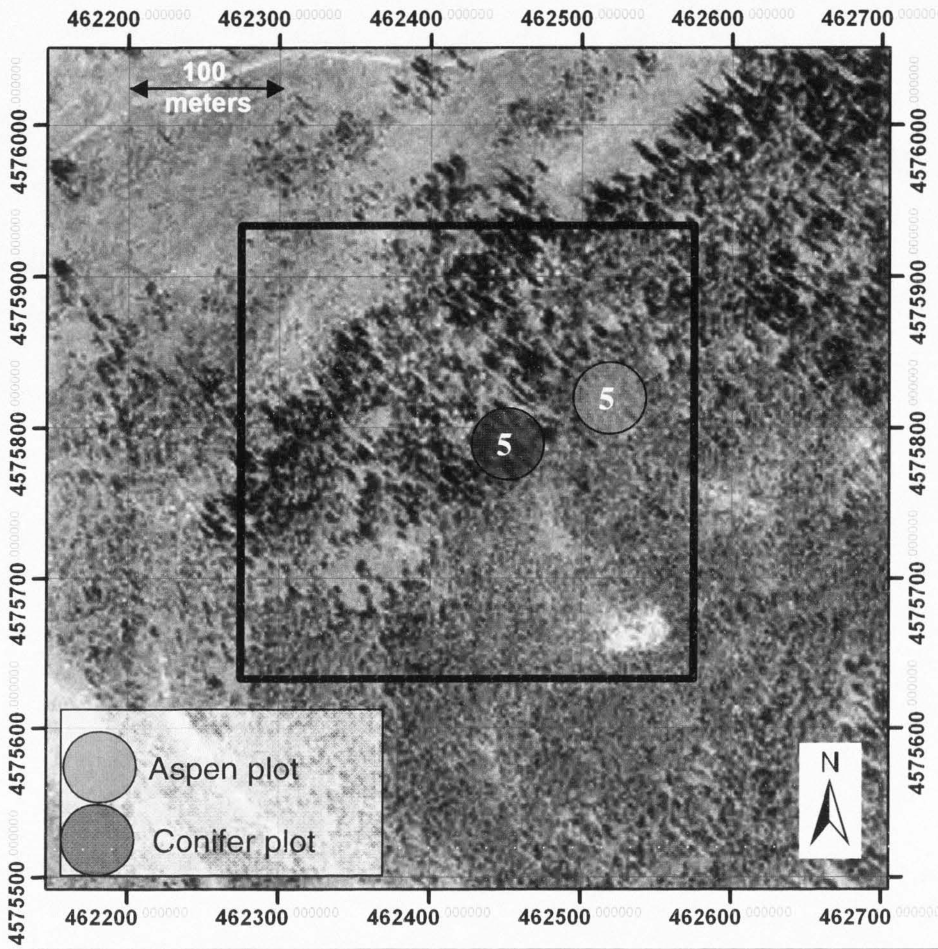
Blocks 1 and 3 paired aspen and conifer plots.



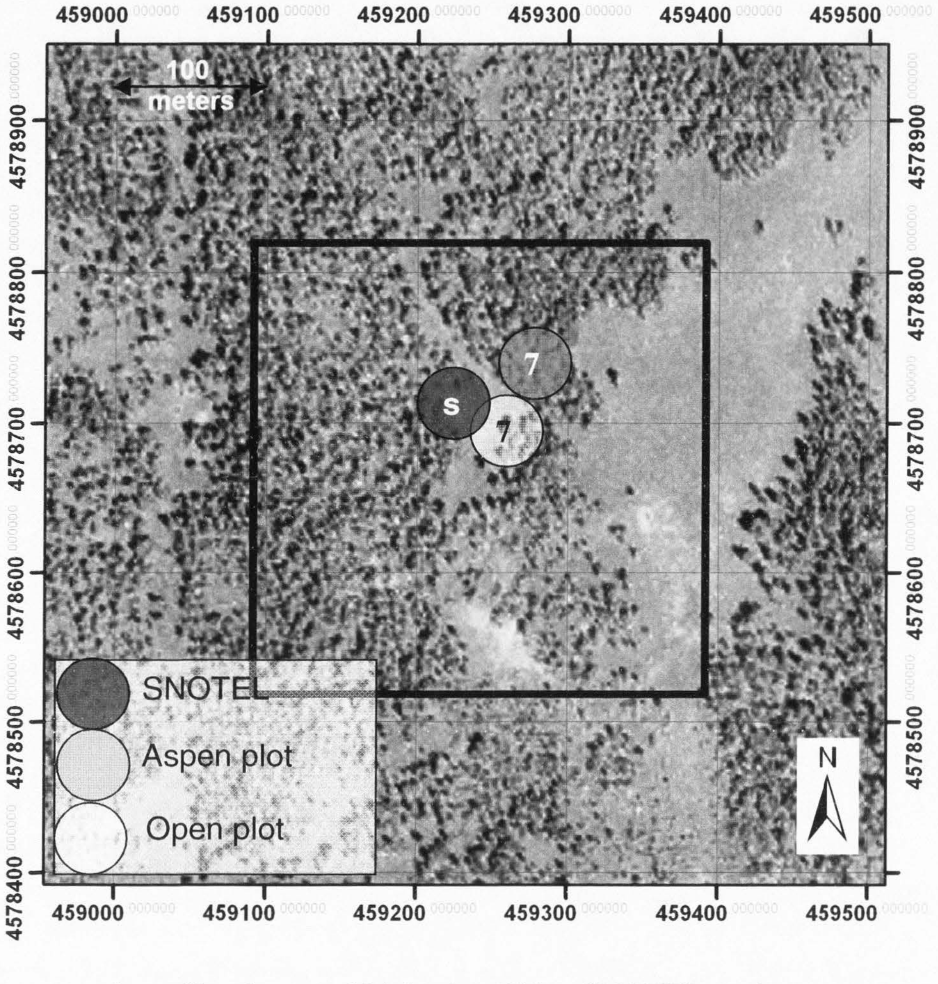
Block 2 open, aspen, and conifer plots.



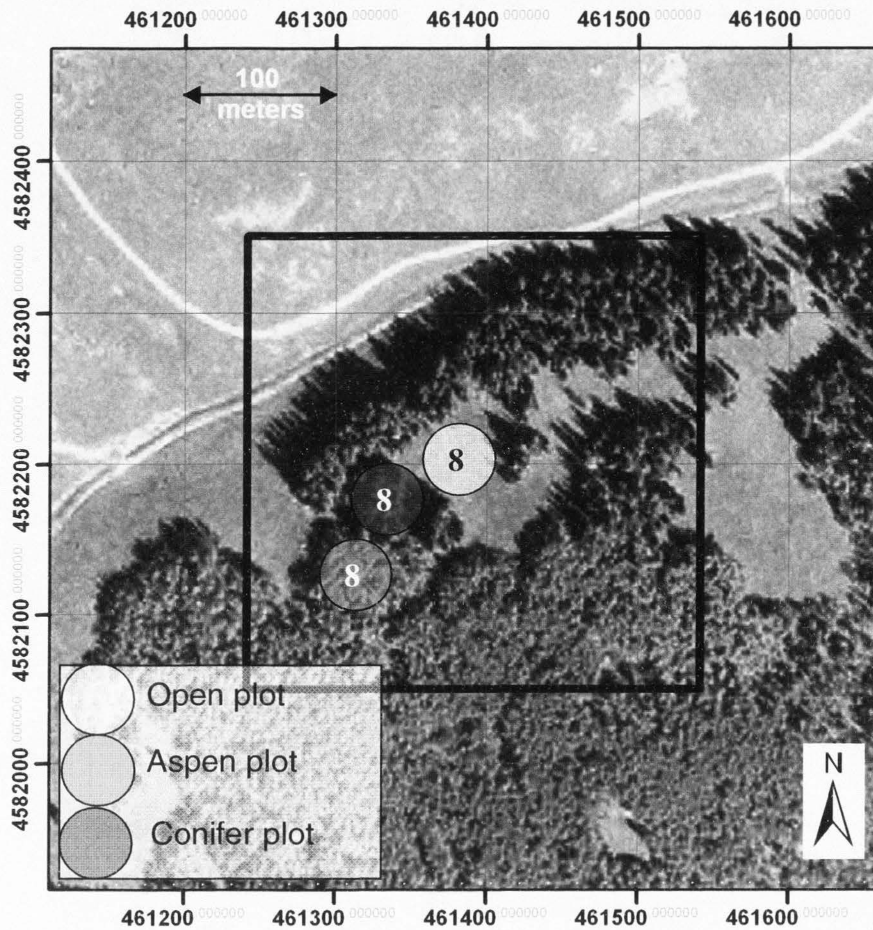
Blocks 4 and 6, aspen and conifer plots.



