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Measurement of Differences in Snow Accumulation, Melt, and Micrometeorology Due to Forest Harvesting

Abstract

Previous studies in the Pacific Northwest have suggested a link between forest logging and increased streamflows. We present a brief overview of previous experimental efforts designed to identify mechanisms for these increases, especially during rain-on-snow (ROS) and spring snowmelt events. To extend the applicability of these data, we describe our measurement of snow accumulation, melt, and micrometeorology in existing uncut forest and shelterwood units as part of the Demonstration of Ecosystem Management Options (DEMO) study. Uncut forest units are dominated by over 100-year-old Douglas-fir (*Pseudotsuga menziesii*) with stand basal areas of ca. 40 m^2/ha. Micrometeorology is measured 2 m above the ground surface in each 13-ha unit. Snow accumulation and melt are measured via weekly snow courses. Snowpack outflow is obtained from two 2.6 m^2 non-weighing snow lysimeters in each unit. Large (25 m^2) weighing lysimeters provide a continuous record of snowpack evolution at scales unaffected by variability in canopy throughfall. Snow interception is measured by continuous weighing of cut trees. Harvest treatments will be imposed during summer 1998 and additional post-harvest data will be collected. Pre-harvest data indicate up to 60% greater (33 mm) 3-day production of runoff and 150% greater (22 mm) 3-day snowmelt (outflow minus throughfall) in the shelterwood than in the uncut forest unit during ROS events. Snowmelt during radiation-dominated spring events is ca. 50% greater (15 mm) in the shelterwood. Results from the weighing lysimeters show high correlation with snow course data from the shelterwood but poor correlation with those from the uncut forest due to small scale spatial variability in tree canopy cover.

Introduction

In recent years, attention to floods during rain-on-snow events has increased. During the winters of 1986, 1990, and 1995-97, the major rivers draining the western Cascade Mountains of Washington and Oregon experienced flooding events with estimated return periods that exceeded 100 years in some watersheds. These events have lead to a widespread perception that the frequency and severity of extreme floods in the Pacific Northwest have increased. Although these perceived increases may be due to climate variability, which has brought an end to the mild, relatively dry winters of the 1970s and 1980s, attention has nevertheless been focused on possible causal links with land use changes, including forest harvesting. Although the connection between forest harvest and increased peak streamflow has only recently gained the attention of the media and the general public, the problem has long been debated in the scientific literature (e.g., Anderson and Hobba 1959; Rothacher 1973; Harr and McCorison 1979; Harr 1981, 1986; Christner and Harr 1982; Jones and Grant 1996).

Anderson and Hobba (1959) appear to be the first to argue that the size of peak flows in western Oregon had been increased by logging. Despite considerable research on snow hydrology in the intermountain west and the Sierra Nevada (where snowmelt is dominated by radiation), the issue of logging effects on snow hydrology in the Pacific Northwest was largely ignored until the 1980s. Building on the work of the USACE (1956), Harr (1981) hypothesized that clearcut logging would increase convective heat transfer to the snowpack and thereby enhance snowmelt rates, especially during rain-on-snow (ROS) events. Through a reanalysis of previous work (Rothacher 1973, Harr and McCorison 1979) in which no effects were detected, Harr (1986) found that peaks in streamflow during ROS events increased significantly due to clearcutting. Christner and Harr (1982) also found evidence for an increase in ROS-induced peak streamflows in an analysis of paired watersheds in the central Oregon Cascades (see also Jones and Grant 1996). Although these studies offer considerable evidence for the effects of forest harvesting on streamflows within a small watershed, they only suggest possible mechanisms for the increase.

Subsequently, in the transient snow zone of the western Oregon Cascades, a series of plot-scale studies (i.e., at the scale of several trees) demonstrated that snow accumulation can be significantly enhanced in clearcut areas (Berris 1984, Berris and Harr 1987). However, in three of five ROS events more snowpack outflow was observed under the forest canopy than in the clearcut. In the remaining two events, the increase in clearcut snowmelt can arguably be attributed to more antecedent snow in the clearcut and not to higher melt rates during the event. Unfortunately, the relatively small area of the snow lysimeters (2.0 m^2) precluded accurate estimation of snowpack outflow underneath the forest canopy for any of the events.

Equivocal results were also obtained from studies in the coastal mountains of British Columbia (Beaudry and Golding 1983). Outflow from two small snowmelt lysimeters with a combined area of 0.9 m^2 had almost no correlation with weekly snow course data. In contrast, large lysimeters (28 m^2) indicated that total runoff from the clearcut snowpack was increased by 10% during heavy rain (194 mm rainfall in 1.5 days) and by up to 19% for smaller events. In two of three events, differences in outflow can be attributed to both differences in melt rates and antecedent snow accumulation.

Recognizing the limitation in design and the small sample size of previous studies, a second more extensive plot-scale study was undertaken in the transient snow zone of northwestern Washington (Coffin and Harr 1992). Unfortunately, a series of logistical and design problems combined with unseasonably cold weather made comparisons among treatments (clearcut versus uncut forest) questionable for the majority of observed ROS events. During four ROS events in which the sample size under the mature canopy was sufficient, 12-44% greater runoff in the clearcut was arguably due to both increased melt rates and greater antecedent snow accumulation.

Combined, these studies present considerable evidence that removal of the forest canopy increases snow accumulation and melt by influencing the moisture and energy fluxes from the forest canopy to the forest floor. Snow is intercepted by the forest canopy and can be subsequently sublimated, melted or released (as snow) off the canopy (e.g., Miller 1962, Satterlund and Haupt 1970). While sublimation represents a direct loss from the soil-snow system, drip of melt-water from the canopy is either stored by the snowpack or routed directly to the soil (depending on the snowpack temperature and liquid water content). Snow released from the canopy adds directly to the water equivalent of the snowpack.

Melt of the ground snowpack is affected by removal of the canopy through the following mechanisms. The canopy greatly attenuates short-wave radiation to the ground surface while enhancing long-wave radiation transfer (e.g., Black et al. 1991). Short-wave radiation absorbed by the canopy is re-radiated to the snowpack as long-wave radiation. Furthermore, the canopy serves to shelter the snowpack from turbulent exchanges of latent and sensible heat which depend directly on windspeed and the near surface gradients of temperature and humidity. During events in which short-wave radiation and turbulent energy fluxes prevail, canopy removal enhances snowmelt. However, the canopy can also hasten snowpack outflow. Because intercepted snow melts rapidly in the transient snow zone, snowpacks under a forest canopy tend to be shallower with higher liquid water contents. Therefore, they can release meltwater or rainfall sooner than snowpacks in clearings (e.g., Berris and Harr 1987)

Given the complex interaction of the forest canopy with meteorological conditions and the transient nature of snow accumulation on and under the forest canopy, previous studies have provided only limited information relevant to a quantitative model of snow accumulation and melt under forest canopies (e.g., van Heeswijk et al. 1996). Snowpack outflow during melt events is influenced by antecedent snow accumulation on the ground, antecedent snow storage in the forest canopy, and the micrometeorological conditions. Therefore, additional studies are needed to more completely characterize the full range of expected differences between harvested and uncut forest sites.

