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Hillslope, canopy, and proximity influences on duff moisture spatial and temporal variability

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by

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Hillslope, canopy, and proximity influences on duff moisture spatial and temporal variability

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Abstract

Distributed moisture modelling of the decomposing organic layer of forest floors (duff) over large scales is an important tool in managing forest resources, yet knowledge of duff characteristics essential for this modelling is limited. The aim of this research is to increase knowledge of duff and its moisture characteristics in order to assist efforts in spatially modelling duff moisture, through both laboratory studies and two field campaigns. Field data, including samples for the laboratory studies, were collected from boreal type forest stands comprised of lodgepole pine, jack pine, black spruce, white spruce and trembling aspen.

Laboratory experiments were conducted to measure and compare the saturated hydraulic conductivities, porosities, desorption characteristic curves, and drying curves of duff. Samples were from six different canopy types, from both between and beside trees, and from the upper and lower portions of the duff layer. Comparisons were made between the samples based on three categories: canopy type, location and layer. The hydrological properties were found to exhibit greater variation vertically within the duff layer than between canopy type and location. The upper duff layer was found to have both a higher saturated hydraulic conductivity (0.34±0.28 cm s^{-1}) and porosity (0.86±0.08 cm^3 cm^{-3}) than the lower duff layer (0.22±0.15 cm s^{-1} and 0.75±0.10 cm^3 cm^{-3}, respectively). Desorption characteristic curves were created for the upper and lower duff layer and applied to Richards equation to produce duff drying curves. Comparisons between modelled and measured drying curves were used for verification. The high heterogeneity in duff, even over small areas, overshadows any of the differences based on canopy type or tree proximity. As a result, spatial models of duff moisture only need to consider the differences in physical characteristics based on depth.

Patterns and spatial variations in the moisture content of duff were analysed based on data collected from two field campaigns, in the summers of 2005 and 2006. Above and below canopy meteorological measurements established that reduction factors should be applied to wind speed and solar radiation when calculating evaporation from duff in a closed pine/spruce canopy using conventional methods. Investigations on the influence of canopy type, tree density, and tree proximity on duff moisture patterns indicated that canopy type and tree proximity are the most important factors affecting duff moisture. Interception is the primary controller of duff moisture patterns with an influence at the centimetre scale. Hillslope was not found to be an important factor in duff moisture variability. While there is a difference in moisture content between duff close to a tree and in the gap between trees, the difference decreases as the duff dries.

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Chapter One: **Introduction**

The boreal forest is the largest ecozone in Canada, occupying over a third of the total landmass of the country. It forms a continuous belt from Alaska to the coast of Newfoundland and Labrador (Rowe, 1972). In the south, it is bordered by temperate forests or grassland, and in the north, by tundra. The boreal forest is characterised by dense mixed forest dominated by conifers, interspersed by areas of muskeg and vast bogs. The trees come from a few key genera including spruce (*Picea*), pine (*Pinus*), fir (*Abies*), larch (*Larix*), birch (*Betula*) and aspen (*Populus*). Because the trees only come from a small number of genera, the boreal forest is considered to have a relatively low biodiversity, especially when compared to tropical forests (Elliot-Fisk, 1988). The low number of genera also results in a uniformity of appearance across the expanse of the ecosystem. However, there is a diversity of species within each genera and this is reflected by the classification of the boreal forest into a number of smaller subregions (Rowe, 1972).

An important characteristic of the boreal forest is the size, frequency and intensity of wildfires. Fires, set by lightning or man, occur on average once every 100 years and can consume areas greater than 1000 km^2 (Johnson, 1992). The size and frequency of these fires are primarily influenced by the meteorological conditions. The boreal forest typically suffers from long, severe winters followed by short, cool summers. This type of climate can result in extremely dry fuel conditions. The weather also provides an ignition source in the form of lightning from convective thunderstorms, and a method of propagation in the form of wind. The weather conditions are ideal during the fire season, which usually begins in the spring and continues through the summer (May through September).

Both the morphology and reproduction of many of the trees in the boreal forest have been adapted to fire (Rowe and Scotter, 1973). Adaptation comes in different forms. Balsam poplar, for example, have a thick bark making them more likely to survive fire (Larsen, 1980). In addition, they have the ability to regenerate by root suckering and stump-sprouting; therefore, as long as at least some of the root system survives fire, new trees will be able to grow. These methods of regeneration are also present in trembling aspen. Conifers, on the other hand, do not share these characteristics. Instead, viable seeds are retained on the trees, providing a seed source after a fire. An additional fire adaptation found in conifers, such as pine and spruce, is the presence of serotinous cones. Serotinous cones require high temperatures, such as those produced by fire, in order to open and release their seeds. Such cones do not open under normal conditions; hence, trees with serotinous cones are not merely adapted to fire, they require it for regeneration. It should be noted that none of these trees rely on buried viable seeds surviving a fire in order to reproduce (Johnson, 1992). This is because during forest fires, large amounts of forest floor, including buried seeds, can be consumed.

Forest floors are covered by a layer of decomposing organic matter known as duff. This decomposing layer is bounded on the top by forest litter and on the bottom by mineral soil. Its degree of decomposition is heterogeneous both vertically, gradually increasing closer to the mineral soil, and horizontally, where decomposition is dependent on factors such as canopy type and climate. Canopy type controls the nature and amount of litter cast off; this, in turn, directly influences the thickness and composition of duff. Duff close to tree boles tends to be thicker and covered by more litter because cast off matter tends to fall directly beneath the tree (Miyanishi and Johnson, 2002). In addition, supporting root networks and diminished snow pack near tree boles provide comparably less long term compaction resulting in lower bulk density. While duff structure is variable depending on its type, location and layer, the question becomes whether or not the variability is greater within or between the groups of each category.

Duff tends to be highly porous (Fosberg, 1977) and as a result, it has a tendency to dry quickly and, hence, can have a low moisture content. Low moisture levels are not normally conducive to either seed germination or seedling survival, both necessary for forest regeneration (Ackerman, 1957; Chrosciewicz, 1970; Weber et al., 1987; Charron and Greene, 2002). Fortunately, forest fires, which by their very nature produce a need for regrowth, usually remove the duff layer through smouldering combustion (Frandsen, 1991). This is beneficial, as tree establishment has a tendency to occur in areas where the mineral soil is exposed (Ackerman, 1957; Chrosciewicz, 1959; Horton and Lees, 1961; Jameson, 1961; Waldron, 1961; Chrosciewicz, 1970, 1974, 1976; Dyrness and Norum, 1983; Zasada et al., 1983; Weber et al., 1987; Charron and Greene, 2002). Consequently, accurately predicting the amount and location of duff consumed (i.e., the spatial distribution of duff consumption) during a forest fire can lead to a greater understanding of the forest recruitment process and regrowth potential.

1.1 Spatial and Temporal Distribution of Duff Moisture

The spatial distribution of duff consumption is a function of several factors including its density, depth and, in particular, moisture content at the time of the fire (Chrosciewicz, 1970, 1978; Frandsen, 1987; Van Wagner, 1972; Kauffman and Martin, 1989; Miyanishi, 2001; Miyanishi and Johnson, 2002). Although depth and density of duff are spatially variable, they tend to have a slow temporal rate of change and remain relatively constant throughout the fire season. Consequently, it is the changes in moisture content that influence consumption within a single season. Duff moisture has a high temporal variability due to its sensitivity to meteorological conditions. The large and variable heat sink properties of water

(Frandsen, 1987) imply that small changes in duff moisture can lead to large changes in the amount consumed. Therefore, it should be possible to determine the spatial distribution of exposed mineral soil after a forest fire simply by knowing the moisture content of the duff prior to the fire.

The spatial distribution of exposed mineral soil can be considered a small scale phenomenon. For example, patterns of duff consumption have been attributed to factors such as tree proximity (Miyanishi, 2001; Hille and Stephens, 2005), which is not something currently considered in predicting duff consumption or in most cases estimating duff moisture. Factors leading to the spatial variation of duff moisture are not well understood, impeding the ability to accurately model distributed duff moisture. The boreal forest is characterised by dense mixed forest dominated by conifers, interspersed by areas of muskeg and vast bogs. The mixed nature of the forest, especially over large areas, in terms of tree type and canopy closure, generates its own type of spatial variability. The importance of this variability on duff moisture is unclear. Therefore, the properties and moisture content of duff produced from a variety of trees must be considered. Tree types comprise lodgepole pine (*Pinus contorta* Dougl.), jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) BSP.), white spruce (*Picea glauca* (Moench.) Voss) and trembling aspen (*Populus tremuloides* Michx.). These trees are found in the boreal forest and are prevalent in most of the forested regions of Alberta.

The flow of water through the duff itself may impact moisture variability. Horizontal movement of water through soils is controlled by capillary forces. The high porosity in duff results in weak capillary forces, and hence negligible horizontal movement of water (Tiktak and Bouten, 1992). However, it is recognized that water will move laterally down a hillslope due to gravitational forces and collect in depressions making downslope areas wetter than topslope areas (Potts et al., 1983). Duff moisture has been observed to be greater at the bottom of a hillslope than the top (Keith, 2009; Potts et al., 1983; Samran et al., 1995). Preferential flow paths on hillslopes corresponding to a precipitation event have also been observed for duff, but with short connective distances (McDonnell et al., 1991; Brown et al., 1999; Noguchi et al., 1999; Kim et al., 2005). These preferential flow paths have been attributed to a hydrophobicity of the mineral soil at the base of the duff during dry conditions, inhibiting infiltration (Sevink et al., 1989). Since these preferential flow paths are short, questions arise as to their applicability along an entire hillslope, and accordingly, to a duff hillslope moisture gradient.

Variability in duff moisture might also be influenced by the moisture content of the mineral soil directly underneath, although studies on this interaction have been limited. Moisture gradients along hillslopes have been observed in the mineral soil. Thus, if duff moisture is influenced by mineral soil moisture then hillslope influences on duff moisture would also be expected.

In theory, moisture content can be determined by finding the balance between precipitation inputs, evapotranspiration losses, and moisture fluxes from both the adjacent soil and duff. However, it is not known to what extent these variables influence duff moisture. In addition, except for precipitation, these water inputs and outputs are affected by physical properties of duff, such as hydraulic conductivity and moisture characteristic. Not only has there been little quantification of these physical properties, but given the highly heterogeneous nature of duff it is unclear how variable these properties are over even small areas.

1.2 Modelling the Spatial and Temporal Distribution of Duff Moisture

Motivation for determining the spatial variation in duff moisture comes from observations in duff combustion patterns following forest fires. Large portions of duff are consumed by smouldering consumption, and the spatial variation in the consumption is a function of several factors including the density, depth, and moisture content of the duff at the time of the fire (Chrosciewicz, 1970, 1978; Frandsen, 1987; Van Wagner, 1972; Kauffman and Martin, 1989; Miyanishi, 2001; Miyanishi and Johnson, 2002). While field measurements of duff moisture provide an accurate representation of the duff moisture conditions at a specific location, given the vast size of forested areas, it is not possible to directly measure duff moisture conditions everywhere. This leads to the necessity for duff moisture models.

Modelling the drying of a soil such as duff, requires knowledge of some of the hydrological properties of that soil, such as its porosity, hydraulic conductivity, and desorption characteristic curve. Information on the hydrological properties of duff is generally limited, and this has restricted the use and development of physically based models. There have been a limited number of models developed to predict the spatial distribution of duff moisture content. These models can be placed into two groups: conceptual and physically based. The conceptual models tend to be based on weather observables and the transfer of energy and mass within the duff layer (Fosberg, 1975, 1977; Frandsen and Bradshaw, 1980). Physically based models, on the other hand, tend to be based on the theory of unsaturated flow through soil. For example, the SWIF (Soil Water in Forested Ecosystems) model (Tiktak and Bouten, 1992), which was developed for use in forest soils, was used to model duff moisture (Vo, 2001) with limited success. The model treated the duff as any other soil layer, taking into account its individual physical properties. A lack of verification studies not only limit the application of these models, but may perpetuate the inappropriate representations of the important factors influencing duff moisture. Essentially, factors leading to the spatial distribution of duff moisture are not understood well enough too accurately model distributed duff moisture. However, a duff moisture drying model based on heat and mass transfer was able to demonstrate that meteorological fluxes lead to diurnal cycles in moisture content of the upper duff layer (Keith et al., 2010a). It also established that duff moisture did not follow a hillslope moisture gradient but that water did collect in convergent areas and disperse from divergent areas based on topography (Keith et al., 2010b).

Currently, the most widely used system for predicting duff moisture in Canada is the Canadian Forest Fire Weather Index System (Canadian Forestry Service, 1970; Van Wagner, 1987). This system uses three indices that relate daily weather observations and empirical drying curves to an average value of the moisture content of duff (at varying levels of decomposition) over large areas. A modification was made to this model by Wotton et. al. (2005) to account for the lower moisture levels observed in more sheltered forests because of increased interception, but still without consideration to the spatial variability. Because the duff is treated as a uniform carpet of constant depth and uniform moisture content, the model cannot provide an estimate of the spatial distribution of duff consumption which is known to be non-uniform over the burned area (Miyanishi and Johnson, 2002).

1.3 Objectives

The overarching aim of this research is to increase knowledge of duff and its moisture characteristics so that it may be used to spatially model duff moisture. Specifically, the novel contributions to knowledge of duff moisture characteristics involve:

- Quantifying the physical properties of different types of duff that are essential to duff moisture modelling yet absent from the literature.
- Determining which factors have the greatest influence on duff moisture at laboratory and hillslope scales.
- Determining how the spatial and temporal variation in duff moisture varies with different canopy types so that canopy influences can more accurately be incorporated in duff moisture modelling.

1.4 Outline

The work in this dissertation is divided into five chapters that build on each other as follows:

- Chapter two describes the duff calibration of a ThetaProbe, a fixed frequency impedance probe that has been designed to measure moisture content in both mineral and organic soils. Probe calibration and accuracy is assessed for duff from different canopy types, tree proximities, and layers within the duff. Calibration values are used throughout the remainder of the dissertation.
- Chapter three quantifies the porosities, desorption characteristic curves, and saturated hydraulic conductivities of different types of duff. These are essential parameters for physically-based duff moisture modelling. Comparisons are again made based on canopy type, tree proximity, and duff layer. This chapter achieves the first objective of this dissertation.
- Chapter four investigates the primary factors shaping the spatial and temporal variations in duff moisture through field measurements. Daily moisture measurements collected at regular intervals in 10m×10m plots representing a variety of canopy types and densities are compared and analysed. Above and below canopy meteorological conditions are also compared as possible spatial variation influences.

- Chapter five specifically addresses the influence of hillslope on the spatial variation of duff moisture. It concludes with a comprehensive discussion of the source of the spatial and temporal variation in duff moisture. Both chapters four and five together achieve the second and third objectives.
- Chapter six gives a general discussion, reviewing the key findings and providing suggestions for future research.

Chapters 2, 3, 4, and 5 have a journal paper format, with an introduction, methodology, results, discussion, and conclusion sections. As such, these chapters begin with a summary that outlines the chapter's content and details the knowledge used from previous chapters.

Chapter Two: **ThetaProbe Calibration for Duff**[1]

Obtaining field values of duff moisture requires a method of measurement. If repeated or continuous moisture values are necessary, then non-destructive techniques have to be applied. For this research, the ThetaProbe was the sensor selected to acquire the field measurements of duff moisture. Reasons for this selection are outlined below. Reliable measurements of moisture content by the ThetaProbe require soil specific calibration. This chapter describes the calibration of the ThetaProbe for duff, specifically addressing calibration error. The calibration

[1]Material in this Chapter was presented in “Theta Probe Calibration for Forest Floor Organic Matter.” *Canadian Journal of Soil Science*, 89(3):315-318 in 2009 with some modifications.

coefficients found here are used in the succeeding chapters four, and five, that present field measurements of duff moisture.

2.1 Introduction

Reliable measurements of soil moisture content are necessary both for direct monitoring and for hydrological model development and verification. This is especially true for the organic layer of the forest floor, known as duff, where moisture content values can be used to predict the potential risk of forest fires (Van Wagner, 1987). Duff is highly porous (Fosberg, 1977), which can make duff moisture content challenging to measure using non-destructive techniques because of difficulties in establishing effective duff-sensor contact. This is compounded by the fact that duff is heterogeneous both vertically and horizontally. There are many techniques and devices that can be used to measure soil moisture content but the ThetaProbe manufactured by Delta-T Devices Ltd., Cambridge, UK, is one of the more popular available due to its low cost, ease of use, and small sampling volume. The ThetaProbe does require calibration, but few studies have investigated the calibration of the ThetaProbe for duff. Wilmore (2001) does provide a calibration for duff under a black spruce canopy. However, the duff in that study was on average over 20 cm thick and was subject to permafrost: conditions that are not prevalent for all duff types. In addition, the calibration was based on only two samples without any examination into measurement accuracy. This chapter determines the calibration parameters for duff when using the ThetaProbe to detect moisture content; and establishes the measurement accuracy.

2.2 ThetaProbe

The ThetaProbe (model ML2x), is a fixed frequency (100MHz) impedance probe that has been designed to measure moisture content in both mineral and organic soils. It is composed of a central transmission line surrounded by three equidistant outer electrodes that act as coaxial shield conductors (Gaskin and Miller, 1996). The four stainless steel electrodes are 60 mm long and enclose an area 26.5 mm in diameter. The area of influence has a diameter of 40 mm, resulting in a sampling volume of approximately 75 cm^3, centred along the central electrode. The probe measures the dielectric constant of the soil, which is a combination of the dielectric constants of the individual components of the soil: solid matter, water, and air (Whalley, 1993). Because the dielectric constant of water is approximately 20 times greater than that of the solid matter, the soil's dielectric constant is primarily dependent on its moisture content. The manufacturer's specified relationship between sensor measured voltage (V) and the dielectric constant (ε) is (Delta-T Devices Ltd., 1999):

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \quad (2.1)$$

where V is in volts. This relationship was established using materials of known dielectric constant. It is also possible to use a linear relationship instead of the third order polynomial; although this is not recommended for organic soils where the moisture content may be greater than 0.5 m^3m^{-3}.

The volumetric moisture content of a soil, θ, and the square root of its dielectric constant can be related using a linear relationship (Whalley, 1993)

$$\sqrt{\varepsilon} = a_0 + a_1\theta, \tag{2.2}$$

where the coefficients a_0 and a_1 depend on the particular composition of the soil. General calibration values provided by the manufacturer for organic soils are a_0 = 1.3 and a_1 = 7.7. These coefficients are optimal for a soil with an organic content of 40% carbon and a bulk density range of 0.2 - 0.7 Mg m^{-3} but are also recommended for use with soils that have organic contents > 7% carbon and bulk densities < 1.0 Mg m^{-3}.

While general coefficients are provided, the manufacturer still recommends soil specific calibration to obtain more accurate soil moisture content values. Fortunately, since all ML2x ThetaProbes are manufactured to respond to the dielectric constant in the same way, calibration needs to be done only once on one probe (Delta-T Devices Ltd., 1999). According to the manufacturer, if the general calibration parameters are applied, then volumetric moisture content values are quoted to be within ±0.05 m^3m^{-3}. If a soil specific calibration is conducted, the values should be within ±0.01 m^3m^{-3}, but this is provided that the soil is highly homogeneous, that the probe is perfectly inserted into the soil completely, and soil compaction is avoided while maintaining full contact with the probe. In practice, particularly in the field, these conditions are difficult to achieve; consequently, so is the quoted accuracy. Delta-T Devices Ltd. (1999) states that overall soil specific calibration error is comprised of three error sources: the repeatability of probe readings (±0.01 m^3m^{-3}), calibration errors (±0.02m^3m^{-3}), and soil variability and insertion errors (±0.04 m^3m^{-3}). This results in a more realistic soil specific calibration error of ±0.05 m^3m^{-3}. However, they do state that errors can be as large as ±0.1 m^3m^{-3}.

The manufacturer suggests a two point soil specific calibration where two voltage readings are taken of a single soil sample: one when the sample is wet and the other after it has been oven dried. The sample must have a known volume so that its volumetric moisture content can be determined. The applicability of a two point calibration on a single sample to a single soil type is questionable. Kaleita et al. (2005) found that a two point calibration was inadequate for field calibration because of the inherent heterogeneity of the soil, and instead recommended that 20 samples be used. In addition, it was recommended that samples of varying moisture contents be used instead of oven drying a single sample because of the problems of contraction and fragility of some soils once oven dried. This is especially true of duff, which becomes very brittle when dried.

2.3 Methodology

Field measurements took place during the summer of 2004 in the boreal forest region near Whitecourt, Alberta (54°08'N, 115°47'W, Elevation 780 m); see Figure 3.1 for location. Measurements and samples were taken in a pure stand of lodgepole pine, jack pine, black spruce, white spruce, and trembling aspen, as well as from a mixed stand that contained all five tree types. All stands were within 20 km of each other.

A total of 33 duff samples were used in the calibration of the ThetaProbe. Two sampling locations were established for each stand, except for the trembling aspen stand where limited resources only allowed for one sampling location, resulting in 11 sampling locations. Duff at each of the 11 sampling locations was, on average, 10 cm thick. Over the total duff thickness three 2.7 cm thick sampling layers were established: upper, middle and lower. The upper layer was considered the top 2.7 cm of duff and lower layer was the bottom 2.7 cm of duff closest to the mineral soil. The middle layer was the 2.7 cm of duff equidistant from the upper and lower layer. The exception to this was the black spruce stand where the bottom of the duff layer was never found. This stand was essentially a bog, with the water table located only 40 cm from the ground surface. Lower layer samples for black spruce, therefore, were considered just above the water table. In all cases moss and litter were removed from the surface of the duff before sampling began.

Field measurements of voltage were made with a ThetaProbe and recorded using a Delta-T Moisture Meter (HH2). The duff next to the selected sampling location was removed to allow for the horizontal insertion of the ThetaProbe into each of the three duff layers at the sampling location. In an attempt to minimise the affect of poor duff-sensor contact, three replicate probe insertions and horizontal voltage measurements of the duff were made for each layer and then averaged. The average standard deviation in the three replicate probe insertions over all sampling locations was 0.25 mv. Average voltages were converted into dielectric constants using Equation 2.1. Following the ThetaProbe measurements, a vertical duff core was extracted from the site of the voltage measurements using a metal cylinder of 5.3 cm diameter and 2.7 cm depth. The volume of the extracted sample was slightly smaller than the volume occupied by the ThetaProbe because of a 0.7 cm difference in sample diameter and probe length. This difference was unavoidable due to equipment limitations, but was not considered to be a major factor in the results mainly because of the high variability in the three voltage measurements as discussed in the results. Duff thickness was checked at all stages of measurement and extraction to ensure minimal compaction. After extraction, the duff samples were weighed, oven dried at 105°C for 24 h, and then weighed again. The volumetric moisture contents were determined by dividing the mass of the water (wet mass – dry mass) by the volume of the container.

Linear relationships between θ and sensor calculated $\sqrt{\varepsilon}$ were developed for several different groupings of the samples in order to determine if, for example, tree type or duff layer require separate calibrations. The first set of relationships was developed based on tree type. Thus, a linear relationship was developed for all samples taken within a single tree stand type regardless of the duff layer the sample was extracted from. This resulted in six groups within the 33 samples, and thus, six relationships for this set. A second set of relationships was developed by distinguishing samples solely by duff layer (i.e., relationships for the upper, middle and lower duff layer). Orthogonal regression (Rao et al., 2007) was used to determine the linear relationships to account for the measurement error in both θ and $\sqrt{\varepsilon}$. A two-way analysis of covariance was used to test the influence of tree type and duff layer as well as their interaction at a 5% significance level.

