THE BIOHYDROLOGY OF DYSART WOODS

A thesis presented to

the faculty of

the College of Arts and Sciences of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Macdonald H. Burgess

November 2006
This thesis entitled
THE BIOHYDROLOGY OF DYSART WOODS

by
MACDONALD H. BURGESS

has been approved for
the Program of Environmental Studies
and the College of Arts and Sciences by

Kim J. Brown
Assistant Professor of Environmental and Plant Biology

Benjamin M. Ogles
Dean, College of Arts and Sciences
Abstract

BURGESS, MACDONALD H., M.S., November 2006, Environmental Studies

THE BIOHYDROLOGY OF DYSART WOODS (84 pp.)

Director of Thesis: Kim J. Brown

Subsurface coal mining is occurring near and underneath Ohio University’s Dysart Woods Land Lab, a 23 hectare old-growth forest. Such mining is associated with changes in groundwater hydrology throughout the region. However, the impacts of these hydrologic changes on forest ecosystems have not been studied. Public controversy over the mining has raised questions for which no answers exist in the peer-reviewed literature. This thesis addresses the question: How much moisture can the soils at Dysart Woods contain- and does groundwater contribute to the site water budget? As a pre-mining observation, volumetric water content of soil was measured in a spatially extensive and temporally intensive manner utilizing a combination of dataloggers, sensors, and hand-held meters in 2005 and 2006. The average soil depth was found to be 1.2 m and the plant-available water holding capacity of the soil was found to be 150mm. Analysis of the stable isotope content of groundwater, precipitation, and xylem water indicated that trees, even in upslope positions, were likely using groundwater during the growing season drought of 2005.

Approved:

Kim J. Brown

Assistant Professor of Environmental and Plant Biology
Acknowledgments

Funding for the research presented in this thesis was provided by The Department of Environmental and Plant Biology, the MSES program, and the Graduate Student Senate Grant for Original Research, the Ohio University Legal Affairs Office, and the Ohio Department of Natural Resources.

Thanks to my advisor, Kim Brown, for guidance in conducting the research presented here. Thanks also to my committee members Mary Stoertz & Jeff Ueland for additional input. Peter Schillig and Shannon Cook provided help understanding the hydrogeology and geomorphology of Dysart Woods.

Assistance in the collection of field data was provided by Peter Schweizer, Seth Crouser, Greg Snowden, Vijay Ramprasad, and Sarah Stewart. Assistance with lab work was provided by Matthew Parker, Greg Snowden, and Gretchen Wakeley.

Thanks to my wife, Jennifer Johnston, for steady support through the long days of fieldwork, analysis, and writing.
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A note to the reader: Chapter 1 of this thesis is written as a general introduction to the non-expert reader. Chapters 2, 3, and 4 are formatted for publication in the peer-reviewed journals *Geoderma*, *Agricultural and Forest Meteorology*, and *Advances in Water Resources*, respectively. This results in some redundancy in site description and discussion.

Chapter 1: Introduction to the Thesis

1.1 Dysart Woods

It is estimated that 95% of the land area of the state of Ohio was forested prior to European settlement in the early 19th century. All that remains of the primary forest are a few small scattered remnants where individual landowners chose not to cut the forest. These rare old-growth forests are important as reservoirs of biological diversity, and as sources of data about the extensive forests which once covered the region (McCarthy, Small *et al.* 2001).

Details about the current management of Dysart Woods are published by Ohio University (Ohio University 2002). Dysart Woods is named for the Dysart family, who farmed much of the property but left the 3 tracts of old-growth forest. The surface rights to the property are now held by Ohio University under an agreement to manage the land in its natural state. Dysart Woods is registered as a National Natural Landmark with the U.S. Department of the Interior. The mineral rights to the property are owned separately by the Ohio Valley Coal Company, which operates extensive underground mining operations in the area.

Ohio University’s Dysart Woods Land Laboratory, including 23 hectares of old-growth forest, is located in Belmont County, Ohio, where coal mining contributes significantly to the local economy. Subsurface coal mining occurring near and directly
under Dysart Woods has the potential to impact the dynamics of shallow groundwater systems.

While the mining plan for Dysart Woods has nominally been designed to prevent impact to the old-growth forest (ODNR 2001), there is documented uncertainty regarding the size of the zone of influence of underground mines (Zipper, Balfour et al. 1997). Public controversy over the mining has raised questions for which no answers exist in the peer-reviewed literature. The key question is whether the old trees in Dysart Woods are able to obtain sufficient water from the precipitation stored in soil, or if occasional drought conditions require them to use groundwater.

There is a legal framework in place for the compensation for or replacement of lost resources of economic value. Coal companies provide replacement water supplies, road repair and structure repair as needed. Hence there is a “paper-trail” documenting the economic losses related to groundwater loss. However, the impact of hydrologic changes on natural systems of special ecological value (e.g. old-growth forests) is undocumented. An assessment of the biological importance of groundwater contribution to the forest is necessary to understand the possible impact of mining on the Dysart Woods ecosystem.

1.2 Coal Mining Near Dysart Woods

The Pittsburg #8 Coal Seam is about 2 meters thick and lies at an elevation of 221 to 244 meters, leaving an overburden of 91 to 189 meters at Dysart Woods (ODNR 2001). The locations of mines near Dysart Woods are shown in Figure 1.1. The geologic profile in Figure 1.2 indicates, approximately to scale, the size and location of the coal seam relative to the surface features. Two types of sub-surface coal mining of the Pittsburg #8 are occurring in the vicinity of Dysart Woods. Longwall mining, shown in
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red on Figure 1.1, entails the complete removal of the coal seam. The roof of the
longwall mine collapses within hours or days of mining, and subsidence or other surface
effects occur soon after. The Ohio Valley Coal Company’s permit (ODNR 2001) allows
for long wall coal mines outside of a ninety meter (300 ft.) zero-subsidence buffer zone
around the old growth tracts at Dysart Woods.

In a room-and-pillar mine, pillars of coal are left behind to support the roof.
Additional metal reinforcement of the roof of the mine is done to ensure the safety of
workers and equipment using the mined areas for access to work areas. The room and
pillar mines shown as grey hatch-marks in Figure 1.1 are designated as “double-density”
mines where 80% of the coal is left in place to support the roof (ODNR 2001).

The impact of longwall coal mining on water resources is well documented
(Pennsylvania Department of Environmental Protection 2001). Loss of water resources,
surface subsidence, and damage to structures are common. Changes in the dynamics of
shallow groundwater aquifers in response to room-and-pillar mining are not as well
documented. However, Zipper, Balfour et al. (1997), in an investigation of the alleged
water-supply impacts of underground coal mining in Virginia, found that de-watering of
aquifers can occur over both high extraction and partial extraction room-and-pillar mines.
Forty-two of fifty-six water supplies they studied outside of the zone of influence of
subsidence were impacted.

1.3 Soil and the Hydrology of Forests.

1.3.1 Water Holding Capacity

One of the important properties of soil is the capacity to store water. Water
stored in soil allows plants growing in the soil to continue transpiration and
photosynthesis through periods of drought. The amount of water a given soil can store
and make available for plant uptake is termed available water capacity (AWC). The
AWC of soil varies spatially and is a function of its depth, rock fragment content,
porosity, and soil moisture characteristic curve (Brady and Weil 1999). Spatial variation
in the soil properties that determine AWC is especially pronounced in areas of dissected
topography where pedogenic, alluvial, and colluvial processes are affected by slope
position (Brady and Weil 1999).

Soil water potential ($\psi$) is a measure of the energy required to extract an
incremental volume of water from soil. The movement of water in all systems, including
soil and plants, occurs along gradients in water potential, where water moves from areas
of high potential to low potential. Water potential is also the biologically-relevant
measure of the water status of living organisms. Establishing the relationship between
soil water content and soil water potential allows for the relation of soil water content to
plant water status using the same units.

The physical properties that determine the AWC of soil can be measured in the
field and by lab analysis of soil samples collected in the field. The first step towards
quantifying the plant available water holding capacity of the soils at Dysart Woods was to
make a systematic survey of the depth, rock fragment content, and texture of the soils.
Estimates of these physical properties are also available in the USDA soil survey (Rubel,
Jenny et al. 1981), however, the unique nature of the undisturbed soils of Dysart Woods
justifies further investigation.

The availability to plants of water stored in soil is dependent upon the ability of
plant roots to grow into the soil. High bulk density or cemented soil layers, inhospitable
pH levels, salinity, and lack of aeration can all prevent the growth of roots in soil. Because these limitations are common, an effective rooting depth of 1 to 2 meters is often assumed for forests (Thornthwaite and Mather 1957, Stone and Kalisz 1991). Rooting depths of up to 4 meters have been observed for white oak (*Quercus alba*) (Stone and Kalisz 1991), one of the dominant species at Dysart Woods. There are documented and suspected cases of tree roots growing into fractures in bedrock and accessing ground water (Nizinski and Saugier 1989, Stone and Kalisz 1991). If the trees of Dysart Woods have roots growing into shallow perched aquifers, they may be using more water than can be stored in the soils, and also may be redistributing ground water up into the soil. The movement of groundwater by tree roots up into surface soil horizons, termed hydraulic lift, has been demonstrated for a wide variety of woody species: sugar maple (Dawson 1993b), *Eucalyptus* and *Grevillea*, (Burgess, Adams et al. 1998) Douglas-fir and ponderosa pine (Brooks, Meinzer et al. 2002), mesquite (Hultine, Scott et al. 2004), creosote bush (Caldwell, Dawson et al. 1998), and others.