Block 5, aspen and conifer plots.



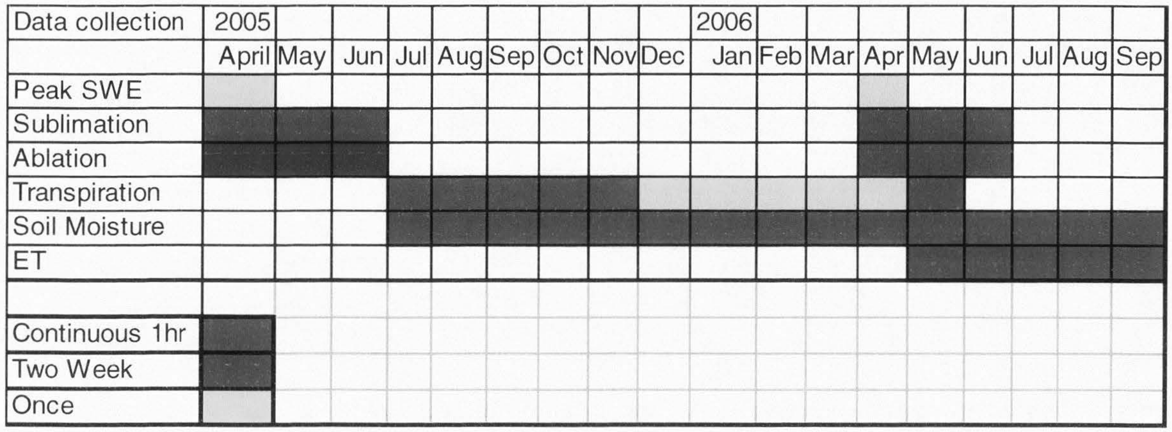
Block 7 aspen and conifer plots, and Lightning Ridge SNOTEL station.



Block 8, open, aspen, and conifer plots.

APPENDIX B

Data Collection Time Line



Data collection timeline for study.

APPENDIX C

NRCS Pedon Descriptions (Block 2)

Block 2 Aspen Pedon Description

Print Date: 07/07/2006
Description Date: 06/22/2005
Describer: Harms, MI, Woldesela, SSIE
Site ID: 05UT057001
Site Note:
Pedon ID: 05UT057001
Pedon Note: Land cover includes aspens and weeds. There was also some litter.
Lab Source ID: SSL
Lab Pedon #: 05N0632
Soil Name as Described/Sampled: SND
Soil Name as Correlated:
Classification:
Pedon Type:
Pedon Purpose:
Taxon Kind:
Associated Soils:
Physiographic Division:
Physiographic Province:
Physiographic Section:
State Physiographic Area:
Local Physiographic Area:
Geomorphic Setting: on summit of interfluve of None Assigned
Upslope Shape: convex
Cross Slope Shape: linear
Particle Size Control Section:
Diagnostic Features: ? to ? cm.

Country: United States
State: Utah
County: Weber
MLRA: 47 -- Wasatch and Uinta Mountains
Soil Survey Area:
Map Unit:
Quad Name:
Location Description: Lightning Ridge SNOTEL site. Main site behind shelter. Wasatch Mountains. Cache National Forest. Horse Ridge topo quad. Soil Survey Number S05UT 057 001.
Legal Description:
Latitude: 41 degrees 22 minutes north
Longitude: 111 degrees 9 minutes west
Datum: NAD83
UTM Zone:
UTM Easting:
UTM Northing:
Primary Earth Cover: Tree cover
Secondary Earth Cover:
Existing Vegetation:
Parent Material: limestone
Bedrock Kind:
Bedrock Depth:
Bedrock Hardness:
Bedrock Fracture Interval:
Surface Fragments:

Cont. Site ID: 05UT057001

Pedon ID: 05UT057001

Slope (%)	Elevation (meters)	Aspect (deg)	MAAT (C)	MSAT (C)	MWAT (C)	MAP (mm)	Frost-Free Days	Drainage Class	Slope Length (meters)	Upslope Length (meters)
2.0	2,503.9	90						well		

A1--0 to 10 centimeters; dark brown (10YR 3/3) loam, very dark grayish brown (10YR 3/2), dry; weak fine granular structure; loose, slightly sticky, nonplastic; common medium and coarse roots; many fine vesicular pores; 5 percent nonflat 2- to 5-millimeter unspecified fragments; gradual boundary. Lab sample # 05N03768

A2--10 to 38 centimeters; dark brown (10YR 3/3) loam, dark grayish brown (10YR 4/2), dry; weak fine granular structure; loose, slightly sticky, nonplastic; common medium and coarse roots; many fine vesicular pores; gradual boundary. Lab sample # 05N03769

Bt1--38 to 76 centimeters; dark yellowish brown (10YR 3/4) loam, brown (10YR 4/3), dry; subangular blocky structure; friable, slightly sticky, nonplastic; few medium and coarse roots; common fine vesicular pores; 10 percent nonflat 2- to 5-millimeter unspecified fragments; gradual boundary. Lab sample # 05N03770

Bt2--76 to 89 centimeters; brown (7.5YR 4/4) silt loam, brown (10YR 5/3), dry; weak fine subangular blocky, and moderate fine granular structure; friable, slightly sticky, nonplastic; few fine and medium roots; common fine vesicular pores; 15 percent nonflat 5- to 75-millimeter unspecified fragments; gradual boundary. Lab sample # 05N03771

2B--89 to 127 centimeters; brown (7.5YR 4/4) sandy loam, brown (10YR 5/3), dry; weak fine subangular blocky structure; friable, nonsticky, nonplastic; few fine and medium roots; 3 percent nonflat 250- to 600-millimeter unspecified fragments and 50 percent nonflat 2- to 250-millimeter unspecified fragments; gradual boundary. Lab sample # 05N03772. Too wet for pores.

Pedon ID: S05UT057001

*** Primary Characterization Data ***

(Weber, Utah)

Print Date: Sep 17 2006 2:02PM

Sampled as :

Revised to :

SSL - Project C2005USUT134 Climate Monitoring Station SNOTEL/SCAN
- Site ID 05UT057001 Lat: 41° 22' north Long: 111° 9' west NAD83 MLRA: 47
- Pedon No. 05N0632
- General Methods 1B1A, 2A1, 2B

United States Department of Agriculture
Natural Resources Conservation Service
National Soil Survey Center
Soil Survey Laboratory
Lincoln, Nebraska 68508-3866

Layer	Horizon	Orig Hzn	Depth (cm)	Field Label 1	Field Label 2	Field Label 3	Field Texture	Lab Texture
05N03768	A		0-10	S05 UT-001-1	1			L
05N03769	A		10-38	S05 UT-001-2	2			L
05N03770	Bt1		38-76	S05 UT-001-3	3			L
05N03771	Bt2		76-89	S05 UT-001-4	5			L
05N03772	2B		89-127	S05 UT-001-5	4			L

Pedon Calculations

Calculation Name	Result	Units of Measure
Weighted Particles, 0.1-75mm, 75 mm Base		% wt
Volume, >2mm, Weighted Average		% vol
Clay, total, Weighted Average	15	% wt
Clay, carbonate free, Weighted Average	15	% wt
CEC Activity, CEC7/Clay, Weighted Average, CECd, Set 1	0.8	(NA)
LE, Whole Soil, Summed to 1m	1	cm/m

