Soil Moisture and Soil Frost Regimes under Annual, Perennial and Agroforestry Crops in Waseca, Minnesota

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Abstract

The potential for agroforestry and other perennial crops to provide hydrologic benefits is of interest in the Minnesota River Basin, where the landscape is dominated by annual row crops and the river is plagued by water quality and quantity issues. Perennial herbaceous and woody crops are thought to have higher annual consumptive use of water than annual corn-soybean crops, influencing antecedent water status, creating more water storage, potentially decreasing discharge, and reducing the duration of soil frost and prevalence of concrete soil frost in the early spring. Quantification of potential hydrologic benefits is needed to provide support for more sustainable agroforestry and other alternative cropping practices in the basin. To this end, in the summers of 2004 and 2005, biweekly measurements of soil moisture under one annual crop (corn/soybean rotation), two perennial herbaceous crops (perennial flax and Illinois bundleflower) and two woody crops (hybrid hazelnuts and hybrid willow) were taken on replicated experimental plots at the University of Minnesota's Southern Research and Outreach Center in Waseca, Minnesota. Similar measurements were taken in a stand of mature hybrid poplar and a field planted in a corn/soybean rotation. Likewise, soil frost depth, duration, and type were measured under the same crop types during the intervening winter. Analysis of soil moisture data showed few significant differences in soil moisture between the various crop types on the experimental plots, perhaps due to a combination of the perennial and agroforestry crops being in the establishment phase and unusually wet weather. The mature poplar stand had consistently drier soils than the cornfield during the 2004 season, although these differences disappeared during the course of the 2005 season, likely due to a change in management of understory plant cover in the poplar stand. During the winter, no significant differences in soil frost duration or type were observed, likely due to uniformly wet fall soil conditions, a lack of snow during the coldest part of the winter and rapid spring warm up. Thus, agroforestry and herbaceous perennial crops appear to provide little hydrologic benefit during the establishment phase or in winters with low snowfall, but when mature or in winters with heavier snowfall, could have the potential to provide such benefits.

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1. INTRODUCTION

1.1 Rivers in the United States

There are more than 250,000 rivers in the United States, flowing over more than 5.6 million kilometers through every state in the country. They have been used for transportation, for electrical power, as a source of food, for waste disposal, for recreation, and for inspiration. Unfortunately, many river basins are under stress. For example, some like the Colorado River Basin suffer from excessive demands on the water available. In others, such as the Klamath River Basin, the needs of competing and seemingly non-compatible ecologic and economic demands are a source of political and social tension. For still others, such as the Minnesota, the ecological health of the river and its tributaries has been significantly and negatively impacted by the predominance of monocropping agriculture on the landscape in the basin.

In the many of these river basins, there are increasing questions about the wisdom of ongoing land use practices. Changes will need to be made to meet the environmental goals of modern society, but these changes must take into account the need to maintain and improve the economies of rural communities. The Minnesota River Basin is a prime example of such a situation.

1.2 The Minnesota River Basin

The Minnesota River begins at Big Stone Lake on the border between Minnesota and South Dakota. It flows 539 kilometers, joining the Mississippi River at Fort Snelling in the twin cities of Minneapolis and St. Paul, Minnesota. The Minnesota River Basin (MRB) drains almost 20 percent of Minnesota and some portions of South Dakota, Iowa and North Dakota, covering about 38,850 square kilometers, including some of the best and richest agricultural lands in Minnesota.

The MRB lies along the 44th parallel in the middle of the North American continent, resulting in long, cold winters. Much of the soil in the basin is clay-rich glacial till, which is heavy and slow to warm in the spring. As any farmer could tell you, this means annual row crops are not planted until relatively late in the year, often not until mid-May.

Prior to European settlement, the MRB was covered largely by wetlands and perennial vegetation. However, with the arrival of European settlers, the basin began to be used for ever-more intensive agriculture. Today, it is estimated that over 90 percent of all land use in the MRB is devoted to agriculture, and a large portion of that agricultural land is used for cultivation of corn and soybeans. To cite one example, Waseca County (one of 38 Minnesota counties in the basin) has a land area of 110,047 ha (Soil

Survey 2004). In 2007, 54,835 ha (or nearly 50 percent) were planted in corn, and 33,548 ha (or 30 percent) in soybeans, for a total of 80 percent of all the land in the county being devoted to corn and soybeans alone (NASS 2008).

Unfortunately, the Minnesota River and its tributaries are contaminated, largely with nonpoint source pollutants, such as phosphorous, nitrogen, and sediments. Many river reaches in the basin have been assessed by the Minnesota Pollution Control Agency as not supporting designated uses, and do not meet Total Maximum Daily Loads (TMDLs) as prescribed under the national Clean Water Act (MPCA 1994).

The highest volumes of streamflow in the basin occur in early to mid spring, during the period before annual crops have begun growing actively, or in many cases, before they are even planted. Much of the pollution that reaches the river arrives in runoff, and much of the high volume spring runoff in the basin is from snowmelt. Snowmelt runoff volumes are largely affected by the extent and degree of frozen soil (which impedes infiltration) in the basin.

Because there are far reaching consequences of this pollution, including, on a local level, the threat of not meeting TMDL standards (which could impede economic development), and further afield, hypoxia in the Gulf of Mexico, many groups have great interest in cleaning up the river.

Although the causes of pollution in the Minnesota River are many and complex, it is generally accepted that the dominance of the corn/soybean rotation on the landscape and the associated removal of native perennials and drainage of wetlands contribute significantly to the water quality problems (Bharati et al. 2002, Zhang and Schilling 2006). In turn, it has been suggested that increasing the presence of perennial vegetation on the landscape in the basin has the potential to improve its hydrology (Brooks et al. 2003a, Boody et al. 2005).

Although hydrologic problems that were created and operate at the catchment scale will need solutions that also come at relatively large scales (Ward et al. 2002), it is unrealistic to suggest what might seem like the simplest solution: returning the landscape to its pre-settlement perennial vegetation. A solution must be created in the context of modern farming and economics, in which land provides economic returns. However, over-reliance on two commodity crops has left many of the basin's farmers in a delicate economic situation, subject to the vagaries of both the global market and federal farm legislation. Perennial crops have the potential to address both the hydrologic condition of the basin and diversify the regional farm economy (Boody et al. 2005).

1.3 Perennial Crops in the Minnesota River Basin

Perennial and agroforestry crops are thought to provide hydrologic benefits to a watershed because of their higher consumptive use of water, which influences antecedent water status, creates more soil water storage capacity, and potentially reduces discharge (Holmes and Wronski 1981). If perennial vegetation can become active and begin transpiring water earlier in the year (Twerdoff et al. 1999), benefits may be gained through reduced runoff during this period when annual crops are not yet established.

Additionally, soil frost type and extent are largely affected by soil moisture in the preceding fall as well as type and extent of vegetative cover (Christopherson 2001). Perennial crops that create drier soils in the fall and provide winter cover that captures and retains snow have the potential to reduce the prevalence of soil frost, especially that of the concrete type.

Today, perennial crops are a minor presence in the Minnesota River Basin. For example, in 2007 in Waseca County, there were a mere 1578 ha (1.4 percent of the land in the county) of planted alfalfa hay (NASS 2008), and in the 2002 National Census of Agriculture, there were no reported hectares of short-rotation woody crops, such as hybrid poplar or willow (NASS 2004).

There is a growing interest in using woody crops for biomass energy production in the area (Willette, 2004), and recent legislation at both the state and national levels to support biomass crops (such as the Biomass Crop Assistance Program which was passed as part of the Food, Conservation, and Energy of 2008 Act, also known as the 2008 Farm Bill) could make adoption of such crops more likely. However, where, how and what types of perennials are planted will impact the effectiveness of increasing perenniality in providing any of these possible benefits. More information quantifying potential hydrologic benefits is needed for such alternative cropping practices to be effectively implemented and to maximize hydrologic benefit.

2. LAND USE, SOIL MOISTURE AND HYDROLOGY

2.1 Land Use

It is well established that changing land use can affect the ability of a landscape to provide ecosystem services, including alteration of local and regional hydrology (Metzger et al. 2006). Urbanization and its associated increase in impermeable surface is the most obvious and dramatic example of land use change that can impact hydrology, but changing from one vegetative system to another, as from forest to pasture or from prairie to row crop agriculture, can have similar hydrologic impacts.

Perhaps the most studied example of such change is in the dryland agricultural region of Australia, where conversion from perennial vegetation to annual crops and pasture has created a water surplus, allowing ground water table levels to rise, in turn causing widespread salinization of the soil. In more temperate climates, an example of such change is an increase in discharge from watersheds in which forest cover is removed (Holmes and Wronksi 1981, Ice and Stednick 2004), or similarly, a decrease in streamflow from catchments where trees are planted extensively (Jackson et al. 2005).

Increasingly, as the potential for negative hydrologic impacts from vegetative change becomes more pronounced and understood, people are turning to a second wave of vegetative change to help mitigate the very same problems that vegetative change created. In Australia, for example, returning perennial vegetation to the landscape through agroforestry (White et al. 2002) or alternative pasture crops, such as lucerne (which is more commonly referred to as alfalfa in the United States), appears to be a promising method to reduce the rate of dryland salinization (see, for example, Ward et al. 2001, Ward et al. 2002, Sandral et al. 2006, Heng et al. 2001, Dolling 2001, Cocks 2001, Ridley et al. 2001).

Although less well studied in temperate areas, returning perenniality to the landscape also appears to have the potential to improve regional hydrology in areas with excess runoff or discharge (Jackson et al. 2005, Boody et al. 2005). In a 2006 modeling study, Ennaanay predicted that replacing corn-soybean crops with hybrid poplar in wet soil areas of the Cottonwood River basin would result in decreased water yield and average annual peak flows, and that these decreases would be proportional to the area converted. Crop conversions in combination with wetland restorations showed the greatest promise for reducing water yield and annual peak flows. Ennaanay also noted that reduced nutrient and sediment loading would be expected to accompany these effects. In another modeling study, Updegraff et al. (2004) predicted that conversion of cropland in the Lower Minnesota River Basin Watershed to short-rotation woody crops could consistently reduce peak flows and watershed outlet loading of sediments and nutrients. Perry et al. (2001) applied field data from a hybrid poplar stand to a hydrologic model and demonstrated that increasing the presence of short rotation hybrid poplar in northwestern Minnesota has the potential to reduce average annual peaks and stormflow volumes, snowmelt runoff and spring flooding. Similarly, in a nine-year study in southwest China, Liu et al. (2004) observed an average of 67 percent less discharge from an agroforestry watershed than from a paired grassland watershed, with lower peak flows on a monthly and per-event basis.

2.2 Evapotranspiration by Perennials

The question remains, however: from where do these hydrologic benefits arise? Radersma and Ridder (1996) point out that changing the vegetative cover on a landscape can affect the water balance largely because of differences in evapotranspiration (ET) between the old and new vegetative types.

In the dry lands of Australia, for example, many studies have shown higher annual water use under perennial pasture crops than annual, with correspondingly drier soils under the perennial pastures. Ridley et al. (2001) observed between two and 109 mm more water use under a perennial lucerne pasture than an annual clover pasture over a four-year period, with an average of 37.5 mm more annual water use under the perennial pasture. Additionally, the soil under perennial pasture reached maximum soil water deficit every year, whereas the soil under annual pasture reached maximum soil water deficit only in the driest years. Similarly, Dolling (2001) saw that perennial pasture treatments used 24-33 mm more water per year than annual pastures in Western Australia. In a study in a more temperate area, Burgess et al. (1996) showed that hybrid poplar in the United Kingdom used about 50 mm more water during the April-August growing season than wheat.

One reason a perennial crop would use more water than an annual crop is longer duration of active growth over the course of a year. Radersma and Ridder (1996) found that perennials in West Africa evapotranspire significantly more water on an annual basis than annuals, mainly because perennials transpire during the dry season at a rate that, while lower than during the wet season, is still higher than that of bare soil. They concluded that water use differences on an annual basis between annual and perennial plants accumulate primarily during the dry season when annuals are inactive, and that the biggest factor in annual water use is how much area and for how much of the year the soil is covered by vegetation, rather than what specific kind of vegetation is present.

Similarly, Ward et al. (2001) showed that established perennial lucerne used more water during a year than an annual clover pasture. Both crops had ET rates near the potential rate during the growing season. However, during the off season when clover had died and thus had negligible water use, lucerne continued to use both stored soil water and additional rainfall, creating a “buffer” of drier soil heading back into the wetter growing season. This study points out that in areas where the ET of annual crops approaches potential ET during the growing season, increasing total water use can only be accomplished through extending the period of active vegetative growth.

Perennials may also show greater annual water use and drier soils than annuals because they may develop deeper roots. Heng et al. (2001) showed that in the high rain zone of southeastern Australia, annual pasture extracted water to 90-120 cm, but perennial pasture was able to extract water as deep as 150 cm during periods of high demand, and that a larger soil moisture deficit was created by the perennial pasture than the annual by the end of the summer. In another Australian study, Ward et al. (2002) showed that perennial lucerne had greater below-ground biomass and roots extending considerably deeper than annual clover pasture, and that the soil beneath the lucerne was dried 60 mm more than clover pastures. In a study in the Midwestern U.S., Asbjornsen et al. (2007) showed that corn and recently reestablished prairie drew water

primarily from shallow surface layers, but savanna oaks and woodland extracted the bulk of their water from much deeper in the soil profile.