Previous studies that compare clearcut and uncut forests are also of limited value in that current harvest practices have become more diverse and now include a range of levels and patterns of retention of live trees (i.e., green-tree retention). Thus, the effect of canopy density on snow accumulation and melt has become an important question. Currently, variation in forest canopy cover is largely ignored in determining the hydrological effects of logging. For example, the Washington State watershed analysis procedure (WFPB 1994) utilizes an overly simple model for predicting snowmelt during ROS events which assumes that wind speed is a linear function of canopy coverage. Because canopy coverage is based solely on stand maturity, hydrologic impacts of partial harvests are not considered. This limitation is not surprising considering the lack of data relating partial harvest to expected snowmelt production in the Pacific Northwest.

Recently, more advanced, quantitative models have used an energy-balance approach to predict snowmelt given a set of micrometeorological variables and antecedent snowpack conditions (Anderson 1976, Marks and Dozier 1992, Yamazaki and Kondo 1992, Wigmosta et al. 1994). However, under-canopy snowmelt and micrometeorological data of sufficient high quality necessary for model validation have been unavailable in the Pacific Northwest (van Heeswijk et al. 1996). A further limitation of these models is that they largely ignore the effect of the canopy on snow accumulation. Unless antecedent conditions can be described, their value as a predictive tool is limited.

Objectives

To address the limitations and expand the applicability of previous data, we have been evaluating changes in snow accumulation and snowmelt in response to partial retention harvests within the context of the Demonstration of Ecosystem Management Options (DEMO) study (Aubry et al. 1999). To review, at each of eight study blocks in western Washington and Oregon, five harvest treatments and a control have been randomly assigned to 13-ha experimental units. Treatments represent retention of green trees at varying levels (15-100% of original basal area) and patterns (trees uniformly dispersed vs. aggregated in 1-ha patches) (Aubry et al. 1999). The specific objectives of the snow hydrology studies are to:

(1) Determine the differences in accumulation of snow under varying levels and patterns of green-tree retention,

(2) Identify differences in outflow rates among treatments during rain-on-snow events,

(3) Identify differences in melt rates during spring radiation-dominated events,

(4) Measure the differences in wind, temperature, humidity, radiation, and turbulent heat exchange among treatments, and

(5) Provide data to improve existing models of snow accumulation and snowmelt at both point (single tree) and stand-level (13-ha treatments) scales of resolution.

Each season of data collection strives to provide a continuous record of near-surface micrometeorology and snowpack outflow at several points in each unit while providing weekly data on snow accumulation over the entire unit. Objective 1 relies on snow course data taken over the 13-ha treatment unit. Point observations of micrometeorology and snowpack outflow support Objectives 2-4. Objective 5 can be satisfied by calibrating a snow accumulation and snowmelt model to point measurements and validating against data over the entire unit. The degree to which alteration of physically measurable parameters such as canopy coverage fraction can explain differences between point observations of melt and areal observations of accumulation will directly test the scalability of such a model.

Micrometeorological and snow data have been collected in uncut, pre-treatment forests and in adjacent shelterwood stands (forest thinned to very wide spacings) at one of the eight experimental blocks, Watson Falls, Oregon. Due to the large number of treatments, the sample size and frequency of the current experimental design are limited. The expense of collecting detailed meteorological and outflow data limits us to one micrometeorology station and four lysimeters per treatment unit. Snow course data are collected weekly. Harvest treatments will be completed during summer 1998 and each harvest unit will then be instrumented with four lysimeters and one micrometeorological station. Three years of post-harvest data will be collected to quantify the effects of varying levels and patterns of canopy retention.

Given the limitation on sampling within each unit and the lack of treatment replication, we may be unable to make definitive statements about the significance of specific treatments on snow accumulation and snowmelt. Although we can detect differences in outflow from an uncut mature forest and a shelterwood (see Results and Discussion), more subtle differences (as would be expected between a 40 and 75% retention harvest) may be undetectable (or insignificant) given our small sample size. Furthermore, the lack of treatment replication (in the snow hydrology study) limits the applicability of findings to the specific units studied. Although the treatment units were selected to be as similar as possible, the lack of replication makes it impossible to differentiate treatment effects from other site level differences (e.g., aspect, exposure to prevailing winds). A true test of treatment effects will require data from replicated samples.

In the following sections we briefly describe the study sites and detail the data collection method. We then present a brief comparison of data from the pre-harvest DEMO units and adjacent shelterwoods. Finally, we describe additional data collection efforts aimed at quantifying process-level controls on snow accumulation and melt (e.g., canopy interception) and the preliminary results of this work.

Methods

Site Description

The study sites are located northwest of Crater Lake, Oregon in the Umpqua National Forest (Figure 1) (see also Aubry et al. 1999). Three DEMO treatment units (2, 5, and 6) are located at 900 m elevation and two (1 and 4) at 1200 m. An additional control treatment (7) is sampled at the low elevation site. Unit 3 (not shown in Figure 1) is not utilized due to difficulties with winter access. To provide a more extensive period during which snow accumulation and melt could be compared between uncut and harvested sites, an additional shelterwood was selected in each elevation band (units 8 and 9).