2.4 Results

The relationship between the dielectric constant, that is indirectly measured by the ThetaProbe, and the moisture content of the duff is presented in Figure 2.1, with the grouping based on tree type highlighted. Orthogonal regressions based on the groupings tree type and duff layer all had significant slopes. For tree type, the analysis of covariance revealed that there was no significant difference in the six regressions ($p = 0.62$) and that the hypothesis that all slopes were equal was acceptable. The same was found for the three regressions grouped by duff layer ($p = 0.47$). The interaction between tree type and duff layer was also found not to be statistically significant ($p = 0.74$). Thus, a single calibration of the ThetaProbe for all duff types and layers (based on the 33 samples) was created, and is depicted in Figure 2.1. Concern could be raised regarding the impact of three moisture content measurements that were > 0.5 m^3m^{-3}, especially considering they were all from the same tree type. However, analysis of covariance verified that there was no significant difference in the regressions with $\theta > 0.5$ m^3m^{-3} and $\theta < 0.5$ m^3m^{-3} ($p=0.53$).

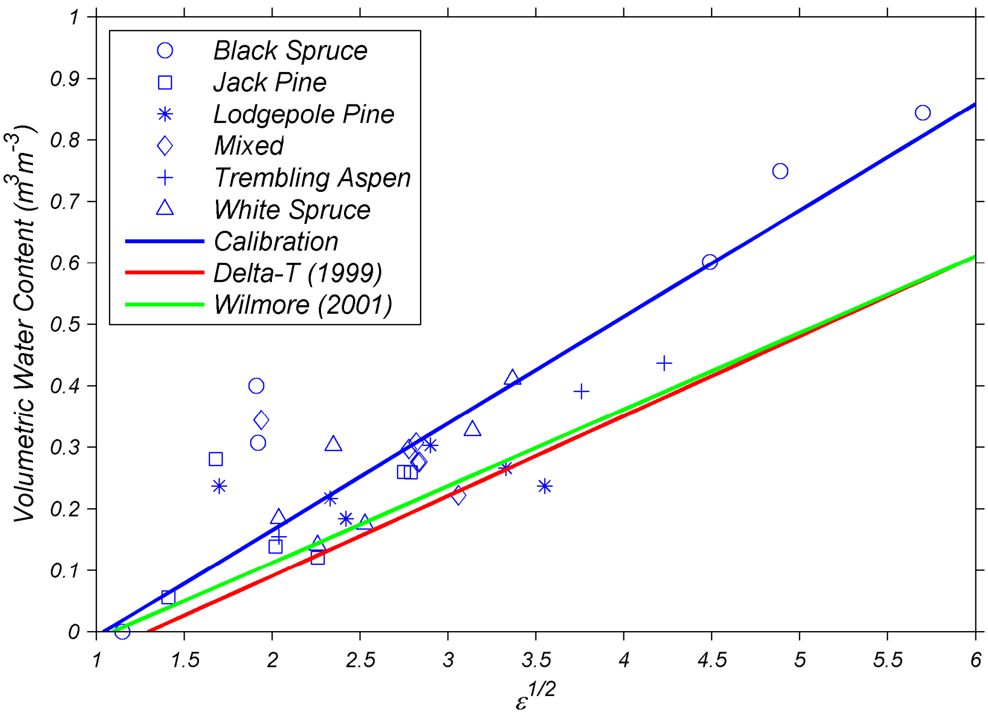

Figure 2.1: Relationship between measurements of the dielectric constant, ε, and volumetric moisture content for duff collected from six tree stands. The resulting orthogonal regression calibration equation is provided along with the manufacturer's suggested fit and that from Wilmore (2001).

The slope of the linear regression (using all 33 data points) was found to be significant ($p < 0.001$), with a coefficient of determination R^2 equal to 0.70. The relationship is,

$$\theta = 0.17\sqrt{\varepsilon} - 0.18. \quad (2.3)$$

The values of the coefficients, a_0 and a_1, were calculated by rearranging Equation 2.3 into the form of Equation 2.2. The coefficients with associated uncertainty are: a_0 = 1.0±0.3 and a_1 = 5.8±0.6. The measured coefficient a_0 is within the manufacturer's expected range (1.0 – 2.0), and includes the manufacturer's general calibrated value (1.3) within its uncertainty. The coefficient a_1, on the other hand, has a measured value that is outside the manufacturer's expected range (7.6 - 8.6), and does not include the manufacturer's general calibrated value (7.7) within its uncertainty. This difference would result in a consistent under-estimation of duff moisture content when using the manufacturer's values, as evidenced by the difference between our calibration and the Delta-T (1999) calibration (Figure 2.1). Wilmore (2001) also found that the generalised calibration provided by the manufacturer under-estimated duff moisture content in their study of black spruce duff. The difference in Wilmore's case was due to the disparity between the bulk density of duff and the optimized bulk density range for the general calibration, which is also suspected to be the reason for the difference in this study. However, the difference between the calibration done by Wilmore and Delta-T is smaller than the difference in this study, as shown in Figure 2.1. The measured coefficient a_0 is comparable to Wilmore's (1.099); however, the measured coefficient a_1 is smaller than what was found by Wilmore (8.03). As stated previously, it is believed these differences could be related to differences in the nature of the duff in the two studies (thickness, density and permafrost conditions), as well as the limited number of samples (2) used in the calibration by Wilmore.

Uncertainty is a key issue in calibrating the ThetaProbe for duff because of the material's high heterogeneity. Figure 2.1 shows that there is a strong linear relationship between the dielectric constant and volumetric moisture content but there is also a large amount of variability. The standard error of the linear fit was ± 0.09 m^3m^{-3}, which is substantially larger than ± 0.05 m^3m^{-3} and even larger than the quoted ideal measurement error of ±0.01 m^3m^{-3}. Even the three replicate probe insertion voltage readings taken for each sample produced an average standard error of ±0.04 m^3m^{-3}. Such a high error may be attributed to the compressibility of duff, the difficulty in probe insertion, and the heterogeneity of duff over very small areas.

2.5 Conclusion

ThetaProbe calibration coefficients for duff were determined to be a_0 = 1.0±0.3 and a_1 = 5.8±0.6. Statistical testing indicated that duff sampled from specific tree types or depth do not require different calibrations but further testing is required because of the limited number of samples and the high heterogeneity of the duff even over small areas. The standard error associated with this calibration is ±0.09 m^3m^{-3}. This error should be considered or propagated through models using these coefficients. However, an error this high may negate any observed differences in moisture content depending on the values of the observations. Therefore, while the large measurement error is always considered in the succeeding chapters, its direct effect is generally ignored so that the relative differences can still be examined.

Chapter Three: **Hydrological Properties of Duff**[2]

This Chapter focuses on the differences in the hydrological properties of duff based on tree type, tree proximity, and layer within the duff. That is because these differences are used to determine where the greatest variability in duff hydraulic properties exists. While the boreal forest is the region driving the motivation for this research, available resources required field locations to include montane forests. Trees of the same type can be found in both forest regions, and comparable stands in the two study locations were selected, making comparisons possible. Both

[2] Material in this Chapter was presented in "Hydraulic Properties of Duff", Water Resources Research, 45, W05502, doi:10.1029/2008WR007396 in 2009 with some modifications.

boreal and montane forested areas were used for study in this chapter, while studies in the montane forest continue in Chapters 4 and 5.

3.1 Introduction

Duff is the decomposing organic layer of the forest floor and the degree of decomposition gradually increases with depth making duff a very heterogeneous material vertically. Spatial variability in duff is also influenced by canopy type and tree proximity.

The objectives of this chapter are to:

1. Quantify some of the physical characteristics of duff that spatially determine moisture content;
2. Determine if there are any significant differences in these characteristics based on three categories: canopy type, location and duff layer;
3. Verify that the quantified physical characteristics can be used to model duff drying.

These objectives are investigated through three laboratory experiments named *conductivity*, *moisture characteristic* and *drying*. The conductivity experiment was designed to determine the saturated hydraulic conductivity of small cross sections of the duff. The moisture characteristic experiment was used to determine both the desorption characteristic curve and the porosity of duff. All three properties are combined to produce the duff's unsaturated hydraulic conductivity.

The final experiment, *drying*, was implemented to measure the drying rate of duff in a controlled environment. The measured drying rate was then compared to the theoretical drying rate calculated using Richards equation (Equation 3.5) and the experimentally determined unsaturated moisture content. Both the drying experiment and modelling are described in a separate section entitled Verification.

3.2 Methodology

Two laboratory experiments were conducted to determine and compare the properties and hydrological responses of duff based on three categories: type, location and layer. Type refers to the tree variety present at the collection site; location refers to whether the sample was collected at a tree or in the gap between trees; and layer refers to either the upper, middle or lower portion of the duff layer. The demarcation of the duff into layers is not based on the degree of decomposition, since it is difficult to create an objective, qualitative, criterion for this division. Instead, it is based on whether the duff is closest to the surface or to the mineral soil as described below.

3.2.1 Samples

Duff samples were collected from forest stands in Alberta, Canada, near Whitecourt (54º08' N, 115º47' W, elevation 780 m) and the Biogeoscience Institute near Barrier Lake in the Kananaskis Valley (51º02' N, 115º03' W, elevation 1390 m), as shown in Figure 3.1. These areas were selected because the trees found in these areas are prevalent in most of the forested regions of Alberta. The soil type of both locations was a sandy loam. Samples were collected from lodgepole pine, jack pine, black spruce, white spruce and trembling aspen stands. In addition, samples were collected from stands comprised of a mix of the five species listed (mixed) as well as stands comprised of only lodgepole pine and white spruce (pine/spruce). A stratified random sampling approach (Petersen and Calvin, 1986) was adopted to obtain samples of duff at both tree and gap locations for the seven canopy types.

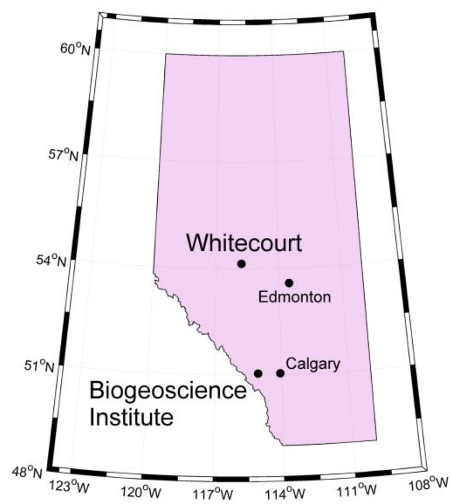

Figure 3.1: Map of the two study locations: Whitecourt and the Biogeoscience Institute.

Samples for both experiments were extracted from the duff using circular metal rings with a diameter of 5.3 cm and a depth of 2.7 cm. Upper layer samples were extracted as the top 2.7 cm of the duff and lower layer samples were extracted as the bottom 2.7 cm of the duff closest to the mineral soil. Middle layer samples were extracted as the 2.7 cm of duff equidistant from the upper and lower layer samples. The thickness of duff at the sampling locations for all canopy types, except black spruce, ranged from 6 cm to 20 cm. For the lowland black spruce stands sampled in this study (no upland black spruce sites were accessible), the bottom of the duff layer was never found. These stands were essentially bogs, with a water table located only 40 cm from the ground surface. Lower layer samples for black spruce, therefore, were collected just above the water table.

A total of 64 and 33 duff samples were collected for the conductivity and moisture characteristic experiments, respectively. The number of samples, *n*, that were collected for each group within each category are provided in Tables 3.1 and 3.2. The 33 samples that were used in the moisture characteristic experiment are the same 33 samples that were used for the ThetaProbe calibration described in Chapter 2. Physical limitations in the moisture characteristic experiment restricted the number of samples that could be tested, which is why fewer samples were used than in the conductivity experiment and why there were no samples from a pine/spruce stand. For the conductivity experiment, 6 samples were collected for each canopy type - 3 at each location: one from each of the upper, middle and lower layers. The exception to this was trembling aspen where samples were only collected at the gap between trees because of limited resources. For the conductivity experiment a minimum of 6 samples were collected for each canopy type: 2 at the trees and 4 from the gaps from both the upper and lower duff layer equally. Resources permitting, duplicate samples were collected, with emphasis placed on balancing the number collected at each location and layer. Middle layer samples were not collected for the conductivity experiment because preliminary results from the moisture characteristic experiment indicated that the differences between the upper and lower layers were more important.

3.2.2 Conductivity

The saturated hydraulic conductivity, K_s, of the duff samples was determined using a constant-head approach (Klute, 1986), where the volume of water that flowed through the sample in 30 s was measured. The flow of water was considered stable when three consecutive 30 s flow measurements produced the same volume of water. The saturated hydraulic conductivity of each sample was averaged with samples of the same kind based on the categories: type, layer and location. ANOVA was used to determine if there were significant differences within the three categories based on α=0.05.

3.2.3 Moisture Characteristic

Desorption characteristic curves for duff were measured using the methods outlined by Klute (1986). Saturated duff samples were placed on a ceramic pressure plate inside a pressure chamber where positive pressure between 0 and 2000 hPa, was applied. Samples were left at a specific pressure until they reached equilibrium and stopped draining, at which point they were weighed. After the experiment the samples were dried in a 105^{o}C oven for 24 h, and their resulting mass measured.

Porosity was determined using the Water Evaporation method and calculated using the difference in volume between the saturated sample (cm^3) and the oven dried sample (cm^3) divided by the volume of the sample (cm^3). The saturated and oven dried sample volumes were obtained from the mass of the sample at saturation (g) and the oven dried mass (g), respectively, and assuming a density of 1 g cm^{-3} for the water. Similar to the saturated hydraulic conductivity, the porosity of each sample was averaged with samples of the same kind based on type, layer and location, and an ANOVA test (α=0.05) was used to determine significant differences. Duncan's multiple-range test was used to find which groups if any in a category that were significantly different (α=0.05).

The volumetric moisture contents, θ, of the samples were plotted against their corresponding suction heads, $-\psi$ [L], to produce the desorption characteristic relationship for each sample. The volumetric water content of the samples at each pressure level was found by subtracting the oven-dried sample mass from the mass of the sample at the specified pressure, and dividing by the volume of the sample. Using non-linear regression, the observed θ and $-\psi$ relationship was fitted to the van Genuchten equation van Genuchten (1980) for the soil moisture characteristic curve,

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\alpha(-\psi)\right)^n\right]^m} \qquad (3.1)$$

where θ_r is the residual volumetric moisture content, θ_s is the saturated volumetric moisture content, α is the capillary length [L^{-1}], and n and m are dimensionless parameters related by m=1-1/n.

Curves were fit by combining like samples in groups based on type, layer and location. The porosity of a fully saturated sample is equivalent to the saturated volumetric moisture content, θ_s. Therefore, the saturated volumetric moisture content, θ_s for each curve was given the average porosity for the group. The residual volumetric moisture content, θ_r, on the other hand, was not directly measured for the duff samples. However, Wiess et al. (1998) found that the van Genuchten model for peat, a material similar to duff, was optimized when θ_r was set to zero. Therefore, for all curves θ_r was given a value of zero. The variables α and n are the soil specific parameters that were calibrated to fit the observed suction head and volumetric moisture content pairs. F-tests (α=0.05) were conducted to determine if the curves for the groups within each category were significantly different.

Using the significant desorption characteristic curves, the relative hydraulic conductivity curves, $K_r(-\psi)$, were determined using the relationship (van Genuchten, 1980),

$$K_r(-\psi) = \theta_r + \frac{\left(1-(\alpha(-\psi))^{n-1}\left[1+(\alpha(-\psi))n\right]-m\right)^2}{\left[1+(\alpha(-\psi))^n\right]^{m/2}} \tag{3.2}$$

The actual unsaturated hydraulic conductivity of the duff, $K(-\psi)$, was found from the relative hydraulic conductivity by,

$$K(-\psi) = K_r(-\psi) \bullet K_s \tag{3.3}$$

The method outlined here only provides the desorption characteristic curve. The absorption curve would differ due to hysteresis effects (Naasz et al., 2005), which are not critical here due to a focus only on modelling duff drying.

3.3 Results and Discussion

Results focus on two aspects of duff: hydraulic conductivity and moisture characteristics.

3.3.1 Conductivity

The average saturated hydraulic conductivity plus/minus the standard deviation for each group along with the number of samples used in each group, *n*, within the three categories are listed in Table 3.1. A large range in conductivity based on canopy type (0.13-0.40 cm s^{-1}) was found. However, the difference between the types is not significant (P = 0.053). There is also no significant difference between tree and gap locations (P = 0.098). However, higher conductivity values (>1 cm s^{-1}) always occur at trees. Conversely, a significant difference between the upper and lower duff layer is observed (P = 0.038), with the upper duff layer exhibiting a higher conductivity (0.34 cm s^{-1}) than the lower layer (0.22 cm s^{-1}). For type and location, the high variability within each group overlaps the variability between the groups evident from the range of standard deviations: 0.10 – 0.35 cm s^{-1}.

Table 3-1: Saturated hydraulic conductivity (± the standard deviation) averaged over grouping.

Category	Group	K_s (cm s^{-1})	*n*
Type	Black Spruce	0.34±0.10	6
	Jack Pine	0.32±0.13	6
	Lodgepole Pine	0.25±0.11	8
	Mixed	0.13±0.08	8
	Pine/Spruce	0.40±0.35	20
	Trembling Aspen	0.17±0.13	8
	White Spruce	0.18±0.13	8
Location	Gap	0.22±0.14	30
	Tree	0.32±0.29	34
Layer	Upper	0.34±0.28	32
	Lower	0.22±0.15	32

3.3.2 Moisture Characteristic

Porosity and the number of samples, n, used to determine the values shown are listed in Table 3.2. Measured porosity values range from 0.81 cm^3 cm^{-3} to 0.92 cm^3 cm^{-3} and are similar to values found in previous studies on duff (Fosberg, 1977; Ferguson et al., 2002; Miyanishi and Johnson, 2002; Redding et al., 2005) and peat (Heiskanen,1999; Weiss et al., 1998; Naasz et al., 2005; Wotton et al., 2005; Schwärzel et al., 2002; Schwärzel et al., 2006). The differences within each category exhibit a pattern similar to that seen with conductivity. Again, there is no significant difference between groupings based on location (P = 0.514). While a significant difference is found based on canopy type (P = 0.005), Duncan's test revealed that no one canopy type is significantly different from all others. The jack pine site, which had an average porosity that was significantly lower than four other canopy types, was a more open site with a denser grass understory. This difference could account for the decreased porosity observed for jack pine. A significant difference was also found based on layer (P = 0.003), however, Duncan's test showed no significant difference between the upper and middle layer. A porosity of 0.86±0.08 cm^3 cm^{-3} is found when the upper and middle layers are combined together.

Table 3-2: Duff porosity averaged over grouping, ± the standard deviation.

Category	Group	Porosity ($cm^3 cm^{-3}$)	*n*
Type	Black Spruce	0.92±0.09ab	6
	Jack Pine	0.73±0.09acde	6
	Lodgepole Pine	0.89±0.06c	6
	Mixed	0.81±0.09b	6
	Trembling Aspen	0.88±0.06d	3
	White Spruce	0.84±0.06e	6
Location	Gap	0.85±0.09	18
	Tree	0.83±0.11	15
Layer	Upper	0.88±0.08f	11
	Middle	0.84±0.07g	11
	Lower	0.75±0.10fg	11

The letters a to g refer to statistically significant differences (P < 0.05) between groups in the same category using Duncan's multiple-range test.

Similar to conductivity and porosity, the derived drainage van Genuchten curves are found to be significantly different only between the combined upper plus middle duff layers and lower duff layer. Curves are not found to be different based on location, and no one group within the category type is significantly different from all other groups. This could in part be related to the large dispersion in the data collected, as seen in Figure 3.2, which shows the relationship between the fitted and measured data. Both of these desorption characteristic curves reveal how quickly duff looses water over small pressure ranges indicating the presence of large pore spaces. After the initial drainage, the upper/middle duff layer has lower moisture content than the lower layer for any given suction, a result of the upper/middle layer being less compact. A clear air-entry suction appears to be absent in the measured desorption characteristic curves, and hence in the fitted curves. The likely cause is a limitation in the experimental apparatus, which could not maintain suction much below 0.2 m, which appears to be greater than the air-entry suction.

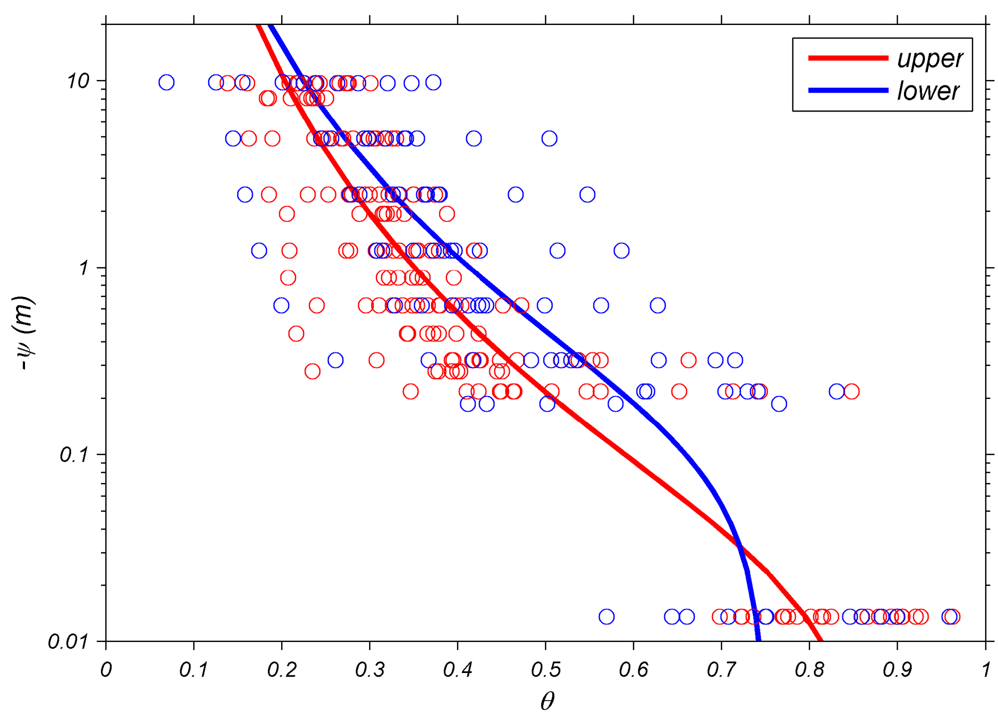

Figure 3.2: Modelled desorption characteristic curves. Circles are the observed values the models were derived from.

The values of α and *n* for Equation 3.1 are found to be 44.10 m^{-1} and 1.24, respectively, for the upper duff layer, and 8.59 m^{-1} and 1.27 for the lower layer.

These values were found by incorporating the measured θ_s for the upper/middle (0.863) and lower (0.749) duff layers in the regression.