Similarly, Wilman and Leitch (1995) found that in some cases where one crop appeared to use more water than another in a given time period, it seemed to be because the crops with greater water use were able to more quickly draw water from successively deeper layers of soil.

Unsurprisingly, while perennial vegetation has been observed to use more water than annual vegetation in many situations, this greater water use is not uniform, varying, for example, over the course of the year. In a study of water use of intercropped wheat and hybrid poplar in the UK, Burgess et al. (1996) saw that wheat and poplar extracted water at about the same rate during the middle of the growing season, but that later in the season water use in wheat declined while poplar maintained a rate close to potential ET. Ridley et al. (2001) saw drier soils under perennial pastures than annual in southern Australia during the dry season, but these differences did not persist through the wet season. Twerdoff et al. (1999) found that perennial forage species evapotranspired more than annual forage species early in the growing season, leaving soils dryer under the perennial forages, although later in the season soil water was similar under both types of forages. Dolling (2001) observed similar soil moisture under annual and perennial pasture in Australia during the wet season, but drier soil under perennial pasture than annuals during the dry part of the year, with variations in the extent of this difference from year to year.

The degree of difference in water use and soil moisture between annual and perennial crops also often varies through the soil profile, even when the depth of water use is thought to be similar. In a study of alternative cropping systems on the distribution of soil water in a subhumid area of Western Canada, Izaurralde et al. (1994) saw that the soil was consistently drier under perennial fescue than under barley, barley intercropped with field pea or faba bean (all annual crops). They noted that the greatest difference in soil water was seen in the upper 60 cm of the soil profile.

On the other hand, in the dryer climate of Australia, Sandral et al. (2006) saw little difference in soil moisture under annual and perennial pasture in Australia near the surface, but did see the benefit of increased soil dryness at depths greater than 0.70 m depth. Dolling (2001) saw the greatest increased water storage capacity from perennials over annuals between 0.5 and 1 m of depth in the soil profile. Ward et al. (2002) found that differences in soil moisture under annual and perennial pasture occurred at depths greater than 0.7 m.

Likewise, the degree of hydrologic benefit may vary from year to year. While Liu et al. (2004) observed an average of 67 percent less streamflow from an agroforestry watershed in southwestern China than from a

grassland watershed, in some years the difference was almost zero, but in others was extremely large. Ridley et al. (2001) saw that while drainage occurred under both annual and perennial crops in Australia in the wettest year of their study, drainage discharge was more likely to occur under annual crops than perennials on a year-to-year basis.

Just as the hydrologic benefits of perennial vegetation over annuals may vary in time and space, the degree and type of benefit varies with specific plant species. For example, while Sandral et al. saw greater drying of the soil profile under all perennial options as opposed to annual options in their 2006 study, lucerne removed water from the profile more quickly than the other perennial pastures. Grieu et al. (2001) compared depth of water uptake between white clover and ryegrass, two perennial options, when subjected to a small soil water deficit. Their experiment showed that while both species used water from deeper in the profile as water deficits increased, white clover always had a deeper mean uptake than ryegrass, reaching 30 percent deeper after three months of competitive growth. Wilman and Leitch (1995) found that water use increased with nitrogen application rate in some plants, including perennial ryegrass, but not in other crops, indicating that water use can also be affected by cultivation practices.

The age of the vegetation can also be important. For example, Ward et al. (2001) showed that while mature lucerne had the potential to reduce the impacts of dryland salinization through its greater annual water use, in the first year of the study (when the lucerne had just been sown), the lucerne behaved much like an annual pasture and had little effect on deep drainage. However, the size of the storage buffer created by its greater water use increased with the crop's age, as the maturing plants' growing root system increased uptake of soil water from deeper soil layers.

Still another factor to consider is the specific location of the perennials on the landscape. In their 2008 study of water use in tree belts and pasture in Australia, Crosbie et al. saw that pasture used about the same amount of water whether it was planted in a recharge area or a discharge area, and that tree belts planted in recharge areas used a similar amount of water as pasture. Trees planted in discharge areas, however, used twice as much water as either the trees planted in recharge areas or the pasture planted in either location.

Differences in interception between perennial and annual crops can also lead to differences in evapotranspiration, largely because perennial crops have greater above ground biomass for a longer portion of the year than annual crops. While differences in interception among annual and herbaceous perennial crops may be minimal, woody crops such as willow and hybrid poplar might be expected to have higher annual interception losses than annual crops (Brooks et al. 2003b, and others). Mature hybrid poplar and natural aspen stands have similar growth patterns and interception relationships in northern Minnesota (Verry 1976, Shank 2002), where annual interception by mature aspen stands averages about 16 percent of

annual precipitation. For example, an aspen stand of 23 m^2/ha basal area has been shown to intercept 123 mm in a year with 756 mm of precipitation (Verry 1976). Similarly, interception studies by Shank (2002) indicated that hybrid poplar stands in northwestern Minnesota with 22 to 25 m^2/ha basal area intercepted between 10 and 30 percent of spring-summer rainfall. Interception studies of corn-soybean crops are sparse, although a modeling study by Frasson and Krajewski (2007) indicates that 90 percent of rainfall on corn reaches the soil via stemflow. Although not conclusive, the results of these studies suggest that the interception component of annual ET could represent a 20 percent greater loss of rainfall under hybrid poplar crops than corn.

2.3 Other Considerations in Using Perennial Vegetation for Hydrologic Benefit

Ward et al. (2002) observed that the positive hydrologic effects of perennial pasture persisted even after the perennial was removed and an annual crop was planted, but that these benefits disappeared within the second year after removal, suggesting that the benefits of perennials can persist after their removal, but that their continuing influence is likely to be short-lived. Ridley et al. (2001) saw that when perennial pasture was grown in rotation with annual crops, the hydrologic benefits of drier soil under the perennial pasture persisted for a limited time under subsequent annual crops, and that the duration of the lingering benefit increased with the amount of time spent in the perennial rotation.

Similarly, in a 2006 study of reforestation in the humid tropics, Zimmermann et al. (2006) observed that the hydrologic function of a re-established forest on land used for annual cropping was affected by the duration and intensity of the land use for annual cropping prior to reforestation. Asbjornsen et al. (2007) saw that the expected hydrologic benefits of returning perennials to the landscape in the Midwestern U.S. were not realized in the first three years after reestablishment of prairie, likely because of the persistence of soil structure developed during the time the land was used for annual cropping.

Updegraff et al. (2004) and Ennaanay (2006) predicted that conversion of cropland in the Lower Minnesota River Basin Watershed to short-rotation woody crops could consistently reduce peak flows and watershed outlet loading of sediments and nutrients. In both cases, there were greater reductions with increased conversion, but in Updegraff et al. the marginal benefit decreased with increasing conversion, as it was assumed that the most erosive areas of the watershed would be converted first, while in Ennaanay the benefit was proportional to the area of conversion. In another modeling exercise, Boody et al. (2005) showed that the degree of benefit of multifunctional agriculture, such as that incorporating perennial vegetation, is very dependent on the type and extent of change in agricultural practices.

Even if conversion to perennial agriculture is possible, it may not be a complete solution. Heng et al. (2001) demonstrated that less deep drainage occurs in perennial pastures than annual in the high rainfall zone of southeastern Australia, but also showed that deep drainage levels vary greatly from year to year, and still occur to some degree under perennial pastures. Their data imply that while there is some benefit from perennial pasture as opposed to annual, a blanket change from one pasture type to another would not entirely fix the hydrologic problem.

Cocks (2001) pointed out that perennial plants used for hydrologic improvement in one region may not be optimal or even possible in other areas, and it is never wise to rely on any single crop over large areas, meaning that multiple perennial species should be considered and developed. Jackson et al. (2005) concluded that the potential benefits of reforestation are greatest in areas previously converted from forest to cropland.

Finally, there may be economic trade-offs in switching from annual to perennial crops or in integrating perennial crops into an agricultural system, such as slower return on investment from woody crops (Ong et al. 2002). Also, just as with annual crops, there may be trade-offs between managing perennial crops for maximum yield or profit and managing for maximum hydrologic benefit (Al-Kaisi and Yin, 2003).

3. SOIL FROST AND HYDROLOGY

A complete review of the literature regarding how soil frost affects hydrology and the factors that affect soil frost is beyond the scope of this paper, but can be found in Christopherson (2001). However, a brief summary of the current knowledge about soil frost follows.

Soil frost affects hydrology by impeding or preventing movement of water through the soil. When snowmelt or spring rain exceeds the infiltration or storage capacity of frozen soils, flooding is often the result.

The presence, type and duration of soil frost are largely a function of climate; specifically, of ambient temperature (magnitude and duration of freezing temperatures) and snow (both depth and timing). Snow can act as an insulating barrier, protecting the soil from the cold air. Thus, soil frost tends to be shallower under deeper snow. At the end of the season, the presence of snow will slow the thawing of the soil. The timing of snowfall is also important, with more influence the earlier (or later) it occurs.

Snow depth, in turn, is dependent first on the amount of snowfall, and then on vegetative cover. Vegetative cover affects snow depth through canopy interception and by trapping and accumulating drifting snow, and by affecting the radiation balance.

Soil frost occurs in two main forms: concrete and porous. The type of soil frost determines the permeability of frozen soil, with porous soil frost slowing but allowing water to pass through the profile, and concrete frost creating an impermeable barrier. Concrete frost is more likely to form in wet or poorly drained soils and in fine textured soils. Baker (1972) showed that concrete frost occurs rarely in the soil under natural forests, but is the norm in the bare soil of fields used to grow annual crops.

In the Minnesota River Basin, it is thought that perennial crops could help reduce spring runoff by trapping more snow than the bare winter fields of annual crops, reducing the penetration of soil frost, and by creating drier fall soils such that porous, permeable soil frost is more likely to form than impermeable concrete frost.

4. THIS PROJECT

While water use differences between annual and perennial crops in the Minnesota River Basin are truly the matter of interest, water use is difficult, if not practically impossible, to measure directly in the field. Soil moisture, however, is fairly easily measured and provides direct insight into soil moisture storage capacity differences under crops, which affects the soil's ability to absorb rain and, in turn, affects runoff volumes. Also, soil moisture measurements can be used to give more direct insight into evapotranspiration through calculation of water budgets.

To this end, throughout the late spring, summer and early fall of 2004 and 2005, approximately biweekly gravimetric measurements of soil moisture under one annual crop (corn/soybean rotation), two perennial herbaceous crops (perennial flax and Illinois bundleflower, or IBF) and two woody crops (hybrid hazelnuts and hybrid willow, both in the early stages of establishment) were taken on two sets of experimental plots, with additional measurements taken under hybrid poplar at one set of experimental plots, at the University of Minnesota's Southern Research and Outreach Center in Waseca, Minnesota. Similar measurements were taken under a nearby agroforestry stand of mature hybrid poplar and in a field in a corn/soybean rotation. Additionally, soil frost measurements were taken during the winter of 2004-2005 under the crops on one set of experimental plots, in the stand of mature hybrid poplar and nearby cornfield, and in establishment phase stands of willow, poplar, and IBF on another series of experimental plots.

This paper presents analysis of these data and discusses implications for potential regional hydrologic benefits. The work described here is meant to mesh with the work of a number of others (a group of researchers led by Prof. Kenneth Brooks at the University in Minnesota, in particular) in describing and quantifying the potential hydrologic benefits that might come from increasing the presence of perennial crops in the MRB, and finds its true value as a piece of a much larger puzzle. The work of Hinck (2008) is of particular interest in providing context for this study as he presents results from the next phase of evapotranspiration research at the same field site.

5. METHODS

5.1 Soil Moisture

5.1.1 Field Site

The University of Minnesota's Southern Research and Outreach Center (SROC) in the town of Waseca in Waseca County, Minnesota is in the south central part of the state, about 100 km to the south and slightly west of Minneapolis (Figure 1). Most of the SROC is in the Le Sueur River Watershed, which drains to the Minnesota River, although a portion is in the Cannon River Watershed, which drains into the Mississippi. Soil moisture measurements were taken in four locations at the SROC.

The study sites are underlain by soils from the Webster, Nicollet, Glencoe, and (to a lesser extent) Canisteo series, all of which are poorly drained clay-loam soils formed from glacial till (Soil Survey).

5.1.1.1 Sampling Locations

A series of seven crops on 21 plots are located in two rows on a gentle southeast-facing backslope on the SROC's agroecology farm (Figure 2). Slopes here range between three and four percent, which is typical of agricultural fields in the region (Colson, 2005). Two repetitions of five of the crops (willow, IBF, corn/soybean rotation, hybrid hazelnut with turfgrass cover, and perennial flax) in the upper row were established as runoff plots, with plastic barriers extending 61 cm into the ground along the top and bottom and 30 cm along the sides. Vegetative and soil moisture measurements were taken in those ten plots, plus the corresponding (uninstrumented) plots in the lower repetition. Plots were 10 m by 20 m for the willows and hazelnuts, 5 m by 20 m for the other three crops, and arranged in a randomized block design.