Pretreatment forest stands range in age form 110-130 years. The canopy is dominated by Douglas-fir (*Pseudotsuga menziesii*) although

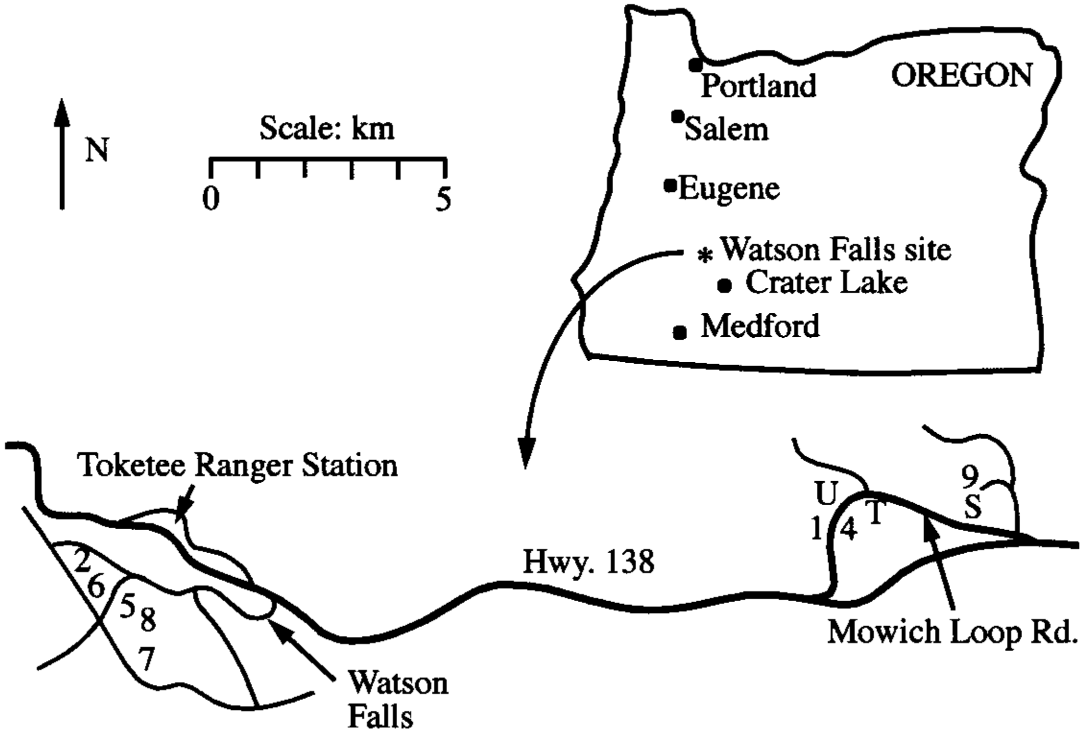

Figure 1. Locations of DEMO green-tree retention units (1, 2, 4-6), other non-experimental units (7-9), and weighing lysimeters (U, S, T) at the Watson Falls study site. U = intact forest, S = shelterwood, and T = tree-weighing lysimeter. Treatment 3 is not utilized for snow hydrology research.

white fir (*Abies concolor*), western hemlock (*Tsuga heterophylla*), and ponderosa pine (*Pinus ponderosa*) are fairly common. Basal areas in the DEMO treatment units range from 36 - 52 m^2/ha (see Halpern et al. 1999 for details).

Micrometeorology

The measurement of forest micrometeorology during winter presents unique difficulties (e.g., Marks et al. 1992). Our sampling and instrumental designs are similar to those of Berris and Harr (1987) and Coffin and Harr (1992). Micrometeorology is measured 2 m above the soil surface and summary statistics are recorded every 30 minutes. Precipitation is measured with a resolution of one millimeter by an unheated gauge. The gauge consists of a 30.5 cm diameter length of PVC pipe 1.2 m tall attached to a rigid PVC base. The gauge is filled to a depth of 25 cm with an antifreeze solution that is a 3:2 mixture of propylene glycol and ethanol (McGurk 1992) topped with a thin layer of 10-30 weight motor oil to prevent ethanol evaporation. The antifreeze is recharged after 500 mm of precipitation to limit dilution and thereby prevent freezing. Outflow from the reservoir is collected by a tipping bucket. To limit catch deficiencies, each gauge is shielded from the wind.

Wind speed is measured with R.M. Young photochopper totalizing anemometers. These measure wind passage each minute and therefore effectively integrate the wind velocity over the observational interval. To prevent snow accumulation on the anemometers, housings were constructed consisting of a 30 by 30 cm square of Plexiglas suspended approximately 15 cm above the anemometer. Comparison of paired anemometers with and without housings showed no noticeable difference in wind speed when the unprotected anemometer was free of snow.

Incoming short-wave radiation is measured with Epply pyranometers. Reflected short-wave radiation, measured with Licor silicon cell pyranometers, is used to estimate albedo and to correct the Epply pyranometers when they are covered with snow. Incoming long-wave radiation is measured by Epply pyrgeometers. Air temperature and relative humidity are measured by Campbell Scientific Vaisala probes protected from direct and reflected radiation by six plate shields.

Snowmelt

Snowpack outflow is measured every 30 min by a non-weighing snow lysimeter with a surface area of 2.6 m^2 which is drained to a 1-l capacity tipping bucket. The lysimeter is lined with an impermeable geo-textile lining (hypalon). A plastic drain is installed flush with the liner in one corner of the lysimeter. The drains, piping, and tipping buckets are buried to prevent freezing. Shadecloth is draped over each lysimeter to prevent litter accumulation from clogging the drains.

Snowmelt is estimated as the difference between snowpack outflow and precipitation. Unfortunately, this calculation is only valid if two assumptions are met. First, any rain falling on the snowpack, along with any melt water, is immediately routed out of the snowpack. Second, precipitation rates over each lysimeter under the canopy are well approximated by estimates of canopy throughfall or precipitation in the open. The first assumption is generally met if snowpacks are shallow, isothermal at 0°C, and at their maximum liquid water holding capacities. Snowpacks in the transient snow zone of the Cascades generally meet these assumptions. If they do not, however, melt rates will be underestimated. Unfortunately, the second assumption is less likely to be valid. Given the high spatial variability of throughfall from a forest canopy, point estimates of precipitation are subject to significant error. Therefore, only measured precipitation from the shelterwood sites is used to estimate snowmelt. Although observations of lysimeter outflow under the canopy are subject to this same variability, they are more robust due to their larger surface areas.

Snow-water Equivalent

Direct observations of snow depth and snow-water equivalent (SWE) are taken in each treatment unit. During winter 1993-94, snow depth was measured at 25 points (80 by 80 m spacing) in each of the five low elevation units at the Watson Falls study site. These data were used to determine the number of sample points needed to detect a 5 cm difference in snow depth (not water equivalent) with a power of 0.7 at $P \leq 0.05$. A minimum of 17 sample points per unit are adequate, thus snow courses are run over a 20-point grid. Water equivalence is obtained with a standard U.S. snow tube. Snow course measurement and sampling procedures follow Natural Resource Conservation Service guidelines (USDA-SCS 1984).