The resulting equations are somewhat comparable to studies done on peat; see, for instance Weiss et al. (1998), or Schwärzel et al. (2006). In particular, the range of the parameter n is similar. The values determined for α, on the other hand, are higher than those in the peat studies; however, they do follow the trend that α decreases with depth.

Applying the computed values of θ and n to Equation 3.2 gives the relative hydraulic conductivity, $K_r(-\psi)$. Using these values in conjunction with the measured saturated hydraulic conductivities for the upper and lower duff layers as presented in Equation 3.3, results in the unsaturated hydraulic conductivity curves shown in Figure 3.3. These curves indicate that while the upper duff layer has a higher saturated hydraulic conductivity compared to the lower layer, the lower layer has a higher unsaturated hydraulic conductivity at higher suction pressures. This is similar to what Schwärzel et al. (2006) found for peat: the unsaturated hydraulic conductivity near saturation decreased with increasing depth and, as the peat became more unsaturated, increased with increasing depth. This phenomenon can be explained by the porosity gradient in the duff that decreases with depth. At saturation, numerous large pores will increase the flow rate of water. As saturation decreases, these numerous large pores inhibit flow. Hysteresis, shrinkage and water repellency have not been taken into account and these characteristics may play a critical role in the wetting and drying cycle of duff, and affect how water is transported through the duff to the mineral soil. But the primary concern in this study is only with the drying rate of duff. If a complete duff drying and wetting model is desired, then these effects should be investigated.

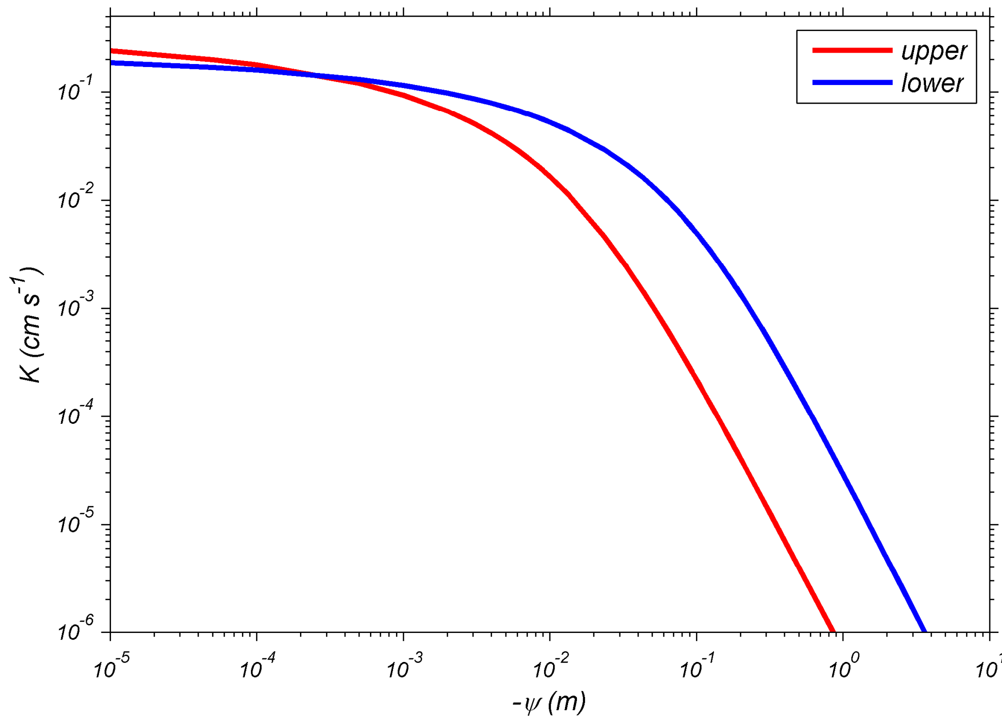

Figure 3.3: Unsaturated hydraulic conductivity curves calculated from van Genuchten.

3.4 Verification

The experimentally determined desorption characteristic and unsaturated hydraulic conductivity curves require verification. This is accomplished by comparing measured with modelled drying rates. The first step involves measuring the drying rates of duff in a controlled environment. The second step is to model the drying rates using the physical properties of the duff and then compare these with the measured values.

3.4.1 Drying

As mentioned above, duff drying rates measured in a controlled environment were used to determine drying curves.

3.4.1.1 Samples

The samples for the drying experiments came from the same study sites as those described in the conductivity and moisture characteristic experiments (see Section 3.2.1). Samples used in the drying experiments involved block sampling in which the entire sample was cut out until mineral soil was reached. When possible, at least one inch of mineral soil was kept with the block sample (5.3 cm). The sample was carefully lifted, keeping it undisturbed, and placed on top of a plastic sheet, which was used to drape and wrap the sample. Samples were then placed in hard plastic bins to protect the *insitu* characteristics of porosity and density during transportation.

A total of 24 duff samples, 60×40 cm square and of varying depths, were collected for the drying experiment: two at each location for each canopy type. The depth of sample reflected the depth of the duff to the mineral soil, with the exception of black spruce where the bottom of the duff was not found (see Section 3.2.1) and the sample depth is the depth to the top of the water table. One of the jack pine gap samples was lost prior to conducting the experiments resulting in 23 samples available for the drying experiment.

3.4.1.2 Method

The drying experiment, which was replicated twice on two different sets of duff samples, was implemented to determine the drying rate of duff over 52 days (corresponding to the Canadian Forest Fire Weather Index System, Van Wagner, 1987). In the first and second trial, 12 and 11 samples were used, respectively. The jack pine gap sample that was lost was not available for Trial 2. All samples were initially fully soaked in water for a minimum of 24 h, until fully saturated. The samples were then allowed to drain for 12 h so that all standing water was removed from the samples. For the next 52 days the samples were left to dry uncovered in their containers in an enclosed area that controlled drafts and wind turbulence, while their moisture contents were recorded.

The moisture content of the duff samples was measured every 15 min using Delta-T ThetaProbe, specifically calibrated for the duff (Chapter 2), and recorded using Delta-T Soil Moisture Loggers (DL6). Three ThetaProbes were placed in the duff samples, one vertically through the top of the duff, one horizontally in the upper duff layer, and one horizontally in the lower duff layer. The only time a lower layer sensor was not installed was when the duff at the installation location was not thick enough (<7 cm) to allow for both a lower and upper layer sensor. For Trial 1 this included both the gap and tree lodgepole pine samples, as well as the tree white spruce sample. For Trial 2 this included the tree mixed sample. As a result, a total of 33 and 32 drying curves were measured for Trials 1 and 2, respectively.

During the duration of the drying experiments, the temperature and relative humidity of the laboratory was monitored every 15 min. In the first trial an onset Temperature/RH smart sensor (THA-M006) and HOBO weather station logger (H21-001) were used, and in the second trial a HOBO RH/Temp/Light/External logger (E-348-H08-004) was used. Attempts were made to keep both temperature and relative humidity constant during the experiments, and to minimize the influence of wind, by sealing in the experimental area. However, because of the large amount of water during the beginning of the experiment, the humidity of the laboratory was higher during the beginning of the 52 day period than the end. The relative humidity ranged between 23% and 89% for Trial 1, and between 23% and 60% for Trial 2.

Drying curves were computed from the measured moisture contents using the relationship

$$\theta = ae^{bt} \tag{3.4}$$

where θ is the duff volumetric moisture content, t is time (days), b is the drying rate (days^{-1}), and a is a constant. The suitability of Equation 3.4 for each sample, trial, and sensor location was determined using an F-test (α=0.05). The drying rates of the groups within each category were compared using ANOVA tests (α=0.05) to determine if there were significant differences between group members. The testing was conducted with the two trials grouped together and with the two trials separated.

3.4.1.3 Results

A total of 33 and 32 drying curves were computed for Trial 1 and Trial 2, respectively, using Equation 3.4. Two of the curves from Trial 1 had to be discarded because they did not show any drying during the 52 day period; a problem likely caused by sensor placement. The fit for the remaining 63 curves is significant and all 63 drying rates are significantly different from each other. There are no significant differences in drying rates when curves are combined based on the categories type, layer or location, even when the trials are compared independently. However, there is a significant difference in the drying rates between the two trials, with Trial 2 having a faster drying rate than Trial 1. The drying rates as a function of their initial moisture content computed using Equation 3.4 for all the curves are shown in Figure 3.4. Highlighted in this figure are the differences between the two trials. Also included is the average for each trial with associated error.

The difference in drying rates between the two trials is attributed to the differences in environmental conditions. While attempts were made to maintain identical conditions for the two trials, there was still a substantial difference in relative humidity: the average relative humidity for Trial 1 was 43±11%, while for Trial 2 it was 27±5%. Therefore, on average Trial 1 was ~62% more humid than Trial 2. The average temperature of both trials was 20±2^{o}C. Calculation of the evaporation rate for the two trials is problematic because relationships representing the conditions of the experiment are lacking. However, since the evaporation rate is directly related to the relative humidity through the vapour pressure deficit, and since the average relative humidity of Trial 1 was larger than that of Trial 2, it is proposed that the evaporation rate during Trial 1 was smaller than during Trial 2. This, in turn, resulted in the higher average drying rate observed for Trial 2. This suggests that the environmental factors have the largest impact on duff drying, not the differences in canopy type, location or layer.

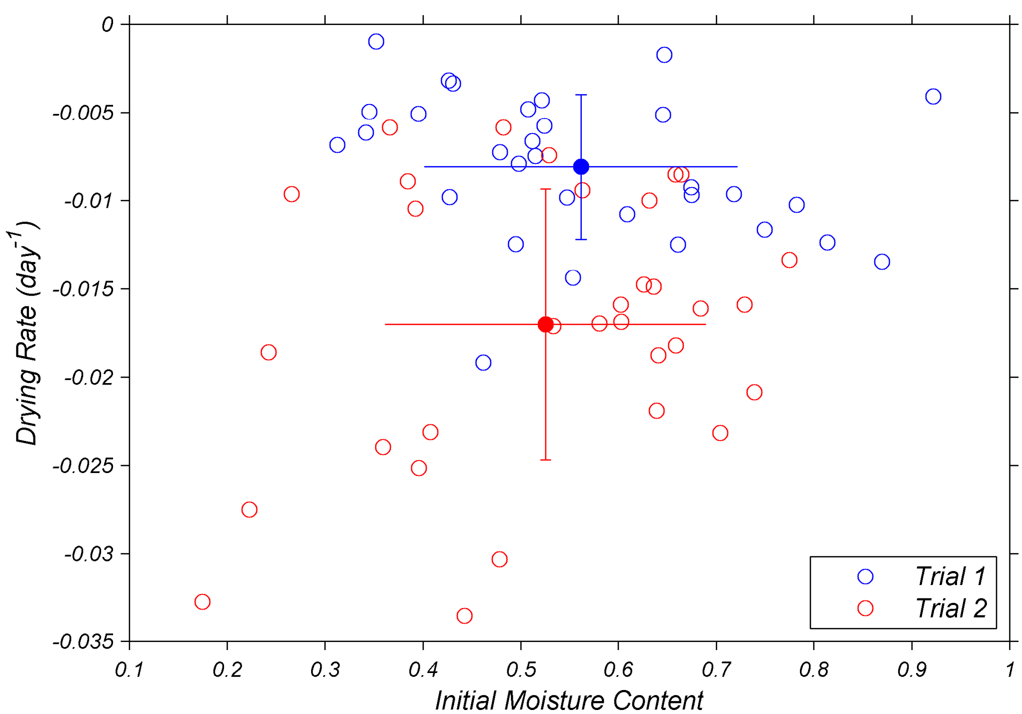

Figure 3.4: Parameters of the exponentially fit drying curves. Solid circles are the parameter means for each trial.

3.4.2 Modelling

The experimentally determined duff desorption characteristic and unsaturated hydraulic conductivity curves were verified by comparing the measured and theoretically calculated drying rates. The theoretical drying rate of duff was calculated using the one dimensional Richards equation (Richards, 1931),

$$C(\psi)\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial z}\left(K(\psi)\left[\frac{\partial\psi}{\partial z}+1\right]\right) \tag{3.5}$$

where C is the specific water capacity [L^{-1}], ψ is the pressure potential [L], t is time [T], $K(\psi)$ is the hydraulic conductivity [L T^{-1}]. The model was solved numerically using the evaporation flux as the upper boundary condition, and a constant flux of zero at the bottom of the duff layer. The duff itself was divided into layers based on the results of the desorption characteristic experiment. The drying rate was calculated as a daily value. Theoretical and measured drying rates were compared by assessing whether or not the theoretical curves fell within the range of the measured curves.

Both the desorption characteristic curve and saturated hydraulic conductivity are required to model the drying rate of duff using Richards equation, Equation 3.5. The desorption characteristic curve is used to convert moisture content, θ, into pressure potential, ψ, and the saturated hydraulic conductivity is used to determine unsaturated hydraulic conductivity using Equation 3.3. Since the only significant difference in these parameters is between the upper and lower duff layer (see Section 3.3), only duff drying rates for the upper and lower duff layer are modelled. A depth of 5 cm was used for both layers for modelling purposes because the average depth of the drying samples is 11 cm.

Another important input parameter for Richards equation is the upper boundary condition: the evaporation rate. However, given that the exact evaporation rate was not known for either trial, an alternative approach has to be employed. Instead of modelling the drying curves for each trial from the evaporation rates, the average drying curves are used to determine the evaporation rates. Evaporation rates for each trial are modified until the resulting drying curves match the average drying curves for each Trial. This results in evaporation rates of 0.185 mm day^{-1} and 0.296 mm day^{-1} for Trial 1 and 2, respectively. Consequently, the evaporation rate of Trial 2 is found to be ~62% of Trial 1, which is similar to the difference observed between the average measured relative humidities.

A limitation of the above modelling technique was the application of a constant evaporation rate. However, observed relative humidity for both trials clearly decrease over the drying period, indicating that the evaporation rate was not constant. Using a variable evaporation rate that increases over time did not notably change the drying curves. Therefore, a constant evaporation rate was considered adequate for the modelling purposes of this experiment.

3.5 Conclusions

In studying the physical characteristics of duff, porosity, desorption characteristic curves, and saturated hydraulic conductivity, all were found to exhibit greater variation vertically within the duff layer than within either canopy type or location relative to the tree. Duff is highly heterogeneous, even over small areas. This heterogeneity overshadows any of the differences based on canopy type or tree proximity. As a result, spatial models of duff moisture only need to consider the differences in physical characteristics based on depth.

Duff drying curves for the upper and lower layer were successfully modelled using the one-dimensional Richards equation for unsaturated flow through soils and the measured physical characteristics. Modelled curves were within the range of those observed in the laboratory resulting in verification of the observed characteristics. The large range in duff drying rates, however, should be acknowledged. Results of the drying experiment indicate that environmental factors are the strongest influence on duff moisture, not the differences in type, location or layer. The lack of distinction in an upper and lower duff drying rate may be an artifact of the experimental process.

Chapter Four: **Factors Influencing the Variation in Duff Moisture**[3]

Knowledge of hydrological properties assists in the development of moisture models, however alone they do not explain spatial or temporal variations. This is especially the case for duff where there is a lack of spatial pattern in the hydrological properties based on tree type or location. The properties of duff are very heterogeneous horizontally; however there is no specific pattern. Therefore, something else must be the cause of the spatial patterns in duff moisture.

The actual patterns of duff moisture need to be observed before the causes of the patterns can be established. In this chapter field observations of the small scale duff

[3] Material in this Chapter has been presented in 2008. "Assessing Factors that Influence Spatial Variations in Duff Moisture", Hydrological Processes, 22:2874-2883 in 2008 in modified form.

moisture patterns are made. Patterns both within and between 100 m^2 areas are analysed and compared. Focus is placed on assessing the relationship between moisture content and tree proximity, investigating the differences based on canopy type, as well as exploring the temporal pattern differences. Results from field observations are used to determine the scale of duff moisture patterns.

To assist in explaining the observed duff moisture patterns, other field observations are made. These included above and below canopy meteorological conditions, and duff depth at moisture measurement locations. Relationships between these field measurements and the moisture patterns are investigated. Patterns and relationships discovered are used in the next chapter to further the discussion on factors influencing duff moisture.

4.1 Introduction

Duff depth and density have a slow temporal rate of change and remain relatively constant throughout the fire season. Duff moisture, on the other hand, has a high temporal variability due to its sensitivity to meteorological conditions. Consequently, it is the changes in moisture content that influence duff consumption due to wildfire within a single season. In addition, while duff consumption is influenced by depth and density, so too is moisture content. For example, duff depth and moisture content have been found to be positively correlated, such that it is possible for duff with a high moisture content to be consumed through smouldering combustion if it is thick enough (Miyanishi et al., 1999; Miyanishi and Johnson, 2002). This makes knowledge of duff moisture a critical factor in determining the spatial distribution of consumed duff and exposed mineral soil.

Duff moisture is ultimately influenced by the input and removal of water by throughfall and evaoptranspiration, respectively. There have been a limited number of studies observing interception processes affecting duff moisture. Within stand variability has been attributed to canopy structure, with duff under tree crowns being significantly drier than duff in the gaps between crowns (Chrosciewicz, 1989; Miyanishi et al., 1999; Miyanishi and Johnson, 2002; Hille and Stephens, 2005). Interception has been identified as the primary cause for this difference. Duff at the edge of a tree crown, or in the gap between crowns, receives more precipitation than duff under a tree crown because of canopy drip or lack of interception, respectively (Crampton, 1982; Johnson, 1990; Bouten et al., 1992). Therefore, it should be possible to explain some of the spatial variation in duff moisture by modelling interception as a function of canopy type, stand density, and distance to the nearest tree. However, these relationships have yet to be quantified. A variety of sub-models and studies exist that can provide estimates of evapotranspiration if meteorological inputs and tree characteristics are known (Burman and Pochop, 1994). The transpiration portion by the trees is affected by meteorological conditions above the canopy; however, the evaporation component is affected only by conditions below the canopy. Often, data from nearby meteorological stations are employed to estimate loss of moisture to evaporation with no regard to the environment experienced by the duff at ground level.

The objective of this chapter is to quantify the patterns of spatial variations in duff moisture, and to ascertain the influence of canopy type, tree density and tree proximity on these patterns. The goal is to provide information that will increase the accuracy and confidence in spatially distributed duff moisture models. This will be accomplished through field observations of (i) interception, (ii) the relationship between above and below canopy meteorology and (iii) the spatial and temporal variation of duff moisture. Attention to the influence of duff depth on moisture content is also considered.

4.2 Methodology

4.2.1 Study Area

Field measurements for this study, which took place during June and August, 2005, were collected near the Biogeoscience Institute in the Kananaskis Valley region of Alberta (51^{o}02'N, 115^{o}03'W, Elevation 1390 m); see Figure 3.1 for location. This forested area, lying in the front ranges of the Rocky Mountains, is a montane ecological region. It is composed of both coniferous and broadleaf deciduous tree species, consisting primarily of lodgepole pine, white spruce, balsam poplar, and trembling aspen. The study area was selected because the trees found there are prevalent in most of the forested regions of Alberta. This is the same study area where some of the hydrological properties samples described in Chapter 3 were collected.

Within the study area, ten 10 m × 10 m plots were established. The description of each plot is listed in Table 4.1. Plots were selected as representatives of the stands from which they were selected with regard to stand age, structure and species composition. Mature stands that did not show signs of disturbance were selected to better emulate possible forest structure before a fire. The ten plots were chosen from four different stand types that differed by canopy composition and/or closure. The four stand types included: closed pine/spruce (plots 1-3), open pine/spruce (plots 4-5), mixed (plots 6 and 10), and aspen (plots 7-9). Multiple plots were selected relatively close together in the same stand to account for observation predictability. The two mixed plots both contained lodgepole pine, white spruce and either 6% or 50% trembling aspen. The closed and open pine/spruce plots had an average of 27 and 17 trees, respectively. The mixed plots had an average of 16 trees, and the trembling aspen plots, 22.

It should be noted that differences in canopy composition and closure result in differences in ground cover between stand types. Pine/spruce stands tended to have a ground cover of patchy moss with understory growth increasing with increasing canopy openness. Therefore, little to no understory vegetation was found on plots 1-3, while plots 4 and 5 had a patchy covering of grass and shrubs. Understory growth was more prevalent in the mixed stand, and included large areas of juniper. The floor of the aspen stand was covered by a lush growth of understory vegetation. Each 10 m × 10 m plot was marked at 1 m intervals with plastic survey flags. These flags were used to establish a local coordinate system for each plot.

The coordinate systems were used to determine the location of the trees within the plots. Average values of the diameter at breast height (DBH) for each tree type, along with the standard deviation, are also provided in Table 4.1.

Table 4-1: Description of the study plots.

Plot Number	Tree Type	Number of Trees	DBH (cm) Mean	σ
1	lodgepole pine	8	19	4
	white spruce	26	10	5
2	lodgepole pine	7	19	4
	white spruce	13	15	6
3	lodgepole pine	11	19	5
	white spruce	15	12	7
4	lodgepole pine	13	20	4
	white spruce	8	11	5
5	lodgepole pine	11	21	3
	white spruce	2	23	7
6	lodgepole pine	7	23	6
	white spruce	1	17	n/a
	trembling aspen	8	22	4
7	trembling aspen	23	17	4
	balsam popular	1	24	n/a
8	trembling aspen	24	20	3
9	trembling aspen	18	20	2
10	lodgepole pine	11	22	6
	white spruce	5	17	11
	trembling aspen	1	21	n/a

4.2.2 In situ Measurements

Meteorological conditions during the study period were monitored using three different sources. Open conditions were obtained from the meteorological station at the University of Calgary Biogeoscience Institute (referred to henceforth as the Field Station). Measurements made by this station include hourly precipitation, solar radiation, average temperature, average wind speed, average wind direction, and average humidity. Meteorological conditions measured at this station are used as the above canopy standard in this study since all measurements are made in the open, and all ten study plots were located within 3 km of its location.

Under canopy conditions were acquired through the installation of an Onset weather station under a canopy of lodgepole pine and white spruce beside plot 2. Meteorological measurements made by the station included temperature and humidity, wind speed and direction, solar radiation, and barometric pressure. Readings from the weather sensors were recorded every 15 minutes from 9 June to 17 August, and then converted to hourly averages.

In order to account for differences in the amount of throughfall under the different canopies, seven tipping bucket rain gauges were installed amongst the ten plots. One gauge was installed at the under canopy weather station. Two gauges were installed between plots 1 and 3, under the pine/spruce canopy. One of these gauges was installed in the gap between trees, while one was installed directly beside a tree. Two more rain gauges were installed on a hillslope under the pine/spruce canopy between plots 1-3 and 4-5 with one on the top of the hillslope, and one on the bottom. An additional gauge was placed in the mixed canopy between plots 6 and 10. The last gauge was installed in the trembling aspen stand, between plots 8 and 9.

Point measurements of the volumetric moisture content of the duff layer were obtained using a Delta-T ThetaProbe, specifically calibrated for the duff (Chapter 2). Moisture measurements for each plot were made every metre at the plastic survey flag marker, as well as in the middle of each marked square. This made a total of up to 222 moisture measurements for each plot. At some locations measurements could not be made because of the presence of a tree. Moisture measurements for each plot were done on ten different days between 8 June and 15 July.

Hand measurements of duff thickness were taken of each plot after all moisture measurements were made to avoid affecting the readings. Depths were taken at every 1m mark for a total of 121 measurements for every plot. Depths were not measured in the middle of each marked square because, by the end of the study, the ground there appeared trampled, which would adversely affect depth readings.