PSDA & Rock Fragments

Layer	Depth (cm)	Horz	Prep	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-
				(- - - - - Total - - - - - -)			(- - Clay - - -)		(- - - - Silt - - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)					(Rock Fragments (mm))				
				Clay	Silt	Sand	Fine	CO_3	Fine	Coarse	VF	F	M	C	VC	(- - - - - - - - Weight - - - - - - - -)				>2 mm
				<	.002	.05	<	<	.002	.02	.05	.10	.25	.5	1	2	5	20	.1-	wt %
				.002	-.05	-2	.0002	.002	-.02	-.05	-.10	-.25	-.50	-1	-2	-5	-20	-75	75	whole
				(- % of <2mm Mineral Soil -)												(- - - - - - - % of <75mm - - - - - -)				soil
				3A1a1a					3A1a1a		3A1a1a	3A1a1a	3A1a1a	3A1a1a	3A1a1a					
05N03768	0-10	A	S	15.1	48.8	36.1			21.0	27.8	20.3	8.2	5.3	1.5	0.8	2	7	13	34	22
05N03769	10-38	A	S	15.2	49.5	35.3			20.9	28.6	16.2	12.6	4.6	1.4	0.5	3	6	4	30	13
05N03770	38-76	Bt1	S	15.4	48.6	36.0			20.5	28.1	16.7	11.8	5.4	1.4	0.7	2	4	5	28	11
05N03771	76-89	Bt2	S	14.7	46.0	39.3			19.7	26.3	15.1	15.6	6.7	1.2	0.7	4	12	12	45	28
05N03772	89-127	2B	S	15.5	48.2	36.3			21.0	27.2	15.8	12.9	5.4	1.6	0.6	2	6	5	31	13

Water Dispersible PSDA

Layer	Depth (cm)	Horz	Prep	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-
				(- Water Dispersible -)											
				(- - - - - Total - - - - - -)			(- - Clay - - -)		(- - - - Silt - - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)				
				Clay	Silt	Sand	F	CO_3	F	C	VF	F	M	C	VC
				<	.002	.05	<	<	.002	.02	.05	.10	.25	.5	1
				.002	-.05	-2	.0002	.002	-.02	-.05	-.10	-.25	-.50	-1	-2
				(- % of <2mm -)											
				3A1a6a					3A1a6a		3A1a6a	3A1a6a	3A1a6a	3A1a6a	3A1a6a
05N03768	0-10	A	S	4.6	52.6	42.8			23.9	28.7	11.6	19.9	8.2	2.0	1.1
05N03769	10-38	A	S	5.5	53.1	41.4			25.3	27.8	16.7	15.4	6.5	1.7	1.1

Bulk Density & Moisture

Layer	Depth (cm)	Horz	Prep	-1- (Bulk Density) 33 kPa	-2- Oven Dry	-3- Cole Whole Soil	-4- (Water Content) 6 kPa	-5- 10 kPa	-6- 33 kPa	-7- 1500 kPa	-8- 1500 kPa Moist	-9- Ratio AD/OD	-10- WRD Whole Soil	-11- Aggst Stabl 2-0.5mm	-12- (Ratio/Clay) CEC7	-13- 1500 kPa
				(g cm^{-3})			(% of < 2mm)						cm^3 cm^{-3}	%		
				DbWR1	DbWR1		DbWR1	DbWR1	DbWR1	3C2a1a		3D1		3F1a1a		
05N03768	0-10	A	S	1.17	1.21	0.010	29.6	27.8	25.6	10.1		1.024	0.16	44	1.11	0.67
05N03769	10-38	A	S	1.27	1.28	0.002	27.2	24.9	22.2	8.5		1.023	0.16	44	0.92	0.56
05N03770	38-76	Bt1	S	1.25	1.29	0.010	30.4	28.1	24.2	8.0		1.021	0.19		0.77	0.52
05N03771	76-89	Bt2	S	1.26	1.32	0.013	32.9	30.1	26.9	7.2		1.017	0.21		0.57	0.49
05N03772	89-127	2B	S	1.18	1.23	0.013	27.7	24.7	20.1	8.0		1.020	0.13		0.73	0.52

Water Content

Layer	Depth (cm)	Horz	Prep	-1- (Atterberg Limits) LL	-2- PI	-3- (Bulk Density) Field	-4- Recon 33 kPa	-5- Recon Oven Dry	-6- (Water Content) Field	-7- Recon 33 kPa	-8- (Sieved Samples) 6 kPa	-9- 10 kPa	-10- 33 kPa	-11- 100 kPa	-12- 200 kPa	-13- 500 kPa
				pct <0.4mm		(g cm^{-3})			(% of < 2mm)							
														3C1d1a	3C1e1a	
05N03768	0-10	A	S											15.7	14.0	
05N03769	10-38	A	S											14.8	12.8	
05N03770	38-76	Bt1	S											14.7	12.3	
05N03771	76-89	Bt2	S											13.2	11.3	
05N03772	89-127	2B	S											15.0	12.3	

*** Primary Characterization Data ***

(Weber, Utah)

Pedon ID: S05UT057001

Print Date: Sep 17 2006 2:02PM

Sampled As :

USDA-NRCS-NSSC-National Soil Survey Laboratory ; Pedon No. 05N0632

Carbon & Extractions

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
				(- - - - - Total - - - - -)			Org	C/N	(- - - Dith-Cit Ext - - -)			(- - - - - - Ammonium Oxalate Extraction - - - - - -)						(- - - Na Pyro-Phosphate - - -)			
	Depth			C	N	S	C	Ratio	Fe	Al	Mn	Al+½Fe	ODOE	Fe	Al	Si	Mn	C	Fe	Al	Mn
Layer	(cm)	Horz	Prep	(- - - - - - % of <2 mm - - - - - -)					(- - - - - - - - - - - - - - - - - - - % of < 2mm - - - - - - - - - - - - - - - - -)								mg kg^{-1}	(- - - - - - % of < 2mm - - - - -)			
				4H2a	4H2a	4H2a			4G1	4G1	4G1		4G2a	4G2a	4G2a	4G2a	4G2a				
05N03768	0-10	A	S	2.90	0.336	0.03		9	0.5	0.1	0.1	0.28	0.15	0.22	0.17	0.01	1212.7				
05N03769	10-38	A	S	2.39	0.203	0.01		12	0.6	0.2	0.1	0.28	0.14	0.22	0.17	tr	1166.5				
05N03770	38-76	Bt1	S	1.65	0.155	tr		11	0.6	0.2	0.1	0.28	0.12	0.22	0.17	tr	1151.1				
05N03771	76-89	Bt2	S	0.83	0.100	--		8	0.7	0.1	0.1	0.22	0.07	0.18	0.13	--	773.3				
05N03772	89-127	2B	S	1.55	0.161	0.01		10	0.6	0.2	0.1	0.30	0.11	0.24	0.18	tr	1269.8				

CEC & Bases

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-
				(- - - - - - NH_4OAC Extractable Bases - - - - -)								CEC8	CEC7	ECEC		(- - - - Base - - - -)	
								Sum	Acid-	Extr	KCl	Sum	NH_4	Bases	Al	(- Saturation -)	
	Depth			Ca	Mg	Na	K	Bases	ity	Al	Mn	Cats	OAC	+Al	Sat	Sum	NH_4OAC
Layer	(cm)	Horz	Prep	(- - - - - - - - - - - - - - - - - cmol(+) kg^{-1} - - - - - - - - - - - - - - - - - - -)							mg kg^{-1}	(- - - - cmol(+) kg^{-1} - - -)			(- - - - - - - - % - - - - - - - -)		
				4B1a1a	4B1a1a	4B1a1a	4B1a1a		4B2b1a1				4B1a1a				
05N03768	0-10	A	S	13.3*	1.5	--	2.3	17.1	7.9			25.0	16.7			68	100
05N03769	10-38	A	S	10.5	1.3	--	2.0	13.8	7.7			21.5	14.0			64	99
05N03770	38-76	Bt1	S	8.1	0.9	--	1.3	10.3	8.9			19.2	11.9			54	87
05N03771	76-89	Bt2	S	5.1	0.7	--	0.3	6.1	7.5			13.6	8.4			45	73
05N03772	89-127	2B	S	7.1	0.8	--	0.5	8.4	9.7			18.1	11.3			46	74

*Extractable Ca may contain Ca from calcium carbonate or gypsum., CEC7 base saturation set to 100.