Canopy Processes

Due to the coarse temporal resolution of the snow courses and the small surface areas of the lysimeters in each treatment, our sampling design is insufficient for rigorous testing of models of snow accumulation and ablation. Although many small lysimeters can characterize the average outflow of a harvest unit and its variability, they cannot fully describe processes at the scale of an individual tree canopy. Since canopy throughfall is highly variable at small spatial scales, any estimate of snowmelt (outflow minus throughfall) measured by small lysimeters may not be representative of the canopy as a whole. Furthermore, because snow accumulation is affected by snowfall, melt, and mass release from the canopy, weekly snow course measurements yield little information on snow interception processes that control snow accumulation. While a model of under-canopy snow accumulation and melt can be used to test the combination of all three factors, the current design (and those used by previous investigators in the Pacific Northwest) does not allow for the separation of effects. Such separation would require continuous measurement of snowpack outflow and water equivalent at a scale at which variability in canopy throughfall no longer dominates observations.

To overcome these limitations, we began a pilot study during winter 1996-97 to extend the existing field program. Two 25 m^2 weighing lysimeters were constructed. Each lysimeter was installed around a ca. 40-m-tall Douglas-fir adjacent to Unit 1 (Figure 2). The lysimeter is continuously weighed by four, 5-ton load cells. Outflow from the lysimeter is measured with tipping-bucket volumetric flow gauges. The weighing lysimeter effectively removes the variability in throughfall by sampling the entire canopy of at least one mature tree while directly measuring changes in

Figure 2. Overview of the under-canopy weighing lysimeters showing 25 m^2 lysimeter, micrometeorological station, and precipitation gauge.

the snowpack water equivalent. Two weighing lysimeters were built to control for inter-canopy variability and equipment failure.

While the weighing lysimeters can generate high-quality data on snow accumulation and ablation under the forest canopy, they cannot, by themselves, provide information on the processes controlling snow interception, mass release, or drip of meltwater to the ground snowpack. To more completely investigate snow interception, one smaller (12.5 m^2) weighing lysimeter was placed in the open, in the upper elevational shelterwood unit. Snow interception and release is then inferred by comparing the SWE of the two weighing lysimeters under the tree canopy to that of the shelterwood lysimeter. To measure snow interception directly, we installed two "cut-tree" experiments similar to those described by Schmidt (1991) and Lundberg (1993) in a forest plantation adjacent to the DEMO units (Figure 1).

Results and Discussion

Pre-treatment Snow Course Data

Weekly snow courses taken during the pre-harvest data collection period can be used to assess treatment level variation, as well as differences between uncut and shelterwood stands. Comparison of data from the high-elevation shelterwood and two nearby uncut units shows that gross accumulation and rate of melt tend to be greater in the shelterwoods (Figure 3a). Inter-annual variability was high, reflecting the timing and magnitude of winter storms. During 1995-96, significant snowfall and accumulation did not occur until January during a series of intense storms. These large events overwhelmed canopy interception and deposited nearly equal amounts of snow in both open and forested areas. In contrast, during winter 1996-97, snow accumulation occurred during many smaller storms. During these small events the forest canopy intercepted a significant fraction of total snowfall. These differences in interception efficiency with storm size have been previously observed (e.g., Satterlund and Haupt 1967, Schmidt and Gluns 1991). Interception efficiency increases initially with snowfall as needles and branch tips are bridged by snow, thereby increasing the interception surface area. However, as snowfall continues, interception efficiency decreases as snow loading overcomes branch stiffness and adhesive-cohesive bonds.

Although interception efficiency controls the retention of snow by the canopy, subsequent melt of intercepted snow controls snow accumulation under the forest canopy. This is evident in the reduced SWE beneath the uncut forest canopy relative to that of the shelterwood unit (Figure 3a). Although sublimation rates of intercepted snow can approach several mm per day in cold climates (Schmidt 1991, Lundberg 1993), opportunities for sublimation of intercepted snow are limited in the transient snow zone of the Cascades. Observations during frequent field visits suggested that melt of intercepted snow and subsequent drip to the ground snowpack were rapid (typically achieving complete removal within 24 hr).

Our observation that a sparser canopy results in reduced SWE is supported by a comparison of snow course data from the two uncut forest sites (Units 1 and 4) at 1200 m (Figure 3b). Although these sites are adjacent and were selected to be as similar as possible, they differ in forest structure. The trees in Unit 4 are larger on average than those in Unit 1 (C. B. Halpern, pers. comm.) and they support fewer branches at lower positions on the trunk (pers. obs.). During winter 1995-96, when early-season differences in snow accumulation between the shelterwood and the two uncut forest sites were minimal, the latter two also behaved almost identically until the melt event in early February. After this event, melt was more rapid under the taller, sparser canopy of Unit 4 (Figure 3b). A similar trend was observed during the following year. The variability of snow course data from two ostensibly similar forest stands underscores the necessity of collecting several seasons of pre-harvest data before inferences can be drawn on the effects of forest harvesting.

Meteorological and Lysimeter Data

Although the weekly snow course measurements provide a reliable estimate of accumulation at the scale of the treatment unit (13 ha), they provide little direct evidence for significant increases in water delivery to the soil during the relatively short periods (one to three days) of ROS or radiation-dominated melt events. This information is available from the snow lysimeters and micrometeorological stations. Unfortunately, since continuous measurement of snowpack within a 13-ha treatment unit is not feasible, the lysimeter data are by necessity limited to point estimates. Moreover,