4.3 Results

4.3.1 Interception Processes and Net Precipitation

Gross precipitation measurements recorded at the Field Station are shown in Figure 4.1, with days provided before the first measurement to account for antecedent moisture conditions. Highlighted in the figure are two rainfall events that had an important impact on duff moisture: one on 17 June, with 128.4 mm in 40 h, and one on 27 June, with 37.4 mm in 28 h.

Normally, direct throughfall data are not available for forested catchments. Rain gauges are traditionally installed in open areas and provide estimates of above canopy, or gross, values of precipitation. Figure 4.2 depicts the ratio of the amount of rainfall collected at an under canopy gauge to that collected at the Field Station averaged over all recorded rainfall events. Error bars in this figure represent one standard deviation. The large standard deviation in the throughfall percentages is caused by the difference in the amount of rainfall that penetrates the canopy based on rainfall intensity and duration; the shorter and lower the intensity of the rainfall event, the less likely it will penetrate to the forest floor.

Based on the average throughfall ratio, the under-canopy gauges can be divided into three groups: pine/spruce canopy gauges that are less than 0.7 m from a tree (tree and mixed gauge), pine/spruce or mixed canopy gauges that are greater than 0.7 m away from a tree (between, top, bottom, mixed and station gauge), and the trembling aspen canopy gauge. A value of 0.7 m was considered the threshold distance that distinguished between a gauge being definitely under a tree canopy or in the gap between tree canopies. Average throughfall ratios can be misleading

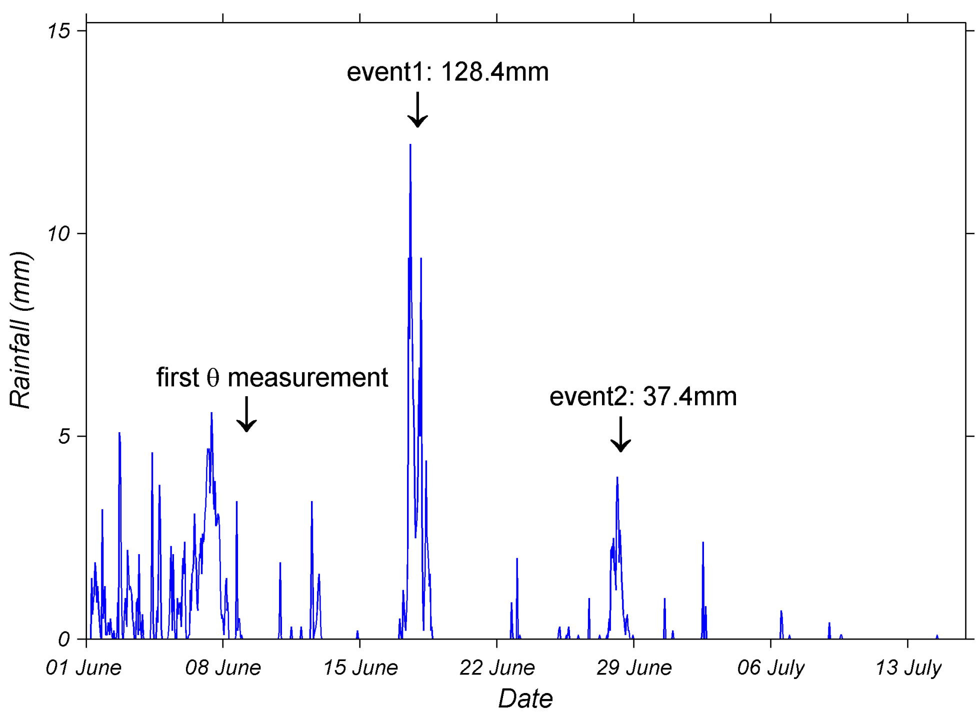

Figure 4.1: Measured hourly rainfall.

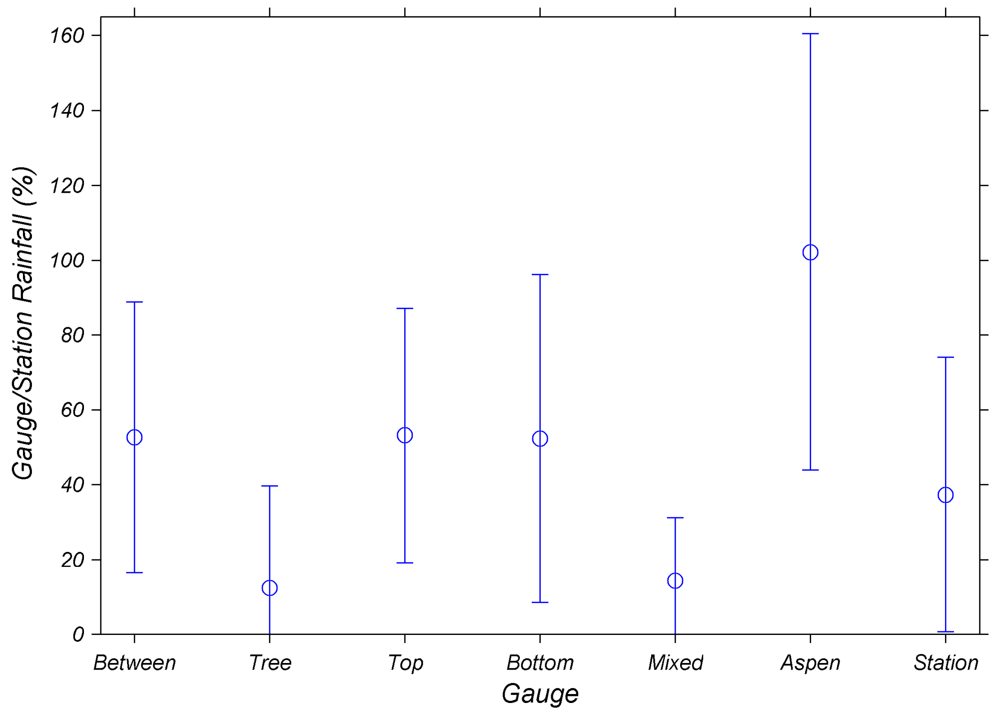

Figure 4.2: Average ratio of gauge rainfall to Field Station rainfall for all events.

because they place more emphasis on the more numerous smaller rainfall events. Smaller rainfall events intercept more rainfall as a percentage of gross precipitation because canopy storage must first be filled. A better way to determine the influence of interception is to consider the linear relationship between gross precipitation and gauge rainfall. The result of this linear interpolation for the three gauge groupings is shown in Figure 4.3. All three interpolated lines fit the data well with coefficients of determination ≥ 0.90. Slopes indicate that pine/spruce gauges that were greater than 0.7 m from a tree experienced interception of approximately 28%. More rainfall was intercepted at gauges that were less than 0.7 m away from a pine or spruce tree, with approximately 62% of the gross rainfall intercepted. Even though only a limited number of rain gauges were employed in this study, the values of throughfall are comparable to other studies under different canopy types (Ford and Deans, 1978; Crockford and Richardson, 2000; Miyanishi and Johnson, 2002), and follow the intuitive trend that throughfall is greater at the edge of tree crowns than under tree crowns. Results for the trembling aspen gauge were inconclusive, but they did indicate that an aspen canopy intercepts less precipitation than a pine/spruce canopy.

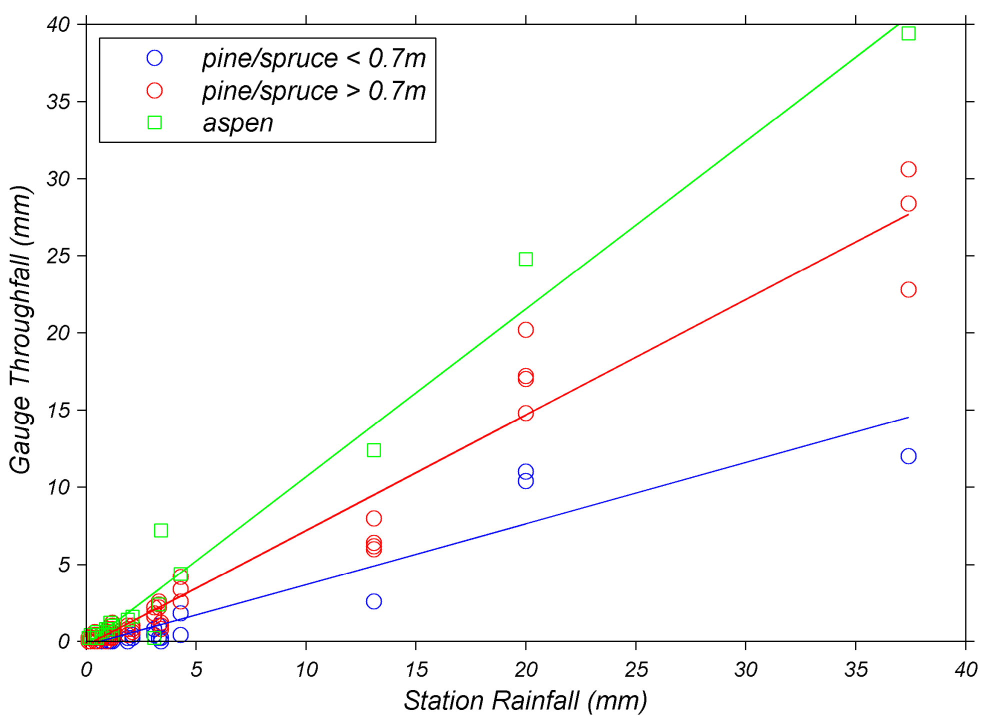

Figure 4.3: Relationship between station rainfall and gauge throughfall for different canopy types and distances to a pine/spruce tree.

Rain gauges were calibrated as per manufactures specification prior to use and their errors are estimated to be anywhere from ±1% up to 20 mm/h (Onset Computer Corporation). These errors however, are considered valid under ideal conditions and the use of these rain gauges as indicators of throughfall may actually involve larger errors. Unfortunately, because of limitations on the number of rain gauges available for this study, duplicate measurements of rainfall in the same location (to reduce random error) could not be made. These errors should be evaluated in future studies. However, discussions made in this work involving multiple rainfall measurements will involve errors that are smaller than the errors involved in single rainfall measurements.

4.3.2 Ground Level Meteorology

Canopy effects on duff affected meteorology are shown in Figure 4.4, where the air temperature, solar radiation, relative humidity, and wind speed are compared between the under canopy pine/spruce station and the above canopy Field Station. Included for reference is the line of identity, which represents the line where there is no difference between the above and below canopy measurements. These plots indicate that there is general agreement between above and below canopy temperature and relative humidity, however the scatter is large. Conversely, there is poor agreement between above and below canopy solar radiation and wind speed. This observation is supported using a paired t-test on the differences between the above and below canopy measurements. The difference in mean and standard deviation, and the probability of the mean difference being zero for each parameter are provided in Table 4.2. While there is no significant difference between above and below canopy temperature and relative humidity, there is a significant difference between solar radiation and wind speed. Solar radiation measured at the pine/spruce station was found to be 14% of that measured at the Field Station, and this fraction was found to be 17% for wind speed.

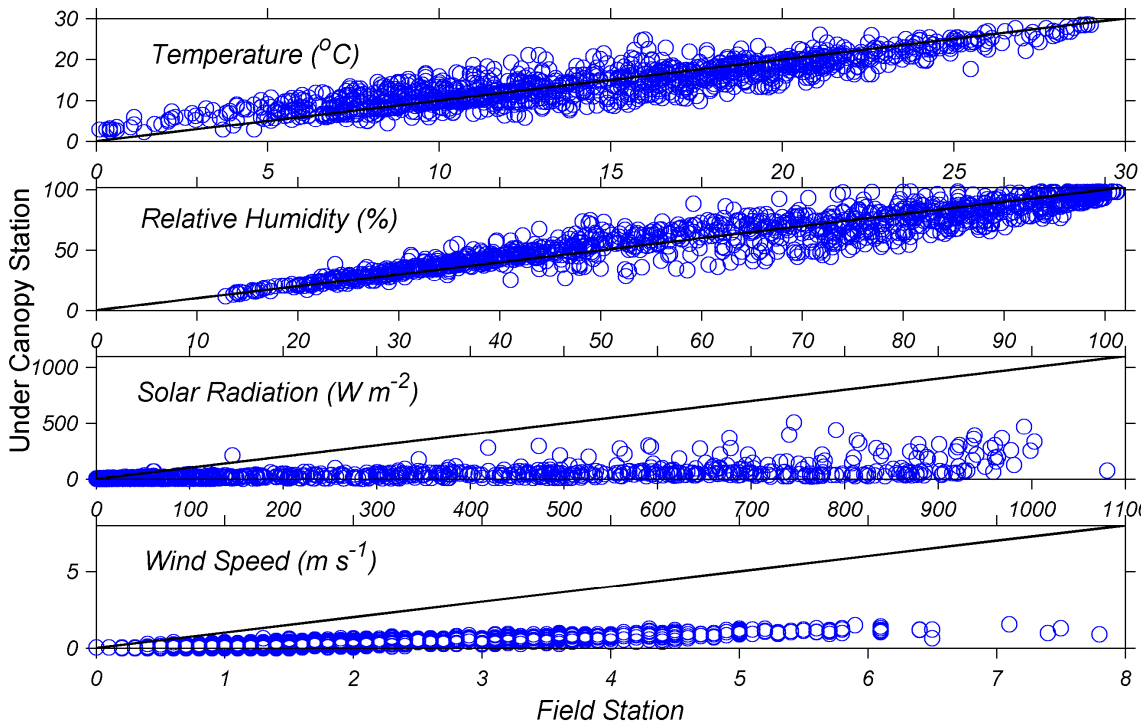

Figure 4.4: Comparison of hourly averaged meteorological observations made under the canopy and at the Field Station. Graph lines indicate a 1:1 ratio.

Table 4-2: Statistics on the difference between above and under canopy weather measurement.

Meteorological Parameter	Mean	σ	Probability (μ=0)
Temperature (°C)	0.1	2.7	0.087
Relative Humidity (%)	0.2	8.5	0.374
Solar Radiation (W m^{-2})	196.8	255.8	<0.001
Wind Speed (m s^{-1})	1.7	1.1	<0.001

Figure 4.4 compares the above and under canopy hourly meteorological measurements over 24 hours, resulting in no significant difference based on

temperature. However, if temperature values are compared at specific times a different pattern is observed. Under canopy temperature measurements are, on average, 2°C higher at midnight and 2°C lower at noon than above canopy measurements. The tree canopy acts as an insulator, slightly sheltering the under canopy from the extremes in above canopy temperatures. Since relative humidity is dependent on the air temperature, it also is affected by the insulating properties of the canopy.

4.3.3 Moisture Variability

The average moisture content for each plot is provided in Figure 4.5, with plots grouped based on canopy type. Also shown on this figure are the dates of the two important rainfall events highlighted in Figure 4.1. After each of these rainfall events there was an increase in the average moisture content of the duff, which is more prominent after the second rainfall event. For example, for Plot 1, the average moisture content for the first measurement after the first rainfall event was 22%, while for the second rainfall event it was 33%. From this it might be concluded that there was a greater rise in moisture content after the second event, even though there was more rain during the first event (37.4 mm compared to 128.4 mm). However, this is an artefact of the time between the end of the rainfall event and when the moisture measurements were taken. Moisture measurements were taken immediately following the second rainfall event, while measurements for the first rainfall event did not take place until 3 days afterward. Average moisture values are similar 3 days after each of the rainfall events, with values being within 1% of each other. While duff calibrated moisture values were found to have an error of nearly 10% (see Chapter 2), the error in the computed averages of repeated measurements is fairly small.

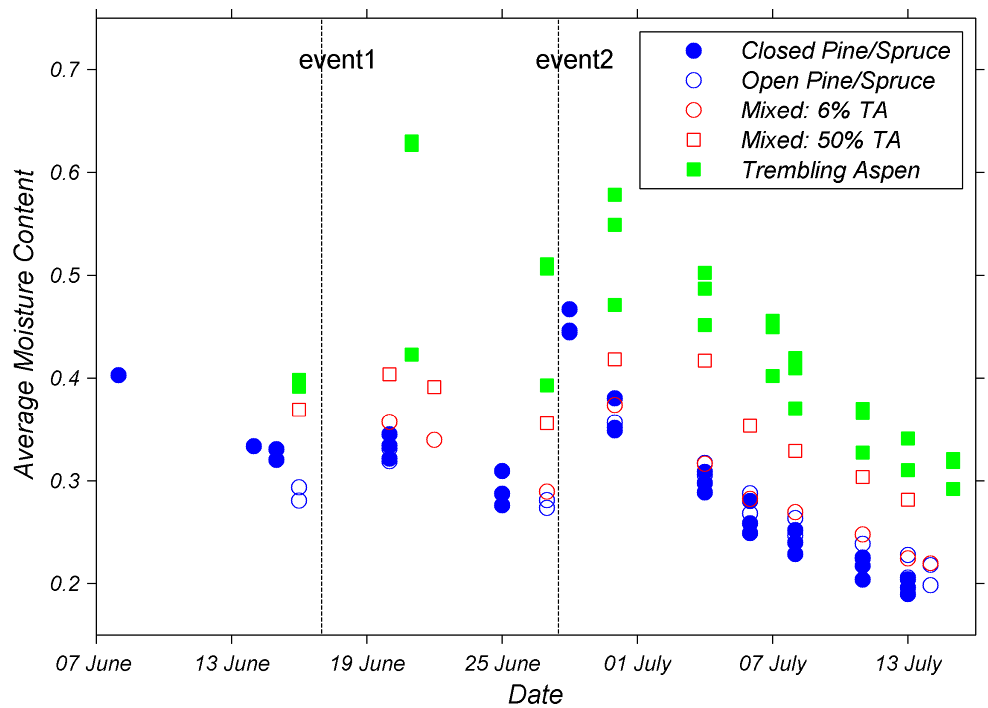

Figure 4.5: Duff averaged volumetric moisture content in the plots. Dashed lines mark occurrence of two significant rain events.

To examine drying rates during the 17 day drying period between 28 June and 15 July, exponential relationships were interpolated for the trembling aspen and pine/spruce plots. These drying curves are dependent on the meteorological conditions, and hence are not strictly transferable to other locations, but are useful for comparison purposes. The resulting drying equations for trembling aspen, open and closed pine/spruce plots are, respectively,

$$\theta = 46e^{-0.048t} \; (r^2 = 0.90, P < 0.001), \quad (1)$$

$$\theta = 28e^{-0.058t} \ (r^2 = 0.96, P < 0.001), \tag{2}$$

$$\theta = 31e^{-0.077t} \ (r^2 = 0.97, P < 0.001), \tag{3}$$

where θ is in %, and *t*, the drying time, is in days. The important component of these equations is the drying rate. Using a t-test, it was found that the drying rate for closed pine/spruce was significantly higher than that for either the open pine/spruce ($P < 0.001$) or the trembling aspen ($P < 0.001$). However, the drying rate for the open pine/spruce and trembling aspen was not significantly different at the 5% confidence level ($P = 0.082$). This lack of difference implies that regardless of canopy type, the duff drying rate is the same. The difference between the closed pine/spruce and the open pine/spruce and trembling aspen plots can be attributed to interception differences between the canopies. The 17 day drying period was not free of precipitation. The eight precipitation events that did occur were caused by small convective storms with an average intensity of 0.4 mm h^{-1}. As the duff dries under the influence of small rainfall events, the average moisture content of the open canopy plots becomes slightly greater than the more closed canopy plots, and its drying rate slows slightly.

In addition to the average moisture content for each plot, it is also instructive to look at the variation in the moisture content (σ_θ). When the variation in the standard deviation of volumetric moisture content was examined for the 17 day drying period it exhibited the same pattern observed in the average moisture content. The higher the average duff moisture content, the greater the variation in moisture content within each plot. Consequently, σ_θ is higher in trembling aspen stands than in pine/spruce stands. Exponential trends can also be interpolated for the standard deviation of the moisture content. For trembling aspen, open and closed pine/spruce, the equations for these lines are, respectively,

$$\sigma_\theta = 9e^{-0.040t} \quad (r^2 = 0.87, P < 0.001), \tag{4}$$

$$\sigma_\theta = 6e^{-0.041t} \quad (r^2 = 0.88, P < 0.001), \tag{5}$$

$$\sigma_\theta = 7e^{-0.050t} \quad (r^2 = 0.90, P < 0.001), \tag{6}$$

where σ_θ is in percent. There is no significant difference in slope between closed pine/spruce and either open pine/spruce ($P = 0.15$) or trembling aspen ($P = 0.064$), or between open pine/spruce and trembling aspen ($P = 0.83$). Therefore, while there is a decrease in variation in moisture content as the duff dries, it is not dependent on canopy type.

Duff moisture has previously been found to be correlated to the proximity to the nearest tree, making it the logical choice for the spatial variation in duff moisture. Figure 4.6 plots the relationship between duff moisture and proximity to the nearest tree for each measurement of Plot 1 on 30 June. This figure demonstrates that duff closer to a tree is drier than duff farther away from a tree. The slope of the linear model was found to be significant ($P < 0.001$), but the coefficient of determination was found to be small ($r^2 = 0.13$). A significant linear relationship relating moisture content to tree proximity was found for a majority of the other plots on the different measurement days. Exceptions to this included Plots 6 and 7. None of the observations of Plot 6, and only three observations of Plot 7, was found to have a significant relationship. The reason for this is attributed to the properties of these plots. The understory of Plot 6 was composed of a large amount of juniper; the implications of which are discussed later. Plot 7 was a very rocky site with thin duff, which did not allow for the proper insertion of the moisture probe at all locations.

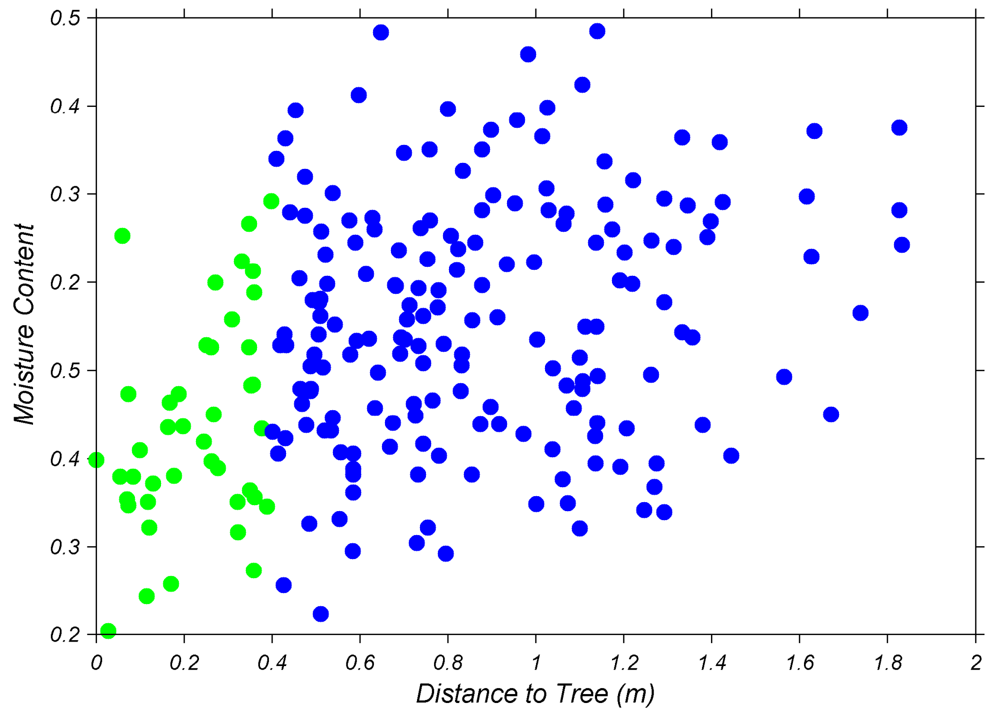

Figure 4.6: June 30th plot 1 moisture content versus distance to the nearest tree (locations within 40 cm are shown in green).