Perennial crops were established on the runoff plots in 2003 and 2004. Complete details regarding establishment parameters are found in Colson (2005), and a summary of vegetative characteristics is found

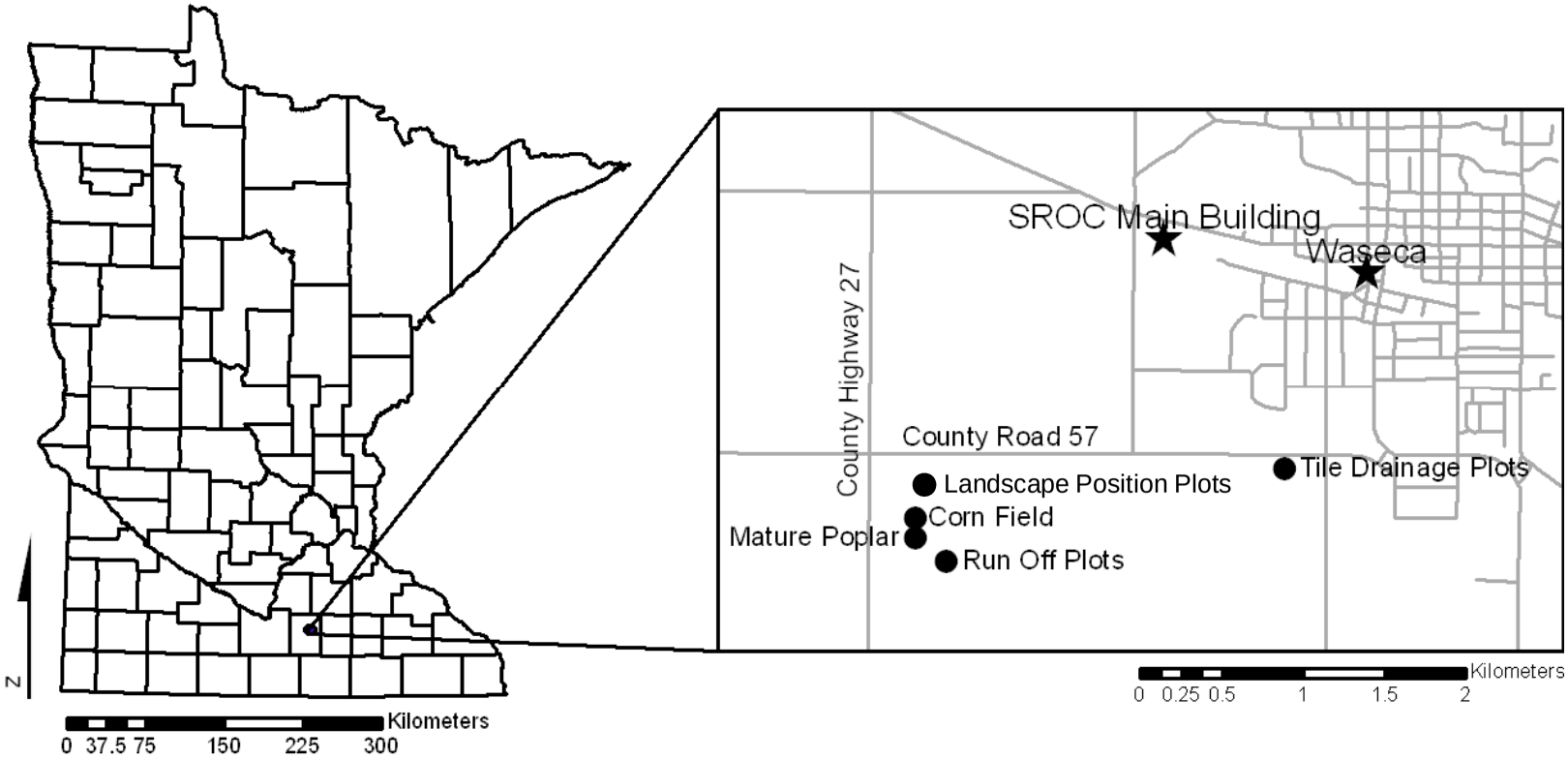


Figure 1: Map of field sites at the Waseca Southern Research and Outreach Center.

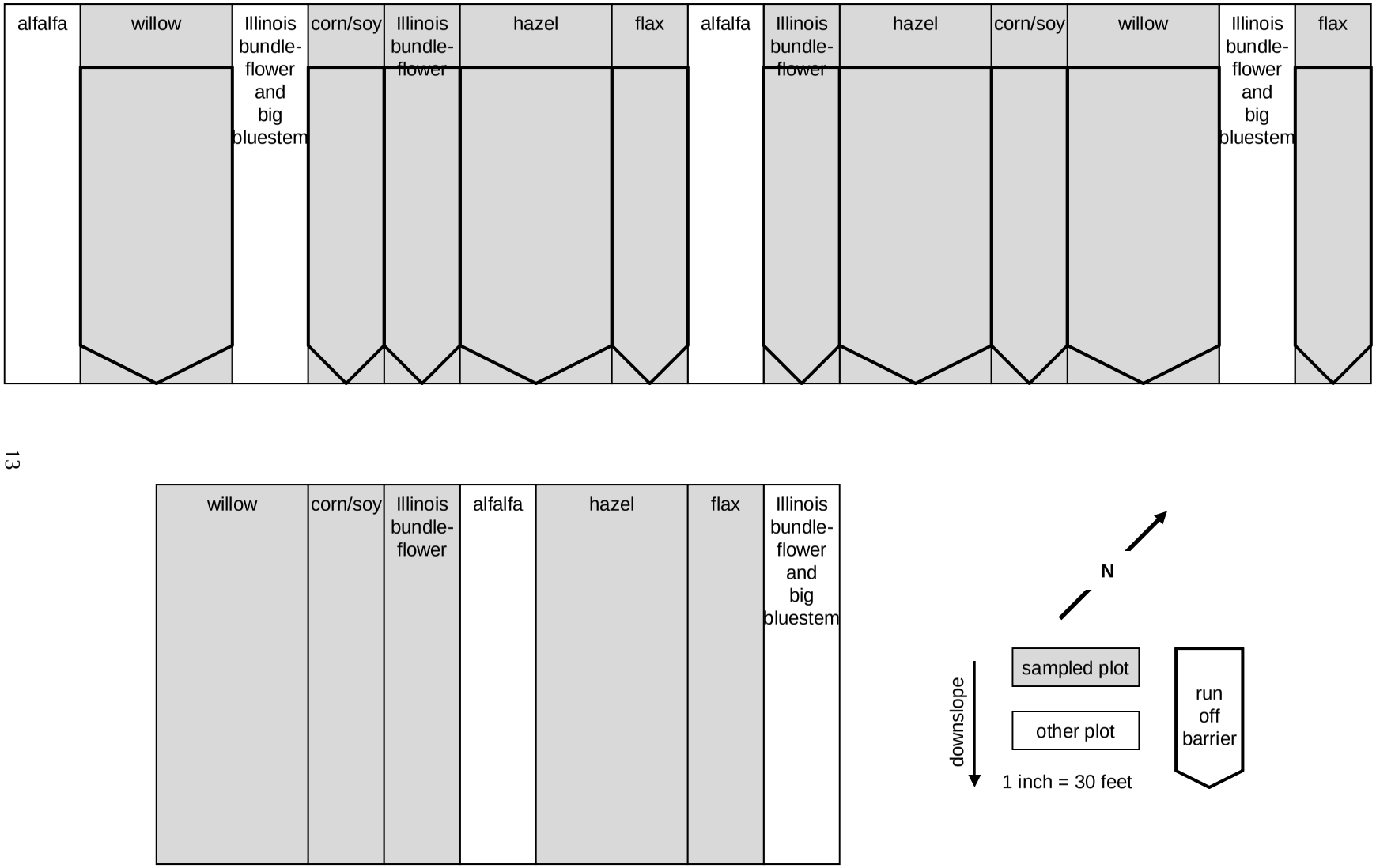


Figure 2: Layout of the runoff plots at the Waseca Southern Research and Outreach Center.

in Table 1 (see also Appendix A). While both woody crops were established with a sodgrass cover crop, the sodgrass was removed from the willow plots during the first week of June 2004 to be better in line with typical cultivation practices. Combined with slow development in both the woody crops, this meant that during most of the 2004 growing season, the willow plots were essentially bare soil, and the hazel plots were essentially sodgrass plots. Thus, the data from these plots in 2004 is likely to be more representative of the behavior of bare soil and sodgrass than that of mature willow and hazel.

A series of tile drainage plots with crops arranged in a random block design are located about 2 km east of the runoff plots on a wide, flat toe slope (Figure 3). Although other crops are planted there as well, soil moisture measurements were taken only in plots with crops corresponding to those monitored on the runoff plots plus hybrid poplar (see Table 1).

A stand of mature hybrid poplar planted in a grid with approximately three meters between trees in both directions extends east-west over a hillslope 0.25 km northwest of the runoff plots (Figure 1). Roughly 100 m north of the poplars, there is a large field in a corn/soybean rotation. Soil moisture measurements were taken from similar landscape positions in the field and mature poplar stand.

5.1.1.2 Climate

The climate in Waseca is temperate, with an average annual temperature of 6.3° C and 822 mm of average annual precipitation, of which 499 mm typically falls in May through September (USDA). Conditions from May to September of 2004 were, on average, slightly cooler and much wetter than normal, with 807 mm of rainfall during the period (Figure 4). In May to September of 2005, conditions were, on average, slightly warmer and wetter than normal, although less so than in 2004, with 666 mm of rainfall during the period, and July actually showing 28 mm less rainfall than average. (See Appendix B.)

Weather data was taken from the climatological observatory near the SROC main building (Station MN8692), as reported on the SROC weather web site.

5.1.2 Measurements

5.1.2.1 Soil Moisture

Soil moisture can be measured in a number of different ways, including with time domain reflectometry (TDR) probes (as in Menziani et al. 2003 or Hupet and Vanclooster 2004), neutron probe (as in Sandral et

Table 1: Crop descriptions. 2004 runoff plot data from Colson (2005); all other data from D. Ide (Pers. Comm. 2006).

			Percent (%) Ground Cover													Ave Height (cm)	Ave Stem Diam. (mm)	Average Biomass (Dry kg/Ha) (3)			
			2004			2005												2005			
Area	Crop	Planting Date	5/21	7/22	10/19	5/9	5/23	6/9	6/22	7/8	7/22	8/15	9/1	9/21	10/10	2005	2005	June	July	Aug	Sept
Runoff plots	Willow (no cover crop) (1)	(replanted) June 2, 2004	90 (1)	6	5	2	5	5	5	47	65	68	68	63	63	208	11 (2)	na	na	na	na
	Illinois bundleflower	June 2003	25	80	60	0	1	4	38	50	58	46	48	50	22	--	--	502	1890	4497	5023
	Corn/soybean rotation (2004 in soybeans; 2005 in corn)	May 10, 2004; May 6, 2005	0	75	60	0	2	5	32	57	82	82	82	72	40	--	--	35	4386	15939	19149
	Hybrid hazelnut (with turf grass)	(replanted) early July 2004	90	82	95	95	95	95	95	95	95	95	95	95	95	--	--	na	na	na	na
	Perennial flax	June 2003	80	80	80	53	58	57	52	47	36	35	40	35	14	--	--	6243	8396	8994	1627
Tile drain plots	Willow (no cover crop)	May 10, 2004	Unavailable			5	22	38	47	62	71	63	93	95	93	304	11	na	na	na	na
	Illinois bundleflower	May 29, 2004				1	5	20	47	73	82	78	80	80	30	--	--	215	1148	5310	2799
	Corn/soybean rotation (2004 in soybeans; 2005 in corn)	May 10, 2004; May 6 2005				0	5	7	33	75	90	80	93	78	60	--	--	26	2132	16246	20860
	Hybrid hazelnut (with turf grass)	May 29, 2004				95	95	95	95	95	95	95	95	95	95	--	--	na	na	na	na
	Perennial flax	May 29, 2004				73	96	97	98	93	97	91	75	77	70	--	--	5167	9042	5920	2476
	Hybrid Poplar	May 10, 2004				5	12	40	67	59	57	62	75	63	5	472	37				
Hillslope	Hybrid Poplar	May 2000														Unavailable					
	Corn/soybean rotation (2004 in corn; 2005 in soybeans)	May 1, 2004; May 31, 2005																			
Landscape Position Plots	Corn/soybean rotation (2004 in corn)	May 1, 2004; May 31, 2005														Unavailable					
	Willow (no cover crop)	June 2, 2004																			
	Illinois bundleflower	June 2, 2004																			
	Hybrid Poplar	June 2, 2004																			
	(1) Originally planted with turf grass cover crop. Turf grass removed first week of June, 2004																				
	(2) Measured at 4 feet																				
	(3) IBF data from combined IBF BB plot																				