Salt				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-	-20-
				(- - - - Water Extracted From Saturated Paste - - - -)																	Pred		
																			Total	Elec	Elec	Exch	
	Depth			Ca	Mg	Na	K	CO_3	HCO_3	F	Cl	PO_4	Br	OAC	SO_4	NO_2	NO_3	H_2O	Salts	Cond	Cond	Na	SAR
Layer	(cm)	Horz	Prep	(- - - - mmol(+) L^{-1} - - - -)				(- - - - mmol(-) L^{-1} - - - -)										(- - - % - - -)		(- - dS m^{-1} - -)		%	
				4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2		4F2	4F1a1a1		
05N03768	0-10	A	S	2.0	0.6	--	3.1	--	2.2	tr	0.6	0.1	--	--	0.3	1.4	1.0	57.5	tr	0.70	0.31	--	--
05N03769	10-38	A	S																		0.22	--	
05N03770	38-76	Bt1	S																		0.13	--	
05N03771	76-89	Bt2	S																		0.04	--	
05N03772	89-127	2B	S																		0.10	--	

*** Primary Characterization Data ***

(Weber, Utah)

Pedon ID: S05UT057001

Print Date: Sep 17 2006 2:02PM

Sampled As :

USDA-NRCS-NSSC-National Soil Survey Laboratory ; Pedon No. 05N0632

pH & Carbonates				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-
				(- - - - pH - - - -)						(- - Carbonate - -)		(- - Gypsum - - -)		
					$CaCl_2$					As $CaCO_3$		As $CaSO_4$*$2H_2O$		Resist
	Depth				0.01M	H_2O	Sat			<2mm	<20mm	<2mm	<20mm	ohms
Layer	(cm)	Horz	Prep	KCl	1:2	1:1	Paste	Sulf	NaF	(- - - - % - - - -)				cm^{-1}
					4C1a2a	4C1a2a	4F2							
05N03768	0-10	A	S		5.9	6.3	6.4							
05N03769	10-38	A	S		5.8	6.5								
05N03770	38-76	Bt1	S		5.4	6.1								
05N03771	76-89	Bt2	S		5.3	6.0								
05N03772	89-127	2B	S		4.9	5.4								

Phosphorous

Layer	Depth (cm)	Horz	Prep	-1- Melanic Index	-2- NZ %	-3- Acid Oxal (mg kg^{-1}) 4G2a	-4- Bray 1 (mg kg^{-1})	-5- Bray 2 (mg kg^{-1})	-6- Olsen (mg kg^{-1})	-7- H_2O (mg kg^{-1})	-8- Citric Acid (mg kg^{-1})	-9- Mehlich III (mg kg^{-1}) 4D6a1	-10- Extr NO_3 mg kg^{-1}
05N03768	0-10	A	S			673.7						106.7	
05N03769	10-38	A	S			536.8						57.2	
05N03770	38-76	Bt1	S			565.3						47.3	
05N03771	76-89	Bt2	S			295.1						22.7	
05N03772	89-127	2B	S			489.9						31.3	

Clay Mineralogy (<.002 mm)

Layer	Depth (cm)	Horz	Fraction	-1- X-Ray 7A1a1 (peak size)	-2-	-3-	-4-	-5- Thermal (%)	-6-	-7-	-8-	-9-	-10- Elemental SiO_2 (%)	-11- Al_2O_3	-12- Fe_2O_3	-13- MgO	-14- CaO	-15- K_2O	-16- Na_2O	-17- EGME Retn mg g^{-1}	-18- Interpretation
05N03768	0-10	A	tcly	KK 3	MI 2	QZ 2	VR 1														CMIX
05N03770	38-76	Bt1	tcly	KK 3	MI 2	QZ 2	VR 1														CMIX

FRACTION INTERPRETATION:

tcly - Total Clay, <0.002 mm

MINERAL INTERPRETATION:

KK - Kaolinite   MI - Mica   QZ - Quartz   VR - Vermiculite

RELATIVE PEAK SIZE: 5 Very Large   4 Large   3 Medium   2 Small   1 Very Small   6 No Peaks

INTERPRETATION (BY HORIZON):

CMIX - Mixed Clay

Block 2 Conifer Pedon Description

Print Date: 07/07/2006	Country: United States
Description Date: 06/22/2005	State: Utah
Describer: MI, Woldesela	County: Weber
Site ID: 05UT057002	MLRA: 47 -- Wasatch and Uinta Mountains
Site Note:	Soil Survey Area:
Pedon ID: 05UT057002	Map Unit:
Pedon Note: Land cover includes aspen and timber. There was also some litter present.	Quad Name:
Lab Source ID: SSL	Location Description: Lightning Ridge SNOTEL Site #2. Across east fork. Wasatch Mountains. Cache National Forest. Horse Ridge topo quad. Soil Survey Number S05UT 057 002.
Lab Pedon #: 05N0633	Legal Description:
Soil Name as Described/Sampled: SND	Latitude: 41 degrees 35 minutes north
Soil Name as Correlated:	Longitude: 111 degrees 47 minutes west
Classification:	Datum: NAD83
Pedon Type:	UTM Zone:
Pedon Purpose:	UTM Easting:
Taxon Kind:	UTM Northing:
Associated Soils:	
Physiographic Division:	Primary Earth Cover: Tree cover
Physiographic Province:	Secondary Earth Cover:
Physiographic Section:	Existing Vegetation:
State Physiographic Area:	Parent Material: colluvium derived from limestone
Local Physiographic Area:	Bedrock Kind:
Geomorphic Setting: on backslope of side slope of None Assigned	Bedrock Depth:
Upslope Shape: linear	Bedrock Hardness:
Cross Slope Shape: convex	Bedrock Fracture Interval:
Particle Size Control Section:	Surface Fragments:
Diagnostic Features: ? to ? cm.	

Cont. Site ID: 05UT057002

Pedon ID: 05UT057002

Slope (%)	Elevation (meters)	Aspect (deg)	MAAT (C)	MSAT (C)	MWAT (C)	MAP (mm)	Frost-Free Days	Drainage Class	Slope Length (meters)	Upslope Length (meters)
13.0	2,514.6	270						well		

A1--0 to 18 centimeters; dark reddish brown (5YR 3/3) loam, brown (10YR 4/3), dry; weak fine granular structure; friable, nonsticky, nonplastic; many fine roots; many fine vesicular pores; gradual boundary. Lab sample # 05N03773

A2--18 to 36 centimeters; dark reddish brown (5YR 3/3) loam, brown (7.5YR 4/2), dry; weak medium granular structure; friable, nonsticky, nonplastic; many very fine and fine roots; many fine vesicular pores; gradual boundary. Lab sample # 05N03774

A3--36 to 58 centimeters; dark reddish brown (5YR 3/3) loam, brown (7.5YR 5/3), dry; weak medium granular structure; friable, nonsticky, nonplastic; many very coarse roots; many fine vesicular pores; 10 percent organic stains; gradual boundary. Lab sample # 05N03775

Bt1--58 to 114 centimeters; dark red (2.5YR 3/6) clay loam, yellowish red (5YR 5/6), dry; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine roots; many fine vesicular pores; 10 percent organic stains; abrupt boundary. Lab sample # 05N03776

*** Primary Characterization Data ***

(Weber, Utah)

Pedon ID: S05UT057002

Print Date: Sep 17 2006 1:42PM

Sampled as :

Revised to :

SSL - Project C2005USUT134 Climate Monitoring Station SNOTEL/SCAN
- Site ID 05UT057002 Lat: 41° 21' 58.60" north Long: 111° 27' 27.00" west NAD83 MLRA: 47
- Pedon No. 05N0633
- General Methods 1B1A, 2A1, 2B

United States Department of Agriculture
Natural Resources Conservation Service
National Soil Survey Center
Soil Survey Laboratory
Lincoln, Nebraska 68508-3866