While the relationship between moisture content and tree proximity is significant in most cases, the relationship itself varies depending on the plot and the day of measurement, making it difficult to obtain a single relationship for even a specific plot. Therefore, a Wilcoxon Rank-Sum test was applied to the data to find, for each canopy type, the critical distance at which the moisture content closer to a tree is significantly drier than the moisture content farther away from a tree. The mean moisture content within a distance x from a tree was compared to the mean moisture content greater than a distance x from a tree. The distance x was expressed in cm and was given values from 10 cm to 100 cm, for every 5 cm. Figure 4.7 shows the results of this analysis. For both the pine/spruce and pine/spruce open plots, the critical distance where the moisture content near the tree was significantly drier than the moisture content farther away from the tree was 40cm. This critical distance is highlighted in Figure 4.6, with the points within 40 cm of a tree highlighted in green. For the trembling aspen canopy, there was no critical distance. This would indicate that for trembling aspen, the spatial variation in duff moisture is not related to tree proximity, at least for the sampling interval in this study. The mixed plots show mixed results. The mixed plot that was made up of 50% trembling aspen, like the pure trembling aspen canopy, had no critical distance. Conversely, the mixed plot that was made up of only 6% trembling aspen had a critical distance of 35 cm, which is comparable to the pine/spruce canopies. This implies that a mixed plots' behaviour can be attributed to its primary species. Pine/spruce plots were found to be significantly drier within 40 cm of a tree. Since this value holds regardless of canopy closure, it can be considered a property of the tree type and not the tree density.

In addition to tree proximity, ground cover can also affect the moisture content of duff. To explore this phenomenon, a more detailed investigation was applied to Plot 6, where approximately 48% of the plot was covered by juniper. No relationship was found between tree proximity and either moisture content or location of juniper. When the duff is wet, such as on the first measurement made after the second significant rainfall event of 30 June (see Figure 4.1), there is a significant difference between the moisture content of the juniper and non-juniper locations ($P < 0.001$). The moisture content of the juniper locations is significantly drier ($\overline{\theta}$ = 27%) than at the non-juniper locations ($\overline{\theta}$ = 33%). However, on 13 July, after a 14 day drying period, there was no significant difference ($P = 0.068$) between duff moisture of the juniper ($\overline{\theta}$ = 17%) and non-juniper locations ($\overline{\theta}$ = 18%). This indicates that juniper intercepts precipitation, preventing it from wetting the duff layer, causing a moisture differential in duff between juniper and non-juniper plots. As the duff dries, the juniper acts as a protective layer, reducing the amount of evaporation from juniper plots. Consequently, the spatial variation in duff moisture decreases as the duff dries. This is the same phenomenon observed to occur because of tree canopies.

4.3.4 Depth Variability

The variation in duff thickness can be investigated in terms of differences both between and within canopy types. Between canopy differences can be found by comparing the average depth for each plot. No significant difference was found between the closed and open pine/spruce plots ($P = 0.28$). Therefore, the closed and open pine/spruce plots were combined and averaged, and are referred to as the combined pine/spruce plots. There was a significant difference between the combined pine/spruce and the trembling aspen plots ($P < 0.001$). In addition, there was a significant difference between the mixed plot, which was made up of 6% trembling aspen, and both the combined pine/spruce (P = 0.002) and trembling aspen plots (P < 0.001). The duff layer was, on average, thicker for the trembling aspen plots than for the pine/spruce combined plots, with an average depth of 11 cm and 9 cm, respectively. The average depth of the mixed plot, 10 cm, was in between that found for the other two canopy types. The standard deviation for all averages was 4 cm.

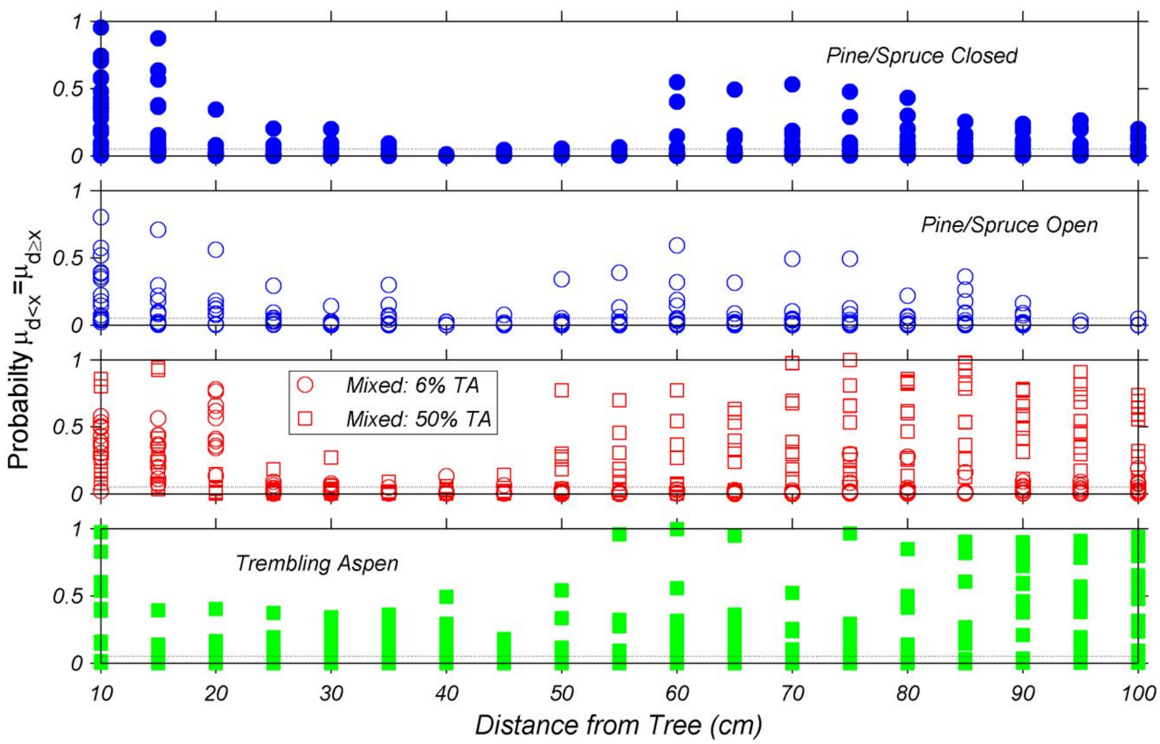

Figure 4.7: Probability that the mean moisture value within a specified distance from a tree is different from the mean moisture value outside that distance. Horizontal dotted lines represent the 0.05 significance.

4.4 Discussion

It is evident that canopy type has the strongest influence on duff moisture both spatially and temporally. This is especially apparent when comparing interception qualities between canopy types. Throughfall measured under the trembling aspen canopy was at times larger than the above canopy rainfall. While this might seem strange, it is not unheard of in broadleaf forests, where throughfall can be channelled by the leaves (Crockford and Richardson, 2000). The trembling aspen canopy essentially had no interception, but it did tend to channel the water. However, since only one throughfall gauge was installed under the trembling aspen canopy, it is not possible to identify locations of greater interception. The trembling aspen gauge recorded throughfall for all rainfall events, even events with as little as 0.1 mm h^{-1}. This was not the case for the pine/spruce canopies where on average ~28% of the rainfall was intercepted, with this value increasing to ~62% within 0.7 m from a tree. This indicates that in pine/spruce canopies a sub-metre scale representation of the canopy should be considered for accurate duff moisture measurements.

Whether or not the duff becomes saturated during a rain event depends upon not only the amount of rainfall, but the antecedent moisture condition of the duff. Preceding both of the significant rainfall events the moisture content of the duff was relatively high, with a value of 22% 3 days before event 1, and 17% 2 days before event 2. While it is believed that both of these rainfall events would have saturated the duff regardless of its antecedent moisture, results from this study cannot explicitly conclude this. Dry duff is slightly resistive to the absorption of water, and therefore, more difficult to wet. However, rainfall of a high enough intensity and/or duration will effectively wet the duff.

Temperature and relative humidity were not affected by a pine/spruce canopy, but wind speed and solar radiation were. Wind speeds under the canopy were 17% of wind speeds above canopy, while the ratio for solar radiation was 14%. Differences in above and under-canopy weather conditions should be taken into consideration when calculating wetting and drying rates of duff.

Regardless of the amount of canopy closure and its effect on ground-level meteorology, duff began to dry immediately following the end of rain so that after only 3 days, its moisture content was considerably reduced. All canopy types exhibited the drying and wetting trend, but with different ranges. As expected, trembling aspen plots were wetter than the pine/spruce plots, and open pine/spruce plots were wetter than the more closed pine/spruce plots. These differences in moisture content based on canopy type follow the trends observed in throughfall, and hence are considered to be related to interception. An interesting observation is the behaviour of the mixed plots, Plots 6 and 10. Their average moisture contents tended to fall between that of trembling aspen and pine/spruce, with one plot always being closer to the trembling aspen values than the other. Not surprisingly, Plot 6, with 50% trembling aspen, falls closer to the trembling aspen values than Plot 10, with only 6% trembling aspen.

As the duff dries, the standard deviation in plot moisture content decreases, increasing again after each of the two significant rainfall events. This pattern can be attributed to the spatial variation in throughfall and evapotranspiration, and has also been found in a study by Schaap et al. (1997). Interception patterns cause the duff in the gaps between trees to be wetter than the duff closer to the trees initially following a rainfall. Evapotranspiration will be greater in these wetter portions of the duff because of greater solar radiation values, and greater root uptake (Ziemer, 1968; Bouten et al., 1992). Therefore, after long periods of drying, the spatial variation in duff moisture becomes negligible and can essentially be considered uniform (Hille and Stephens, 2005).

Pine/spruce plots were found to be significantly drier within 40 cm of a tree. Since this value holds regardless of canopy closure, it can be considered a property of the canopy (tree) type and not the tree density. A distance of 40 cm falls directly in the middle of the critical distance values for complete duff removal following a forest fire found in a study done by Valeo et al. (2005). In their study, they found that the probability of duff consumption was approximately double within 30 cm of a jack pine tree and within 50 cm of a black spruce tree. Since duff consumption is related to moisture content, the critical distance values for consumption are most likely related to the critical values for locations of drier duff. Because the pine/spruce plots are essentially mixed plots, it stands to reason that they exhibit a critical value between that of a pure pine and pure spruce canopy. The difference in the critical distance between canopy types is likely related to the different extents of the canopies. That is, canopy shape, size and structure, which are the same factors influencing throughfall.

With regard to duff depth, observations from this study indicate that trembling aspen plots have thicker duff than pine/spruce plots, and that mixed plots have depths in between these two. This pattern is similar to that seen in duff moisture, where trembling aspen plots have higher moisture contents than pine/spruce plots. This could lead to the conclusion that, at the canopy scale, wetter duff is thicker. Indeed, other studies have found that duff tends to be thicker in wetter and colder plots (Potts et al., 1983; Kasischke and Johnstone, 2005), and have even attributed the depth differences to a hydraulic hillslope gradient (Miyanishi and Johnson, 2002). However, it could be argued that it is also the canopy type and structure that influences both duff depth and moisture. For example, trembling aspen canopies have greater annual litter fall and have lower interception rates than pine/spruce canopies, making their duff both thicker and wetter. Within canopy variation of duff depth should, like duff moisture, be related to tree proximity. Hille and Stephens (2005) found duff depth to be larger closer to trees than between trees, primarily due to increased litter fall directly beneath canopies. However, this pattern was not observed in any of the plots in this study, where no relationship was found between duff depth and tree proximity. In addition to the lack of a linear relationship between duff depth and tree proximity, there was also a lack of a critical distance defining significantly different depths. Even though no relationship was found between duff depth and tree proximity, it does not mean that such a relationship does not exist. Qualitative observations made in the field did indicate that duff depth was larger near the base of trees. However, this was true primarily for locations between the major roots of the trees. Duff depth on top of the major roots was limited by the presence of the roots. Since depth measurements were made on a regular grid and root location was not taken into consideration, shallower than expected duff depths were measured for some of the points closer to a tree. In addition, larger than expected duff depths were measured at areas farther away from trees often due to the presence of things such as decaying logs. Therefore, while duff depth is likely influenced by tree proximity, it is also affected by other factors that can mask this relationship. Problems with relating duff depth to tree proximity made it difficult to relate moisture content to duff depth, since there is a relationship between duff moisture and tree proximity.

4.5 Conclusions

The 2005 field season provided a good range of meteorological observations beginning with a wet spring and ending with a dry late summer. This provided the opportunity to observe duff moisture under a variety of conditions; however, further studies and fieldwork are required in order to make greater generalizations about the processes observed. Field observations made at very high spatial resolutions in pine/spruce canopies demonstrated that canopy type, tree density and tree proximity all have some influence on the spatial distribution of duff moisture through the processes of interception and evaporation. However, unlike pine/spruce canopies, interception did not appear to be a factor in trembling aspen canopies because of leaf water channelling which allowed significant fractions of throughfall. Tree proximity affects duff moisture in pine/spruce canopies but no relationship between tree proximity and duff moisture was found for trembling aspen canopies. Furthermore, no relationship was found between duff depth and moisture content.

Temperature and relative humidity remained unaffected by pine/spruce canopies when compared over a day, but wind speed and solar radiation were reduced below the canopy. There is a difference in above and below canopy temperature and relative humidity when specific times are taken into consideration because of the shielding of the canopy to both increases and decreases in temperature. Reduction factors should be applied to these parameters if a conventional method of evaporation such as the Hargreaves Method is to be used to estimate evaporation from duff in a closed mature canopy. The relationship between the reduction factor and canopy closure however, requires further research.

This study demonstrated that canopy type and tree proximity at the centimetre scale are the most prominent spatial influences on duff moisture and therefore, when developing a large scale spatially distributed duff moisture model, appropriate weight and consideration should be given to the centimetre scale of canopy composition and tree proximity.

Chapter Five: **Hillslope Effects**

This chapter directly investigates the influence of soil moisture and topography on duff moisture. This is accomplished through measurements of both soil and duff moisture along different hillslopes. The interrelated effects of tree proximity and hillslope position are questioned and resolved. Results from Chapter 4 are heavily drawn upon; specifically that duff moisture overall shows lower values within 0.4 m from a tree. The reason for the decrease in spatial variability as duff dries is resolved.

5.1 Introduction

Duff water-balance results from precipitation inputs, evapotranspiration losses and moisture fluxes from both the adjacent soil and duff. The largest influence on this water balance is from net precipitation resulting from the interception process.

Therefore, duff at the tree crown edge or in the gap between tree crowns receives more precipitation than duff under a tree crown (Crampton 1982; Johnson 1990; Bouten et al. 1992) resulting in significantly drier duff closer to trees than in the gap between trees (Miyanishi and Johnson, 2002; Hille and Stephens, 2005). In Chapter 4, duff was found to be significantly drier within 40 cm of a tree for a pine/spruce canopy, suggesting that interception affects the spatial variability of duff at the centimetre scale. In addition higher tree densities provide increased canopy closure, which will result in decreased duff moisture conditions when similar canopy types are compared. Structural variations between tree species lead to differences in interception patterns and rates. Consequently, duff moisture is also influenced by the tree species present, with considerable differences observed between coniferous and broadleaf canopies (Chapter 4).

Duff drying and moisture loss is mainly affected by evapotranspiration, and therefore, primarily determined by meteorological conditions such as net radiation, relative humidity, wind, and temperature. These meteorological conditions are generally considered large scale phenomena. As a consequence, it is unlikely that evapotranspiration is a principle factor in small-scale (ie., centimetre scale) spatial variations in duff moisture. A common system for predicting average duff moisture over large area in Canada, known as the Duff Moisture Code, uses daily weather observations along with empirical drying curves (Van Wagner, 1987). The Duff Moisture Code, however, only generates average values for large areas, ignoring smaller scale variability.

The flow of water through the duff itself may impact moisture variability. Horizontal movement of water in level duff is normally considered negligible because of the high porosity (Tiktak and Bouten, 1992); however, it is recognized that water will move laterally down a hillslope and collect in depressions making downslope areas wetter than upslope areas (Potts et al., 1983). Duff moisture has been observed to be greater at the bottom of a hillslope than the top (Potts et al., 1983; Samran et al., 1995). Preferential flow paths on hillslopes corresponding to a precipitation event have also been observed for duff, but with short connective distances (McDonnell et al., 1991; Brown et al., 1999; Noguchi et al., 1999; Kim et al., 2005). These preferential flow paths have been attributed to a hydrophobicity of the mineral soil at the base of the duff during dry conditions, inhibiting infiltration (Sevink et al., 1989). Since these preferential flow paths are short, questions arise as to their applicability along an entire hillslope, and accordingly, to a duff hillslope moisture gradient.

Variability in duff moisture might also be influenced by the moisture content of the mineral soil directly underneath, although studies on this interaction have been limited. Moisture gradients along hillslopes have been observed in the mineral soil, thus, if duff moisture is influenced by mineral soil moisture then hillslope influences on duff moisture would also be expected.

The purpose of this chapter is to establish the influence of the hillslope on the spatial variation of duff moisture. This was accomplished by focusing on two objectives. The first objective is to determine the relationship, if any, between the moisture content of the duff and the mineral soil along a hillslope. Applying the observations of the first objective, the second objective is to ascertain what relationship hillslope had on the spatial variability of duff moisture in conjunction with tree proximity. These relationships were investigated both spatially and temporally, with temporal relationships relating to the wetting and drying processes of the duff.

5.2 Methodology

5.2.1 Study Area

Data for this study was collected over two field campaigns, in the summer of 2005 and 2006, referred to as Field 1 and Field 2, respectively. The study sites, which were primarily composed of a mix of lodgepole pine and white spruce, were located near the Biogeoscience Institute in the Kananaskis Valley region of Alberta, Canada (51^{o}02'N, 115^{o}03'W, Elevation 1390 m); see Figure 3.1.

5.2.2 Field 1 Moisture Measurements

For the first field campaign, conducted between June 22 to August 5, 2005, two opposite facing hillslope transects were established: Slope 1-1 facing 20^{o} N and Slope 1-2 facing SE. Slope 1-1 had a length of 36 m and a 29% slope, and Slope 1-2 was 27 m long with a 22% slope. For both Slopes 1-1 and 1-2, 1 m Profile Probe access tubes were installed at the top and bottom of the hillslopes in the gaps between trees. Measurements of duff and soil volumetric moisture content were carried out at these locations using a Delta-T Profile Probe type PR1. This field campaign was designed to determine the moisture relationship between the duff and the mineral soil directly beneath. Therefore, for this field campaign only, profile probe readings taken at 10, 20, and 30 cm were considered. Measurements of duff moisture occurred at the 10 cm depth, at the bottom of the duff layer, while soil moisture was measured depths of 20 and 30 cm from the top of the duff surface. Measurements were made on six days over a two week period: 29 June, 1 July, 5 July, 7 July, 12 July, and 14 July. For analysis, moisture content at each measurement location and depth was averaged over the six day period. Comparison between averaged top and bottom hillslope moisture values at each of the three depths were made using t-tests (α=0.05).

Continuous point volumetric moisture measurements were also made in the gap between trees at the top and bottom of Slope 1-1 using Delta-T ThetaProbes and DL2 soil moisture loggers. The ThetaProbes were specifically calibrated for the duff (Chapter 2), but the general mineral soil calibration provided by the manufacturer was used for the soil. Duff moisture was monitored both vertically and horizontally. Vertically, the probe was inserted through the top of the duff perpendicular to the soil surface. Horizontally, the probe was placed 5 cm from the mineral soil parallel to the soil surface. The total duff depth was 10 and 12 cm for the top and bottom of the hillslope, respectively. Soil moisture was also monitored at each location, just below the duff layer. Daily noon moisture values were logged from 22 June to 5 August.

5.2.3 Field 2 Moisture Measurements

In the second field campaign, conducted between July 20 and August 4, 2006, two new 60 m hillslope transects were established: Slope 2-1 and Slope 2-2. The two transects are shown in Figure 5.1, where the bottom of Slope 2-1 coincided with the top of Slope 2-2. Each transect was 2 m wide with Slope 2-1 facing 300° N with a 12% slope, and Slope 2-2 facing 20° N with an 11% slope. The difference in height from the bottom of Slope 2-2 to the top of Slope 2-1 was found by levelling, with measurements made every 3 m in the middle of the two transects. In addition, the location of the trees inside and within 2 m of the edges of each transect were manually measured and recorded. Within 2 m of the transect edges, there were 44 and 22 trees along Slope 2-1 and Slope 2-2, respectively.

Profile probe access tubes were installed 3 m from both transects' edges at the top, middle and bottom of the slope. Because of the orientation of the two transects, three access tubes were installed at the bottom of Slope 2-1 and the top of Slope 2-2 resulting in a total of 11 tubes. The placement of the access tubes is shown in Figure 5.1. When a 1 m profile probe access tube is fully installed, a profile probe can measure moisture contents at depths of 10, 20, 30, 40, 60 and 100 cm. However, problems with the sensor did not allow for reliable readings at the 40 cm depth, therefore, these reading were discarded. In addition, difficulty in installing some of the access tubes did not allow for the full insertion to the 1 m depth. In these cases, depth corrections were applied so that the actual depths were represented. For example, if the profile probe access tube could only be inserted to a depth of 90 cm, measurements were taken at 10, 20, 50 and 90 cm. Profile probe measurements of soil moisture were made daily over the 16 days, and the values at each depth at each location averaged over the 16 days. For analysis purposes, multiple readings at each hillslope location were also averaged, resulting in a single moisture value for the top, middle and bottom at the six depths.