### 1.4 Purpose of this Study

Subsurface coal mining is an economically important and spatially extensive activity throughout the Unglaciated Alleghany Plateau, which is largely forested. Subsurface coal mining has been shown to result in the loss of wells and springs (Pennsylvania Department of Environmental Protection 2001). The effect of mining-related changes in hydrology on forest ecosystems is not well studied. A preliminary study of the hydrogeology of Dysart Woods (Schillig 2005) showed that shallow groundwater systems do occur at Dysart Woods. The impact of the mining at Dysart Woods on these water systems remains to be seen.
This major goal of this study was to document pre-mining conditions of groundwater contribution to the forest at Dysart Woods. To meet that objective, my research was carried out at Ohio University’s Dysart Woods Land Lab in 2005 and 2006. The following chapters were written as stand-alone manuscripts for submission to separate peer-reviewed journals. Redundancy in introductory material is a consequence of this.
During the 2005 study period, longwall mines East of the woods were being developed. The Room and Pillar mine directly under Dysart Woods was not yet developed at the time of this study.
Figure 1.2 Generalized cross section of Dysart Woods and underlying mines.
The thickness and depth of the Pittsburgh #8 coal seam, the soil depth, the elevation of water-bearing layers, and the height of trees are approximately to scale.
Chapter 2: Water Holding Capacity of the Soils of an Old-Growth Eastern Deciduous Forest

For submission to Geoderma

2.1 Introduction

The capacity of soil to store water and release it to plants during periods of insufficient rainfall is an important abiotic filter in the structuring of plant communities. The availability of sufficient water is one of the major factors governing the spatial distribution of different types of plant communities (e.g. grassland, coniferous forest, deciduous forest). Even in the relatively wet climates of the eastern United States, storage of water by soils is necessary for growth and survival of the deciduous forest. Moreover, soil water holding capacity is known to affect the distribution of species within forest communities (Tromp-van Merrveld and McDonnell 2006).

It is estimated that 95% of the land area of the state of Ohio was forested prior to European settlement in the early 19th century. All that remains of the primary forest is a few small scattered remnants where individual landowners chose not to cut the forest. These rare old-growth forests are important as reservoirs of biological diversity, and as sources of data about the extensive forests which once covered the region (McCarthy, Small et al. 2001). Surviving eastern old-growth forests, while rare, are the subject of intensive scientific study. The spatial extent, value, and preservation issues of eastern old-growth forests are discussed by Davis (1996).

The Dysart Woods Land Laboratory, including 23 hectares of old-growth forest, is located in Belmont County, Ohio. Coal mining is a major part of the economy locally and throughout the Unglaciated Allegheny Plateau. Subsurface coal mining occurring
near and directly under Dysart Woods may impact the contribution of groundwater to the forest. Subsurface coal mining in the region is known to frequently result in impacts to surface property, including mechanical disturbance (subsidence) which leads to hydrologic disturbance (loss of wells and springs) (Pennsylvania Department of Environmental Protection 2001).

Consideration of the hydrology of a forest system includes biological and abiotic components. Trees and other plants move water from soil into the atmosphere through evapotranspiration. Soils act as a reservoir for water; perched aquifers feed springs that recharge soil moisture in a spatially variable manner. Local climate drives the system. Just as different species of trees vary in their water demands, different soils vary in the amount of water they can hold.

The objective of this study was to describe the available water capacity (AWC) of the soils of an old-growth forest in southeast Ohio. For purposes of this study, AWC is defined as the amount of water held by soil between field capacity and permanent wilting point. AWC is expressed as a volumetric fraction of soil or, where the depth and rock content of a soil is known, as a depth of water. An accurate assessment of the AWC of the soils is necessary to predict the risk of changes to the forest from changes in the groundwater hydrologic regime.

The USDA Soil Survey for Belmont County provides a wealth of useful information about the soils, including horizon-specific estimates of AWC (Rubel, Jenny et al. 1981). Severe erosion hazard, steep slopes, and hillside slippage are major limitations to agriculture and development in much of the county, so one major explicit aim of the soil survey is to inform readers of these limitations. About 35% of the land in
Belmont County was being farmed as of 1981, but many areas that were farmed or grazed in the past have reverted to brush and woodland. The type-locations for the many of the soils mapped at Dysart Woods are in other counties or states, and are typically in areas that were cleared for farming or grazing over 100 years ago and have potentially been subject to severe erosion (Rubel, Jenny et al. 1981). The official series descriptions for the most common soils mapped at Dysart Woods include Ap (plowed) horizons. The soils of Dysart Woods are unique in never having been cleared or cultivated. There might be important differences from similar soils that have been impacted by human management. For example, a previous study demonstrated differences in rock content and bulk density between old-growth and second-growth forest soils (Gathany 2004).

The local topography at Dysart Woods is highly dissected, and the most extensive map unit is an association of soils which occur in a pattern too complex to be mapped at the scale of the soil survey detailed map sheets (1:15,840). The definition of a soil series allows for variation in texture as well as degree of erosion. Campbell and Edmonds (1984) document one example of 3 distinct soil orders being found within a radius of 7 meters within 1 map unit on soils formed from parent materials similar to those at Dysart Woods.

Because we are interested in understanding the spatial variability of the soils and their AWC at the scale of the forest, our principle objective was to make a site-specific estimate of the AWC of soils of Dysart Woods. Specifically we focused on measuring the depth, texture, and rock content of the soils. Additionally, time-series measurements of volumetric water content ($\theta$) and soil water potential ($\psi$) provide insight into the
properties of the soil at one hillside location. Ultimately these data will provide critical insight into the baseline hydrologic budget for the forests of Dysart Woods.

2.2 Methods

2.2.1 Site Description

Ohio University’s Dysart Woods Land Laboratory consists of 205 hectares in sections 33 and 28 of Smith Township R4W, T8N, Belmont County, Ohio (39°59’55”N, 80°59’50”W). Twenty-three hectares are designated as old-growth forest. Surface elevations range from 335 to 410 meters. The forest was described in detail by McCarthy, Small et al. (2001), who determined the forest community type to be mixed mesophytic. Fourteen tree species were found to be present, with white oak (*Quercus alba*), beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and tulip poplar (*Liriodendron tulipifera*) as respective dominants. White oak was found almost exclusively as large diameter mature trees. Many individual trees in excess of 100cm diameter at breast height (DBH) and 300 years of age were described. The understory vegetation was described as being remarkable for its high degree of cover and diversity. The forest as a whole was described as relatively healthy. Based upon the regeneration data, a community transition from an oak-dominated forest to a beech-maple forest seems to be under way. Fungal pathogens (e.g. *Armillaria*) were present and active in some locations. Because this site is an ecotone between two diverse forest types, effects of aspect and microclimate on plant distribution are especially pronounced.

Dysart Woods is located on the Little Switzerland Plateau of the Unglaciated Allegheny Plateau physiographic region. Bedrock is of Permian origin and the region was not covered during the Pleistocene glaciation, leaving rugged terrain and well weathered
soils (Rubel, Jenny et al. 1981). The Pittsburg #8 Coal Seam is about 2 meters thick and lies at an elevation of 221 to 244 meters, leaving an overburden of 91 to 189 meters (ODNR 2001).

The soils of Dysart Woods are generally of the Westmoreland-Lowell association. The Westmoreland-Lowell association consists of well drained soils on narrow ridges and steep, benched, or irregular hill slopes. Benches on hill slopes may be the result of rotational slumps caused by positive pore pressures resulting from groundwater discharge from perched aquifers (Mary Stoertz, Personal Communication). Upland soils are formed from parent material of residuum of limestone, shale, siltstone and sandstone (Figure 2.1). Minor extents of bottomland soils formed from local alluvial and colluvial deposits. Midslope accumulations of loess blown in from the Ohio River Valley at the end of the last glacial epoch (about 10,000 y.b.p.) are of minor extent but are locally important (Greg Springer, Personal Communication).

The Detailed Soil Map Sheet (Rubel, Jenny et al. 1981) shows nine map units describing patterns of occurrence of eight soil series on the Dysart Property. To allow spatial analysis of the soil physical properties, the soil survey map sheet was digitized using ARCGIS 9.1 (ESRI 2005), and map unit polygons were joined to tables of soil physical properties. Physical properties, including estimates of AWC, (Rubel, Jenny et al. 1981) of the soil map series at Dysart Woods are summarized in Table 2.1. The soil map units of Dysart Woods, their relative proportion, and the dominant soil series are show in Table 2.2. Ranges of whole-profile AWC were calculated on a map-unit basis by summing the product of soil horizon depth and horizon AWC (in %) for each horizon in a profile. Ranges of whole-profile soil AWC are mapped in figure 2.2.
2.2.2 Soil Depth

Soil depth was measured with a 1.5m tile probe (Forestry Suppliers Inc., Jackson MS). In the 9.1 ha south-facing old growth stand, soil depth was measured at twenty-three locations on a 61m square grid (Figure 1.1). The probe was inserted vertically until it reached a hard stop indicative of contact with rock. The presence of rock fragments up to 30% by volume of lower soil horizons, as predicted in the soil survey (Rubel, Jenny et al. 1981), and verified at this site in a previous study (Gathany 2004), confounded the measurement of soil depth with a tile probe. To attempt to circumvent this limitation, 4 measurements were taken at each sampling location and the maximum was selected as a measure of soil depth at that location.