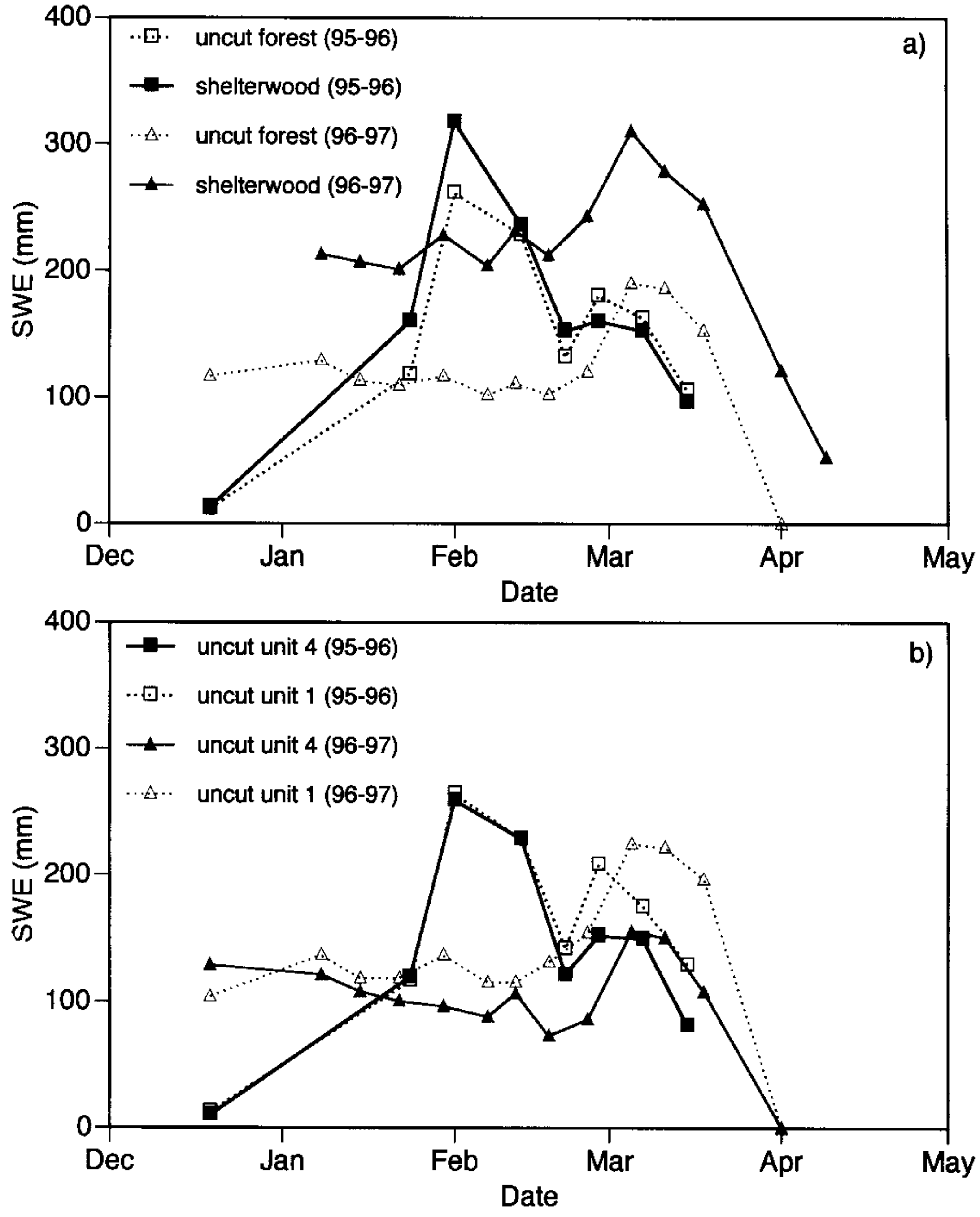

Figure 3. a) Snow course data during winter 1995-96 and 1996-97 for a shelterwood stand (Unit 9) and two uncut forests (average of Units 1 and 4). b) Variability in snow course data in the two uncut forest units (1 and 4) during winter 1995-96 and 1996-97.

because of their relatively small surface area (2.6 m^2), estimates from individual lysimeters are strongly influenced by their position under the canopy. This variability can be estimated by examining large numbers of lysimeters. For the results described below, outflow from the shelterwood represents the average of two adjacent lysimeters (neither is directly beneath a tree canopy); outflow for the uncut forests represents the average of four lysimeters at 1200 m or five lysimeters at 900 m. Comparisons of outflow, precipitation, and micrometeorology are limited to units of similar elevation.

Rain-on-snow Event

A ROS event occurred at the upper units (1, 4 and 9) during February 1996 (Figure 4a). During the event, average precipitation in the shelterwood and forested units was nearly identical (32 and 36 mm, respectively). However, snowpack outflow was greater at the shelterwood site than the uncut forest (89 and 56 mm, respectively). This corresponds to 59% greater snowpack outflow and 150% greater snowmelt due to shelterwood harvest. Near-surface micrometeorological data show noticeable differences between the shelterwood and uncut units (Figure 4b, c). Near-surface wind speed and air temperature were greater in the shelterwood than the uncut forest leading to increased melt rates in the former. Incoming long-wave radiation was nearly identical for both sites. Short-wave radiation was greater in the shelterwood than beneath the uncut forest and contributed to increased melt rates during the afternoon of 7 February.

A larger ROS event occurred over six days in late December 1996 and early January 1997 (Figure 5). The average precipitation recorded in the shelterwood was 165 mm. Average accumulated snowpack outflow was greater in the shelterwood (312 mm) than beneath the uncut forest (250 mm) (Figure 5a). This corresponds to 25% greater snowpack outflow and 72% greater snowmelt due to shelterwood harvest. Once again, near-surface meteorology shows considerable differences between the shelterwood and uncut forest sites (Figure 5b, c). Incoming long-wave radiation was greater beneath the uncut forest, especially during evening hours. Air temperature and windspeed were greater in the shelterwood than beneath the intact canopy, most noticeably during periods corresponding to maximum differences in snowpack outflow.

Individual lysimeter outflows during ROS events were highly variable. For example, during the period from 6 to 9 February 1996 (Figure 4a) the two shelterwood lysimeters at 1200 m recorded total outflows of 102 and 88 mm. Under the uncut forest canopy, variability was noticeably greater. Lysimeters in Unit 1 recorded outflows of 51 and 42 mm and those in Unit 4, 76 and 75 mm. Greater outflow under the sparser canopy of Unit 4 is consistent with the more rapid melt observed in the snow course data. Similar variability was observed at the lower elevation site during the same event. The shelterwood yielded outflows of 121 and 135 mm while the uncut forest yielded outflows of 72-99 mm. A non-parametric rank sum test to test the null hypothesis that outflow rates are similar in the shelterwood and uncut forest (at 1200 m) indicates that outflow in the shelterwood is greater than under the uncut forest ($p<0.1$).

Radiation-dominated Event

During a radiation-dominated snowmelt event at the high elevation site, three-day snowmelt volumes were 44% greater in the shelterwood site than beneath the uncut forest (Figure 6a). This increase corresponded to the greater net (incoming minus outgoing) short-wave radiation in the shelterwood than beneath the uncut forest (Figure 6b). However, net long-wave radiation was consistently greater beneath the uncut forest than in the shelterwood. In fact, beneath the intact canopy, net long-wave radiation represents a larger energy flux than net short-wave radiation over the entire event. The full canopy absorbs incoming short-wave radiation during daylight hours and radiates this energy as long-wave radiation during the evening. Consequently, during the evening of 7 March and the morning of 8 March, snowmelt rates at the uncut forest unit were greater than in the shelterwood unit. Since the net long-wave flux at the uncut site was near zero, even small fluxes of sensible or latent heat to the snow surface were translated directly to melt. (Although not shown in Figure 6b, air temperatures remained above freezing with light winds throughout the evening.) At the shelterwood site, the negative (i.e. away from the snow surface) flux of long-wave radiation prohibited melt.