Layer	Horizon	Orig Hzn	Depth (cm)	Field Label 1	Field Label 2	Field Label 3	Field Texture	Lab Texture
05N03773			0-18	S05UT-002-1	1			SIL
05N03774			18-36	S05UT-002-2	2			L
05N03775			36-58	S05UT-002-3	3			L
05N03776			58-114	S05UT-002-4	4			L

Pedon Calculations

Calculation Name	Result	Units of Measure
Weighted Particles, 0.1-75mm, 75 mm Base		% wt
Volume, >2mm, Weighted Average		% vol
Clay, total, Weighted Average	20	% wt
Clay, carbonate free, Weighted Average	20	% wt
CEC Activity, CEC7/Clay, Weighted Average, CECd, Set 1	0.5	(NA)
LE, Whole Soil, Summed to 1m	2	cm/m

PSDA & Rock Fragments

Layer	Depth (cm)	Horz	Prep	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-
				(- - - - - Total - - - - - -)			(- - Clay - - -)		(- - - - Silt - - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)					(Rock Fragments (mm))				
				Clay	Silt	Sand	Fine	CO_3	Fine	Coarse	VF	F	M	C	VC	(- - - - - - - - Weight - - - - - - - -)				>2 mm
				<	.002	.05	<	<	.002	.02	.05	.10	.25	.5	1	2	5	20	.1-	wt %
	Depth			.002	-.05	-2	.0002	.002	-.02	-.05	-.10	-.25	-.50	-1	-2	-5	-20	-75	75	whole
Layer	(cm)	Horz	Prep	(- % of <2mm Mineral Soil -)												(- - - - - - - % of <75mm - - - - - -)				soil
				3A1a1a					3A1a1a		3A1a1a	3A1a1a	3A1a1a	3A1a1a	3A1a1a					
05N03773	0-18		S	17.1	50.0	32.9			25.2	24.8	12.8	13.2	5.8	1.0	0.1	1	tr	--	21	1
05N03774	18-36		S	16.8	49.6	33.6			24.7	24.9	14.2	12.3	6.3	0.8	--	1	tr	--	20	1
05N03775	36-58		S	15.0	48.5	36.5			24.0	24.5	13.5	15.3	6.7	0.9	0.1	tr	--	1	24	1
05N03776	58-114		S	24.6	46.2	29.2			28.1	18.1	10.0	11.4	6.8	0.8	0.2	tr	tr	--	19	tr

*** Primary Characterization Data ***

(Weber, Utah)

Pedon ID: S05UT057002

Print Date: Sep 17 2006 1:42PM

Sampled As :

USDA-NRCS-NSSC-National Soil Survey Laboratory ; Pedon No. 05N0633

Water Dispersible PSDA

Layer	Depth (cm)	Horz	Prep	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-
				(- Water Dispersible -)											
				(- - - - - Total - - - - - -)			(- - Clay - - -)		(- - - - Silt - - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)				
				Clay	Silt	Sand	F	CO_3	F	C	VF	F	M	C	VC
				<	.002	.05	<	<	.002	.02	.05	.10	.25	.5	1
	Depth			.002	-.05	-2	.0002	.002	-.02	-.05	-.10	-.25	-.50	-1	-2
Layer	(cm)	Horz	Prep	(- % of <2mm -)											
				3A1a6a					3A1a6a		3A1a6a	3A1a6a	3A1a6a	3A1a6a	3A1a6a
05N03773	0-18		S	6.7	51.9	41.4			28.5	23.4	12.7	18.6	7.9	1.9	0.3
05N03774	18-36		S	7.4	53.0	39.6			28.7	24.3	14.5	15.9	7.6	1.3	0.3

Bulk Density & Moisture				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-
				(Bulk Density)		Cole	(- - - - - - - - - - Water Content - - - - - - - - - -)						WRD	Aggst		
				33	Oven	Whole	6	10	33	1500	1500 kPa	Ratio	Whole	Stabl	(- - Ratio/Clay - -)	
	Depth			kPa	Dry	Soil	kPa	kPa	kPa	kPa	Moist	AD/OD	Soil	2-0.5mm	CEC7	1500 kPa
Layer	(cm)	Horz	Prep	(- - - g cm^{-3} - - -)			(- - - - - - - - - - - % of < 2mm - - - - - - - - - - -)						cm^3 cm^{-3}	%		
				DbWR1	DbWR1		DbWR1	DbWR1	DbWR1	3C2a1a		3D1		3F1a1a		
05N03773	0-18		S	0.99	1.06	0.023	32.8	30.5	28.0	10.3		1.026	0.18	52	0.90	0.60
05N03774	18-36		S	1.10	1.13	0.009	31.8	29.9	25.8	9.0		1.021	0.18	41	0.77	0.54
05N03775	36-58		S	1.31	1.44	0.032	25.1	23.2	21.6	7.4		1.015	0.19		0.61	0.49
05N03776	58-114		S	1.68	1.77	0.018	17.4	16.4	15.2	9.0		1.012	0.10		0.23	0.37

Water Content				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-
				(- - Atterberg - -)		(- - - - - Bulk Density - - - - -)			(- Water Content -)							
				(- - - Limits - - -)		Field	Recon	Recon	Field	Recon	(- - - - - - - - - - - - - Sieved Samples - - - - - - - - - - - -)					
				LL	PI		33	Oven		33	6	10	33	100	200	500
	Depth						kPa	Dry		kPa	kPa	kPa	kPa	kPa	kPa	kPa
Layer	(cm)	Horz	Prep	pct <0.4mm		(- - - - - - - - g cm^{-3} - - - - - - -)			(- % of < 2mm -)							
														3C1d1a	3C1e1a	
05N03773	0-18		S											19.1	15.8	
05N03774	18-36		S											18.1	14.9	
05N03775	36-58		S											15.8	12.8	
05N03776	58-114		S											16.5	14.5	

Pedon ID: S05UT057002

*** Primary Characterization Data ***

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Carbon & Extractions

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
				(- - - - - Total - - - - -)			Org	C/N	(- - - Dith-Cit Ext - - -)			(- - - - - - Ammonium Oxalate Extraction - - - - - -)						(- - - Na Pyro-Phosphate - - -)			
	Depth			C	N	S	C	Ratio	Fe	Al	Mn	Al+½Fe	ODOE	Fe	Al	Si	Mn	C	Fe	Al	Mn
Layer	(cm)	Horz	Prep	(- - - - - - % of <2 mm - - - - - -)					(- - - - - - - - - - - - - - - - - - - % of < 2mm - - - - - - - - - - - - - - - - - -)								mg kg^{-1}	(- - - - - - % of < 2mm - - - - -)			
				4H2a	4H2a	4H2a			4G1	4G1	4G1		4G2a	4G2a	4G2a	4G2a	4G2a				
05N03773	0-18		S	3.24	0.299	0.01		11	0.8	0.1	0.1	0.22	0.17	0.16	0.14	--	566.2				
05N03774	18-36		S	2.32	0.233	0.01		10	0.8	0.1	0.1	0.21	0.17	0.16	0.13	--	559.8				
05N03775	36-58		S	1.22	0.102	--		12	0.7	0.1	0.1	0.20	0.12	0.15	0.13	--	519.2				
05N03776	58-114		S	0.33	0.086	--		4	1.6	0.1	tr	0.09	0.04	0.06	0.06	--	333.2				

CEC & Bases

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-
				(- - - - - - NH_4OAC Extractable Bases - - - - -)								CEC8	CEC7	ECEC		(- - - - Base - - - -)	
								Sum	Acid-	Extr	KCl	Sum	NH_4	Bases	Al	(- Saturation -)	
	Depth			Ca	Mg	Na	K	Bases	ity	Al	Mn	Cats	OAC	+Al	Sat	Sum	NH_4OAC
Layer	(cm)	Horz	Prep	(- - - - - - - - - - - - - - - - - cmol(+) kg^{-1} - - - - - - - - - - - - - - - - - - -)							mg kg^{-1}	(- - - - cmol(+) kg^{-1} - - -)			(- - - - - - - - % - - - - - - - -)		
				4B1a1a	4B1a1a	4B1a1a	4B1a1a		4B2b1a1				4B1a1a				
05N03773	0-18		S	13.0*	1.6	--	0.9	15.5	9.2			24.7	15.4			63	100
05N03774	18-36		S	10.6	1.1	--	0.7	12.4	8.7			21.1	13.0			59	95
05N03775	36-58		S	6.9	0.6	--	0.3	7.8	6.4			14.2	9.2			55	85
05N03776	58-114		S	4.5	0.4	--	0.1	5.0	3.6			8.6	5.7			58	88

*Extractable Ca may contain Ca from calcium carbonate or gypsum., CEC7 base saturation set to 100.