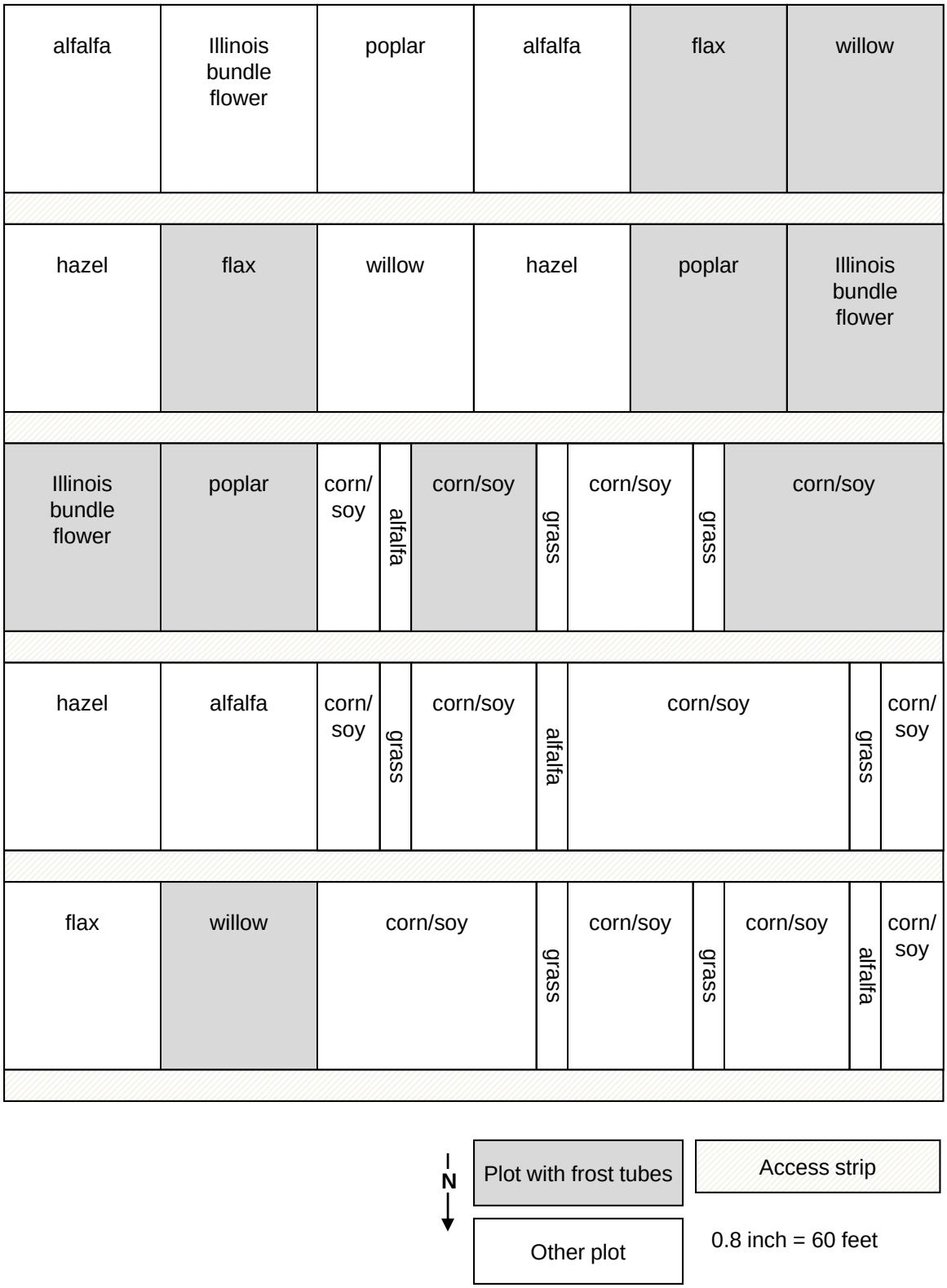


Figure 3: Layout of the tile drainage plots at the Waseca Southern Research and Outreach Center.

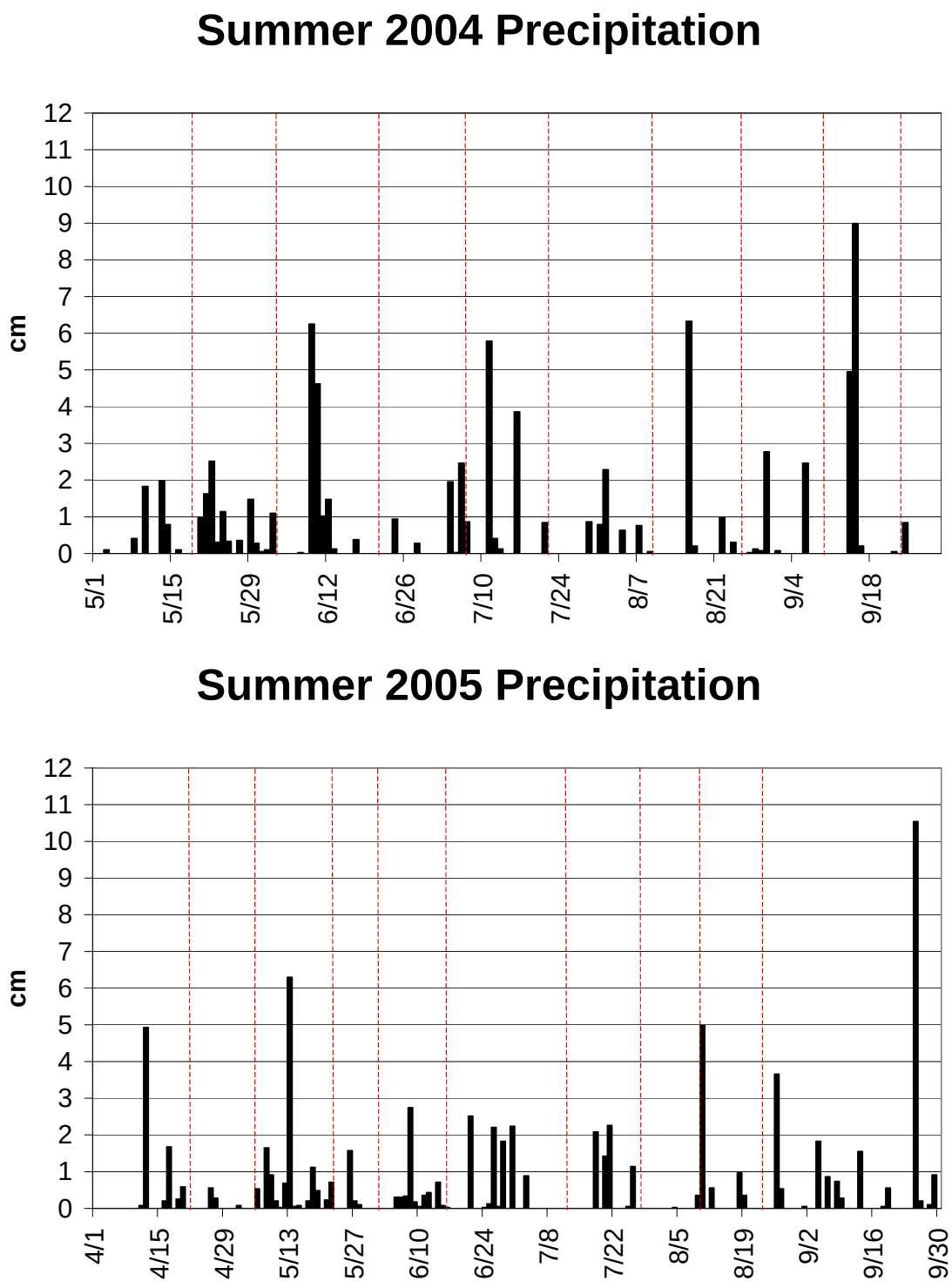


Figure 4: Summer precipitation at the Waseca SROC. Soil moisture sampling dates are indicated as dashed lines.

al. 2006, Ridely et al. 2001, Dolling 2001 or Burgess et al. 1996), tensiometers (although tensiometers are typically used more for applications of scheduling irrigation), electrical resistance sensors (as in Murphy and Lodge 2004), and gravimetric sampling (as in Liu et al. 2004).

Gravimetric sampling was used for this study for several reasons. Gravimetric sampling is the gold standard for accuracy and dependability; it is almost always used to calibrate other methods of sampling, and is much less prone to equipment malfunction. Unlike TDR, it is reliable even in heavy, fine textured soils such as those at the SROC, and unlike tensiometers, is able to measure soil moisture even in relatively dry conditions. It has low equipment costs and does not suffer from the serious safety concerns of the neutron probe. It does, however, have high labor demand, which reduces the number of samples that can be taken on any given sampling date. It is also destructive, effectively limiting the feasible frequency of sampling in a limited space, such as the experimental plots in Waseca.

While many studies achieve good results through very frequent (multiple measurements per day) sampling such as is permitted by TDR or electrical resistance sensors coupled with data loggers (as in Menziani et al. 2003, Lascano 2000, or Murphy and Lodge 2004), others manage to gain insight with more infrequent sampling (with sampling periods ranging from two days to as long as six weeks) (see for example, Izaurralde et al. 1994, Hupet and Vanclooster 2004, Twerdoff et al. 1999 or Ridley et al. 2001), especially in the context of seasonal water budgets (as in Dolling 2001).

For this study, gravimetric soil moisture measurements were taken on an approximately biweekly basis from May to September of 2004 and April to August of 2005 in randomly selected positions within the respective plots. Although logistics necessitated a small sample size (between two and eight samples per crop cover—see Appendix A), other studies have had acceptable results with similarly small sample sizes (see Sandral et al. 2006, for example).

At each sample location, a soil auger was used to collect four soil samples, one each at the surface, 30 cm, 75 cm, and 120 cm of depth. The approximate level of the water table was also recorded, if observed. The soil samples were placed in watertight tins, sealed with tape, and taken back to the lab and analyzed for gravimetric moisture content following standard procedures.

5.1.2.2 Bulk Density

Bulk density measurements were made at the SROC in 1983 (G. Johnson, pers. comm. 2004), and again in 2005 adjacent to the experimental plot sites (A. Steber, pers. comm. 2005).

5.1.2.3 Runoff

A separate, concurrent study collected surface runoff data from the instrumented plots in the runoff plot area (Colson 2005, A. Colson, pers. comm. 2005 and 2006, D. Ide, pers. comm. 2005 and 2006). In some cases, instrument malfunction meant a runoff measurement was not available for a given plot during a given precipitation event.

5.1.2.4 Vegetation

Vegetative data were collected as a part of the concurrent study on the runoff plots (Colson 2005), and also by SROC staff on the other study areas (D. Ide, pers. comm. 2005 and 2006).

5.1.3 Calculations and Analysis

Data from the soil moisture measurements was analyzed to determine if crop cover had a significant effect. Many of the analyses that follow require that the collected data be assumed to be normally distributed and spatially independent. While examination of the collected data did not in any way exclude this possibility, the small sample size made it challenging to confirm this. However, other studies (such as Hupet and Vanclooster 2004) have shown hydrologic data, even those collected in a relatively small, homogeneous field, to be normally distributed and spatially independent, making such an assumption reasonable in this case. The standard of significance of these analyses was α=0.10.

5.1.3.1 Volumetric Soil Moisture

Analysis of the bulk density measurements indicated that bulk density did not differ among crop cover types, likely because of the virtually identical soils, recent planting of all crops, and similar land use prior to planting. An overall bulk density value for each sample depth was calculated. Using the bulk density information, the gravimetric soil moisture measurements were converted to volumetric moisture content.

5.1.3.2 Layer-by-Layer Soil Moisture

Soil moisture data were first examined on a layer-by-layer basis for each sample location. Soil moisture was compared among crop types for each layer using ANOVA analysis. The null hypothesis was that the mean soil moisture at the specified depth was equal across all crop types, and the alternative hypothesis was that at the specified depth, the soil moisture under all crops was not equal. In cases where ANOVA analysis indicated that the null hypothesis was incorrect, a multiple-comparisons procedure following the

Bonferroni method was used to determine which pairs of crop covers had significantly different soil moisture at the specified depth.

5.1.3.3 Total Soil Moisture in Column

The volumetric soil moisture measurements for each sample date and location were extrapolated to estimate total water content in a 130 cm soil column by multiplying the volumetric water content by the depth of each section. The values of total water in the soil columns were first compared using the single factor ANOVA test for each sampling location. Calculations were made of the 90 percent confidence intervals for the total water in each soil column for each crop type and sampling location. In constructing these intervals, bulk density measurements were assumed to be constant, and while measurements at each depth were assumed to be normally distributed, the values within any measured column were not considered independent. Finally, for the sampling dates when data were available for both the runoff plots and the tile drainage plots, a two-way ANOVA analysis was performed with the two factors being crop cover and drainage status. The null hypothesis was that neither crop cover nor drainage status nor the interaction between the two had an effect on soil moisture.