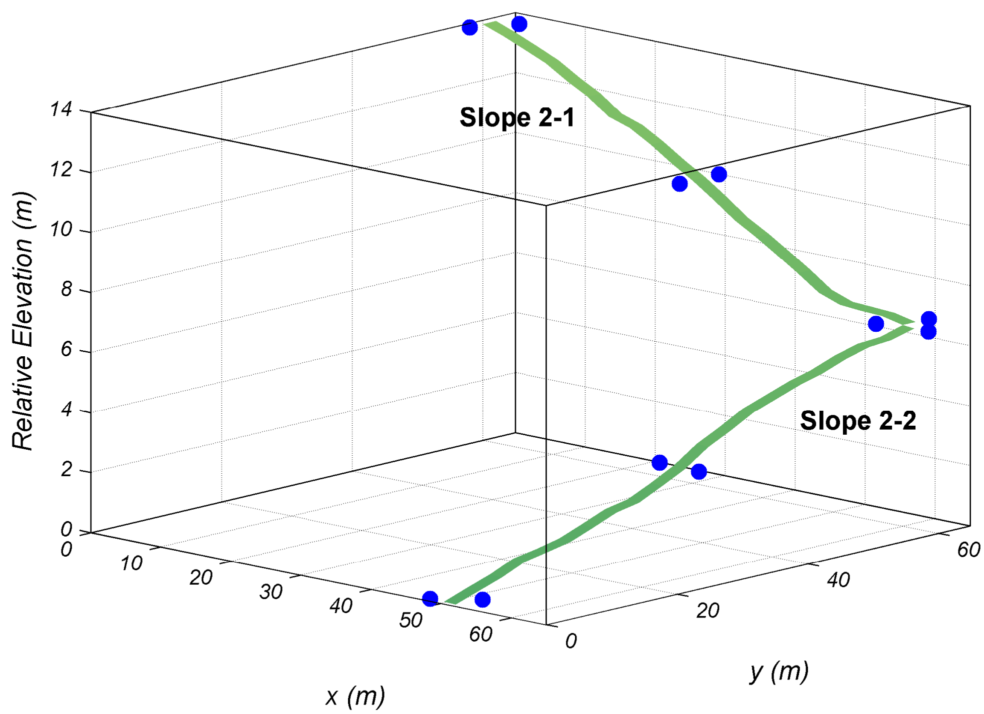

Figure 5.1: Relative position of the two hillslopes monitored during Field 2. Blue dots mark the location of the profile probe access tubes.

Daily point measurements of duff moisture were made using a Delta-T ThetaProbe every 3 m along each edge of the two transects, representing a moisture grid along the transects. In addition, daily noon moisture measurements were logged at the top of Slope 2-1 (Top 1), the bottom of Slope 2-1 and top of Slope 2-2 (Middle), and the bottom of Slope 2-2 (Bottom 2). At Top 1 and Bottom 2 a total of six ThetaProbes were installed at each location: 1 horizontally in the soil directly below the duff layer (soil), 2 horizontally in the duff directly above the soil layer (lower duff), 2 horizontally in the duff just below the duff surface (upper duff), and one vertically through the top of the duff (vertical duff). At Middle a total of 9 sensors were installed: 2 soil, 2 lower duff, 2 upper duff, and 3 vertical duff. All sensors at a given slope location were installed within 20 cm of each other, with sensors at the same depth inserted next to each other. The depth of the duff at Top 1, Middle, and Bottom 2 was 10, 8, and 13 cm, respectively. Duff is very heterogeneous even over small areas, which can result in considerable differences in moisture measurements even when samples are taken next to each other. Since the objective of the daily noon day values was to investigate the differences along the hillslope and not the differences within 20 cm, average moisture values were used at locations where there were multiple sensors at the same location. In all cases, duff specific calibration was applied (Chapter 2).

5.2.4 Meteorological Measurements

Hourly precipitation during the two field campaigns was obtained from the meteorological station at the University of Calgary Biogeoscience Institute (referred to henceforth as the Field Station). Meteorological conditions measured at this institute are ideal for use as the above canopy standard in this study since all measurements are made in the open, and all hillslope transects were located within 1 km of its location. In addition to the above canopy conditions, throughfall was also monitored using tipping bucket rain gauges during both field campaigns. Rain gauges were installed at the top and bottom of Slope 1-2 in the first field campaign, and at the top and bottom of both Slope 2-1 and Slope 2-2 during the second field campaign. In all cases the rain gauges were installed at least 1 m away from the closest tree and were provided to give a relative indication of the amount of throughfall experienced by the duff. Since the number of rain gauges was limited, exact throughfall values could not be extracted.

5.3 Results

5.3.1 Field 1

The summer of 2005 was a wet summer for the Kananaskis area. The amount of rainfall during June, July and August, 555 mm, was approximately 240% greater than the climatic normal for the same time period, 231 mm (Environment Canada, 2007). Most of this excess rainfall occurred during the month of June, representing a high antecedent moisture condition for both the duff and soil. The rainfall measured at the Field Station during the study period is shown in Figure 5.2. Of particular interest, because of the impact on duff and soil moisture, are four rainfall events: event 1 on 27 June, with 37.4 mm in 28 h, event 2 on 2 July, with 3.4 mm in 5 h, event 3 on 16 July, with 20 mm in 9 h, and event 4 on July 24, with 1.9 mm in 6 h. The majority of the other rainfall events during the study period represent short duration thundershowers of less than 1 mm. Throughfall values for the four prominent rainfall events measured at the top and bottom of Slope 1-1 ranged from

30-100% of the station rainfall. There was no appreciable difference between the throughfall values at the top and bottom of the hillslope.

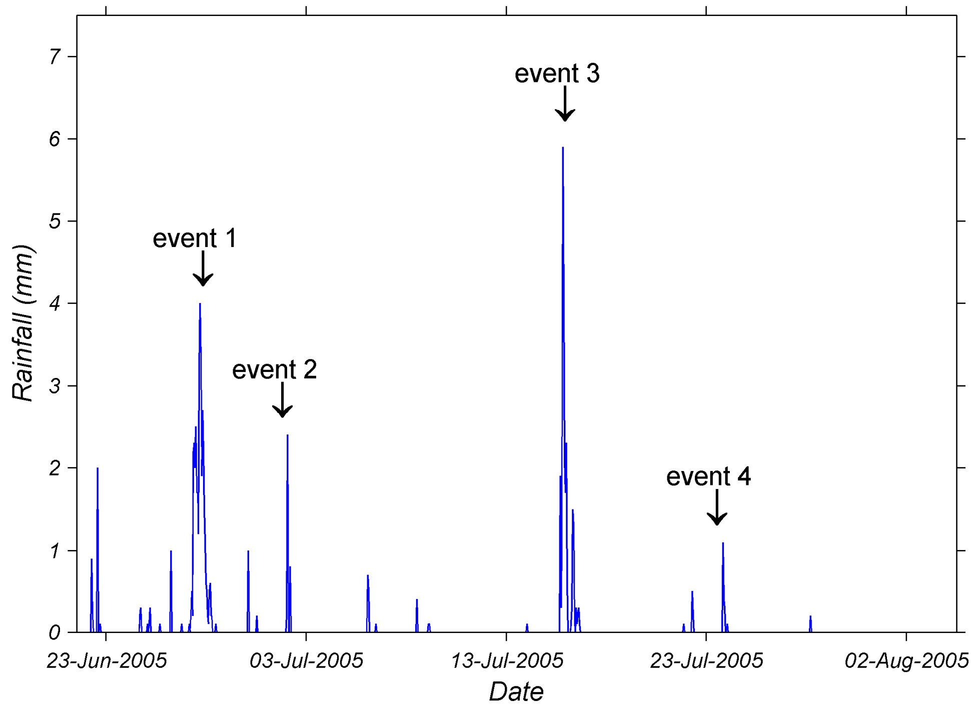

Figure 5.2: Hourly rainfall measured at the Biogeoscience Institute from 22 June to 5 August, 2005 (Field 1).

The averaged profile probe moisture measurements for the two hillslopes are shown in Figure 5.3. The averaged moisture contents of the duff, represented as the -10 cm depth, and the top 20 cm of mineral soil (-20 and -30 cm depths) are shown along with their standard deviations. Average values were compared to provide information on the general trend in moisture content, irrespective of the meteorological conditions. In addition, the pattern observed in the averages was representative of what was observed when the trends in daily values were compared. A lack of significant difference in average moisture content corresponded to conditions where the moisture content switched from being wetter at the top or being wetter at the bottom of the hillslope. This switch was not found to depend on meteorological conditions.

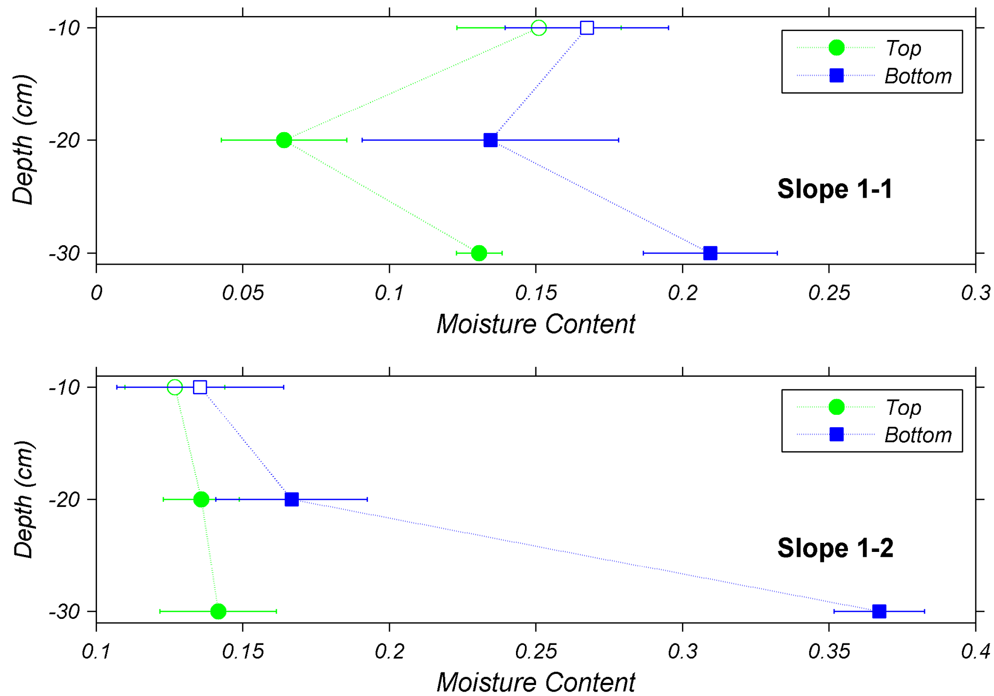

Figure 5.3: Relationship between average moisture content and hillslope position for Field 1. Open and solid shapes represent duff and soil moisture, respectively. Error bars represent the standard deviation.

While the moisture contents of the two hillslopes were different, there were similarities in the wetness patterns. Average duff moisture was not significantly different between the top and bottom of the hillslope for either Slope 1-1 or 1-2 ($p = 0.336$ and $p = 0.537$, respectively). However, for both slopes, the average mineral soil moisture at a depth of 20 cm was higher at the bottom of the hillslope than at the top ($p = 0.005$ and $p = 0.026$, for Slope 1-1 and 1-2, respectively). The same hillslope moisture gradient was also exhibited in the mineral soil at a depth of 30 cm ($p < 0.001$ for both slopes). The lack of difference in duff moisture between the top and bottom of the hillslopes along with an apparent moisture gradient in the mineral soil, questions the influence of the mineral soil moisture on duff moisture.

The continuous noon point measurements of duff and soil moisture are shown in Figure 5.4. Duff moisture was measured and compared at the top and bottom of the hillslope vertically through the top of the duff layer and horizontally through the bottom. Comparisons were also made on the horizontal measurement of soil moisture made just below the duff layer. The most pronounced feature of Figure 5.4 is the influence of the four prominent rainfall events. As expected, the moisture content of the vertical duff, horizontal duff and soil increased following rainfall events, and then decreased as they experienced a period of drying. Rainfall events 1 and 3 had the largest impact on moisture content for both the top and bottom of the hillslope. Events 2 and 4 resulted in a smaller increase in duff moisture, due to the lower amount of rainfall, and an almost negligible increase in soil moisture.

For the vertical duff, the difference in moisture content between the top and bottom of the hillslope was not significant. However, for both the horizontal duff and soil layer, there was a significant difference between the top and bottom of the hillslope. At the beginning of the study period, horizontal duff and soil moisture was higher at the bottom of the hillslope than the top. However, by the end of the study period, the difference in moisture content became negligible for the horizontal duff, and was greater at the top of the hillslope for the soil.

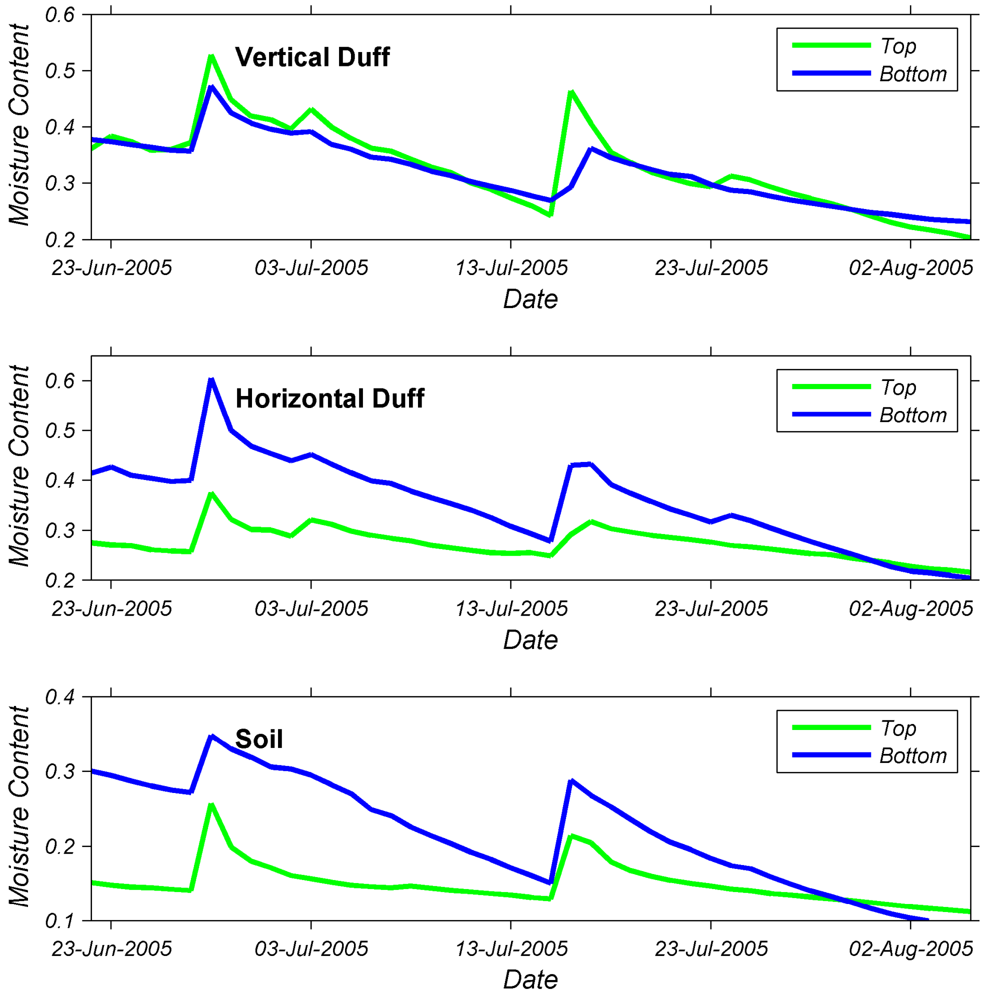

Figure 5.4: Relationship between continuous noon moisture measurements of Slope 1-1 and hillslope position for the vertical and horizontal duff, and soil layers, for Field 1.

The presence of a hillslope moisture gradient in the soil and horizontal duff, and the lack of gradient for vertical duff, can be used to infer how water moves through duff and along the hillslope. Vertical duff measurements represent the top 6 cm of the duff layer while horizontal duff measurements represent the bottom 2.7 cm of the duff layer next to the mineral soil, as defined by the geometric shape and insertion orientation of the ThetaProbes. It is expected that following a rainfall event, water will move vertically through the duff and eventually through the mineral soil, due to gravity. The speed of this movement depends upon the hydraulic conductivity and storage capacity of both the duff and the mineral soil. This appears to happen for the top portion of the duff, where water moves vertically through the duff to the lower layers. This can be observed in the relative response of the layers to the four rainfall events. The vertical duff responds to all four rainfall events, while the response to the smaller of the two rainfall events, events 2 and 4, is not observed for the soil layer. The lack of difference between the top and bottom of the hillslope for vertical duff implies that the vertical movement of water is all that occurs in that layer. A hillslope difference in moisture in the horizontal duff and soil implies that water also moves along the hillslope in those layers. Therefore, water will enter the top of the duff, travel to the lower layer and then travel along the hillslope. If there is enough precipitation, water will enter the mineral soil. Water will tend to travel down the hillslope through the lower layers in the duff before entering the mineral soil because of the duff's higher hydraulic conductivity (Chapter 3).

An example of this phenomenon can be observed with rainfall event 4. Event 4 increases the moisture content of vertical duff at both the top and bottom of the hillslope. For the horizontal duff, however, only the bottom of the hillslope appears to respond to the rainfall event, while the soil layer does not respond at all. This would indicate that water enters the vertical duff, travels vertically to the lower layer of the duff, and moves down the hillslope, but does not move into the mineral soil.

These observations tend to support the notion of a duff moisture hillslope gradient, with duff moisture greater at the bottom of hillslopes than at the top, especially during wet periods. If such a gradient is present, it would be expected to be more dominant in the lower duff layers, where the horizontal moisture measurements were made, because of interactions with the mineral soil (Samran et al., 1995). The mineral soil does not appear to contribute to the moisture content of the duff, but instead provides a barrier to further infiltration that promotes water movement along a hillslope.

5.3.2 Field 2

Figure 5.5 shows the two rainfall events that occurred during Field 2, one on 28 July, with 10 mm in 3 h, and one on 30 July, with 2.9 mm in 2 h. Throughfall measured at Top 1, Middle and Bottom 2 ranged between 20-90% for these two events. Interception was greater for the second rainfall event at all locations because of the lower intensity of rainfall. Interception was found to be greater at Middle, followed by Top 1 and lastly by Bottom 2. This is reflected in an increased tree density at Middle as compared to Bottom 2.

The results of the continuous noon measurements of duff and soil moisture content are shown in Figure 5.6. The absence of data for Bottom 2 before July 24 was a result of the sensors being pulled out of the ground by an animal and subsequently being replaced. Because the sensors could not be placed in exactly the

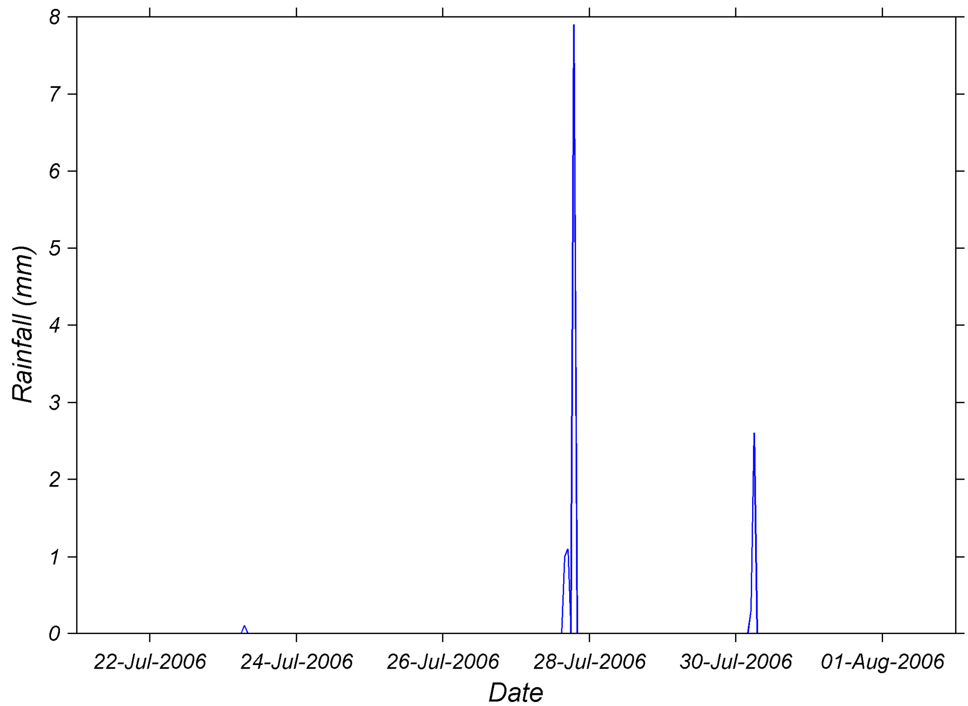

Figure 5.5: Hourly rainfall measured at the Biogeoscience Institute from 21 July to 2 August, 2006 (Field 2).

same location, only the data after the reinstallation are included. The continuous noon measurements show that all layers and locations responded immediately to the first rainfall event on July 28 with an increase in moisture content, but only the vertical duff showed an increase in moisture content following the second rainfall event on July 30. The soil layer consistently had moisture values that were lower than any of the duff layers, while the lower duff layer tended to have higher moisture content than its corresponding upper layer. However, the moisture content of the upper and lower layers overlapped when the two sample sites are compared. There was no consistency when vertical duff moisture was compared with the upper and lower duff moisture. These observations reflect the variability in duff moisture, and also the presence of a vertical moisture gradient within the duff layer.

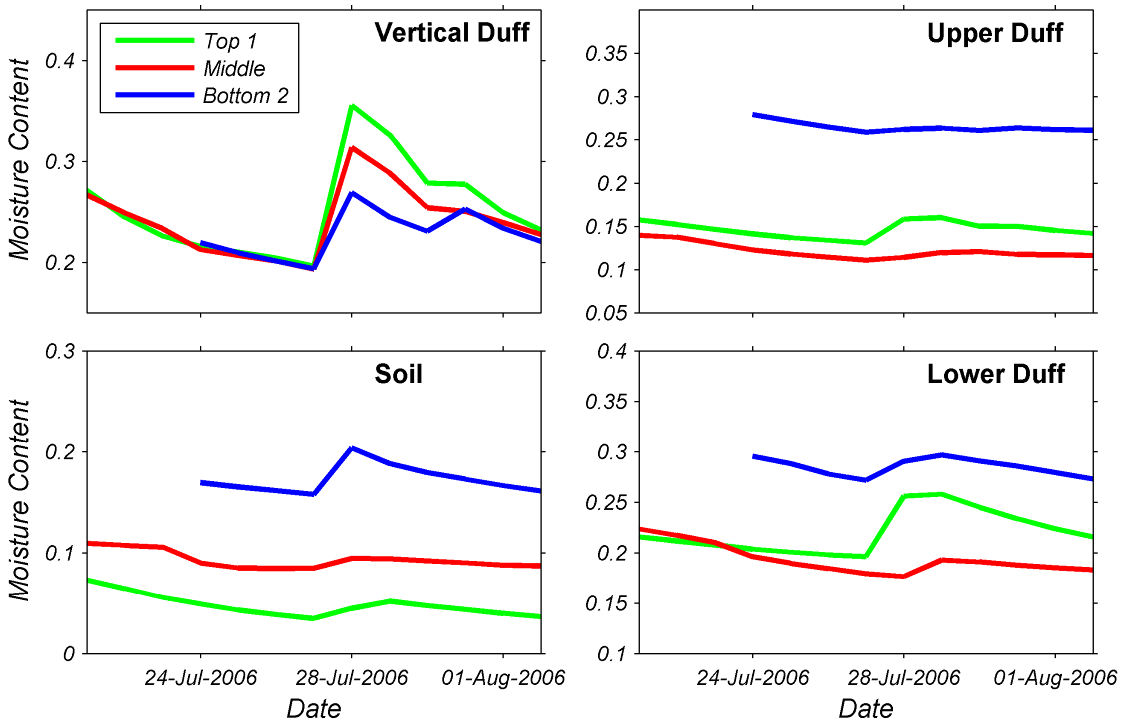

Figure 5.6: Relationship between continuous noon moisture measurements and hillslope position for the vertical, upper and lower duff, and soil layers, for Field 2.