Weighing Lysimeters

The results of our pilot study to measure canopy processes at the scale of an individual tree illustrate

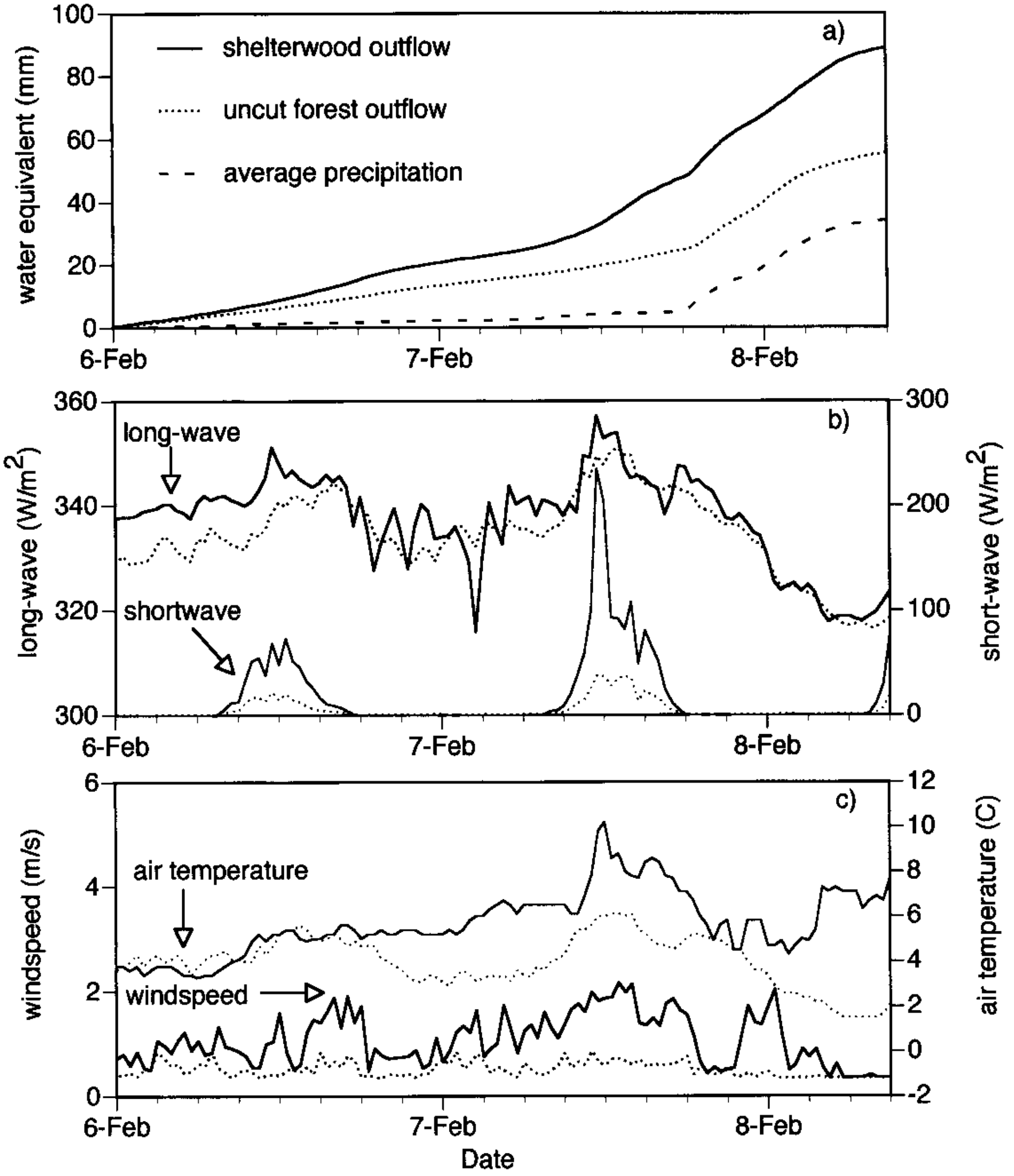

Figure 4. a) Accumulated snowpack outflow for uncut forests (average of Units 1 and 4) and a shelterwood site (Unit 9), and precipitation (Unit 9) during a rain-on-snow event, February 1996. b) Incoming short- and long-wave radiation for the same sites and period (solid lines are shelterwood, dotted lines are uncut forest). c) Air temperature and windspeed for the same sites and period (solid lines are shelterwood, dotted lines are uncut forest).