5.1.3.4 Evapotranspiration

While transpiration can be measured directly with techniques such as sapflow velocity sensors for trees (White el al 2002), there is no method to directly measure total evapotranspiration (ET) over an area of land. However, a water budget can be used to estimate ET for an area. A water budget is calculated as

$$(P + SF_i) - (RO + ET + SF_o) = S_2 - S_1$$

Where P = precipitation
SF_i = subsurface flow in
RO = runoff
ET = evapotranspiration
SF_o = subsurface flow out
S_2 = soil water storage at end of period of interest
S_1 = soil water storage at beginning of period of interest

Evapotranspiration (ET) can thus be calculated as

$$ET = (P + SF_i) - (RO + SF_o) - (S_2 - S_1)$$

Estimates of ET are simplified when measurements are made over a dry period when both P and RO can be eliminated from the equation. However, rain fell at the field site during every interval between sampling dates during both 2004 and 2005 (Figure 4), making this simplification inappropriate.

In calculating the water budget for the runoff plots, given that barriers were established to stop leakage into or out of the plots, it was assumed that there was no subsurface leakage into or out of any of the plots, yielding an ET calculation of

$$ET = P - RO - (S_2 - S_1)$$

This is likely a reasonable assumption given the extremely heavy soils and plastic barriers between plots. However, even if some leakage did occur, given the close proximity and consistent soil characteristics between the plots, it would likely have been similar in magnitude between the plots. This means that while it is possible that absolute ET calculations could have errors, the relative comparison of ET between the plots would still be valid.

After total ET for each sampling period was calculated, a daily average ET rate was calculated by dividing the total amount of ET by the number of days in the sampling period.

5.2 Soil Frost

5.2.1 Field site

5.2.1.1 Sampling Locations

Soil frost was monitored from December 2004 to April 2005 on three sites at the SROC. The first two, which were the mature poplar grove and experimental plots underlain by tile drainage, were also monitored for soil moisture, and are described above. The third site was a series of crop strips just north of the mature poplar grove, which will be referred to as the landscape position plots (Figure 1, Table 1).

Eight frost tubes were placed at random within the mature poplar grove, although site selection was limited to locations at least two feet from a tree trunk, as that was the minimum required by the installation equipment.

In the tile drain plots, four frost tubes were placed at random in each of two plots of six crops (willow, poplar, hybrid hazelnut, IBF, perennial flax, and corn/soybean rotation) (Figure 3). The willows on the tile

drain plots were cut to the ground in November 2004 to simulate the conditions of willows grown for biomass.

The landscape position plots consist of four three-meter wide strips of different perennial crops, running east-west approximately perpendicular to topographic lines over a small valley between two highpoints, thus traversing a continuous spectrum of landscape position. The strips of perennial crops were abutted on both sides by large fields in corn/soybean rotation, which had just come out of corn and had been disc plowed, with a small amount of stubble left in the field. Frost tubes were placed in the willow, IBF, and poplar strips, as well as in the section of field directly south of the strips. Willow on these plots was also trimmed to the ground in November of 2004, but the poplar and IBF strips were left untouched following the growing season. Six tubes were put in each crop strip in groups of two each on the foot, backslope and topslope of the east-facing slope. The tubes were placed down the center of the perennial crop strips, and in a line approximately 2.5 meters from the crop strips in the cornfield.

5.2.1.2 Climate

The 2004-2005 winter was, on average, warmer than a typical winter, with less than average snowfall. The winter still had several extended periods where the temperature barely exceeded freezing, if at all, and several days with bitterly cold temperatures (Figure 5). These cold periods were sandwiched around periods of unseasonable warmth, including highs above 10°C on New Year's Eve, February 5, 6 and 13, and a high of 17°C on March 7.

An average winter at the field site has 1280 mm of snowfall (meaning actual depth of snow on the ground, as distinct from snow water equivalent) and 92 days with at least 25 mm of snow on the ground. The study winter had only 900 mm of snowfall and 72 days with at least 25 mm of snow on the ground. Even these numbers are somewhat deceptive, as February and March were much snowier than normal, and the early part of the winter, and December in particular, was much less snowy than usual. In fact, until January 6, there were only a total of ten days during which any snow cover at all was recorded (Figure 5). In addition to snow, there were several rainfall events during the winter, the most significant of which were 12 mm of rain on January 2, and 28 mm of rain on March 31.

Snow was first observed on the sample sites on January 12, and last observed on March 26 (see Appendix C). Snow cover on all the sites was minimal throughout the winter, although some accumulation was observed, with a maximum of 156 mm observed in the tile drainage poplar on March 25. On January 28,

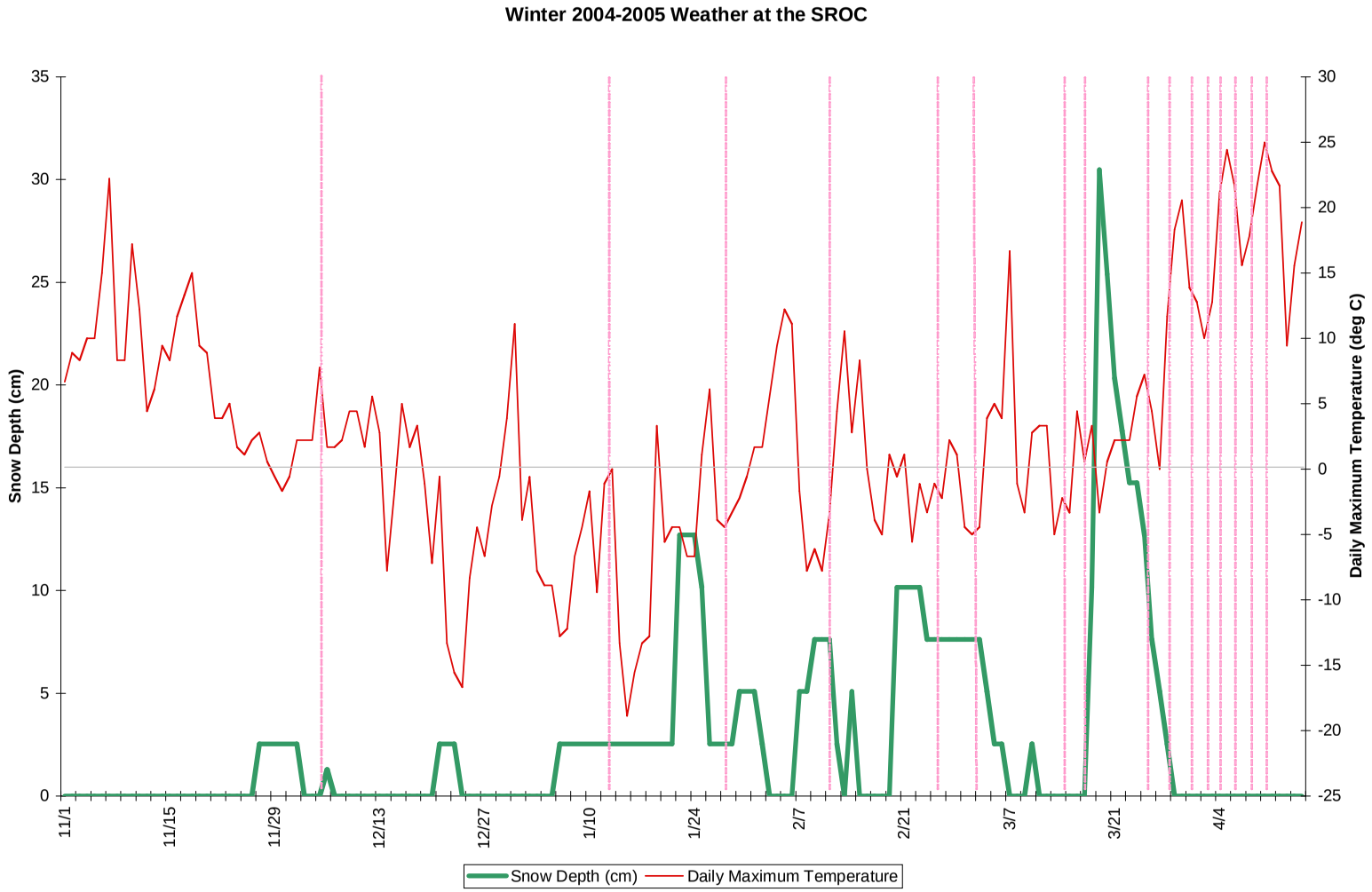


Figure 5: Snow cover and maximum daily temperature at the Waseca Southern Research and Outreach Center weather station for the winter of 2004-2005. Dates of soil frost monitoring are shown as dashed lines.

the poplar, flax and IBF on the tile drainage plots and mature poplar grove and on March 25, the same crops plus the corn/soy field in the tile drainage plots had noticeably more snow than the other locations, largely due to drifting, although these differences disappeared by the next sampling date.

During each of the warm periods of the winter, melted snow and rain accumulated in the surface of the soil and froze into a solid ice layer at the soil surface, which persisted until the soil began to thaw in March.

5.2.1.3 Antecedent Soil Moisture Conditions

Although soil moisture in the various locations was measured (as described in the above soil moisture section) at the end of the summer, several centimeters of rain fell after these measurements were taken, and the soil froze before it was possible to measure soil moisture again. Visual observation suggested that the soils in all sampling locations were very wet prior to freezing. With the heavy snowfall in late March followed immediately by temperatures consistently well above freezing, surface conditions were also extremely wet at the end of winter just prior to frost disappearance.

5.2.2 Frost Tubes

Frost tubes were constructed following the methodology described by Christopherson (2001), who modeled his design after that used by the USDA Forest Service (1969) and US Army Corps of Engineers (1972). Seventy-five percent of the tubes constructed for this study extended 120 cm below the surface, and the remaining tubes extended 137 cm below the soil surface. The tubes were installed in the fall of 2004, with a marker stake to aid location in deep snow placed approximately one foot from each tube.

5.2.3 Measurement

An initial soil frost measurement was taken December 15, followed by approximately bi-weekly measurements from mid-January through the beginning of March. Once the soil began to thaw, the measuring frequency was gradually increased, with measurements taken every other day during the first ten days of April. Measurements were recorded to the nearest 0.5 cm.

Snow depth and snow water equivalent were also measured next to each frost tube on each sampling date. Snow depth was measured with a ruler, and a snow sample was collected and taken to the lab to be weighed for snow water equivalent. Using a shovel to excavate soil on each plot, soil frost type was determined visually.

5.2.4 Calculations and Analysis

The soil frost measurements are different from the soil moisture measurements in that they are repeated measurements, but alike in that much of the analysis assumes that the data are normally distributed and spatially independent. Once again, while examination of the data did not exclude normality, the small sample size made interpretation difficult. The level for determining statistical significance among crop types was α=0.10.

Maximum frost depth, maximum snow depth and time from maximum frost depth to complete thaw were all compared between crop covers using ANOVA for a random block design. Maximum frost depth also corresponds to maximum frost thickness, as the deepest frosts were all recorded when the ground was frozen to the surface. In this analysis, the null hypothesis being tested was that the mean of each of the measured items was equal across all crop types, and the alternative hypothesis was that the specified measurement under all crops was not equal. In cases where ANOVA analysis indicated that the null hypothesis was incorrect, a multiple-comparisons procedure following the Bonferroni method was used to determine which pairs of crop covers had significantly different maximum frost depth, maximum snow depth, or time from maximum frost depth to complete thaw.

6. RESULTS AND DISCUSSION

6.1 Soil Moisture

6.1.1 Layer-by-Layer Comparisons

Analyzing soil moisture layer-by-layer between the various crop covers showed few significant differences between crops. However, examination of the seasonal soil moisture by layer showed some interesting trends (see Figures 6–8 and Appendix D).

6.1.1.1 Runoff Plots

Soil moisture was most variable, both between crop covers and over the season, in the surface layer of the runoff plots (Figure 6). Since the surface would be most influenced by air temperature, direct evaporation, and removal of water by shallow plant roots, this is not surprising. In all layers below the surface, differences between crops are minimal, and seasonal variation is less as well. Additionally, the soil became, in general, wetter the deeper it was sampled.