2.2.3 Soil Texture

Ten soil samples were collected for textural analysis from 0-15cm depth from the 9.1 ha south-facing old growth stand at locations referenced to the surveyed grid system. Soil physical properties (e.g. clay content, parent material) described in the soil survey, and DEM-based descriptions of the landscape (e.g. slope, aspect etc.) for these exact locations were noted for analysis. Twenty-four additional soil samples were collected from depths of 15, 30, and 45 cm when holes were dug for the installation of soil moisture sensors on one south-facing hill slope. Thirty-six additional samples from a previous study of soil organic matter and rock content (Gathany 2004) were also analyzed for soil texture. Soil texture was determined using a modified Bouyucous Hydrometer method (McCarthy 1997), and classified following USDA protocols (Schoeneberger, Wysocki et al. 2002).
2.2.4 Soil Water Characteristic

The soil water characteristic, sometimes also called a water retention curve (Teepe, Dilling et al. 2003) or moisture release curve is the relationship between soil water content ($\theta$) and soil water potential ($\psi$). Two theoretical points on this curve, field capacity and permanent wilting point, describe the upper and lower bounds of plant available water. Field capacity (FC) is defined by Brady and Weil (1999) as $\theta$ after 1-3 days of drainage after a saturating rain. Permanent wilting point (PWP) is defined as the state where $\psi <-1.5\text{MPa}$. Plant species differ in their ability to extract water from dry soil (Hinckley, Dougherty et al. 1979); however, the non-linear nature of the water characteristic curve is such that there is only a small change in $\theta$ associated with large changes in $\psi$ as soils approach permanent wilting point. The amount of water stored between FC and PWP determines plant available water capacity (AWC).

Different techniques of measuring the soil water characteristic are better suited to one end of the moisture spectrum or the other. Salter and Williams (1965) note that drying and sieving of soil for laboratory analysis destroys the macropore structure which plays a large role in the value of $\theta$ at FC. The in-situ analyses presented in this paper are especially important considering the undisturbed nature of the soils at this site.

Hourly time-series measurements of $\theta$ over the course of a growing season show the actual amount of water taken up from the soil by plants. Assuming that both extremes of wet and dry conditions are observed, the AWC of the soil can be calculated by simple subtraction. The soil water characteristic, the relationship between soil volumetric water content ($\theta$) and soil water potential ($\psi$), was determined in-situ at one
location and in the lab for the 24 soil samples collected at the 3 depths and 8 locations of θ monitoring probes.

An in situ soil water characteristic curve was generated from hourly measurements of θ from a water content reflectometer (Model: CS 616, Campbell Scientific, Logan Utah, USA) and measurements of ψ from thermocouple psychrometers (Model PST-55, Wescor Inc., Logan Utah, USA). The CS616 sensor was installed vertically, averaging θ for 0-30cm depth. A thermocouple psychrometer was installed at a depth of 15 cm. Both sensors were located in a dry, upslope position on a southwest facing aspect (Figure 3.1). This location was chosen as being most vulnerable to changes in groundwater hydrology.

A total of 24 CS 616 and 6 TDR probes were installed as shown in Figure 3.1 and logged hourly. Data from these sensors was analyzed to determine values of θ at permanent wilting point and field capacity to determine the AWC of the soil.

Laboratory measurements of soil water characteristic curves were made on twenty-four air-dried and sieved (<2mm) soil samples using a dewpoint potentiometer (Model WP4-T, Decagon devices Inc, Pullman WA, USA) following the protocol recommended by the manufacturer (Decagon 2005). Values of gravimetric water content were converted to volumetric water content using bulk density measurements made in a previous study of the soils at the same site (Gathany 2004).

2.2.5 Calculation of AWC for the Soil Profile

The physical properties of soil that determine the water characteristic (e.g. texture, structure, organic matter content) vary with depth at a single location. The AWC of individual soil horizons was calculated in terms of a volume fraction (or percent) of the
bulk soil. The depth of the individual horizons was then multiplied by the volume fraction AWC to determine the horizon AWC in units of a depth of water. This was repeated for all of the horizons down to the full depth of the soil to determine AWC for the whole soil profile. The resulting measure of AWC as a depth of water is directly analogous to a depth of rain measured in a rain gauge or evapotranspiration frequently expressed in units of mm.

2.3 Results

2.3.1 Soil Depth

Average soil depth was 1.2m (±0.3 sd, n=23). This is in close agreement with the soil survey description of the depth of the Lowell, Westmore, and Westmoreland soils as 1.27 meters. GIS analysis of the digitized soil survey (Rubel, Jenny et al. 1981) map sheet indicates that these 3 soil series account for approximately 85% of the ground surface area on the Dysart Woods property.

2.3.2 Soil Texture

Soils sampled for textural analysis fall into USDA classifications of Loam, Silt Loam, and Clay Loam (Figure 2.3). Clay content ranged from 10% to 30%. At locations where soils were sampled at multiple depths, an increase in clay content with depth was observed, consistent with the diagnosis of an argillic (Bt) horizon. While still usually sufficient to support the diagnostic argillic horizon, the clay content at depths of 15-45 cm was consistently lower than the range listed in the soil survey for the Lowell series. In some cases, the clay content was much lower than expected (10% instead of 27-33%). Because of the limited sampling depth relative to the depth of the A and B horizons of the Lowell soils, it may be that we simply did not sample from deep enough to find argillic
accumulations of clay. It is likely that the surface horizons at Dysart Woods are deeper and more variable in depth than described in the soil survey because these soils have not been subjected to the erosion and compaction associated with land clearing, cultivation, and grazing.

There was an apparent relationship between the texture of the surface horizon and soil parent material mapped from data in the soil survey. Specifically, soils formed from wind-blown loess (Figure 2.1) on middle slope positions (Westmore Series) had less sand and more silt & clay (Figure 2.3) than the surface horizon of upslope soils formed from residuum.

2.3.3 Soil Water Characteristic

Soil AWC was calculated from analysis of the season-long trends (Figure 2.4a), and detailed examination of drainage to field capacity (Figure 2.4b), utilization of stored moisture (Figure 2.4c), and unavailability of remaining soil water (Figure 2.4d). Contemporaneous measurement of soil water potential (Figure 2.5), indicates that soil water potential does rapidly approach wilting point (i.e. $\psi<1.5\text{MPa}$) as soil VWC approaches 10% at this location.

Field capacity at this location, calculated as defined by Brady and Weil (1999) as $\theta$ after 1-3 days of drainage with no rainfall, was determined to be 32%. Subtracting the minimum observed $\theta$ (10%) from $\theta$ at field capacity (32%), we found an AWC of 22%. Similar analyses of 15 other sensors in the dry upslope position indicate a mean AWC of 19% for soil depth of 0-30 cm and AWC of 15% for soil at 45cm depth. Similar analyses of data collected from sensors at downslope positions was confounded by the fact that
continuous input of groundwater from seeps kept the soil moist throughout the growing season.

Laboratory analysis of the soil water characteristic yielded additional insight into the effect of soil texture (Figures 2.3, 2.7) on the amount of water held at PWP. For soils with clay contents ranging from 14% to 24%, we found that the value of \( \theta \) at which \( \psi \) approaches -1.5MPa ranges from about 6% to 11% (Figure 2.7). This compares favorably with minimum observed in-situ values of \( \theta \) ranging for 6% to 13%.

2.3.4 Soil Profile AWC

Whole-profile AWC (in units of depth of water) was calculated for the same dry-upslope location by summing the product of the AWC of each soil horizon and the depth of the horizon. By this method, the AWC for depth 0-30 cm was 57mm. Taking measurements at 45cm depth to be representative of the 30-45cm depth range, AWC for this depth range was found to be 22.5 mm. Summing, the total AWC of the top 45cm of the soil was estimated to be 79.5mm. The soil survey (Rubel, Jenny et al. 1981) lists an AWC of 77-97 mm for this depth range of the Lowell soil, putting our estimate at the low end of the range.

Because of high excavation difficulty and the desire to minimize impacts on the soils, our investigation was limited to 45 cm depth. However, medium and course tree roots were observed at this depth, and the soil survey describes profile conditions and AWC down to a depth of 127 cm.
2.4 Discussion

Although there was considerable variability in soil texture, with clay content ranging from 10%-30%, and some of that variability was associated with soil parent material, mapping the intricate patterns of variability was not feasible. This sort of variability is acknowledged in the soil survey, and has been described generally in the literature about soil taxonomy. Individual soil survey map units are human-created geographic abstractions encompassing variability of a degree thought to be insignificant to the management options appropriate to a specific location (Campbell and Edmonds 1984).

The horizon-specific estimates of AWC, measurements of soil depth, and previous site-specific measurements of rock content are all within the ranges estimated in the soil survey for the predominant soils at Dysart Woods. We were only able to look at depths 0-45 cm, so our best estimate of physical properties of the soils below this depth comes from the soil survey. Because of the generally good agreement between our observations at this site and the descriptions in the soil survey, reliance upon the total profile AWC values is reasonable.

This verification and analysis of the AWC of the soils of Dysart Woods provides a key parameter for further modeling of soil water dynamics at Dysart Woods. Groundwater contributions to the forest may be changing as a result of subsurface mining, so an understanding of the AWC of the soils is critical for future analyses of the biological impact of these changes. The soil water characteristic provided by this study allows modeling of \( \psi \) (and plant water stress) as a function of measured values of \( \theta \).
Patterns of soil moisture and drought response in forests with many of the same tree species as Dysart Woods, but on soils only half as deep, have been described (Hinckley 1975, Tromp-van Merrveld and McDonnell 2006). Similar soils, classified as having moderate depth and AWC, occur and support forests throughout the region. However, given a history of groundwater input, the current plant communities at Dysart Woods may have developed xylem hydraulic architecture and canopy and leaf characteristics appropriate for wet conditions. Bhaskar and Ackerly (2006) describe how the minimum value of soil water potential experienced by a plant is expressed in phenotypic plasticity in xylem structure and other hydraulic traits.