When comparing along the hillslope, the soil is the only layer to exhibit a pattern consistent with a hydraulic gradient; that is, the bottom of the hillslope is the wettest and the top of the hilllslope is the driest. Both the upper and lower duff layers were wettest at the bottom of the hillslope, but the middle of the hillslope was the driest, not the top. The vertical duff shows the opposite trend as the soil with the top of the hillslope the wettest and the bottom the driest. The discrepancies in the moisture trends along the hillslope between the soil and duff layers indicate that the soil moisture does not have a prominent influence on duff moisture.

Profile probe measurements were made to determine the trend in soil moisture both with depth and along the two hillslopes. The averages of the moisture measurements made over the study period, along with their standard deviations, are shown in Figure 5.7. For both slopes at all locations there is an increase in moisture content with depth. Since water drains vertically due to gravity, this is an expected trend. What is not clearly observed at any depth for either slope is a moisture gradient with the top of the hillslope being drier than the bottom. In some instances the middle of the hillslope is the wettest, while in others it is the driest. Averaging is not the cause of the differences, because no pattern was found when daily values were compared with each other and with the rainfall events. Therefore, it is unlikely that a topographic wetness index (Beven and Kirkby, 1979) representation of slope would be applicable for modelling soil moisture in this area.

5.3.3 Field 2 Transects

Field data collected during the second field campaign was specifically tailored to assist in discovering what best describes the spatial variation in duff moisture along a hillslope. Moisture values were measured in a grid pattern along two hillslope transects with known relative hillslope positions and tree locations. Observations from both the first and second field campaign indicate that while duff moisture is influenced by a hillslope gradient, especially in the lower layers, it is not directly influenced by the moisture content of the mineral soil. In addition, previous studies have indicated the importance of tree proximity on duff moisture spatial variability. Therefore, it was important to investigate how the effects of tree proximity and hillslope position jointly influence duff moisture.

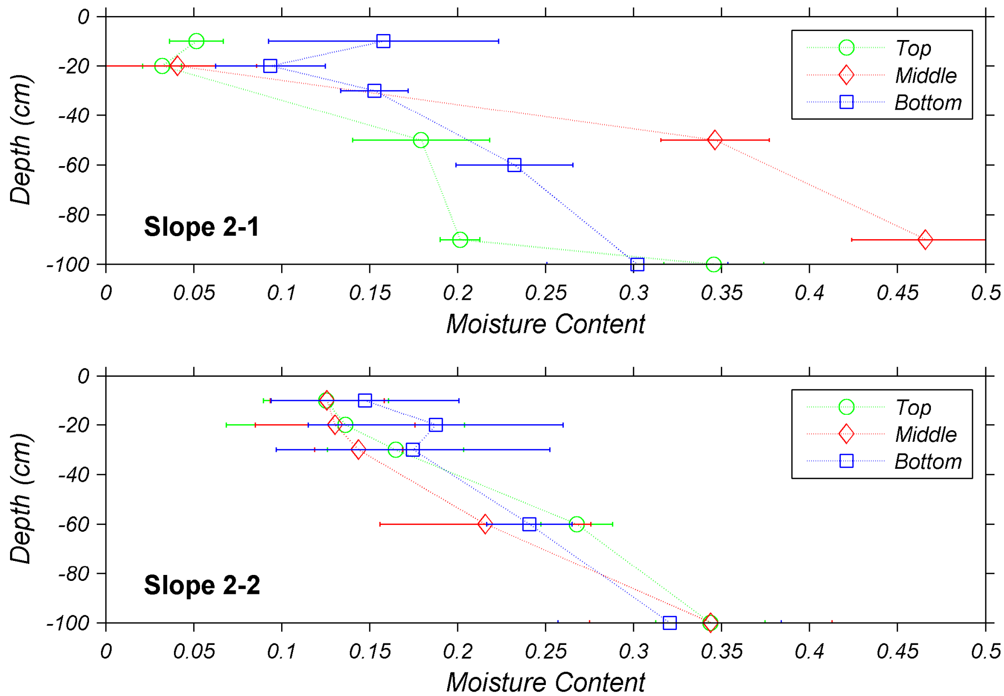

Figure 5.7: Relationship between average soil moisture content and hillslope position for Field 2. Error bars represent the standard deviation.

Figures 5.8 and 5.9 trace the moisture content of each measurement location over time for Slope 2-1 and 2-2, respectively. Specifically delineated in these figures are the gap and tree measurement locations. Tree locations are those sites that are within 40 cm of a tree (as defined in Chapter 4), while gap locations represent all other sites. Slope 2-2 clearly exhibits a moisture pattern based on tree proximity: tree locations tend to be drier than gap locations. The same pattern is not clearly

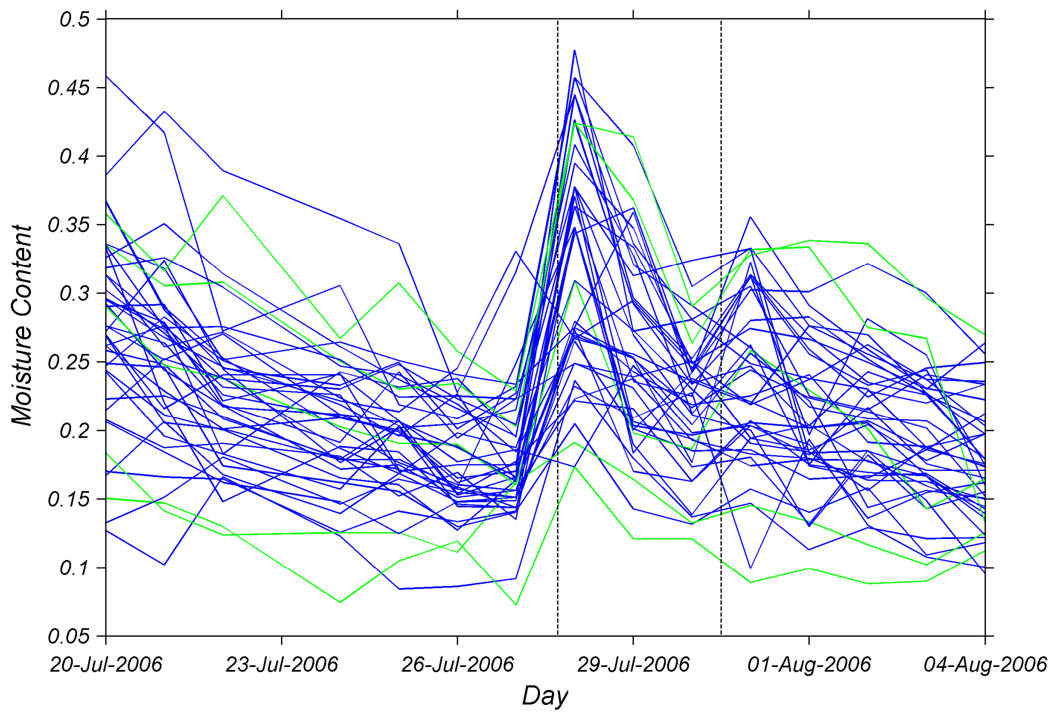

Figure 5.8: Slope 2-1 moisture content at each location traced over time. Blue lines are the gap locations and green lines are the tree locations. Dashed black lines represent the two rainfall events.

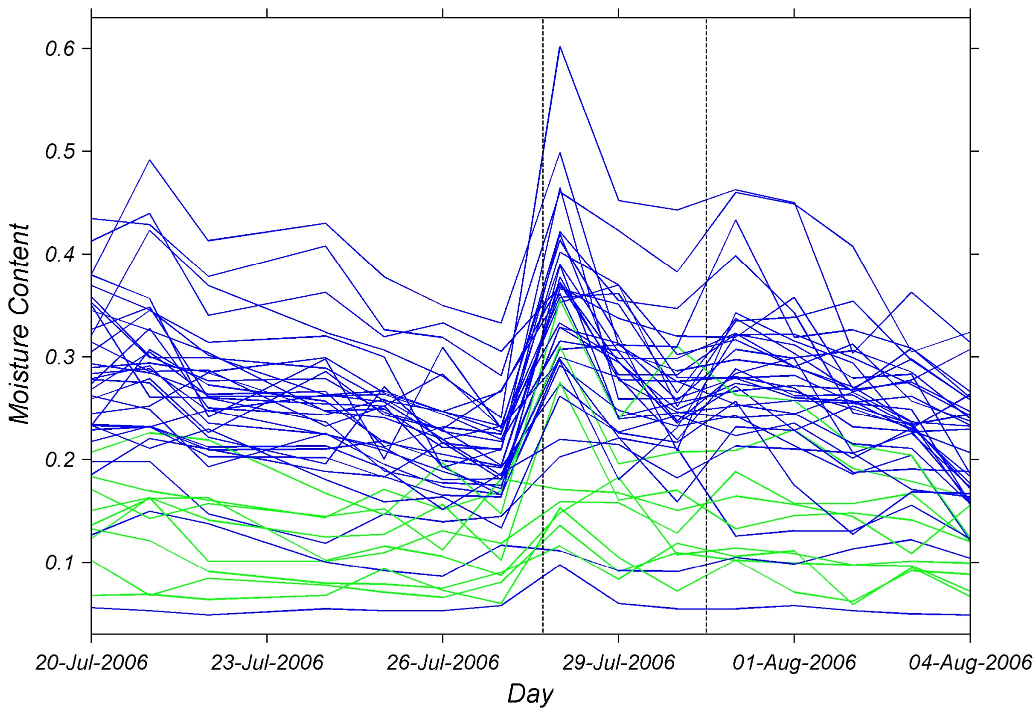

Figure 5.9: Slope 2-2 moisture content at each location traced over time. Blue lines are the gap locations and green lines are the tree locations. Dashed black lines represent the two rainfall events.

defined in Slope 2-1, however, this could be related to the limited number of tree locations. For Slope 2-1 there were only 5 tree locations, while Slope 2-2 had 9.

The average moisture contents of the two hillslopes for each day of measurement are compared in Figure 5.10. This figure shows that while Slope 2-2 does have slightly higher moisture content on most days than Slope 2-1, the difference is not significant. This indicates that these two hillslopes are hydrologically similar. However, when the moisture content is traced along the transects for each day of measurement (Figures 5.11 and 5.12) a difference is observed between the two hillslopes. Slope 2-1 does not show a moisture trend with hillslope position, while Slope 2-2 does. For Slope 2-2, there appears to be a general increase in moisture content downslope, indicating a duff moisture gradient. The question becomes, why is this gradient present in Slope 2-2 but not Slope 2-1?

Since tree proximity had been previously shown to significantly influence duff moisture, it was thought to also be the possible cause for the gradient difference between the two slopes. As stated above, Slope 2-2 had more tree locations than Slope 2-1, and Slope 2-2 showed a clear moisture trend with tree proximity while Slope 2-1 did not. Figures 5.13 and 5.14 illustrate the location of all the trees within 2 m of the two transects for Slope 2-1 and 2-2, respectively. From these figures it is clear that there are more trees on Slope 2-1 (67) than on Slope 2-2 (40). What is not clear is whether or not the trees on the two hillslopes are randomly distributed or are clumped. If the trees are clumped then distinct pockets of drier duff would be expected than just the drier areas around trees. The Nearest Neighbour Test for complete spatial randomness was used to determine if

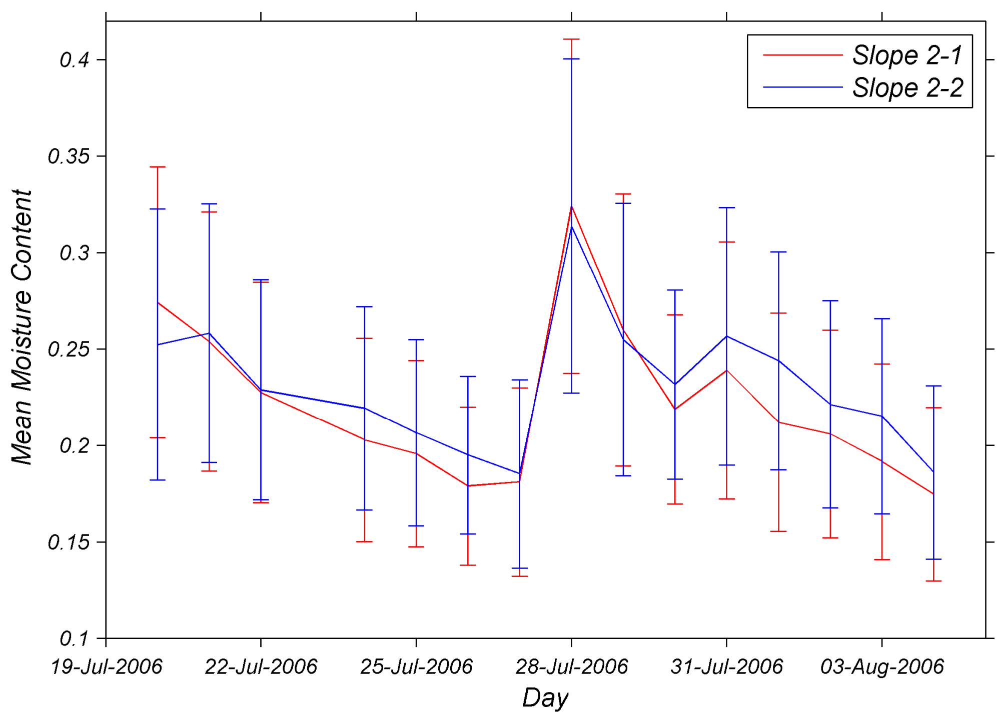

Figure 5.10: Mean duff moisture content for both hillslopes. Error bars represent the standard deviation.

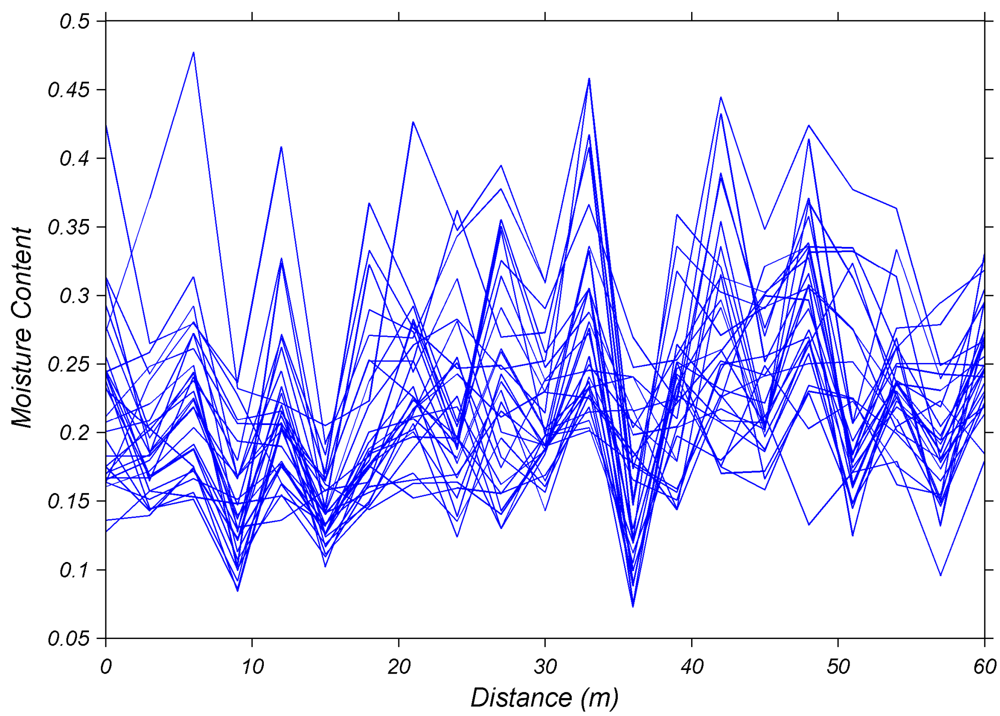

Figure 5.11: Slope 2-1 moisture content on each day traced along the hillslope.

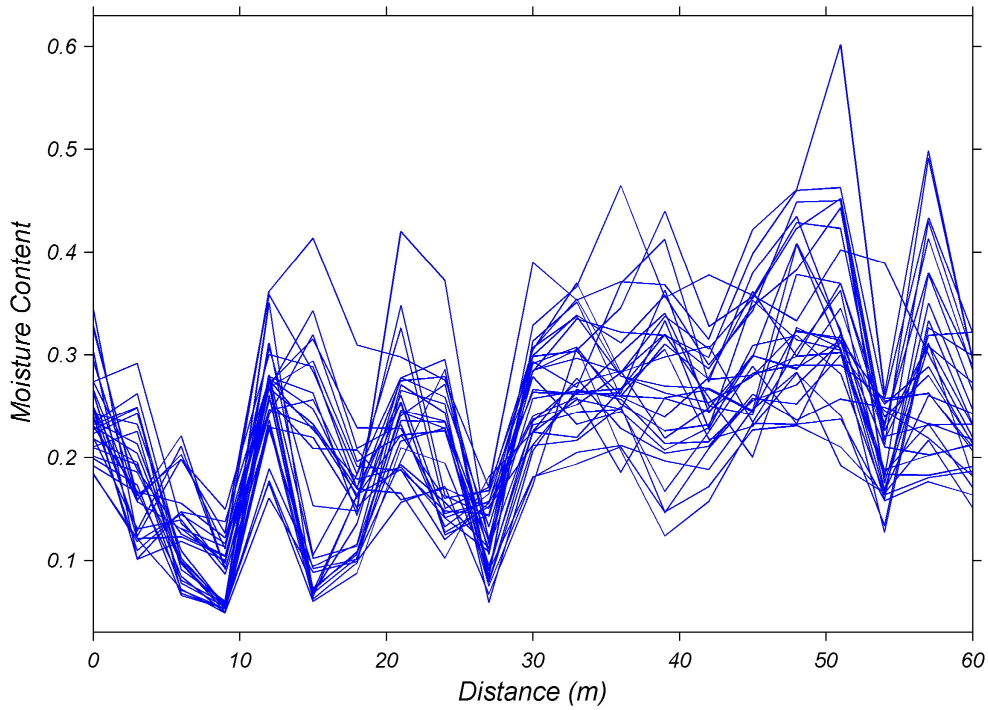

Figure 5.12: Slope 2-2 moisture content on each day traced along the hillslope.

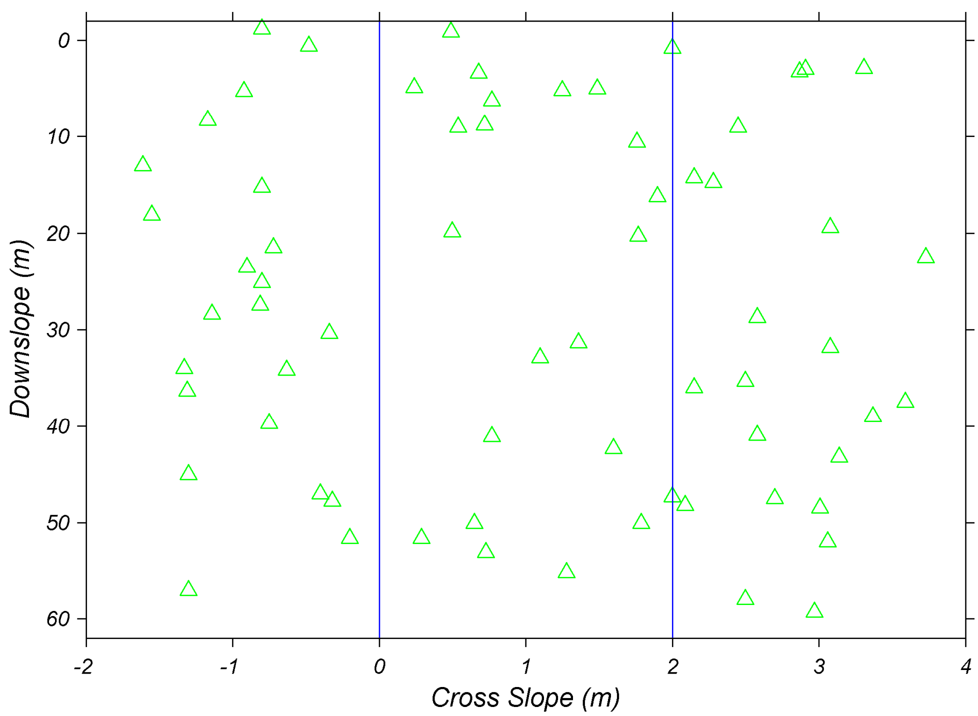

Figure 5.13: Location of trees within 2 m of measurement the transects of Slope 2-1. Transects are represented by blue lines.

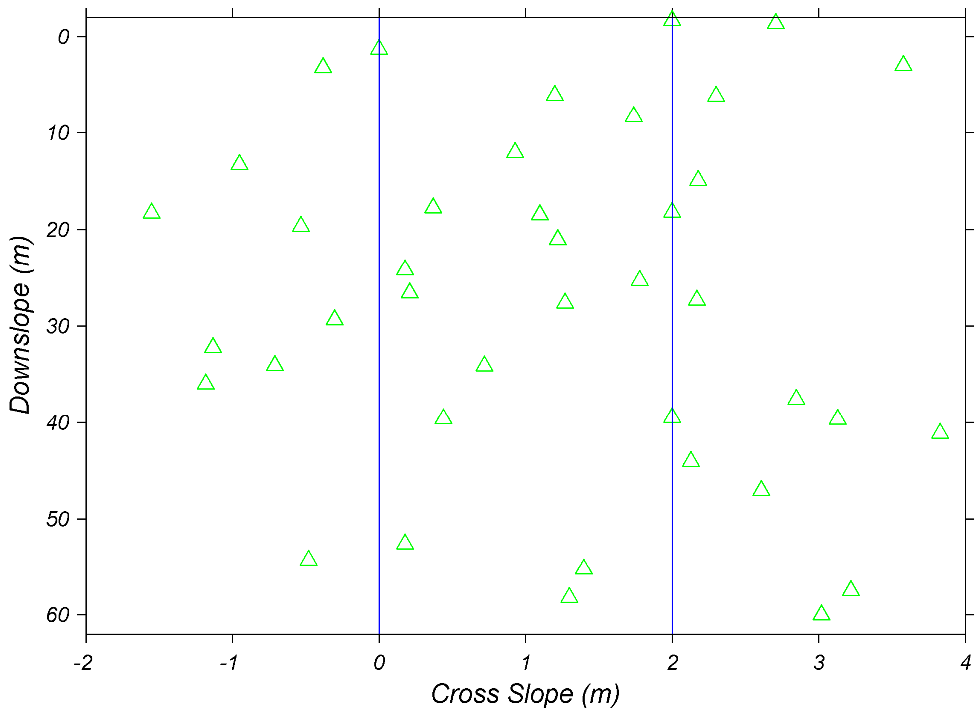

Figure 5.14: Location of trees within 2 m of measurement the transects of Slope 2-2. Transects are represented by blue lines.

the trees were random or clumped. The nearest neighbour test examines the distance between each tree and the closest tree for every tree, and then compares these distances to expected distances for a random sample of points from a complete spatially random pattern. A completely spatial random pattern is generated based on the assumptions that all places are equally likely to have a tree, and all trees are located independently of one another. Table 5.1 shows the results of the nearest neighbour test, including the observed and expected distances, the variance, and, most importantly, the Z-statistics. The two-tailed Z value of a normal distribution for α = 0.05 is ±1.96, and since both of the Z-statistics in Table 5.1 are less than 1.96, the null hypothesis of complete spatial randomness cannot be ignored. Therefore, the trees on both hillslopes can be considered randomly distributed.