Salt				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-	-20-
				(- - - Water Extracted From Saturated Paste - - -)																	Pred		
																			Total	Elec	Elec	Exch	
	Depth			Ca	Mg	Na	K	CO_3	HCO_3	F	Cl	PO_4	Br	OAC	SO_4	NO_2	NO_3	H_2O	Salts	Cond	Cond	Na	SAR
Layer	(cm)	Horz	Prep	(- - mmol(+) L^{-1} - -)				(- - - mmol(-) L^{-1} - - -)										(- - % - -)		(- - dS m^{-1} - -)		%	
				4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2	4F2		4F2	4F1a1a1		
05N03773	0-18		S	3.1	1.1	--	1.1	--	2.6	tr	0.3	tr	--	--	0.4	0.8	0.9	62.1	tr	0.61	0.32	--	--
05N03774	18-36		S																		0.19	--	
05N03775	36-58		S																		0.06	--	
05N03776	58-114		S																		0.03	--	

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pH & Carbonates				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-
				(- - - pH - - -)						(- - Carbonate - -)		(- - Gypsum - - -)		
					$CaCl_2$					As $CaCO_3$		As $CaSO_4$*$2H_2O$		Resist
	Depth				0.01M	H_2O	Sat			<2mm	<20mm	<2mm	<20mm	ohms
Layer	(cm)	Horz	Prep	KCl	1:2	1:1	Paste	Sulf	NaF	(- - - % - - -)				cm^{-1}
					4C1a2a	4C1a2a	4F2							
05N03773	0-18		S		5.7	6.1	6.2							
05N03774	18-36		S		5.4	5.8								
05N03775	36-58		S		5.3	6.1								
05N03776	58-114		S		5.3	6.0								

Phosphorous

Layer	Depth (cm)	Horz	Prep	-1- Melanic Index	-2- NZ %	-3- Phosphorous: Acid Oxal (mg kg-1) 4G2a	-4- Bray 1 (mg kg-1)	-5- Bray 2 (mg kg-1)	-6- Olsen (mg kg-1)	-7- H_2O (mg kg-1)	-8- Citric Acid (mg kg-1)	-9- Mehlich III (mg kg-1) 4D6a1	-10- Extr NO_3 mg kg-1
05N03773	0-18		S			637.0						108.0	
05N03774	18-36		S			631.1						96.2	
05N03775	36-58		S			540.0						109.4	
05N03776	58-114		S			212.0						47.9	

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Clay Mineralogy (<.002 mm)

Layer	Depth (cm)	Horz	Fraction	-1- X-Ray 7A1a1 (peak size)	-2-	-3-	-4-	-5-	-6- Thermal (%)	-7-	-8-	-9-	-10- Elemental SiO_2 (%)	-11- Al_2O_3	-12- Fe_2O_3	-13- MgO	-14- CaO	-15- K_2O	-16- Na_2O	-17- EGME Retn mg g-1	-18- Interpretation
05N03773	0-18		tcly	KK 3	MI 2	QZ 1	VR 1														CMIX
05N03776	58-114		tcly	KK 3	MI 3	QZ 1	VR 1	GE 1													CMIX
				HE 1	FK 1	FP 1															

FRACTION INTERPRETATION:

tcly - Total Clay, <0.002 mm

MINERAL INTERPRETATION:

FK - Potassium Feldspar	FP - Plagioclase Feldspar	GE - Goethite	HE - Hematite	KK - Kaolinite
MI - Mica	QZ - Quartz	VR - Vermiculite		

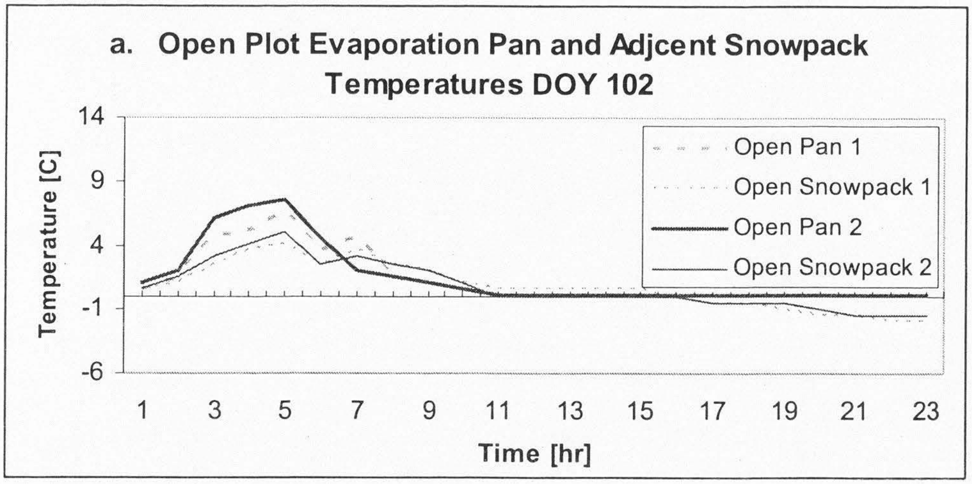
RELATIVE PEAK SIZE: 5 Very Large 4 Large 3 Medium 2 Small 1 Very Small 6 No Peaks

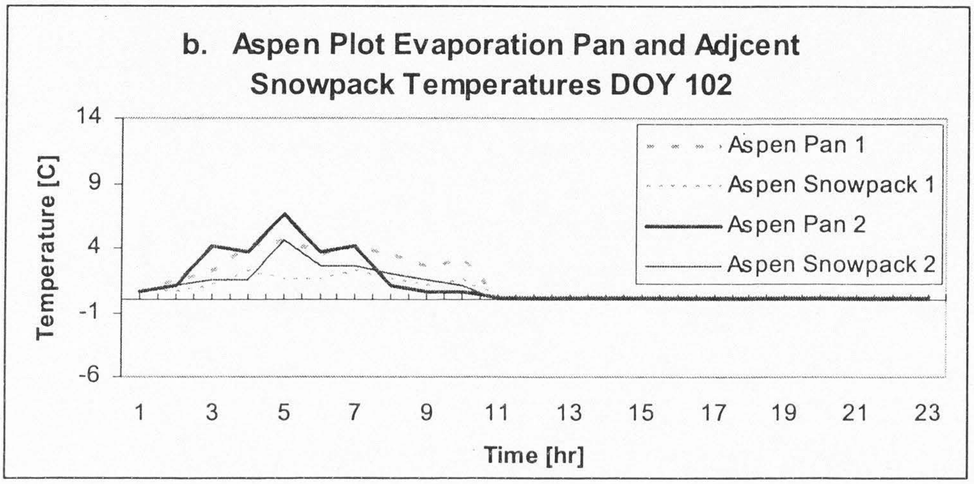
INTERPRETATION (BY HORIZON):