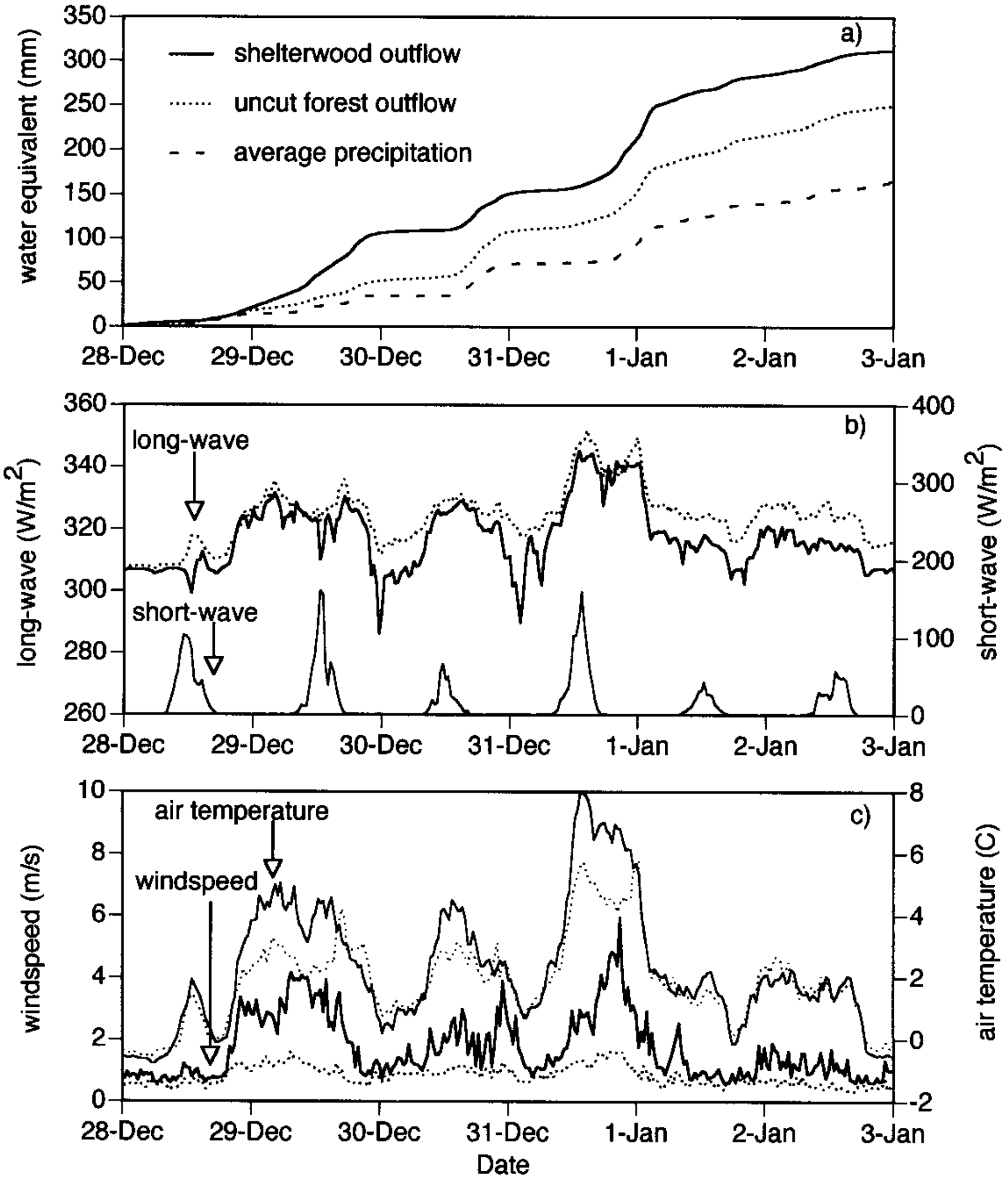

Figure 5. a) Accumulated snowpack outflow for uncut forests (average of Units 1 and 4) and a shelterwood site (Unit 9), and precipitation (Unit 9) during a rain-on-snow event, 1996-97. b) Incoming short- and long-wave radiation for the same sites and period (solid lines are shelterwood, dotted line is uncut forest). c) Air temperature and windspeed for the same sites and period (solid lines are shelterwood, dotted lines are uncut forest).

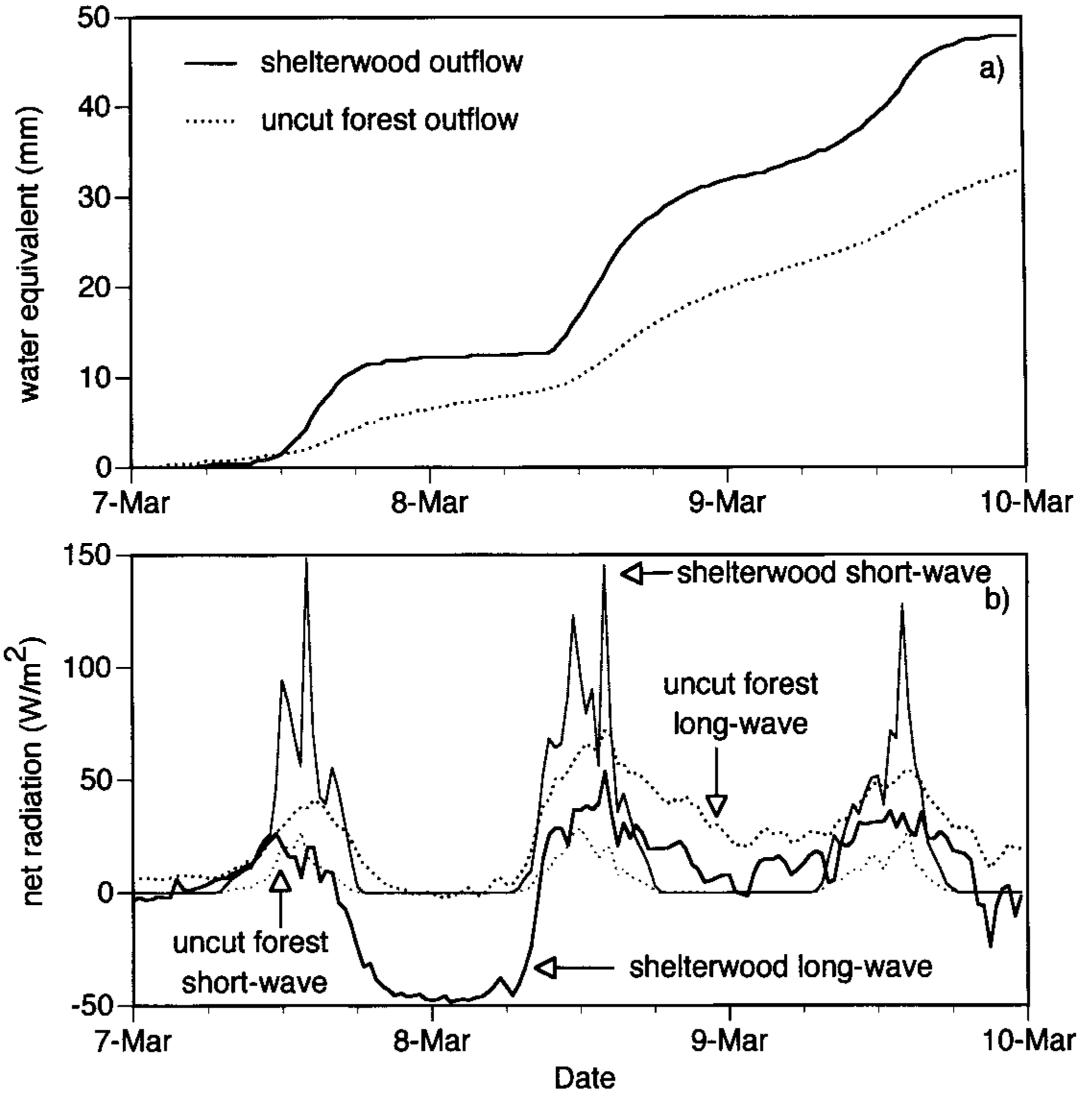

Figure 6. a) Accumulated snowmelt for uncut forests (average of Units 1 and 4) and a shelterwood site (Unit 9) during a spring snowmelt event, March 1996 (solid line is shelterwood, dotted line is uncut forest). b) Incoming net short- and long-wave radiation for the same sites and period. Net short-wave radiation is based on measured incoming and an observed albedo of 0.75. Net long-wave radiation is based on measured incoming and assumes that the snowpack acts as a blackbody emitter at 0°C (solid lines are shelterwood, dotted lines are uncut forest).