It has been observed, in southeastern Ohio, that white oak only seems to regenerate under dry conditions, where faster growing, more mesic species are not able to survive (Iverson, Dale et al. 1997). McCarthy and Small et al. (2001) speculate that oaks may have become dominant on the drier upslope locations of Dysart Woods during a time of dryer climate, but the understory, now dominated by beech and maple, may be dependent upon current moisture conditions which are at risk of being changed due to coal mining.
Figure 2.1 Map of soil parent material types at Dysart Woods.
Data from USDA soil survey (Rubel, Jenny et al. 1981).
Figure 2.2 Map of soil AWC ranges at Dysart Woods. Data from USDA soil survey (Rubel, Jenny et al. 1981).
Figure 2.3 Texture of soils sampled at Dysart Woods. Soil sampled from locations mapped in the soil survey as formed from residuum (squares), and loess (circles).
Figure 2.4 Hourly VWC measurements. Hourly measurements of VWC 0-15cm depth, upslope position. (A) seasonal fluctuations in VWC, (B) drainage to field capacity during a time with low ET, (C) diurnal cycle of soil water utilization during a time with high ET demand and ample soil moisture, and (D) unavailable soil water not being utilized despite continued high ET demand.
Figure 2.5 Time series soil VWC (θ) and water potential (ψ).
Daily averages of measurements of θ from 0-30 cm depth and ψ from 15cm depth at 1 dry upslope location. Soil water potential was below -1 MPa on 8/14 and 8/15 2005.
Figure 2.6 In-situ soil water characteristic curve.

Daily average measurements of $\theta$ from 0-30 cm depth and $\psi$ from 15 cm depth at 1 dry upslope location. Soil water potential ($\psi$) decreases abruptly as soil water content decreases below 10%.
Figure 2.7 Laboratory soil water characteristic curves.
Lab measurement of soil water characteristic curves for soil from 3 depths at the same location.
Table 2.1 Physical Properties of the Soil Series of Dysart Woods.
Data summarized from Belmont County Soil Survey (Rubel, Jenny et al. 1981). AWC estimates expressed in mm were calculated by multiplying horizon depth by volume-fraction AWC. Profile AWC was calculated by summing the AWC contribution from each soil horizon.

<table>
<thead>
<tr>
<th>Series &amp; (Primary Parent Material)</th>
<th>Depth (cm)</th>
<th>clay%</th>
<th>AWC %</th>
<th>%&gt;2mm</th>
<th>%&gt;3*</th>
<th>Horizon AWC (mm)</th>
<th>Whole profile AWC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowell (limestone)</td>
<td>0 - 18</td>
<td>18 - 27</td>
<td>18 - 23</td>
<td>0 - 5</td>
<td>0 - 0</td>
<td>32 - 41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 - 46</td>
<td>27 - 33</td>
<td>16 - 20</td>
<td>0 - 5</td>
<td>0 - 2</td>
<td>45 - 56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46 - 107</td>
<td>40 - 55</td>
<td>9 - 13</td>
<td>0 - 5</td>
<td>0 - 5</td>
<td>55 - 79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>107 - 127</td>
<td>27 - 35</td>
<td>5 - 14</td>
<td>20 - 45</td>
<td>5 - 20</td>
<td>10 - 28</td>
<td></td>
</tr>
<tr>
<td>Westmoreland (sandstone)</td>
<td>0 - 20</td>
<td>15 - 27</td>
<td>16 - 20</td>
<td>0 - 20</td>
<td>0 - 0</td>
<td>32 - 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 - 71</td>
<td>18 - 35</td>
<td>12 - 18</td>
<td>5 - 45</td>
<td>0 - 15</td>
<td>61 - 92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>71 - 127</td>
<td>18 - 35</td>
<td>6 - 10</td>
<td>5 - 45</td>
<td>0 - 15</td>
<td>34 - 56</td>
<td></td>
</tr>
<tr>
<td>Upshur (shale)</td>
<td>0 - 15</td>
<td>27 - 35</td>
<td>12 - 16</td>
<td>0 - 5</td>
<td>0 - 0</td>
<td>18 - 24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 - 71</td>
<td>40 - 55</td>
<td>10 - 14</td>
<td>0 - 5</td>
<td>0 - 0</td>
<td>56 - 78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>71 - 152</td>
<td>27 - 45</td>
<td>8 - 12</td>
<td>0 - 35</td>
<td>0 - 0</td>
<td>65 - 97</td>
<td></td>
</tr>
<tr>
<td>Westmore (loess over limestone)</td>
<td>0 - 20</td>
<td>15 - 27</td>
<td>17 - 21</td>
<td>0 - 10</td>
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<td>64 - 127</td>
<td>35 - 60</td>
<td>12 - 16</td>
<td>5 - 35</td>
<td>0 - 15</td>
<td>76 - 101</td>
<td></td>
</tr>
<tr>
<td>Hartshorn (alluvium)</td>
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<td>18 - 27</td>
<td>20 - 24</td>
<td>0 - 25</td>
<td>0 - 5</td>
<td>122 - 146</td>
<td></td>
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<tr>
<td></td>
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<td>4 - 10</td>
<td>3 - 6</td>
<td>50 - 70</td>
<td>0 - 15</td>
<td>12 - 25</td>
<td></td>
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<tr>
<td>Brookside (colluvium)</td>
<td>0 - 18</td>
<td>27 - 40</td>
<td>18 - 23</td>
<td>0 - 25</td>
<td>0 - 5</td>
<td>32 - 41</td>
<td></td>
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<tr>
<td></td>
<td>18 - 55</td>
<td>30 - 60</td>
<td>7 - 14</td>
<td>10 - 35</td>
<td>0 - 15</td>
<td>26 - 52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 - 80</td>
<td>30 - 60</td>
<td>5 - 12</td>
<td>25 - 55</td>
<td>5 - 25</td>
<td>13 - 30</td>
<td></td>
</tr>
<tr>
<td>Dekalb (sandstone)</td>
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<td>10 - 20</td>
<td>8 - 12</td>
<td>15 - 25</td>
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<td></td>
<td>15 - 71</td>
<td>7 - 18</td>
<td>6 - 12</td>
<td>20 - 60</td>
<td>5 - 40</td>
<td>34 - 67</td>
<td></td>
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<tr>
<td></td>
<td>0 - 23</td>
<td>15 - 26</td>
<td>22 - 24</td>
<td>0 - 0</td>
<td>0 - 0</td>
<td>51 - 55</td>
<td></td>
</tr>
<tr>
<td>Elkinsville (alluvium)</td>
<td>23 - 142</td>
<td>22 - 30</td>
<td>18 - 22</td>
<td>0 - 0</td>
<td>0 - 0</td>
<td>214 - 262</td>
<td></td>
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<td></td>
<td>142 - 172</td>
<td>16 - 30</td>
<td>15 - 20</td>
<td>0 - 0</td>
<td>0 - 0</td>
<td>45 - 60</td>
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Table 2.2 Extent and Included Series of Soil Map Units at Dysart Woods.
Data summarized from Belmont County Soil Survey (Rubel, Jenny et al. 1981). Area extent was calculated using ARCGIS 9.1 (ESRI 2005), and a manual digitization of the maps in the printed soil survey.

<table>
<thead>
<tr>
<th>Map Unit Name</th>
<th>Symbol</th>
<th>% of Area</th>
<th>Dominant Series</th>
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</thead>
<tbody>
<tr>
<td>Lowell-Westmorelant silt loams</td>
<td>Lo</td>
<td>39%</td>
<td>Lowell, Westmoreland</td>
</tr>
<tr>
<td>Lowell silt loam</td>
<td>Le</td>
<td>21%</td>
<td>Lowell</td>
</tr>
<tr>
<td>Westmore silt loam</td>
<td>Wk</td>
<td>15%</td>
<td>Westmore</td>
</tr>
<tr>
<td>Westmoreland silt loam</td>
<td>Wm</td>
<td>7%</td>
<td>Westmoreland</td>
</tr>
<tr>
<td>Westmoreland-Upshur complex</td>
<td>Wo</td>
<td>4%</td>
<td>Westmoreland, Upshur</td>
</tr>
<tr>
<td>Hartshorn silt loam</td>
<td>He</td>
<td>5%</td>
<td>Hartshorn</td>
</tr>
<tr>
<td>Brookside silty clay loam</td>
<td>Bs</td>
<td>3%</td>
<td>Brookside</td>
</tr>
<tr>
<td>Dekalb loam</td>
<td>Dk</td>
<td>3%</td>
<td>Dekalb</td>
</tr>
<tr>
<td>Elkinsville silt loam</td>
<td>El</td>
<td>3%</td>
<td>Elkinsville</td>
</tr>
</tbody>
</table>
Chapter 3: Spatial and Temporal Variation in Soil Water Content in an Old-Growth Deciduous Forest in Ohio

For submission to Agricultural and Forest Meteorology

3.1 Introduction

The availability of sufficient water is a key factor limiting the distribution of plants. Even within the relatively wet deciduous forests of southeastern Ohio, the distribution of tree species is associated with availability of water (McCarthy, Small et al. 2001, Dyer 2003). Changes in climate and other factors that influence water availability therefore have the potential to shift forest community composition through time.

It is estimated that 95% of the land area of the state of Ohio was forested prior to European settlement in the early 19th century. All that remains of the primary forest are a few small scattered remnants where individual landowners chose not to cut the forest. These rare old-growth forests are important as reservoirs of biological diversity, and as sources of data about the extensive forests which once covered the region (McCarthy, Small et al. 2001). In addition, these forest remnants provide an endpoint in biogeochemical chronosequences, allowing us to characterize forest function from very young to old-growth forests.

Ohio University’s Dysart Woods Land Laboratory, which includes 23 hectares of old-growth forest, is located in Belmont County, Ohio, where coal mining is a major part of the local economy. Subsurface coal mining occurring near and directly under Dysart Woods may impact the dynamics of shallow groundwater systems at Dysart Woods. Controversy over the mining has raised questions for which no answers exist in the peer-reviewed literature. Sub-surface coal mining occurring near the study site may lead to a
change in the dynamics of shallow, perched, groundwater systems which contribute to soil moisture through contact springs. Changes in groundwater resources (e.g. loss of wells and springs) have been documented extensively in areas where subsurface coal mining has occurred (Pennsylvania Department of Environmental Protection 2001). Of interest is whether the forest community is able to obtain sufficient water from precipitation stored in soil, or if occasional drought conditions require trees to access groundwater directly. Groundwater-fed seeps and springs have been observed to contribute to soil moisture at Dysart Woods, but the spatial extent of this phenomenon has not been documented.