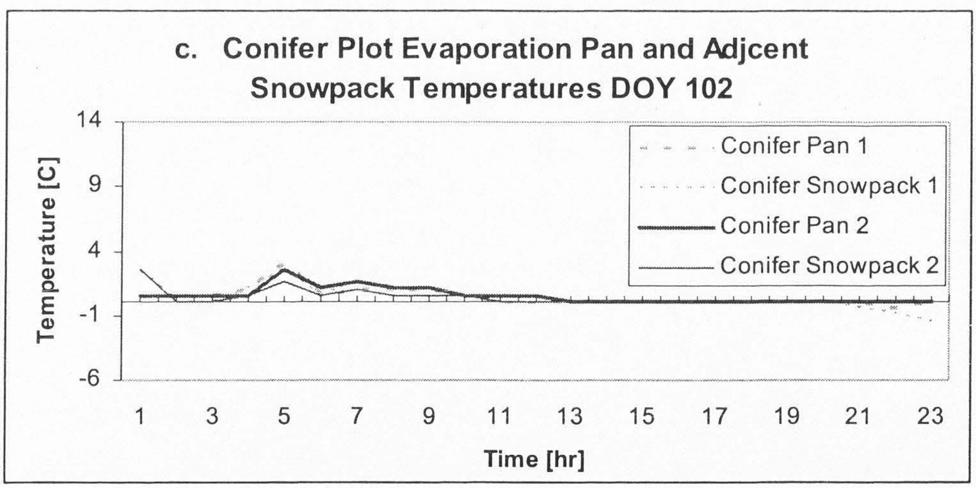
CMIX - Mixed Clay

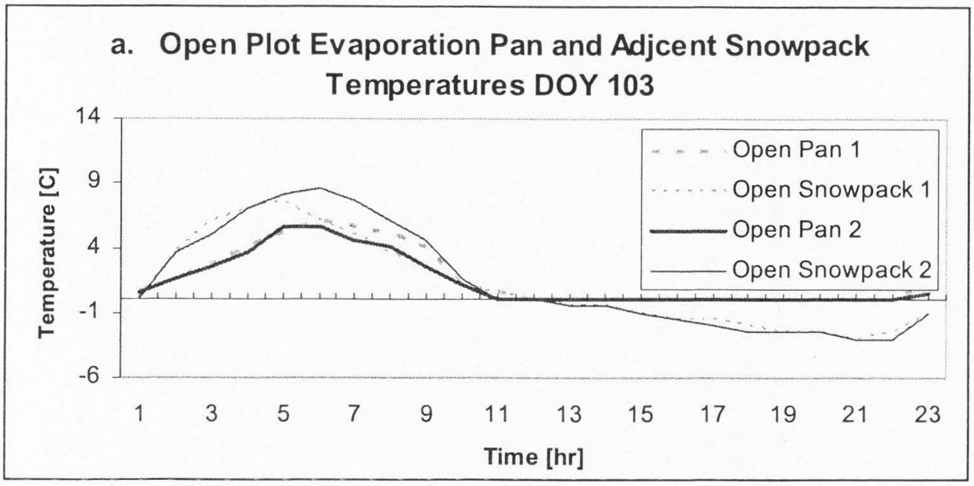
APPENDIX D

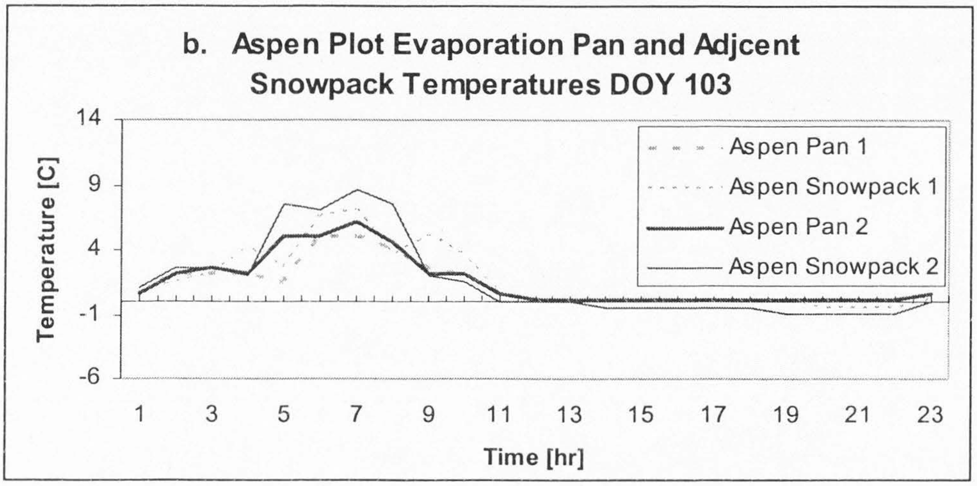
Evaporation Pan Temperature Measurements

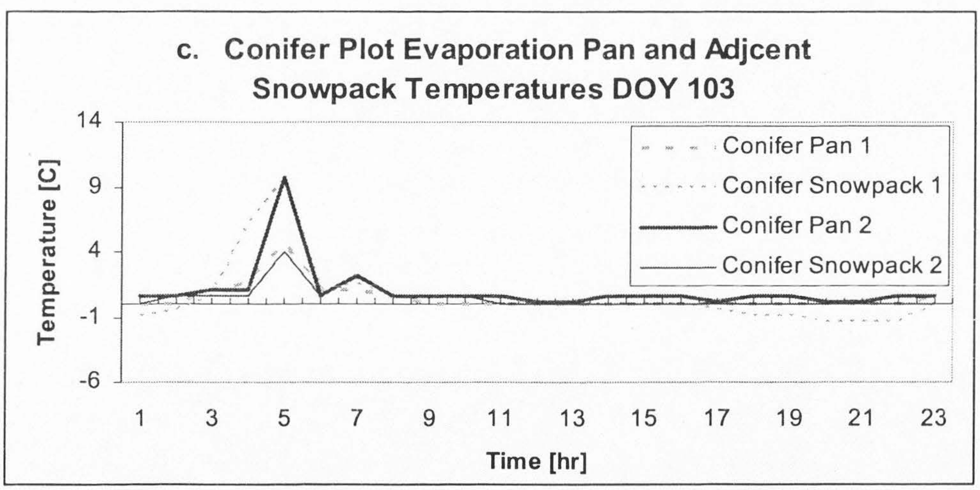

a. Open Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 102
Temperature [C]
14
9
4
-1
-6
Open Pan 1
Open Snowpack 1
Open Pan 2
Open Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]

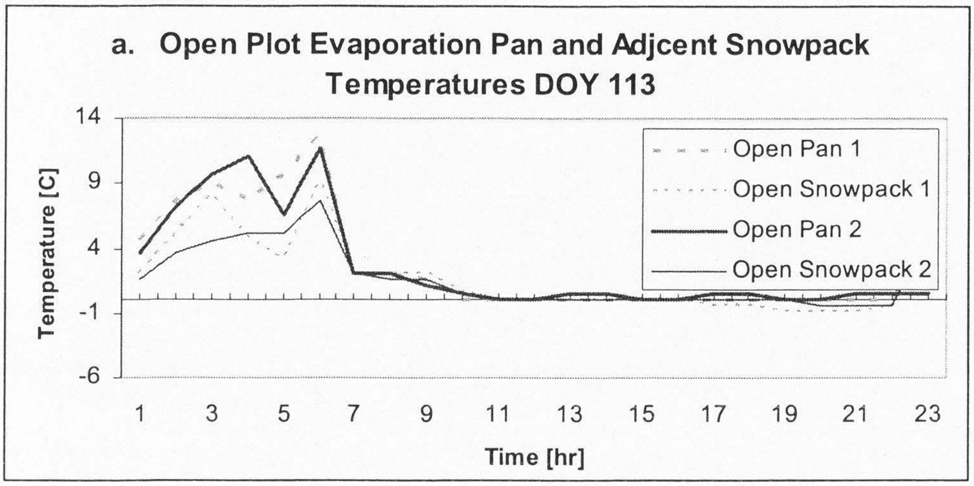

b. Aspen Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 102
Temperature [C]
14
9
4
-1
-6
Aspen Pan 1
Aspen Snowpack 1
Aspen Pan 2
Aspen Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]