that the weighing lysimeters are capable of continuous measurement of SWE and snowpack outflow (Figure 7). The overall effect of the canopy on seasonal snow accumulation was dramatic. During the early accumulation season, canopy interception and subsequent melt limited the under-canopy SWE to approximately 50% of the shelterwood value. Loss of SWE during the ROS event of 1 January 1997 is clearly shown. Canopy interception and snowmelt were even more dramatic during the secondary snow accumulation period (beginning on 1 February). During this

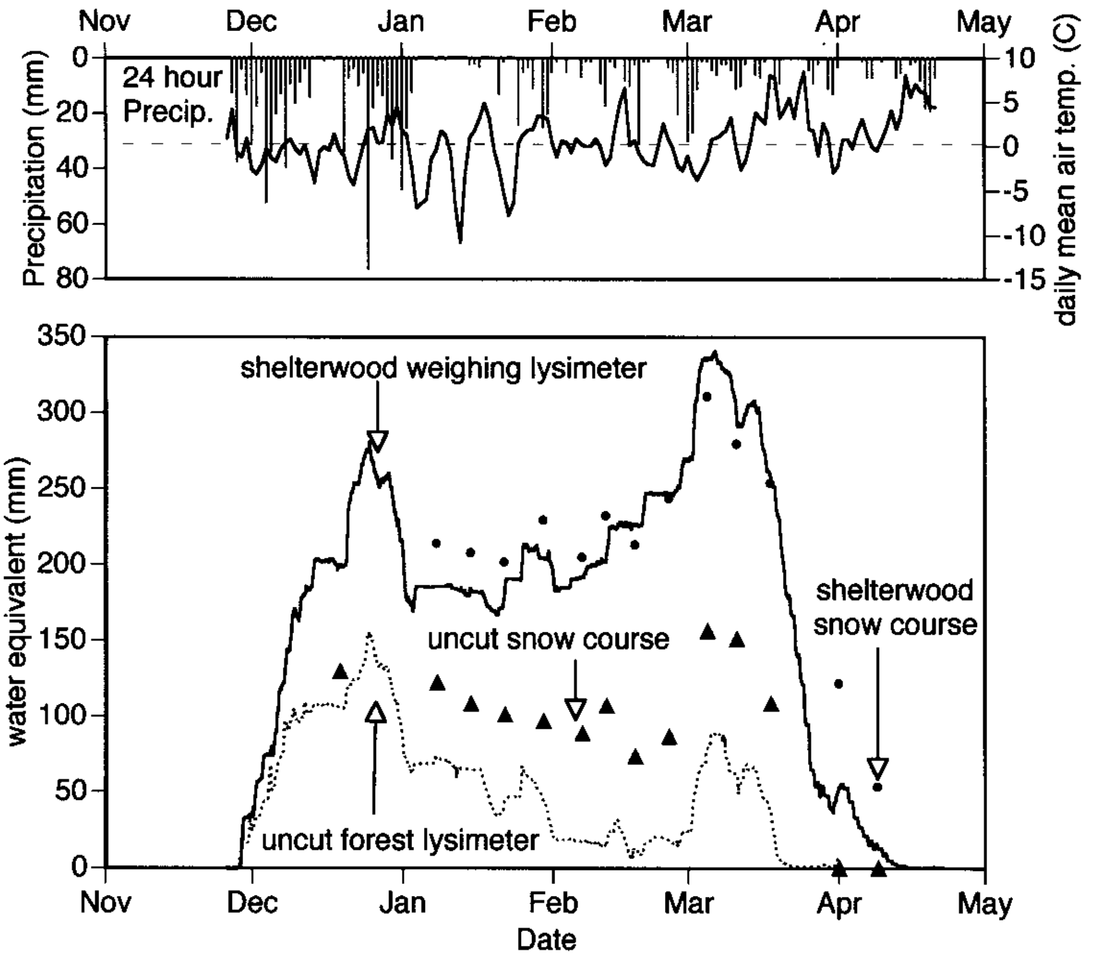

Figure 7. Precipitation, temperature, and weighing lysimeter data for shelterwood and uncut forest sites during 1996-97. Snow course data from shelterwood (Unit 9) and uncut forests (average of Units 1 and 4) during 1996-97.

period, the majority of snowfall occurred near freezing. While significant snow accumulated at the shelterwood site, there was no snow accumulation under the canopy until the snowfall of 1 March, which occurred at much colder temperatures.

Snow course data correlate well with the continuous measurement of SWE in the shelterwood site but poorly under the intact canopy. The relatively poor agreement of the latter is best explained by the dependence of snow accumulation on canopy coverage. Although each canopy lysimeter was situated entirely under a continuous canopy, the average unit canopy closure was ca. 80%. Thus, as the snow course samples the entire treatment unit and the weighing lysimeters sample under a full canopy, we would expect the observations of snow accumulation to differ. However, this difference provides a unique opportunity for model validation. Any model of snow accumulation and melt under a forest canopy should account for this difference through its parameterization of canopy closure. Given the success of the pilot program in continuously measuring SWE during the accumulation and melt season, we are continuing the weighing lysimeter experiment to supplement the data collected by the snow courses and non-weighing lysimeters.

Acknowledgements

The first author has received support from a NASA Earth System Science Fellowship. Many individuals have contributed to various aspects of this research. We would especially like to thank those who have collected snow course data: Joe Brett, Beth Evans and John Scott. Rick Abbott has been especially helpful in facilitating field work and site access. Critical reviews of this paper were provided by Matt Brunengo, David Post, Jim White, and three anonymous reviewers. This is a product of the Demonstration of Ecosystem Management Options (DEMO) study, a joint effort of the USDA Forest Service Region 6 and Pacific Northwest Research Station. Research partners include the University of Washington, Oregon State University, University of Oregon, Gifford Pinchot and Umpqua National Forests, and the Washington State Department of Natural Resources.

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