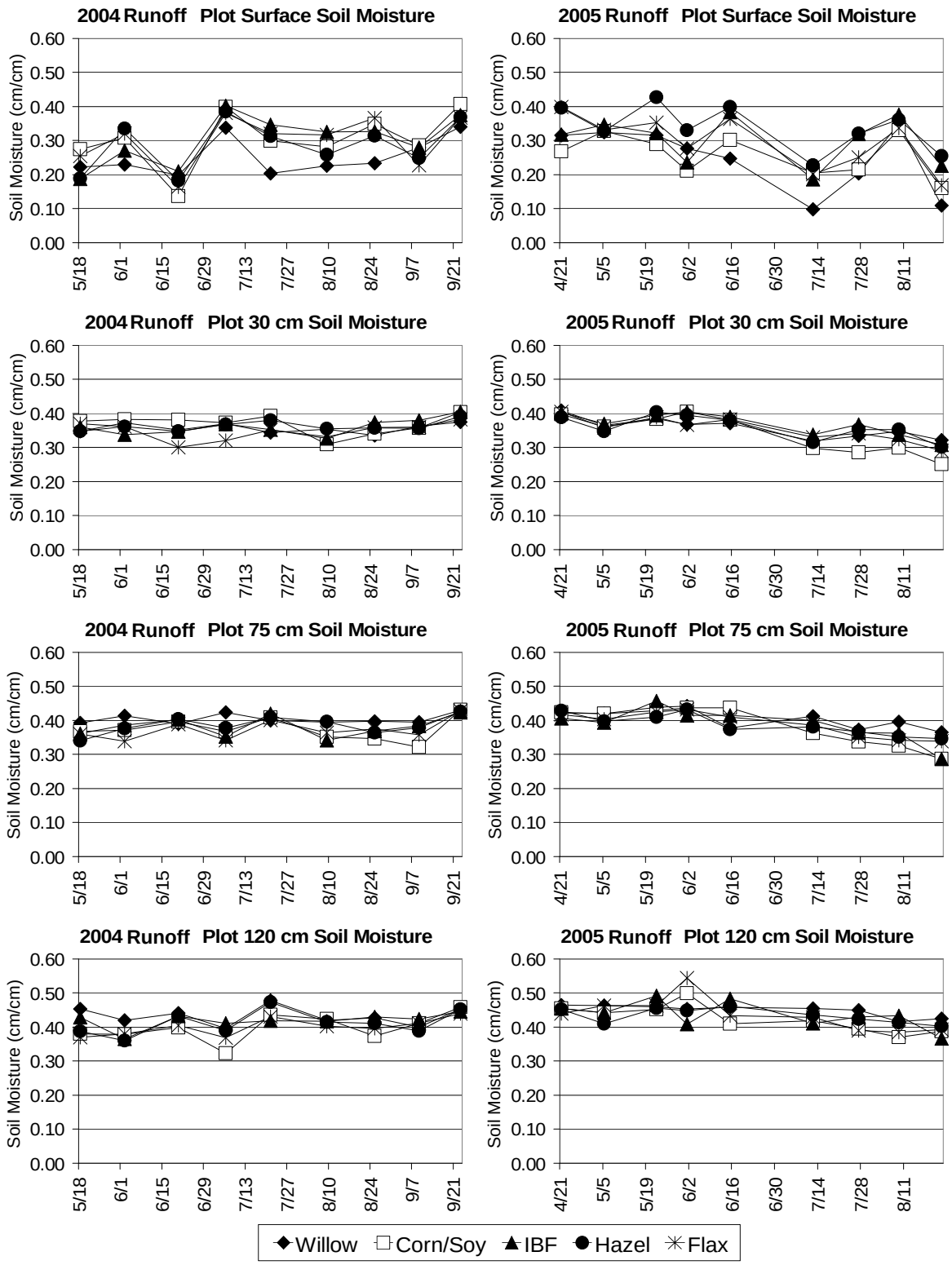


Figure 6: Soil moisture (cm/cm) by depth in the runoff plots.

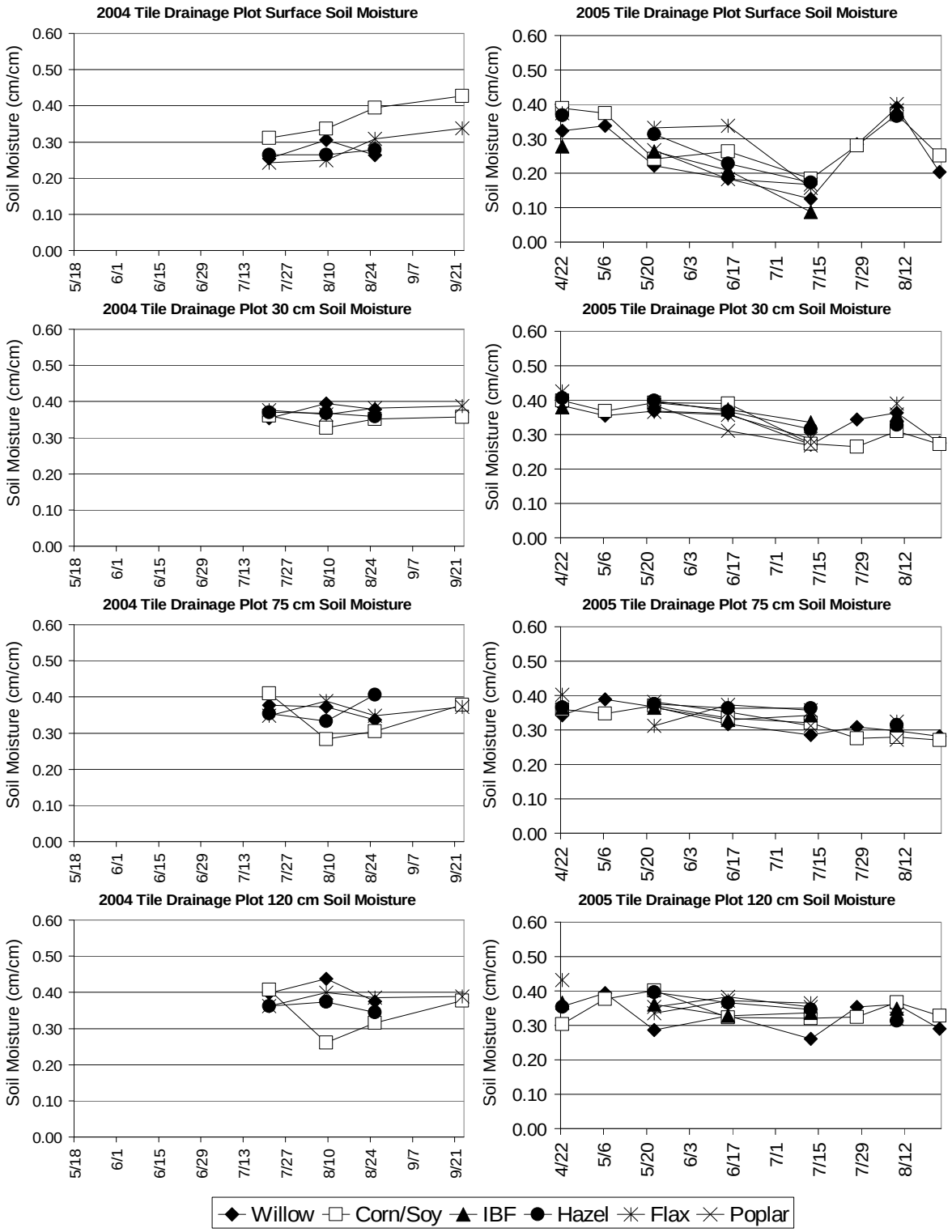


Figure 7: Soil moisture (cm/cm) by depth in the tile drainage plots.

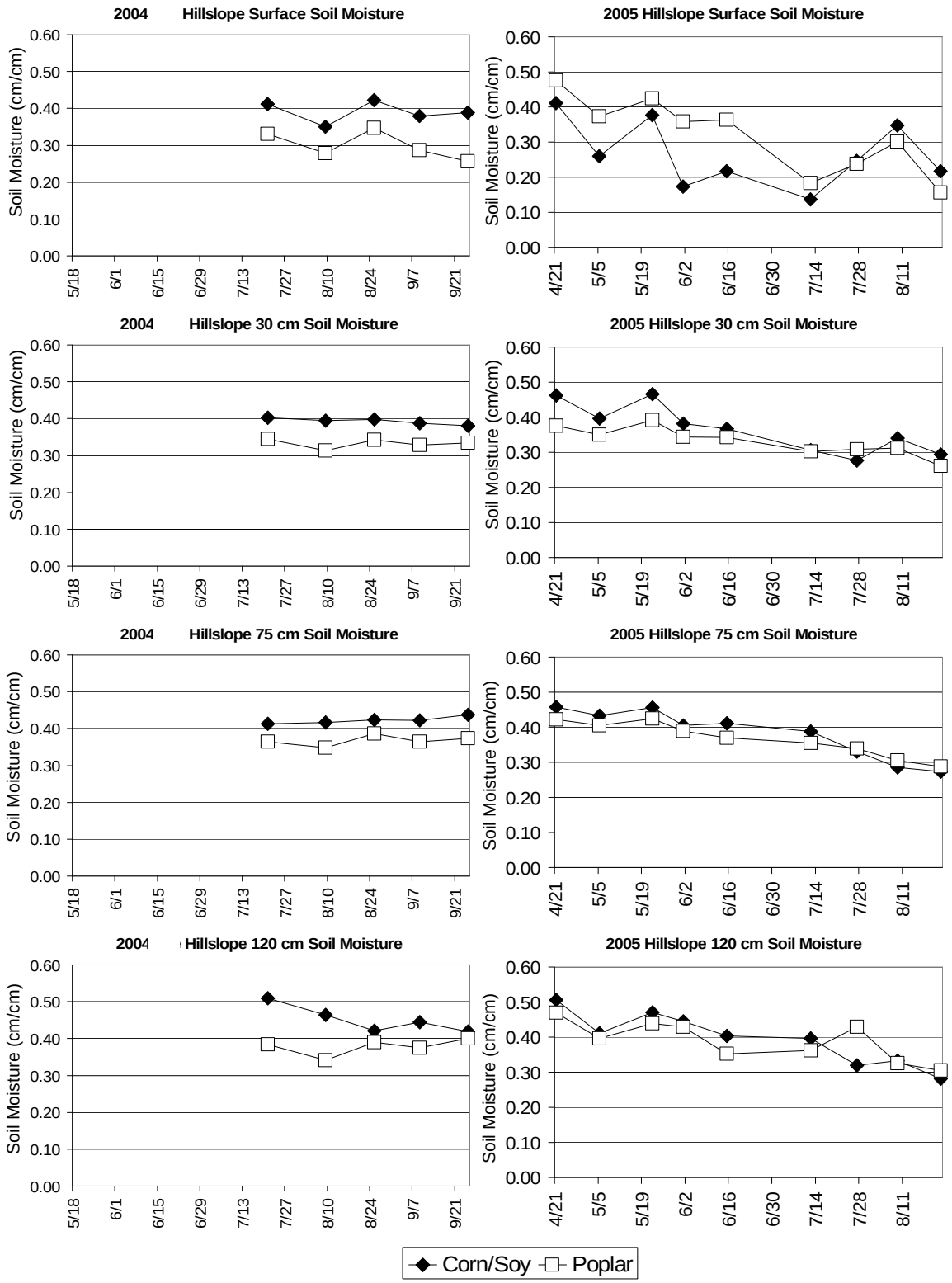


Figure 8: Soil moisture (cm/cm) by depth on the hillslopes.

For 2005, an overall drying trend was somewhat difficult to spot in the surface layer, which was obviously heavily influenced by rainfall in the days immediately preceding sampling, but was quite apparent at 30 and 75 cm. At 120 cm, the drying trend was much more subtle, likely because the water table hovered at or around 120 cm for most of both years.

6.1.1.2 Tile Drainage Plots

Once again, soil moisture was most variable both between crop covers and over the season in the surface layer of the tile drainage plots (Figure 7). However, soil moisture varied more among crops in the below-surface layers than in the runoff plots, and the pattern of increasing water with depth was not observed.

A tendency for the soil moisture to actually decrease at the deepest layers was observed on the tile drainage plots. It seems likely that the deeper layers on the tile drainage plots were drier due to water removed by the tile drainage system, with water in the middle depths being less likely to be either pulled up to the surface by plant roots or down through the drainage system by gravity.

6.1.1.3 Hillslope

High variability in soil moisture in the surface layer was also observed on the hillslope locations (Figure 8). In 2004, the difference in soil moisture between the two crop covers was apparent throughout the profile, but differences between the two crop types were muted below the surface in 2005, although the overall drying trend was visible throughout the profile.

6.1.2 Total Water in Column

6.1.2.1 Runoff Plots

Total water content in the soil profile was remarkably consistent among crops on the runoff plots for both 2004 and 2005 (Figure 9). In both years, there were no significant differences in total soil moisture in a 130 cm column between any of the crop types. This suggests that even in the second year following establishment that the rooting depth and above ground biomass of the perennial crops was not sufficient to show any effect, especially in years with above average rainfall.

For 2004 and the beginning of 2005, total soil moisture showed no distinct trends. However, beginning in June of 2005, soil water content showed a fairly consistent decline over the rest of the season, likely due to the low rainfall in July and normal rainfall in August.