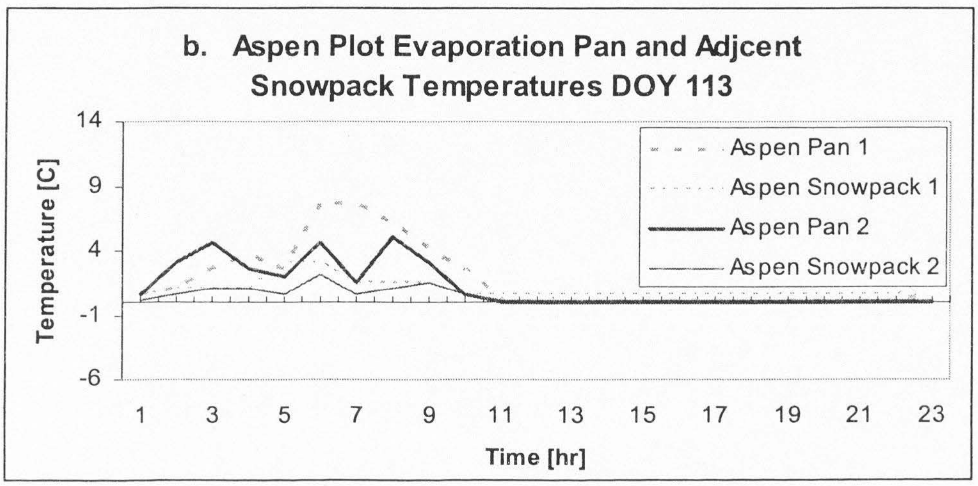

c. Conifer Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 102
Temperature [C]
14
9
4
-1
-6
Conifer Pan 1
Conifer Snowpack 1
Conifer Pan 2
Conifer Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]

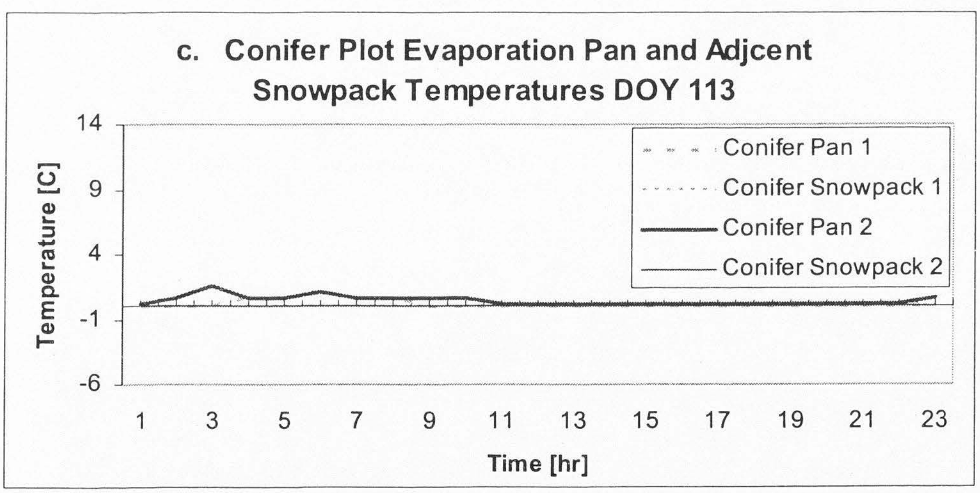

a. Open Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 103
Temperature [C]
14
9
4
-1
-6
Open Pan 1
Open Snowpack 1
Open Pan 2
Open Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]

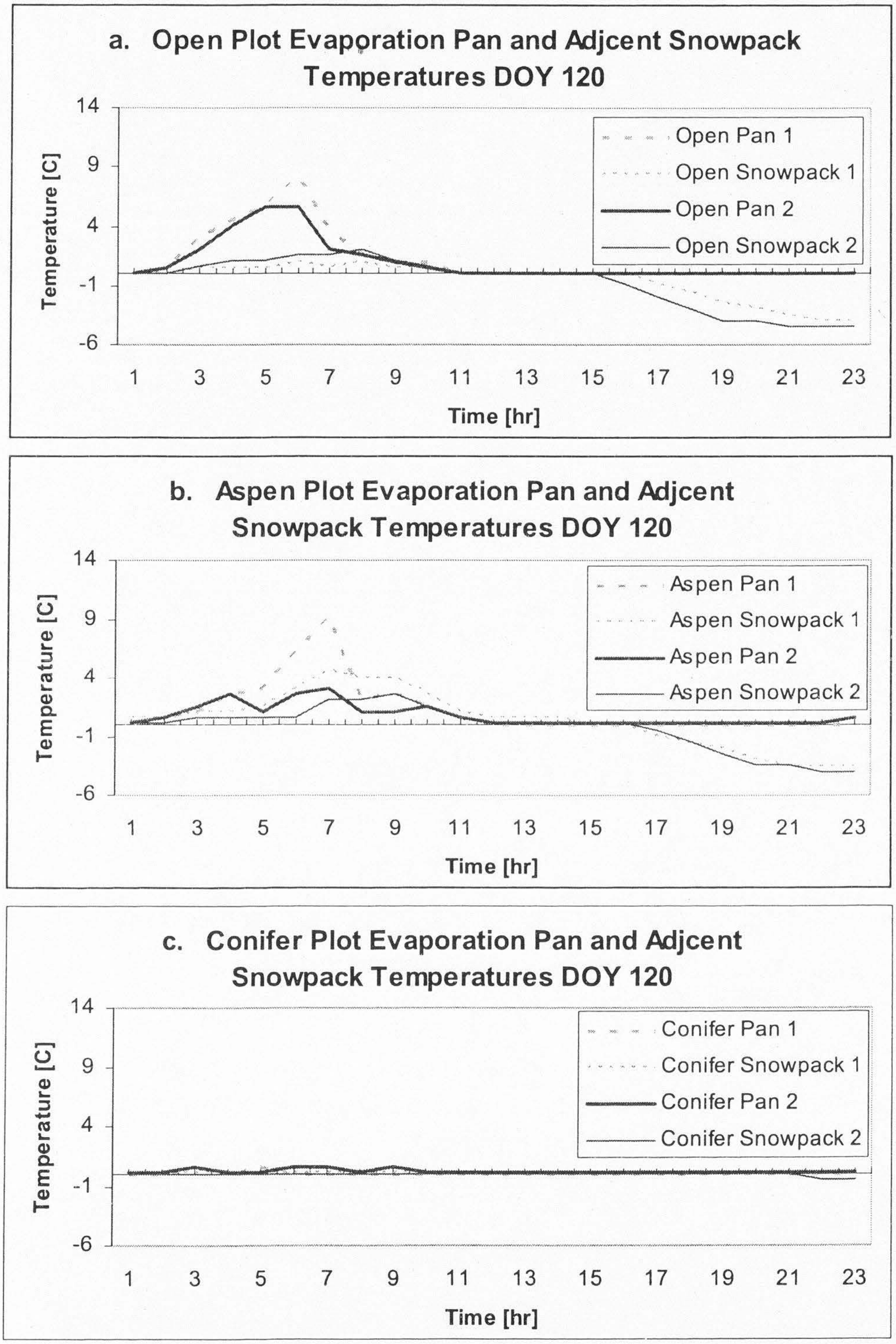

b. Aspen Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 103
Temperature [C]
14
9
4
-1
-6
Aspen Pan 1
Aspen Snowpack 1
Aspen Pan 2
Aspen Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]


c. Conifer Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 103
Temperature [C]
14
9
4
-1
-6
Conifer Pan 1
Conifer Snowpack 1
Conifer Pan 2
Conifer Snowpack 2
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]


a. Open Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 113
Temperature [C]
14
9
4
-1
-6
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]
Open Pan 1
Open Snowpack 1
Open Pan 2
Open Snowpack 2


b. Aspen Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 113
Temperature [C]
14
9
4
-1
-6
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]
Aspen Pan 1
Aspen Snowpack 1
Aspen Pan 2
Aspen Snowpack 2


c. Conifer Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 113
Temperature [C]
14
9
4
-1
-6
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]
Conifer Pan 1
Conifer Snowpack 1
Conifer Pan 2
Conifer Snowpack 2


a. Open Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 120
Temperature [C]
14
9
4
-1
-6
1 3 5 7 9 11 13 15 17 19 21 23
Time [hr]
Open Pan 1
Open Snowpack 1
Open Pan 2
Open Snowpack 2
b. Aspen Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 120
Aspen Pan 1
Aspen Snowpack 1
Aspen Pan 2
Aspen Snowpack 2
c. Conifer Plot Evaporation Pan and Adjcent Snowpack Temperatures DOY 120
Conifer Pan 1
Conifer Snowpack 1
Conifer Pan 2
Conifer Snowpack 2