The major objective of this study was to describe the spatial and temporal variation in soil water content as a pre-mining control study. Additionally, the spatial extent of groundwater contributions to the forest water budget is described.

Soil water content is measured as a gravimetric or volumetric fraction ($\theta$). It is convenient to think in terms of volume when tabulating a soil water budget, but the availability of soil water to plants is better measured by soil water potential ($\psi$). The relationship between $\theta$ and $\psi$ is non-linear, and is primarily a function of soil texture, structure, and organic matter content (Salter and Williams 1965, Saxton, Rawls et al. 1986).

In highly dissected terrain, on soils formed from intricately interbedded parent material of differing physical properties, and with a high degree of species and age-class diversity, there are numerous drivers for spatial heterogeneity in soil water content. Tromp-vanMerrveld and McDonnel (2006) found spatial patterns in soil water content in relation to a soil depth gradient on a hillslope. The effect of variability of canopy
architecture on canopy interception capacity of different tree species has also been shown
to affect soil water content (Jost, Heuvelink et al. 2005). Jacquot and Armentano et al.
(1992) describe increased water use by trees near the edge of an old-growth forest
fragment in a matrix of agricultural land. Interspecies differences in transpiration
response to changes in soil moisture can also be partially responsible for the spatial
structuring of soil water content (Schume, Jost et al. 2003).

A Topographic Relative Moisture Index (TRMI) is a scalar index of quantities
derived from a digital elevation model (DEM). The quantities considered are: relative
slope position, slope steepness, slope shape, and aspect. This method was developed by
Parker (1982), and has been shown to correlate well with soil moisture in some areas of
high to moderate slope relief. Other researchers have found only weak correlations
between TRMI and measured soil water content in forested areas of southeastern Ohio
(Iverson, Prasad et al. 2004). Dyer (2003) used several similar indices, some including
soils data, to try to predict the spatial distribution of beech in southeastern Ohio, but was
only able to explain about 27% of the variance in beech dominance.

The TRMI is a useful tool for predicting the spatial distribution of soil moisture
based purely on topography. Topography may not be independent of groundwater
contributions, because topography is directly related to both recharge and discharge of
groundwater. Groundwater discharge may contribute to streams which cause the erosion
that results in the topography being analyzed in the TRMI. Substantial deviations from
predicted patterns are indicative of processes at work in the real world which are not
considered in the model. In the case of Dysart Woods, localized occurrence of elevated
θ may be due to hydrogeologic conditions (i.e. seeps), or may simply occur where
topographic conditions contribute to the accumulation of surface run-off and lateral flow in soils. Such accumulative landscape positions are also associated with important pedogenic factors, and so may be associated with deeper or more weathered soils.

The specific objectives of this study were to characterize θ in a spatially extensive and temporally intensive manner, and to determine what variables control the variability of soil water content prior to the initiation of mining. In particular, this study examines the contribution of groundwater to soil water content, with implications for detection of future changes in groundwater contribution induced by underground coal mining. This approach utilizes a combination of datalogger and manual techniques. A GIS database of soil properties and modeling of TRMI allow modeling of soil water availability at any location at Dysart Woods.

3.2 Methods

3.2.1 Site Description

Ohio University’s Dysart Woods Land Laboratory consists of 205 hectares of mixed-mesophytic forest in sections 33 and 28 of Smith Township R4W, T8N, Belmont County, Ohio (39°59′55″N, 80°59′50″W). Twenty-three hectares are designated as old-growth forest. The forest was fully characterized by McCarthy, Small et al. (McCarthy, Small et al. 2001), who noted the presence of individual trees in excess of 300 years old. Surface elevations range from 335 to 410 meters. The Pittsburg #8 Coal Seam is about 2 meters thick and lies at an elevation of 221 to 244 meters, leaving an overburden of 91 to 189 meters (ODNR 2001).

Dysart Woods is located on the Little Switzerland Plateau of the Unglaciated Allegheny Plateau physiographic region. Bedrock is of Permian origin and the immediate
area was not covered with ice during the Pleistocene glaciation, leaving rugged terrain and well weathered soils (Rubel, Jenny et al. 1981).

The soils of Dysart Woods are generally of the Westmoreland-Lowell association. The Westmoreland-Lowell association consists of well drained soils of moderate depth on narrow ridges and steep, benched, or irregular hill slopes (Rubel, Jenny et al. 1981). Benches on hill slopes may be the result of rotational slumps caused by positive pore pressure groundwater seeps from perched aquifers (Mary Stoertz, Personal Communication). Upland soils are Ultic Alfisols formed from residuum of limestone, shale, siltstone and sandstone. Minor extents of bottomland soils formed from local alluvial and colluvial deposits. Midslope accumulations of loess blown in from the Ohio River Valley at the end of the last glacial epoch (about 10,000 y.b.p.) are of minor extent but are locally important (Greg Springer, Personal Communication).

3.2.2 Temporally Intensive Measurements

Weather data were collected with a Campbell Scientific CR10-X datalogger and the following sensors: CS-500L Vaisala Air Temperature and Relative Humidity Probe, TE525-M Tipping Bucket Rain Gauge, LICOR LI-200X Pyranometer, MET-ONE 034B-L Wind Set, CS-616 Soil Water Content Reflectometer. All weather station components were obtained from Campbell Scientific (Logan Utah). Sensors were scanned every 5 seconds. Average, cumulative, and min/max values were saved to a data file every hour. Penman-Monteith potential evapotranspiration was calculated by the datalogger based on hourly average conditions. The weather station was installed on April 10, 2005 in an open field, approximately 1 km from the edge of the forest.
Soil and forest canopy data were collected with a Campbell Scientific CR10-X datalogger and the following sensors: 24 CS616 soil water content reflectometers switched by 4 AM16/32 multiplexers, 6 CS605-L TDR probes controlled by a TDR100 time domain reflectometer and an SDMX50 multiplexer, 4 thermistors measuring soil temperature, and 2 Licor LI-190 quantum sensors measuring photosynthetically active radiation (PAR) under the forest canopy.

Soil moisture and temperature measurements were made and recorded hourly. PAR sensors were read every 30 seconds; data were recorded as hourly averages. Additionally, soil water potential was measured using a Wescor PSYPRO datalogger and 4 thermocouple psychrometers (model PST-55)

CS 616 probes were inserted vertically from the soil surface (to average to a depth of 30 cm), and horizontally (at depths of 15 and 45 cm) into the upslope face of a small hole dug to a depth of 45 cm using a garden spade and digging bar. For the horizontally oriented probes, a guided tool with the same configuration as the CS 616 probes was hammered in place to provide straight holes for the CS 616 waveguides to go into. Holes were backfilled with soil horizons preserved as well as possible. Two holes were instrumented as described above at up-and-downslope positions at two different aspects (Figure 3.1).

TDR probes were buried horizontally at depths of 15, 30, and 45 cm in the holes marked “B” in Figure 3.1 at up-and-downslope locations. Because of the configuration of the TDR probes, they could not be inserted into the undisturbed soil at this site and were buried as the holes were back-filled. Measurements of volumetric water content of soil which has been disturbed cannot be compared directly to measurements from
(relatively) undisturbed soil because the configuration of pore space plays a large role in the movement and retention of water in soil. Comparison of measurements from TDR and CS616 probes buried at the same depth in the same location is provided in Appendix A.

3.2.3 Spatially Extensive Measurements

Soil volumetric water content (VWC, or $\theta$) to a depth of 20 cm was measured with a handheld water content reflectometer (Hydrosense, Campbell Scientific, Logan Utah). Spatially extensive measurements of $\theta$ were made on 8 days during the 2005 growing season on the dates and locations shown in Figure 3.6. At each location, 4 measurements of soil VWC were made within 1 meter of the location marker and the mean was used for further analysis.

3.2.4 Topographic Relative Moisture Index

The TRMI model was made following the technique of Urban (1999) after (Parker 1982) using the model-builder module of ARCGIS 9.1 (ESRI 2005) and a 10m digital elevation model (DEM) obtained from the USGS (USGS 2006).

Slope was calculated as % rise/run, and classified into values of 1-10. Slope steepness contributes up to 10 of the 60 points in the final TMRI value. It is expected that areas with steeper slopes should shed surface water more readily, be more prone to erosion, and therefore retain less moisture.

Relative slope position was calculated as the relative distance from each cell to the top and bottom of the local slope (i.e. distance to ridge top/total slope length). A higher value is associated with downslope positions, where water would be expected to accumulate. Relative slope positions were classified into values of 1-10.
The bottom of the local slope was determined from a classified output of the flow accumulation tool in the Hydrology toolbox in ARCGIS. All cells that accumulate flow from more than 100 cells were considered streams; the output of this classification corresponded well with observed locations of perennial streams. Hilltops were defined as areas with an elevation more than 5 meters above the mean elevation of a 150 x 150 meter square neighborhood.

Slope curvature (e.g. concave/convex) was calculated using the curvature tool in ARCGIS. Slope curvature was calculated as the 2\textsuperscript{nd} derivative of the elevation of the neighborhood of each cell. Cells with concave slope configuration should accumulate water from adjacent cells, while cells with convex configuration should shed water. Slope curvature values were classified into values of 1-10.