Table 5-1: Nearest Neighbour test for complete spatial randomness for the distribution of trees within 2 m of the transects for each hillslope.

Slope	Number of Trees	Mean Nearest Neighbour Distance		Variance	Z statistic
		Observed (m)	Expected (m)		
2-1	67	1.376	1.208	0.007	1.947
2-2	40	1.797	1.634	0.023	1.067

The selection of measurement locations along transects can be considered a random process in terms of tree locations as long as the trees on the hillslope are randomly distributed. Since the trees on both hillslopes are randomly distributed, then measurement locations can also be considered random. If the measurement locations are random, is the number of tree locations observed equal to those expected by chance? To answer this question the 384 m^2 (6 m x 64 m) hillslopes were divided into 0.6 m^2 quadrants. The size of the quadrants was selected to represent the area occupied by a single tree. The average DBH (diameter at breast height) of the trees on both hillslopes is 0.6±0.3 m. Table 5.2 shows the average DBH of the two hillslopes independently, as well as the hillslopes divided up based on the top or bottom half. Also included in Table 5.2 is the total number of quadrants, number of quadrants with trees, and number of quadrants without trees. Again the hillslopes are presented independently as a whole and divided based on top or bottom half. The probability of a tree being in a quadrant was determined by dividing the number of quadrants with trees by the total number of quadrants. The resulting probabilities, shown in Table 5.2, confirm that there is a higher probability of selecting a tree location on Slope 2-1 than Slope 2-2. They also establish that there is no difference in the probability of selecting a tree location at the top and bottom half of Slope 2-1, but there is a slightly higher probability of selecting a tree location at the top half of Slope 2-2 than the bottom.

The actual number of tree measurement locations along both hillslopes contradicts the established probability. There are more tree measurement locations on Slope 2-2 than Slope 2-1, there are more tree locations on the bottom of Slope 2-1 than the top, and there are a lot more tree locations on the top of Slope 2-2 than the bottom. Table 5.3 shows the tree location counts for the two hillslopes, along with the probability of getting these tree location counts based on the probabilities calculated in Table 5.2. The probabilities in Table 5.3 reveals that slightly more tree locations than expected were found on Slope 2-1, with the extras being observed on the bottom half of the hillslope. More importantly, the probabilities show a lot more tree locations were found on Slope 2-2 than would be expected, especially the number observed on the top half of the hillslope. It is possible, therefore, that the tree locations are adversely influencing the moisture content of duff along Slope 2-2.

Table 5-2: The number of trees within 2 m of the transects for Field 2, and the resulting probability of finding a tree. Quadrants are based on a cell size of 0.6 m x 0.6 m.

Slope	Location	Number of Trees	Average DBH (cm)	Quadrants			Probability of Tree
				Total	With Trees	Without Trees	
2-1	All	67	54	2400	67	2333	0.028
	Top	27	46	1200	34	1166	0.028
	Bottom	40	60	1200	33	1167	0.028
2-2	All	40	74	2400	40	2360	0.017
	Top	16	75	1200	23	1177	0.019
	Bottom	24	74	1200	17	1183	0.014

Table 5-3: The number of trees moisture measurements along the hillslopes and the probability of measuring that number of trees based on the probability of finding a tree on the hillslope.

Slope	Location	Number of Moisture Measurements	Number of Tree Moisture Measurements		p
			Observed	Percent of Total (%)	
2-1	All	42	5	12	0.005
	Top	21	1	5	0.335
	Bottom	21	4	19	0.002
2-2	All	42	9	21	<< 0.001
	Top	21	8	38	<< 0.001
	Bottom	21	1	5	0.224

Figure 5.15 is the same plot as Figure 5.12, showing the moisture content traced along the transects of Slope 2-2 for each day of measurement, except the tree measurement locations have been removed. Once the tree measurement locations are removed, the apparent moisture trend with hillslope position disappears. The moisture hillslope gradient was simply an artefact of a higher than expected number of tree measurement locations at the top of the hillslope. Tree locations have been shown to have lower duff moisture than gap locations, and this persists as the most influential factor on duff moisture, even along hillslopes.

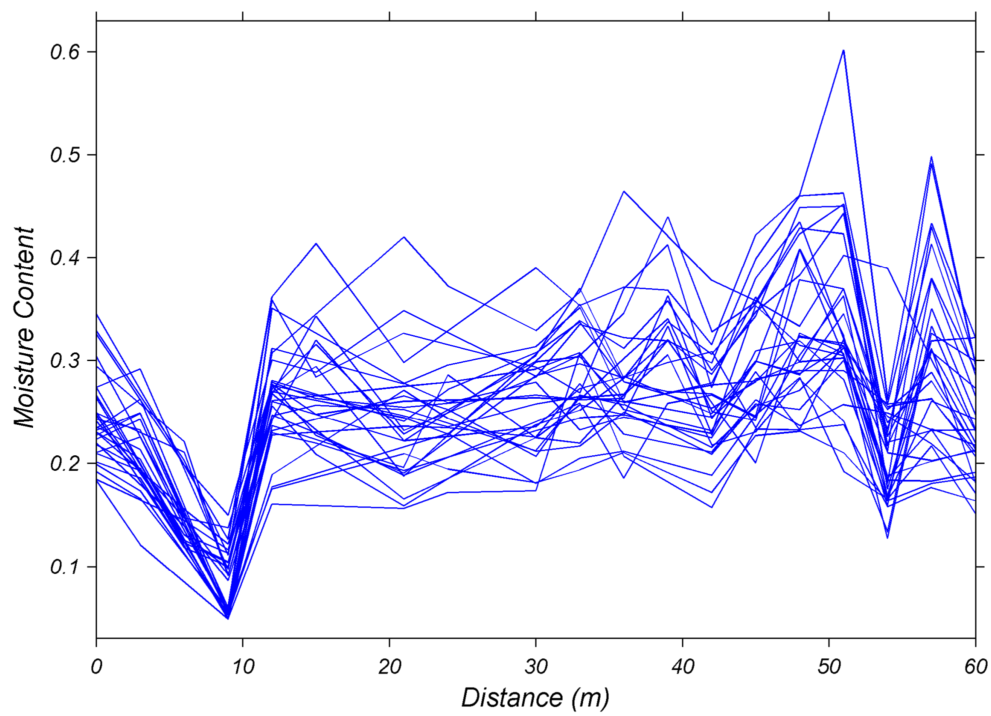

Figure 5.15: Slope 2-2 moisture content on each day traced along the hillslope with tree locations removed.

5.3.4 Tree and Gap Temporal Moisture Difference

Duff tends to be drier at tree locations than gap locations primarily due to interception, which influences how the duff is wetted. In Chapter 4 it was shown that the variation in duff moisture decreases as the duff dries. Therefore, during drying, does the difference in duff moisture at tree and gap locations change? Figure 5.16, which shows the gap-tree duff moisture difference as a function of time, demonstrates that the gap-tree moisture difference decreases as duff dries between rainfall events. A possible explanation for the decrease would be a difference in the duff drying rate at gap and tree locations. Duff has been found to follow an exponential drying rate (van Wagner, 1970). Therefore, the drying rates at each measurement location were calculated by fitting an exponential equation, using nonlinear least squares, of the form

$$\theta = a * e^{-bt} \tag{5.1}$$

where a is a constant, b represents the drying rate in units of day^{-1}, and t is time in days. To allow for comparisons between drying events, time was reset to 0 after each rainfall event, and the measurement days were adjusted to represent time since rainfall. Table 5.4 shows the resulting parameter averages and standard deviations of all the locations, as well as grouping the data based on gap and tree locations. The drying rates, b, were not found to be significantly different between gap and tree locations. This means that a difference in drying rate cannot be the cause of the decrease in the gap-tree difference as duff dries.

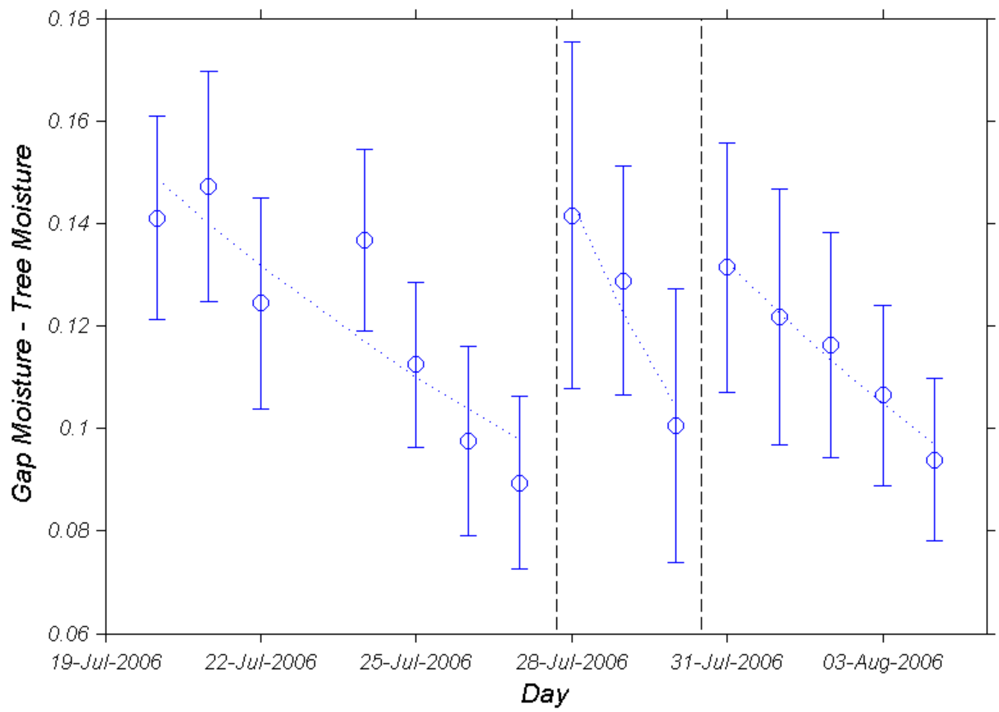

Figure 5.16: Difference between gap and tree moisture values for each day of measurement. Vertical dashed lines represent the two rainfall events. Dotted lines are the exponential fits between the rainfall events.

Table 5-4: Mean exponential drying fit parameters with their standard deviations.

Grouping	*a* (cm^3cm^{-3})	*b* (day^{-1})	*k* (day^{-1})
All	0.29±0.10	0.10±0.09	0.10±0.08
Gap	0.27±0.13	0.10±0.09	0.09±0.09
Tree	0.02±0.06	0.01±0.04	0.01±0.0.04

The parameter *a*, on the other hand, was found to be different between gap and tree locations. This is to be expected because the initial moisture content of duff is lower at tree locations because of interception. The exponential drying rate equation described by van Wagner (1970) is,

$$\frac{\theta_t - \theta_o}{\theta_{t-1} - \theta_o} = e^{-kt} \tag{5.2}$$

where θ_t and θ_{t-1} is the moisture content at time t and $t-1$, respectively. The time, t, is in days, and k is the drying rate in day^{-1}. θ_o is the equilibrium moisture content signifying the lowest possible moisture content. The drying rates, k, found by applying Equation 5.2 to the data are provided in Table 5.4. These drying rates are the same as those found by applying Equation 5.1.

Given that Equation 5.2 describes the drying rate of duff, then the following equation will describe the difference in gap (θ_G) and tree (θ_T) moisture:

$$\theta_{G_t} - \theta_{T_t} = (\theta_{G_{t-1}} - \theta_{T_{t-1}})e^{-kt} . \tag{5.3}$$

Table 5.5 provides the fit parameters to the gap-tree difference as a function of time for the three drying events using both Equation 5.1 (a_d and b_d) and 5.3 (k_d). Figure 5.16 shows the exponential curves of the gap-tree moisture differences. The drying rates presented in Table 5.5 (k_d) are the same, within the uncertainty, as those presented in Table 5.4 (k), demonstrating that Equation 5.3 is describing the decrease in the gap-tree moisture difference as duff dries. This indicated that the spatial variability in duff moisture is only a concern when the duff is wet.

Table 5-5: Mean exponential drying fit parameters to the difference between gap and tree moisture with their standard deviations.

Drying Event	a_d (cm^3cm^{-3})	b_d (day^{-1})	k_d (day^{-1})
1	0.17±0.02	0.06±0.02	0.08±0.12
2	0.14±0.04	0.16±0.27	0.17±0.11
3	0.138±0.004	0.08±0.01	0.08±0.0.03

5.4 Discussion and Conclusions

One objective for this study was to determine if there was a relationship between the moisture content of the duff and the mineral soil. Numerous models and research have been applied to the estimation of mineral soil moisture content. Therefore, if a simple and direct relationship between duff and mineral soil moisture could be established then it might be possible to use mineral soil moisture models to determine duff moisture. Conflicting patterns of both the duff moisture along the hillslopes studied and the relationships with mineral soil moisture do not give confidence to a simple relationship between duff and mineral soil moisture along a hillslope. Indeed, duff moisture does not appear to be influenced by a hillslope hydraulic gradient, something that is normally expected along hillslopes. However, the data also questions the applicability of a hilllslope hydraulic gradient in the mineral soil in this study. Regardless, the mineral soil does not appear to directly influence duff moisture, based on the observation that wetter mineral soil does not always result in wetter duff.

The second objective was to ascertain what relationship hillslope had on the spatial variability of duff moisture in conjunction with tree proximity. As expected from Chapter 4, tree proximity was found to significantly influence duff moisture. The influence of tree proximity decreased as the duff dried, which was consistent with observations that the spatial variation in duff moisture decreases as the duff dries (Chapter 4). The distance from the top of the hillslope was not found to be an important factor in duff moisture variability. The spatial variation in duff moisture is more prominent during periods of wetness and become insignificant during dry conditions because of the exponential nature of the duff drying curve. Tree proximity, a factor that describes the impact of interception, should be used when spatial models of duff moisture are desired. The influence of tree proximity decreases as duff dries, and as a consequence, the spatial variation in duff moisture decreases as duff dries and increases after precipitation events. This may imply then that because fires tend to occur during periods of dryness, for the purposes of insight into forest regeneration processes, high spatial distribution modelling of duff moisture may not be warranted.

Tree proximity does not explain all the spatial variation observed in duff moisture, as demonstrated by the large variation of moisture content along Slope 2-2 in Figure 5.15. The heterogeneous nature of duff and the large variation in duff hydraulic properties (Chapter 3) can account for moisture variations, but there may be other unconsidered factors. Of particular interest is the influence of microtopography. A forest floor is not a smooth surface but a surface with great variability in microtopography that include many little valleys and peaks. While duff moisture was not found to be influenced by long hillslopes, it may be influenced by microtopography. Water could infiltrate through the duff to the surface of the mineral soil, and then because of the high hydraulic conductivity of the duff (Chapter 3) as compared to the mineral soil, travel along the duff-mineral soil boundary and collect in the microtopographic valleys. Duff moisture content in these microtopographic valleys would be higher than in the microtopographic peaks, resulting in centimetre scale variation that is not directly related to tree proximity. The direct influence of microtopography on duff moisture requires further study.

Chapter Six: **Conclusions and Recommendations**

As described in Chapter 1, this dissertation's research objectives are:

1. To quantify the physical properties of different types of duff that are essential to duff moisture modelling yet absent from the literature.
2. To determine which factors have the greatest influence on duff moisture at laboratory and hillslope scales.
3. To determine how the spatial and temporal variation in duff moisture varies with different canopy types so that canopy influences can more accurately be incorporated in duff moisture modelling.

To achieve these objectives, a variety of field and lab studies were carried out as presented in the preceding chapters. The following discusses the contributions of this dissertation to knowledge with text in bold highlighting specific novel contributions to research that are not found in the literature.

6.1 Duff Properties: Achieving Objective 1

Chapter 3 provided several physical properties of duff that are required for the development of physically based hydrological models. These included duff porosity, desorption characteristic curves and saturated hydraulic conductivity. Much of this analysis was possible through the ThetaProbe calibration for duff moisture in Chapter 2. **Different ThetaProbe calibrations are not required based on tree type or duff depth.** However, it was recognized that further testing would be prudent because of the limited number of samples and the high heterogeneity of duff. The heterogeneous nature of duff, even under the same canopy type, results in a high moisture measurement error for the ThetaProbe.

Duff is highly heterogeneous, even over small areas. **Analysis in Chapter 3 showed that this heterogeneity completely overshadowed any of the differences that may be present due to canopy type or tree proximity**. Indeed, the physical characteristics of duff were all found to exhibit greater variation vertically within the duff layer than the same variations due to either canopy type or tree proximity. Therefore, when applying the physical characteristics of duff to spatial duff moisture models, only depth differences need to be considered.

6.2 Factors Influencing the Spatial and Temporal Distribution of Duff Moisture: Objectives 2 and 3.

Duff moisture is affected by its wetting and drying processes. As mentioned above, duff wetting is influenced by interception, which is the primary cause of the spatial variation in duff moisture. Duff drying, or evaporation, is influenced by the meteorological conditions. Chapter 4 showed that **duff drying rates were not found to be different based on parameters such as tree proximity, however they were different based on the meteorological conditions.** Normally only above canopy meteorological conditions are available for modelling purposes. While temperature and relative humidity remain relatively unaffected by pine/spruce canopies when compared over a day, wind speed and solar radiation are reduced below the canopy. There is a difference in above and below canopy temperature and relative humidity when specific times are taken into consideration because of the shielding of the canopy to both increases and decreases in temperature. Therefore, reduction factors should be applied to these parameters if a conventional method of evaporation such as the Hargreaves Method is to be used to estimate evaporation. The relationship between the reduction factor and canopy closure, however, requires further research.

Chapters 4 and 5 presented two field studies that examined three key factors for their influence on duff moisture: canopy composition, tree proximity, and hillslope position. The first field study specifically addressed variation based on canopy composition and tree proximity by monitoring duff moisture in ten 100 m^2 grids at one metre intervals over a period of approximately two months. The ten plots came from four different canopy compositions and/or closures. The second field study focused on moisture variation due to hillslope position, while still taking into consideration tree proximity, by measuring duff moisture along two 60 m hillslopes at three metre intervals over a period of two weeks. Hillslope effects were also investigated through continuous monitoring of duff and mineral soil moisture during both field studies. In addition, for both field studies, vertical profiles of the mineral soil along hillslopes were measured.

Canopy composition and tree proximity at the centimetre scale were found to have the greatest influence on the spatial variation in duff moisture. Both factors affect duff moisture through interception. Duff under the canopy of a tree receives less precipitation then duff in the gaps between tree canopies. Tree type dictates the amount of precipitation that is intercepted, with coniferous trees intercepting more than deciduous trees. Therefore, when developing a spatially distributed duff moisture model, appropriate weight and consideration should be given to the canopy composition and tree proximity.

In contrast to canopy type and tree proximity, hillslope was not found to be an important factor in duff moisture variability. The mineral soil below the duff does not directly influence duff moisture, since wetter mineral soil does not always result in wetter duff. Therefore, any hillslope moisture gradient that may be present in the mineral soil is not directly translatable to a duff hillslope moisture gradient. **The distance from the top of the hillslope is not an important factor in duff**

moisture variability. Water moves vertically through the duff to the mineral soil below, but because of a high porosity, does not move horizontally, especially through the upper duff layers.

Temporally, the spatial variation in duff moisture decreases as the duff dries. **Therefore, while there is difference in moisture content between duff close to a tree and in the gap between trees, the difference decreases as the duff dries**. This is a result of the exponential nature of the duff drying curves, and not related to any difference in duff drying rates. Indeed, there were no significant differences in the duff drying rates, particularly based on tree proximity. Due to interception, the spatial variation in duff moisture is more prominent during periods of wetness. During dry conditions, however, the variation becomes insignificant. Therefore, during dry periods it is likely not necessary to consider the spatial variation in duff moisture.

6.3 Perspective

The overreaching aim of this research was to increase knowledge of duff and its moisture characteristics so that duff moisture could be spatially modelled. The primary purpose of the spatial duff moisture model, in turn, is to assist in determining regrowth potential following forest fires by using duff moisture as an indicator of duff consumption. Since forest fires are generally a large scale phenomenon, consuming at times areas greater than 1000 km^2 (Johnson, 1992), spatial patterns of duff moisture need to be applicable at large scales. Therefore, investigations into factors that could affect spatial variations in duff moisture at large scales were made. These included exploring the influence of hillslope as well as the differences between canopy types. An important conclusion from this research was that hillslope does not affect the spatial distribution of duff moisture. Conversely, canopy type was found to influence the duff moisture spatial distribution, but only as a result of the differences in canopy interception. Interception was found to be the leading cause of the spatial variation of duff moisture and its influence was established at the centimetre scale. Hence, large scale variation in duff moisture can be determined at the centimetre scale using information on canopy type and the spatial distribution of trees.

This study adds valuable knowledge that was either missing or limited in the literature. Direct measurements of the hydrological properties of duff, such as the porosity, hydraulic conductivity and moisture characteristic, have not been widely made; rather, values obtained for peat have generally been assumed. Duff specific calibration for the ThetaProbe has been limited, with no mention made to the accuracy of the calibration. The conclusions outlined above have also not previously been published. To reiterate, this study was able to conclude that hillslopes do not affect duff moisture, and that tree proximity has the largest impact on duff moisture because of interception. In addition, this study was able to demonstrate how the spatial variation decreases as the duff dries due to the exponential nature of the duff drying curve.

6.4 Further Research

The motivation of this research was to provide information that could be used to assist in the development of spatial models of duff moisture, if desired. The overarching goal was achieved, but did leave room for further research:

- Confirm lack of difference in physical properties based on canopy type: Duff is very heterogeneous, and the number of samples used to determine the physical properties for each canopy type was limited. More samples would help confirm that duff heterogeneity is greater within a canopy type than it is between canopy types.
- Determine how the reduction factors for wind speed and solar radiation vary based on canopy closure: Meteorological measurements under different canopy types and closures will help determine the reduction factors from above canopy measurements. This will assist in being able to establish evaporation rates, and hence duff drying rates, under different canopies. This would be helpful for modelling duff over large areas.
- Determine if there is a duff moisture gradient out from a tree: Duff was found to be drier next to a tree than in the gap between trees; however a clear relationship between duff moisture and distance to tree was not found. Direct multiple measurements of duff moisture at set distances from trees would help assess whether there is a moisture gradient based on distance from tree, or if it is simply a case of duff being drier under a tree. Size and shape of the tree canopies should be taken into consideration.

- Determine if any large scale factors are influencing duff moisture variation: Variation in duff moisture has been attributed to the centimetre scale with additional variability attributed to canopy type. Hillslope, a potentially large scale variation factor, was not found to influence duff moisture. Investigations into whether or not there are spatial variations in duff moisture over large scales need to be done, as well as investigations to their possible causes if present.
- Determine the influence of microtopography on duff moisture. It was speculated that some of the variation in duff moisture could be explained by microtopography on the forest floor. The influence of microtopography on duff moisture needs to be confirmed.

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