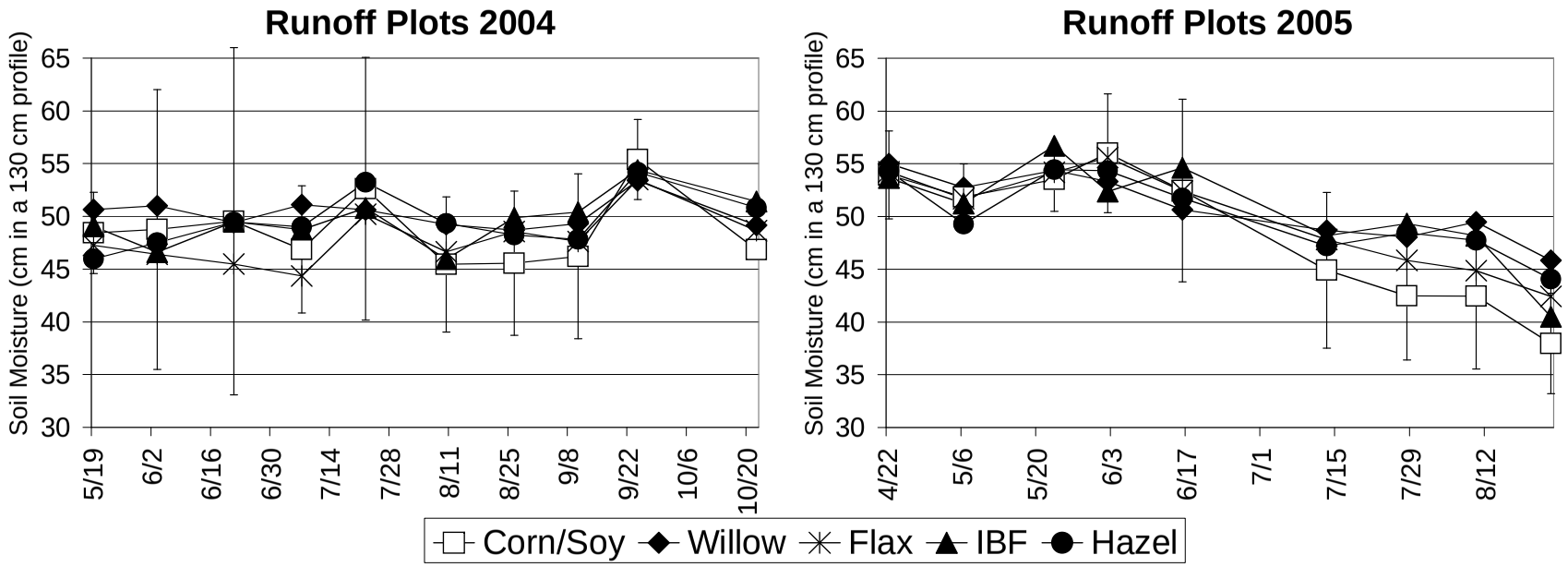


Figure 9: Soil moisture (cm in a 130 cm profile) in the runoff plots in 2004 and 2005. Error bars are shown for the corn/soy plots only (90% confidence interval).

6.1.2.2 Tile Drainage Plots

Total water content in soil water profile was also remarkably consistent between crops on the tile drainage plots (Figure 10). Once again, there were no significant differences in soil moisture among crop types, with the exception of a significant difference between soy and flax and soy and willow on August 10, 2004. On the whole, the lack of difference between the annual and perennial crops once again is likely a result of the immaturity of the perennial crops combined with the above average rainfall in both years.

In the case of the situation on August 10, 2004, the soil moisture was lower under the soy crop than the two perennial crops in question. As this sampling date followed a relatively dry period of a very wet summer, it is possible that in this case the difference represents greater water use on the part of the soy crop as compared to the two perennial crops, perhaps attributable to the immaturity of the newly established perennial crops, as the soy crop was growing vigorously by this date.

The drying trend observed on the runoff plots during the second half of the 2005 season was apparent but more subtle in the tile drainage plots. The drying trend would be expected once again due to the lower rainfall amounts in July and August. The more subtle nature of the drying trend could be explained by the presence of drainage tiles on the plots, as the tiles would provide some soil moisture regulation by removing excess water during the wetter part of the season, leaving less water to be withdrawn from the soil during the drier part of the season. In fact, the soil at the tile drainage plots was drier early in the season than the soil at the runoff plots.

6.1.2.3 Hillslope

A different picture emerged on the hillslope, where in 2004 the soil under the mature poplar was consistently and significantly drier than that under the field, which was planted in corn (Figure 11). In 2005, the field was planted in soy, and the soil under poplar was significantly drier only on the sampling dates in April, May and June, but no significant differences were observed in July or August.

At first glance, it might be assumed that the disappearing significant differences in soil moisture observed in 2005 might be due to the reduced sampling size in these locations (from eight samples in each in 2004 to five samples in each in 2005). While this may have contributed, it is also worth noting that the differences between the two were much smaller in 2005 (with an average difference of 3.2 cm water over a 130 cm profile) than in 2004 (when the average difference was 8.2 cm of water over a 130 cm profile). Some of this might be attributable to the switch in the field from corn to soy. However, there was also a change in the understory in the poplar grove. In 2004, there was a thriving understory of weeds, many of which

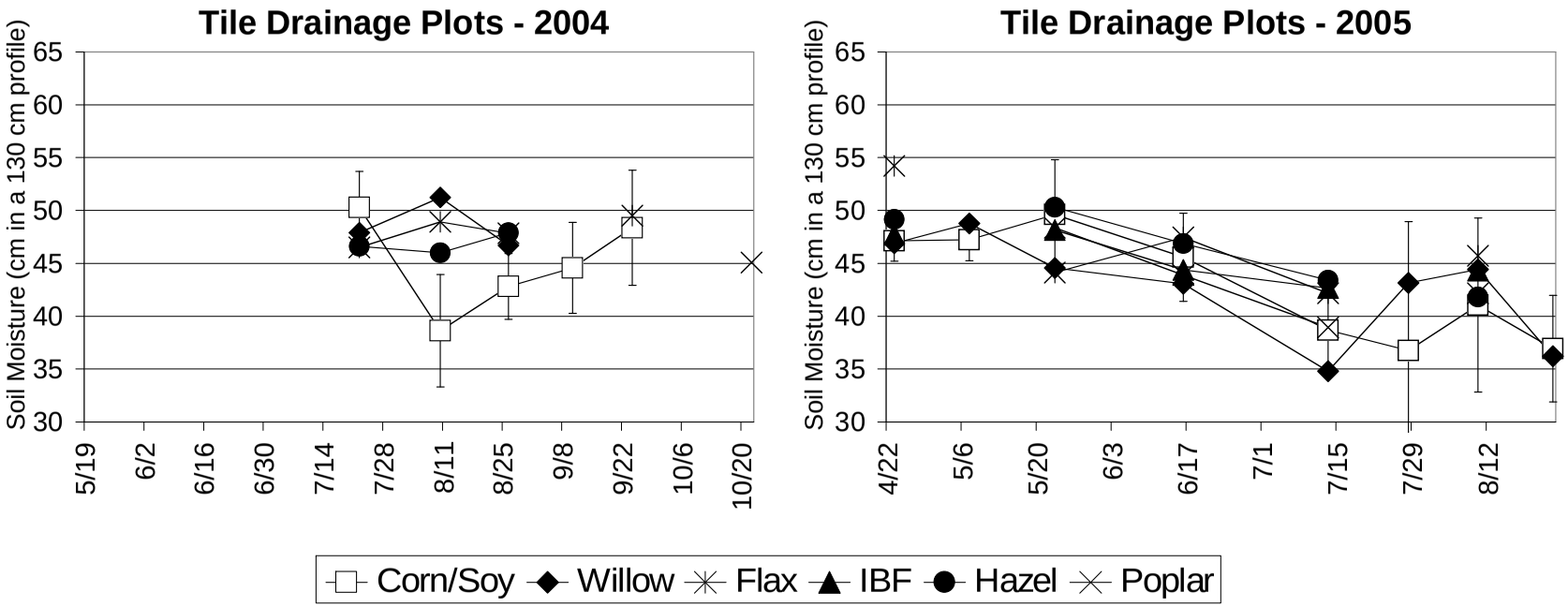


Figure 10: Soil moisture (cm in a 130 cm profile) in the tile drainage plots in 2004 and 2005. Error bars are shown for the corn/soy plots only (90% confidence interval).

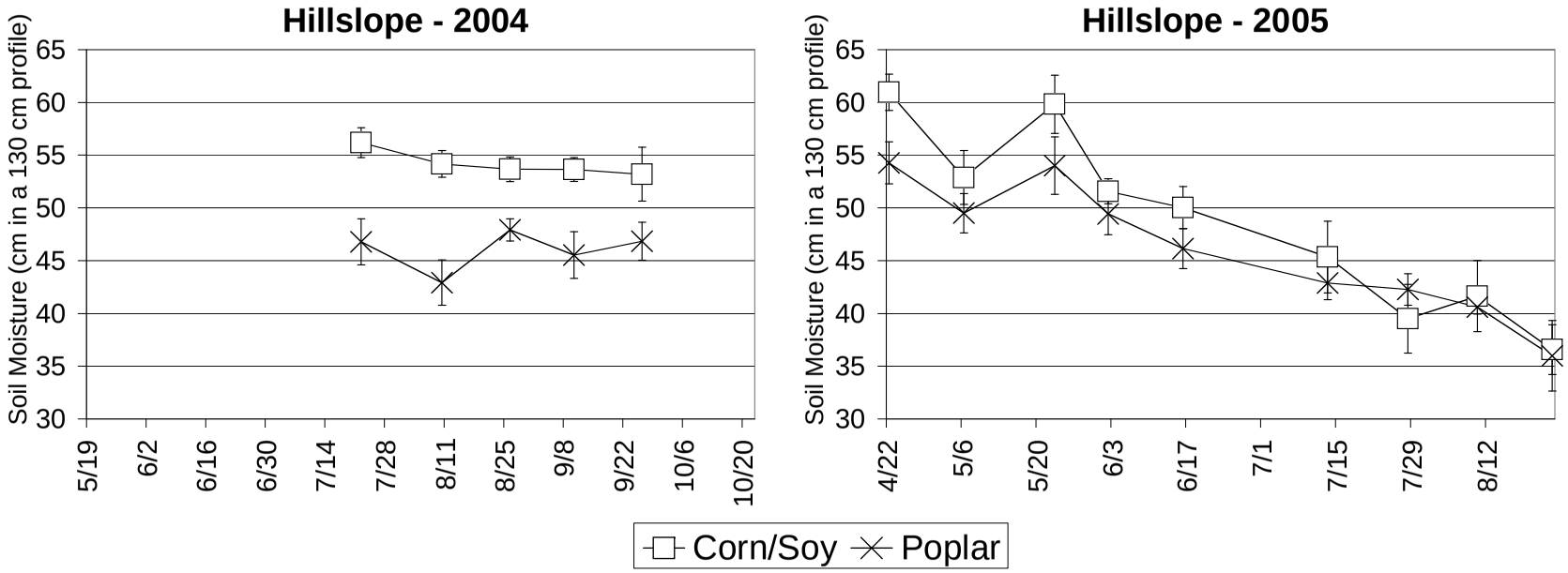


Figure 11: Soil moisture (cm in a 130 cm profile) in the hillslope plots in 2004 and 2005. Error bars are shown for both crop covers (90% confidence interval).

reached four to five feet in height by mid-summer. In early 2005, an herbicide was applied between rows of poplars, such that the weedy understory only existed in narrow bands along each row of trees. The weeds also consume soil water, and it seems reasonable that removing them would reduce water consumption in the grove. Sandral et al. (2006) saw the impact that weeds can have on soil moisture when, in their study, uncontrolled weeds extracted more water from a soil profile than clover pasture. This suggests that during the period of peak growth late in the summer, the transpiration rates of soybean crops can equal those of mature trees.

The drying trend observed on the runoff plots in late 2005 was also observed on the hillslope plots.

6.1.2.4 Comparison of Locations

Although the tile drainage plots, runoff plots and hillslope have different slopes and crops of slightly varying developmental stages, it is interesting to compare observations from the three locations (Table 2, Figure 12).

Two-way ANOVA analysis of soil moisture measurements from the sampling dates when data was available from both the runoff plots and tile drainage plots showed that drainage can be a factor in influencing soil moisture. On two of four sampling dates in 2004 and five of seven in 2005, this analysis showed a significant effect from drainage status. In all cases where a significant difference was observed, the drained soil was drier than the undrained (Figure 13). Not surprisingly, this two-way ANOVA analysis revealed no significant effects from crop cover except for the August 10, 2004 sampling date just as in the analysis of the tile drainage plots alone.

When comparing only the woody crops, the mature poplar showed generally drier soils than the immature woody crops on the runoff plots (Figure 14). This is not surprising, as one would assume mature trees would use more water than immature. However, the soil under mature poplar was not consistently drier than that on the tile drainage plots. This seems to indicate that artificial drainage might be able to more than make up for the reduced water usage of younger trees in drying the soil, as the tile drainage would remove the excess water in the period before the trees were mature enough to have greater water use.

When considered together, this implies, not surprisingly, that both crop cover and drainage status can influence soil water. However, it is worth remembering that the goal of planting perennials on the landscape is not drier soils per se, but rather greater capacity for the soil to store excess water during precipitation events. While drainage does appear to have the capacity to create drier soils, it will not

Table 2: Two-way ANOVA analysis of soil moisture for dates in 2004 and 2005 in which samples were available for both the runoff plots and tile drainage plots. The two factors considered were crop and drainage status (drained or undrained).