Aspect is associated with intensity, timing, and duration of solar radiation to a site. Solar radiation is a major driving force for evapotranspiration, so areas receiving more sunlight would be expected to be drier. Aspect was classified into 18 classes assigned 0-20 points in the TRMI. North facing slopes were expected to be wettest, south facing slopes driest.

The final step in the TRMI model was to sum all of the points from the 4 individual indices. The final TRMI score is a scalar value from 0 to 60 which should be indicative of the relative year-round average water content of a site.

3.2.5 Soil Water Budget

A monthly soil water budget was prepared using the Thornthwaite method (Thornthwaite and Mather 1957). Normal monthly rainfall data were used from records from Barnesville, Ohio from 1971 to 2000 (NCDC 2002). Monthly potential
evapotranspiration (PET) was calculated following Thornthwaite’s protocol. Actual evapotranspiration (AET) modeled by Thornthwaite’s method takes into consideration water stress when water stored in the soil becomes inadequate to supply plant needs. Soil AWC of 150 mm was assumed based on the estimate made in Chapter 2 of this thesis. Additionally, a soil water budget was calculated using Thornthwaite’s basic monthly accounting scheme, but using actual precipitation and PET calculated from data obtained from the on-site weather station.

3.3 Results

3.3.1 Climate Data and Modeled VWC

Time series data from the weather station and forest soil VWC dataloggers are summarized in Figure 3.2. The ratio between daily total photosynthetically active radiation (PAR) (µmol m⁻²) under the forest canopy and net radiation (J m⁻²) in the open provides a measure of light penetration of the forest canopy (Figure 3.2a). In this deciduous forest, this measurement shows the fall senescence and spring emergence of leaves, indicating a period of dormancy from November through April.

Monthly rainfall for 2005 was less than half of normal for the months of May, June, and July. Remnants of Hurricane Katrina brought some drought relief at the end of August, but drier than normal conditions continued through September (Figure 3.2b). Precipitation was also substantially below normal for July and August of 2006.

Thornthwaite’s soil water budget model predicted that potential evapotranspiration would exceed rainfall in the months of June, July, August, and September of a year with normal rainfall. With soil AWC of 150 mm and normal monthly precipitation, modeled actual evapotranspiration fell short of potential
evapotranspiration only in August, and only by 7% of the total monthly PET (Figure 3.2c). With the actual rainfall at Dysart Woods, Thornthwaite’s model predicted more substantial moisture deficits during dry periods of both 2005 and 2006 growing seasons. Modeled AET was 53% of potential for July 2005 and 58% of potential for August 2006. Soil moisture storage predicted by Thornthwaite’s model (Figure 3.2d) shows the extent to which utilization of moisture stored in soil can compensate for below-normal rainfall.

### 3.3.2 Temporal Variability of Soil VWC

Daily average values of $\theta$ at 15cm and 45cm depth (sensors installed horizontally, and for 0-30 cm (sensor installed vertically) with two replicates at two slope positions and two aspect locations are summarized in Figure 3.3 (upslope) and Figure 3.4 (downslope). Differences in the values and temporal dynamics between sensors reflect a high degree of small-scale spatial variability in soil structure, texture, and rock content. The expected minimum value of $\theta$ corresponding to permanent wilting point ($\psi$ $\leq$ -1.5MPa) ranged from 6 to 13%. Local variations in soil bulk density (e.g. earthworm burrows, root channels, rocks) probably account for some of the large variation in measurements between sensors. Comparison of mean values for up-and-downslope positions between 2005 and 2006 indicate that downslope positions were wetter than upslope positions during both the dormant and growing seasons (Figure 3.5).

### 3.3.3 Spatial Variability of Soil VWC

Spatially extensive measurements of $\theta$ from throughout the 2005 growing season (Figure 3.6) show spatial and seasonal trends in soil moisture. Classification categories were chosen to represent VWC approaching growth-limiting soil water potential ($<12\%$
VWC), about 50% utilization of AWC (<23% VWC), and ample soil moisture (>23% VWC).

Spatial patterns were most apparent under relatively dry conditions (e.g. 10/4/2005). Insight into the temporal dynamics at the scale of the whole forest can be gained from analysis of the patterns which develop from 9/4/2005 to 10/4/2005. Soil moisture was replenished nearly to field capacity by 92mm of rain from that fell from 8/29 to 8/31 2005. On September 4, 2005 surface soil moisture was almost uniformly above 23% (Figure 3.6). September 2005 rainfall was about 50% of normal. By October 4, 2005 soil moisture was approaching wilting point at upslope locations across the site, but wet spots remained adjacent to streams and where springs and seeps contribute to soil moisture (Figure 3.6).

3.3.4 The Topographic Relative Moisture Index

The spatial pattern of soil moisture observed on October 4, 2005 was compared to the predictions of the TRMI model. Areas which remained wet after a period of dry weather corresponded well with topographic positions expected to accumulate and preserve moisture (Figure 3.7). In some cases, the spatial scale of both the TRMI model (10m) and our measurements of \( \theta \) (61m) were insufficient to capture the intricacies of spatial variability in the rugged terrain at Dysart Woods. Tree roots extend much deeper than the 20 cm probes of the Hydrosense unit and laterally for several meters, so trees growing in locations shown as dry in Figure 3.6 may also have access to groundwater either at depth or from nearby wet spots.
3.4 Discussion

Comparison of daily measurements of $\theta$ from upslope (Figure 3.3) and downslope (Figure 3.4) positions show the contribution of groundwater, especially at the Southwest facing location. Some of the variation in VWC in the downslope position can be attributed to the shrink-swell activity of the soil in the water content range. Even at relatively high levels of $\theta$ (e.g. >30%) as measured by the Hydrosense, vertical cracks of approximately 1 cm were observed at the surface during August 2005. Cracks of this size have the potential to alter the flow path of rainwater hitting the soil surface as well as confound measurement of $\theta$. The interruption of data collection at the south-facing downslope position from December 2005 through May 2006 was due to animals chewing through the datalogger wires.

Thornthwaite’s model predicted substantially more limitation of AET by moisture stress, and more dependence upon stored soil moisture for dry periods of both the 2005 and 2006 growing season than for a year with normal rainfall (Figure 3.2c,d). Actual measurement of $\theta$ indicated a temporal pattern of soil water depletion similar to that predicted by the Thornthwaite model. Because the model was calculated on a monthly time-step, and our measurements of $\theta$ were made hourly and reported in Figure 3.2e as daily averages, there was greater temporal detail in the measured values.

Because extreme events (e.g. drought), or the lack thereof (i.e. in an area fed by groundwater) influence the survival of and competitive interactions between plants of different species, consideration of spatial and temporal patterns of soil water content are important.
The results of this study are important as a documentation of the pre-mining relationships between weather and soil moisture. Groundwater, emerging as springs and seeps, maintains soil moisture through periods of below-normal rainfall over a wide spatial extent at Dysart Woods. While we have documented the spatial extent of this contribution, the actual reliance of the forest on this water is difficult to quantify. The actual use of this water by trees can be demonstrated by analysis of the isotopic content of groundwater, precipitation, and tree xylem water. This is the subject of the next chapter of this thesis.
Figure 3.1 Locations of hourly soil volumetric water content measurements. Locations marked A,B,C,D are the locations of 3 CS616 water content reflectometers. At each location, sensors are buried horizontally at 15 and 45 cm depth, and 1 sensor is inserted vertically, averaging soil water content for depth 0-30 cm. Room-and-pillar mining indicated in grey hatching was permitted, but had not yet begun at the time of this study.
Figure 3.2 Time series measurements and model results.
(A) Fraction of PAR reaching the forest floor near location K-13 (Figure 3.1); (B) normal (1971-2000) and actual (2005-2006) monthly precipitation for Barnesville Ohio, and Dysart Woods, respectively; (C) potential evapotranspiration and modeled actual evapotranspiration for normal and actual rainfall; and (D) modeled soil water storage for normal and actual evapotranspiration.
Figure 3.3 Daily average volumetric water content for upslope locations. Locations correspond to upslope locations marked A,B,C,D on Figure 3.1 where the 4 panels depict replicate sampling locations along one elevation profile. Each panel depicts daily average measurements from 3 depths at 1 location: 15cm (triangles), 45 cm (circles), and 0-30 cm (diamonds). The 0-30 cm sensors were buried vertically, providing an average value for that depth range. 15cm and 45cm depth probes were installed horizontally. Monitoring sites were paired replicates at each slope position, i.e. A&B were 12m apart at the same elevation.
Figure 3.4 Daily average volumetric water content for downslope positions. Locations correspond to downslope locations marked A,B,C,D on Figure 3.1, where the 4 panels depict replicate sampling locations along one elevation profile. Each panel depicts daily average measurements from 3 depths at 1 location: 15 cm (triangles), 45 cm (circles), and 0-30 cm (diamonds). The 0-30 cm sensors were buried vertically, providing an average value for that depth range. 15 cm and 45 cm depth probes were installed horizontally. Monitoring sites were paired replicates at each slope position, i.e. A&B were 12 m apart at the same elevation.
DORMANT SEASON

GROWING SEASON (15 may – 15 oct)

Figure 3.5 Annual mean soil water content. Mean (±1sd) annual values of soil water content (θ) comparison of 2005 and 2006 Dormant and Growing season, by slope position. Values are annual means of values from 8 sensors each at the 2 slope locations.
Figure 3.6 Spatially extensive measurements of volumetric water content.
Mean values of 4 measurements of $\theta$ at each location in a spatially extensive monitoring program. Measurements were taken with a CS 616 hydrosense handheld water content reflectometer (Campbell Scientific, Logan Utah). The locations of springs in Figure 1.1 correspond to the perennially wet locations.
Figure 3.7 Actual and modeled (TRMI) spatial patterns of soil moisture. The Topographic Relative Moisture Index (TRMI) was modeled using ARCGIS 9.1. Point measurements of soil water content ($\theta$) were taken on 10/4/2005 with a handheld soil moisture probe (Cambell Scientific, Logan, Utah.).
Chapter 4: Water Sources of an Old-Growth Eastern Deciduous Forest: Stable Isotope Methods

For submission to Advances in Water Resources.

4.1 Introduction

It is estimated that 95% of the land area of the state of Ohio was forested prior to European settlement in the early 19\textsuperscript{th} century. All that remains of the primary forest are a few small scattered remnants where individual landowners chose not to cut the forest. We know that old-growth forest remnants are important as reservoirs of biological diversity, and as sources of data about the extensive forests which once covered the region (McCarthy, Small \textit{et al.} 2001). More importantly, hydrologic and biogeochemical studies in old-growth forests help define endpoints of functional chronosequences. Because they are so rare, very few forest ecosystem function studies have been conducted in Eastern old-growth deciduous forests.

The Dysart Woods Land Laboratory, including 23 hectares of old-growth forest, is located in Belmont County, Ohio, where coal mining is a major part of the local economy. Subsurface coal mining occurring near and directly under Dysart Woods threatens to impact the contribution of groundwater to the forest ecosystem. In this study we test the hypothesis that trees in upslope positions may be accessing groundwater by sending roots down into shallow perched aquifers. Trees in nearby downslope positions (Figure 4.1) are suspected to have access to groundwater because they are growing in soil that is kept perennially wet by groundwater seepage.

Fractionation of $^2$H (Deuterium, or D) and $^{18}$O occurs with phase changes throughout the hydrologic cycle. Mixing of isotopically distinct water vapor masses
occurs in the atmosphere as storm systems move inland. Ultimately, there is a very strong relationship between air temperature and the isotopic composition of inland precipitation (Gat 1996). Seasonal variation in isotopic composition of precipitation is especially pronounced inland from the ocean and at higher latitudes (Clark and Fritz 1997), and has been documented at Coshocton, OH (IAEA/WMO 2004), about 100 km from Dysart Woods (Figure 4.5).

Potential evapotranspiration at Dysart Woods usually exceeds average precipitation during the months of June, July, August, and September (Figure 3.2). Because of this seasonality, most groundwater recharge occurs during the colder part of the year when rainfall is more depleted of D and $^{18}$O. Groundwater is therefore expected to be depleted in D and $^{18}$O relative to summer precipitation.

Analysis of the relative abundance of naturally occurring stable isotopes of hydrogen and oxygen has been used to determine the water sources of plants when suspected potential sources have different isotopic compositions (Ehleringer and Dawson 1992, Dawson 1993a). While terrestrial plants are typically thought to obtain water from soil, they have also been shown to use groundwater (Thorburn and Walker 1993, Walker, Brunel et al. 2001), and fog (Dawson 1998). Other studies have confounded conventional assumptions about the water use of streamside trees (Dawson and Ehleringer 1991). Stable isotopes have been used to show a change in water source with time, to demonstrate that different plants in a community use different water sources, and that plants can redistribute water between soil horizons (Walker, Brunel et al. 2001).

Dawson, Mambelli et al. (2002) reviewed the application of stable isotope analysis to plant ecology. An important distinction is that the mere presence of roots in a
particular soil horizon does not necessarily indicate that those roots are contributing to the water supply of a plant at any one time. Additionally, plants have been found to extract water from multiple sources simultaneously, mix water within root and stem tissue, and move water between soil horizons.

In an inland temperate deciduous forest, as the growing season progresses, trees use up the winter precipitation water stored in the soil, and soil moisture typically begins to take on the less depleted isotopic signature of summer precipitation (Brodersen, Pohl et al. 2000). If, during late summer, soil water is replaced by less depleted summer precipitation and tree xylem sap is observed to have the more depleted isotopic signature of groundwater, this is good evidence that the tree is using ground water.

Our specific objectives were to determine the spatial extent of tree utilization of groundwater at Dysart Woods. Because groundwater-fed springs have an obvious and visible contribution to soil moisture at certain locations, we expect trees growing in those wet spots to have the isotopic signature of groundwater. We looked for the isotopic signature of groundwater in white oak (*Quercus alba*) trees growing in an area kept wet by a groundwater seep, and in an upslope area where soil moisture quickly dries up during the growing season. Trees in apparently dry upslope positions may be accessing groundwater by having roots growing through fractured bedrock directly into shallow perched aquifers which have been found at elevations of 360 to 390 meters (Schillig 2005). If this is occurring, the importance and spatial extent of groundwater contribution to the forest ecosystem may be larger than is immediately apparent from analysis of the location of seeps.
4.2 Methods

4.2.1 Site Description

Ohio University’s Dysart Woods Land Laboratory consists of 205 hectares in sections 33 and 28 of Smith Township R4W, T8N, Belmont County, Ohio (39º59’55”N, 80º59’50”W). Twenty-three hectares are designated as old-growth forest. Surface elevations range from 335 to 410 meters. Dysart Woods is located on the Little Switzerland Plateau of the Unglaciated Allegheny Plateau physiographic region. The bedrock consists of marine sedimentary rocks of Permian origin and the immediate area was not covered by the Pleistocene glaciation, leaving rugged terrain and well-weathered soils (Rubel, Jenny et al. 1981). The Pittsburg #8 coal seam is about 2 meters thick and lies at an elevation of 221 to 244 meters above sea level, leaving an overburden of 91 to 189 meters (ODNR 2001).

A series of shallow perched aquifers occurs between 365 and 400 meters elevation, where contact occurs between geologic formations of differing hydraulic conductivity (Schillig 2005). Aquifers occur in secondary porosity in sandstone and appear as a series of springs and seeps where the water-bearing layers outcrop.

The soils of Dysart Woods are generally of the Westmoreland-Lowell association. The Westmoreland-Lowell association consists of well drained soils of moderate depth on narrow ridges and steep, benched, or irregular hill slopes (Rubel, Jenny et al. 1981). Benches on hill slopes may be the result of rotational slumps caused by positive pore pressures resulting groundwater seepage from perched aquifers (Mary Stoertz, Personal Communication). Upland soils are ultic alfisols formed from residuum of interbedded limestone, shale, siltstone and sandstone. Minor extents of bottomland soils formed from
local alluvial and colluvial deposits. Midslope accumulations of loess blown in from the Ohio River Valley at the end of the last glacial epoch (about 10,000 y.b.p.) are of minor extent but are locally important (Greg Springer, Personal Communication). Soil depth is variable, but averages about 1.2m. According to the USDA soil survey (Rubel, Jenny et al. 1981), soil available water capacity (AWC) varies with the depth of the soil, and ranges from 127-204mm in the residuum based soils that cover about 70% of the property. Our best site-specific estimate of AWC for the soils of the specific mid-upslope position of this study is 150 mm. The sampling location for tree tissue and soils was a dry, southwest facing, slope dominated by large white oaks (the most drought-resistant tree species at Dysart) (Figure 4.1).

4.2.2 Sampling Methodology

Samples of soil, tree root tissue, groundwater and rainwater were collected on April 20, June 4, July 2, August 6, September 4, and October 4, 2005. Soil samples were collected with an Oakfield 36” tube sample soil probe (Forestry Suppliers Inc., Jackson MS) at depths of up to 75 cm in 15 cm increments adjacent to each tree sampled. Groundwater samples were collected from monitoring wells located alongside the road on the ridge (Figure 1.1), using a standard well bailer. Additional groundwater samples were collected from a spring flowing in the woods. Rainfall was captured in a funnel-topped section of PVC pipe filled with 1 cm of mineral oil to prevent evaporation.

A total of six mature (>60cm DBH) white oak (Quercus alba) trees were selected for sampling, 3 each from upper and lower slope positions. 3 root xylem samples were taken from each tree at each sampling period. Tree root samples were taken from buttress roots with a Hagloff increment hammer (Forestry Suppliers Inc., Jackson MS),
yielding a wood sample of ~1 cm$^3$ for each sample. The lower slope position trees were located in an area with perennial seepage of groundwater. The upper slope position trees were located in an area where plant-available available soil moisture down to 45 cm was depleted completely during dry periods of the 2005 growing season. All water, soil, and tree tissue samples were stored immediately in paraffin-sealed glass vials and packed on ice for overnight shipment to the Stable Isotope Ratio for Environmental Research (SIRFER) lab at the University of Utah. Replicate soil and tree tissue samples were stored in a freezer for later analysis. Extraction of water from the soil and wood samples was done at the SIRFER lab by cryogenic vapor distillation. Analysis of the D and $^{18}$O content was done at the SIRFER lab by mass spectrometry and reported as $\delta$D and $\delta^{18}$O as per-mil (‰) difference from Vienna Standard Mean Ocean Water (VSMOW).

### 4.3 Results

Content of D and $^{18}$O in the rain and groundwater samples (Figure 4.2) were found to be generally on or above the global meteoric water line (GMWL) after Craig (1961). Craig’s GMWL is a line in $\delta$D-$\delta^{18}$O space with the equation $\delta$D$=8 \cdot \delta^{18}$O + 10, and is generally taken to describe the D-$^{18}$O relationship of rain or snow water which has not been subjected to evaporation since falling as precipitation. Water extracted from some tree and soil samples were found to be more depleted in D than $^{18}$O relative to meteoric water (i.e. plot substantially below the GMWL in Figure 4.2). Deviation of tree water from the GMWL varied through the year, being largest during the months of May and June (Figure 4.2).
Soil water isotopic content should be interpreted carefully. Technical difficulties in sampling (especially when soil was very dry) resulted in inconsistent sampling depths over the course of the season. For the months that soils from depths below 30 cm could be sampled, isotopic composition varied considerably with depth and between slope positions (Figure 4.3).

Many studies using stable isotopes to determine the water sources of plants have used only one isotope for analysis (Dawson and Ehleringer 1991, Burgess, Adams et al. 2000, Zencich, Froend et al. 2002). This approach simplifies analysis, and is valid for determining the proportional use of two known sources (Dawson, Mambelli et al. 2002). This single-isotope approach was taken for preliminary analysis in the present case. δD for tree water and potential water sources is shown by source (Figure 4.4) and by month for downslope (Figure 4.5) and upslope (Figure 4.6) positions.

Figures 4.5 and 4.6 show the seasonal changes in tree and water source δD. The δD composition of groundwater was stable through the season with mean δD = -53‰ and ranged from -46‰ to -57‰. δD of 2005 growing season precipitation varied from -73‰ in April to -8‰ in July. Tree xylem water δD varied from -81‰±11 (sd) in April to -47‰±2 (sd) in August, reflecting both the changing precipitation input and possible contribution of groundwater to tree water use. From analysis of the δD data alone, trees in both upslope and downslope positions appear to have been using groundwater during August and September of the 2005 growing season.
4.4 Discussion

It is expected that trees growing in the down-slope position would be using groundwater because groundwater seepage kept the soil at this location moist through the growing season. This finding that trees growing in the dry upslope position also use groundwater indicates that the spatial extent of groundwater contribution to the forest is greater than previously thought.

Soil water, as well as wood, had the δD signature of groundwater during August and September of 2005. This suggests that trees may be picking up ground water with deep roots and releasing that water through shallow roots into the soil. This phenomenon, termed hydraulic lift, has been shown in a variety of different ecosystems (Dawson 1993b, Burgess, Adams et al. 1998, Caldwell, Dawson et al. 1998)

Analysis of both δD and δ18O of the tree water and the tree’s potential sources (i.e. groundwater, soil water, precipitation) (Figure 4.2) indicates that during May, June, and July, some of the water found in xylem and soil samples had been subjected to evaporative enrichment into a low-humidity atmosphere sometime after falling as rain or snow. One process that could account for such enrichment is evaporative enrichment of canopy interception. The interception and evaporation of water by a forest canopy has been shown to account for 14.2% of the total precipitation in a deciduous Appalachian forest (Kendall 1993, Gat 1996). Enrichment of the 18O content by 0.36‰ has been described for a beech forest (Brodersen, Pohl et al. 2000). However, Gat (1996) indicated that the evaporative enrichment of canopy throughfall is often negated by selective enrichment of the already enriched rainfall associated with low-intensity rainfall periods during a storm. The amount of 18O enrichment observed (Figure 4.2) is an order
of magnitude greater than the evaporative enrichment from canopy interception described by Brodersen Pohl et al. (2000).

One possible explanation for the apparent evaporative enrichment of the water extracted from soil and tree tissue is that evaporation occurred from the samples during collection. This would have been despite measures taken to prevent such enrichment. All soil and tree samples were sealed in a new glass vial with a sealed screw-cap lid as quickly as possible after collection.

Because the extraction of water from tree tissue or soil is itself an evaporative process, there is the potential for isotopic fractionation during the process. Extraction of water from clay-containing soils is especially problematic because there is an immobile pool of water tightly bound to clay particles at a plant-unavailable potential. Extraction of all of the water present in a sample is necessary; otherwise the extracted water will be depleted in heavy isotopes relative to the water actually present. Araguas-Araguas, Rozanski et al. (1995) tested the effect of cryogenic vacuum extraction of water from soil and found a 5-10‰ depletion of D relative to actual water used to wet the test soils. They also found a ±3‰ reproducibility of $\delta$D for replicate extractions from clay soils.

Brunel, Walker et al. (1995) did a validation study of the methods of comparison of the isotopic composition of soil and plant water. They found an unbiased and randomly distributed 5% total error in D composition considering errors from extraction, spatial heterogeneity in soil profiles, and time-lag effects of water movement in plants. It is noted that this amount of error is small compared to the natural variations in $\delta$D which underlie the application of these methods to plant ecology.
The amount of deviation of soil and xylem water from the GMWL varied from month to month (Figure 4.2), and was less extreme during August and September when tree water took on the $\delta^D$ signature of groundwater and the soil water budget indicated that heavily depleted winter-time precipitation stored in soil should have been depleted.

The isotopic composition of May 2005 precipitation was much more depleted than the mean value reported from the GNIP (IAEA/WMO 2004) monitoring from 1966-1971 (Figures 4.5, 4.6). It is possible that the deviation from the GMWL seen in May, June, and July tree water (Figure 4.2) is a result of evaporative enrichment of May precipitation at the soil surface. During early spring, before tree leaves emerge, sunlight hits the forest floor potentially driving evaporation from the soil surface.

By the time that soil moisture became depleted in 2005 (i.e. August) (see Figures 3.2, 3.3), most of the deviation from GMWL of tree water was less than 20‰ $\delta^D$. It is therefore more reasonable to interpret the July-September tree water as having come partially from groundwater. There is some uncertainty to exactly where the water in the tree tissue came from, and that uncertainty cannot be resolved with the available data. However, there is no indication that summertime precipitation was the major water source for these trees during the late-summer drought of 2005.
Figure 4.1 Sampling locations for stable isotope analysis. Upslope wood and soil samples were collected 50m upslope from survey marker K-13. Downslope samples were collected approximately 25m downslope from survey marker K-13.
Figure 4.2 $\delta D$ and $\delta^{18}O$ of water from tree tissue and potential water sources.
Figure 4.3 Monthly variation in δD of soil water by depth and slope position.
Figure 4.4 δD and tree water and potential water sources by season for 2005.
Figure 4.5 δD for tree tissue water and possible sources, downslope position. Global Network for Isotopes in Precipitation (GNIP) data are historical averages from 1966-1971 (IAEA/WMO 2004).
Figure 4.6 δD for tree tissue water and possible sources, upslope position.
Chapter 5: Conclusion to the Thesis

The purposes of this study were to document the water holding capacity of the soils of Dysart Woods, to document the spatial and temporal dynamics of soil moisture, and to determine the spatial extent to which trees use groundwater. The soil of Dysart Woods has been shown to have an available water capacity (AWC) about equal to 1 month of evapotranspiration demand during the peak of the growing season as determined in 2005. The soil water budget presented here indicated that this amount of storage capacity should be sufficient to maintain adequate soil moisture during times of normal rainfall. During both 2005 and 2006, growing season rainfall was sufficiently below normal to result in depletion of soil moisture to levels limiting to plant growth. Groundwater contribution to soil moisture appears to have occurred over a wide spatial extent. Trees growing in apparently dry upslope positions also seem to be accessing groundwater based on the isotope data.

The documentation of the available water capacity (AWC) of the soils of Dysart Woods presented in Chapter 2 of this thesis is an important contribution to future research at this site. A more sophisticated water budget model is the best way to characterize the relationship between rainfall, evapotranspiration, and soil water content, and soil AWC is an important and fundamental part of any such model.

The documentation of spatial and temporal patterns of actual soil water content at Dysart Woods during the 2005 growing season, presented in Chapter 3 of this thesis, is also an important contribution to future research at Dysart Woods. This pre-mining data will serve as a baseline for comparison for future efforts to detect changes in hydrology at Dysart Woods.
The stable isotope data presented in Chapter 4 of this thesis should be interpreted carefully. The isotope data indicate the presence of winter-time precipitation in tree tissue at a time when any such water would likely have been depleted from soil. The best interpretation of this finding is that the trees are accessing groundwater. There is no indication, however, of the amount of groundwater being used or its biological importance or necessity. Future research to address these issues will need to actually quantify the amount of water being used by trees. One approach to this problem would be to instrument trees with xylem sap flow probes, a project under development in the Brown Ecophysiology Lab at Ohio University.

The distribution of tree species at Dysart Woods is attributed partially to spatial variation in soil water availability (McCarthy 1997). The tree species present at Dysart Woods vary in their capacity and mechanisms of avoiding and tolerating drought, with white oak being the most drought tolerant species. The white oaks of Dysart Woods are of interest because they are among the largest and most magnificent trees present.

The effect of drought on large trees is difficult quantify. Trees are able to survive dry periods by using water stored in their trunks, and large trees are known to be more reliant on this stored water (Phillips, Ryan et al. 2003). Despite the ability to store water diurnally and to close stomata in response to insufficient water, white oaks are susceptible to water stress. Hinckley et al. (1979) described reduced growth, increased die-back, decreased photosynthesis, and impacts on following-year phenology in response to severe drought. Jacquart et al. (1992) describe similar drought responses in an old-growth deciduous forest in Indiana, while noting that dominant canopy trees seem better able to maintain xylem water potential.
While large white oak trees seem quite resilient in response to drought, the long
term, cumulative effect of stress must also be considered. Desprez-Loustau, Marcais et
al. (2006) reviewed the published work on interactions between drought and forest
pathogens. They found that 63% of published studies describing a drought/pathogen
interaction in the genus *Quercus* described a positive drought-disease interaction.
Specifically, a positive interaction with *Armillaria*, a fungal pathogen present at Dysart
Woods is noted, though the strength differs between different species of oaks.

In this study we have documented that the spatial extent of groundwater
contribution to the forest is greater than the areas where surface soil appears obviously
wet. What we were not able to determine is whether the trees of Dysart Woods depend
upon this moisture. Knowledge of the subtle and long-term effects of water stress on old
trees in incomplete. The impact of possible future changes in hydrology at Dysart Woods
on forest biology will be difficult to quantify or separate from other factors. Nonetheless,
this study makes a contribution to the understanding of the functioning of hydrologic
processes at work in this unique ecosystem.
References


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Appendix A

upslope depth=15cm

upslope depth=45cm

downslope depth=15cm

downslope depth=45cm