Two-Way ANOVA Analysis of Soil Moisture

		Effect Significant at alpha=0.10 ?		
Date	**Crops Measured**	**Crops**	**Drainage**	**Interaction**
7/22/2004	Willow, Corn/Soy, Flax, Hazel	no	YES	no
8/10/2004	Willow, Corn/Soy, Flax, Hazel	YES	no	no
8/26/2004	Willow, Corn/Soy, Flax, Hazel	no	no	no
9/24/2004	Corn/Soy, Flax	no	YES	no
4/22/2005	Willow, Corn/Soy, Flax, Hazel, IBF	no	YES	no
5/6/2005	Willow, Corn/Soy	no	YES	no
5/23/2005	Willow, Corn/Soy, Flax, Hazel, IBF	no	YES	no
6/16/2005	Willow, Corn/Soy, Flax, Hazel, IBF	no	YES	no
7/13/2005	Willow, Corn/Soy, Flax, Hazel, IBF	no	YES	no
7/28/2005	Willow, Corn/Soy	no	no	no
8/10/2005	Willow, Corn/Soy, Flax, Hazel, IBF	no	no	no

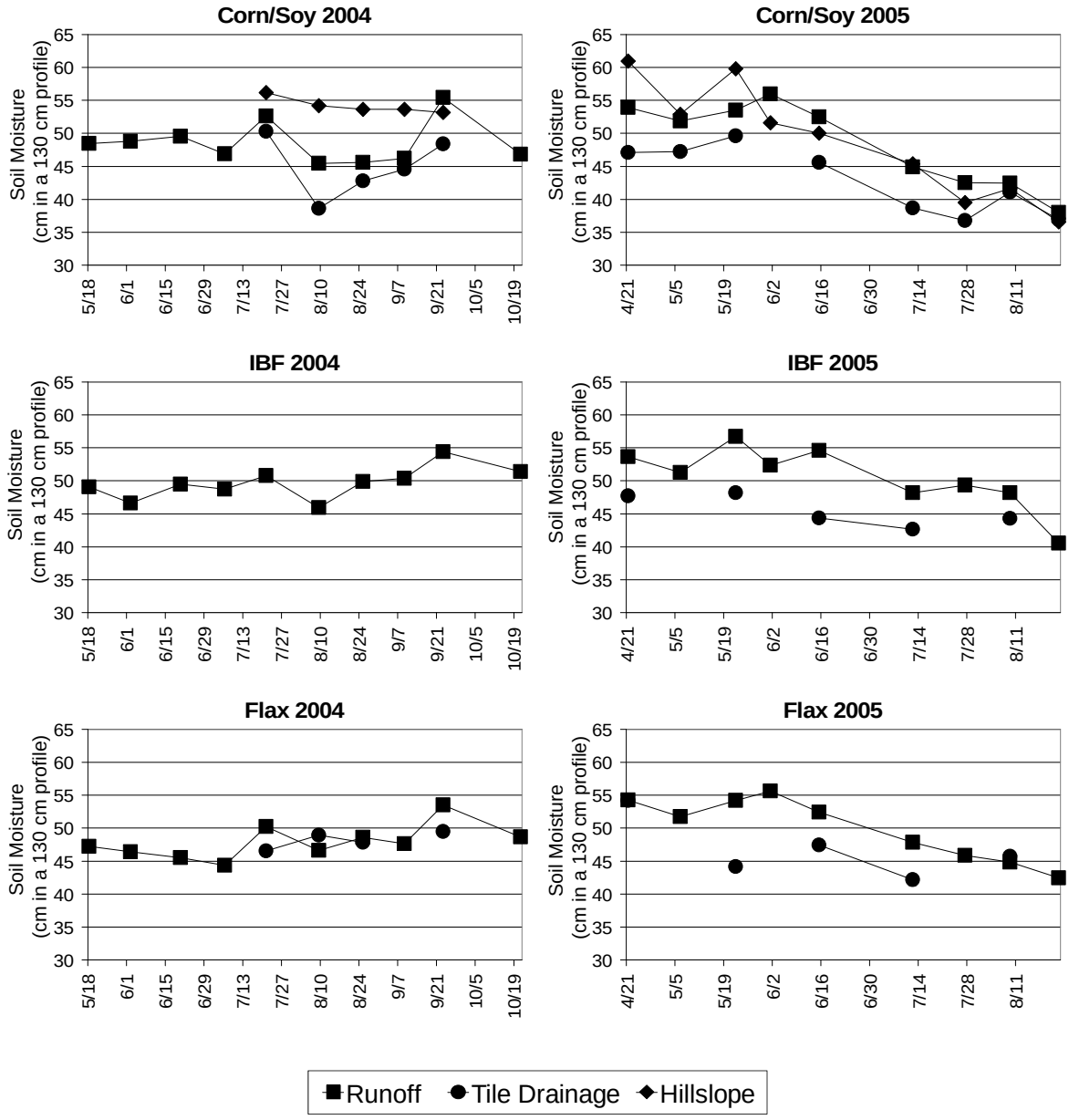


Figure 12a: Comparison of soil moisture under each crop type between sampling locations. (Samples from tile drainage plots were taken on 4/23/2005 and 5/8/2005.)

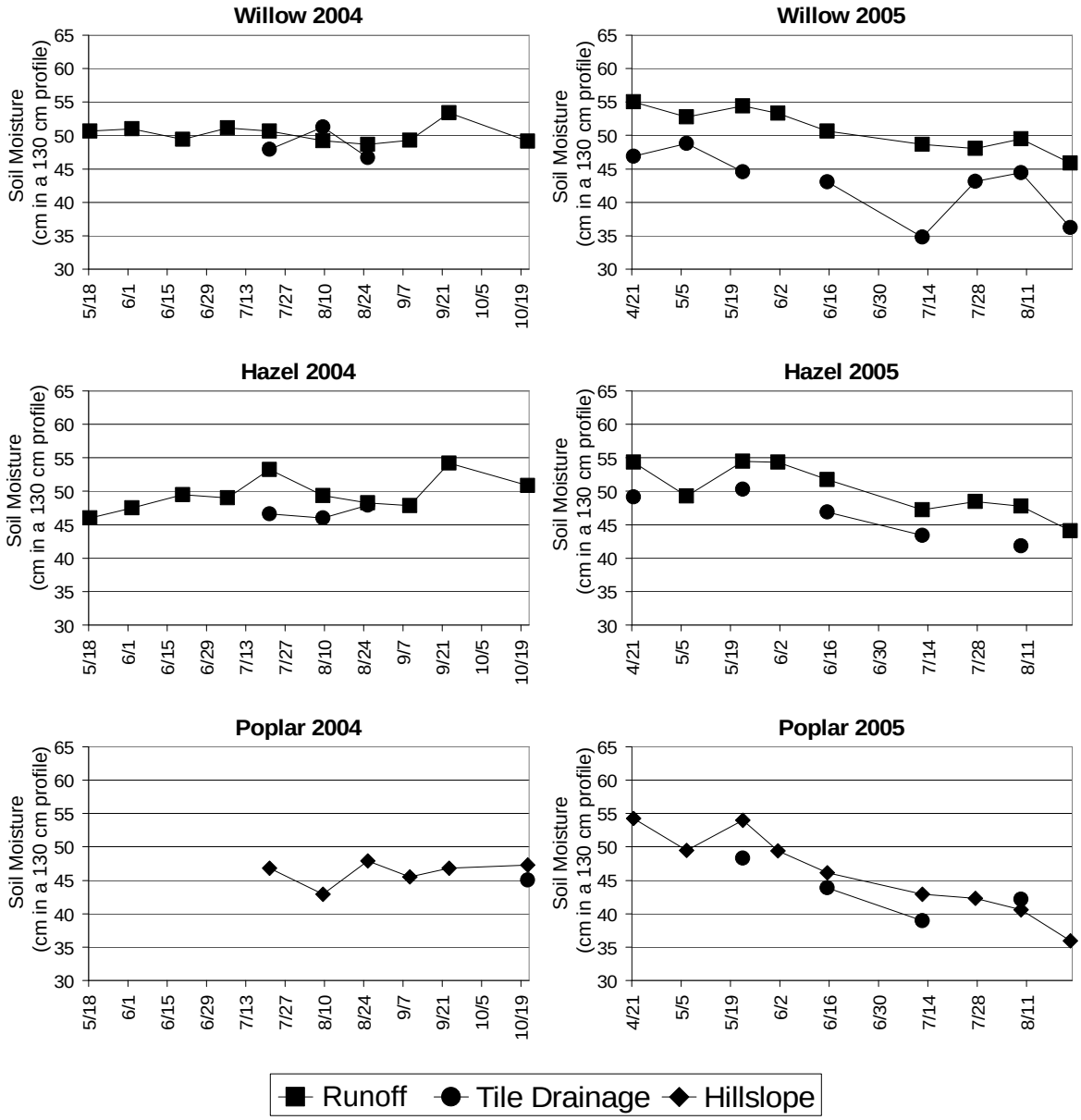


Figure 12b: Comparison of soil moisture under each crop type between sampling locations. (Samples from tile drainage plots were taken on 4/23/2005 and 5/8/2005.)

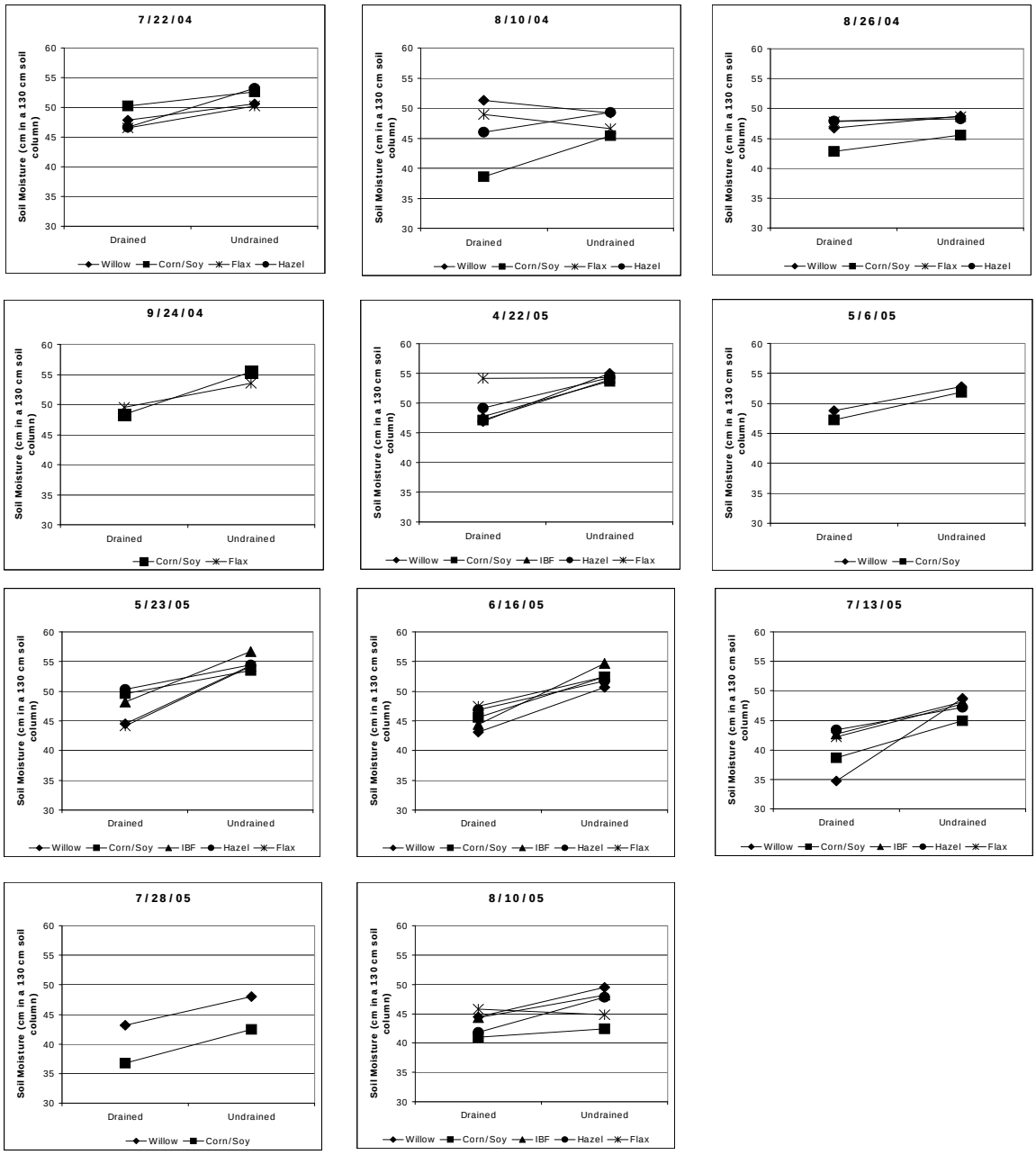


Figure 13: Soil moisture (cm in a 130 cm soil column) for selected dates on the runoff plots and tile drainage plots.

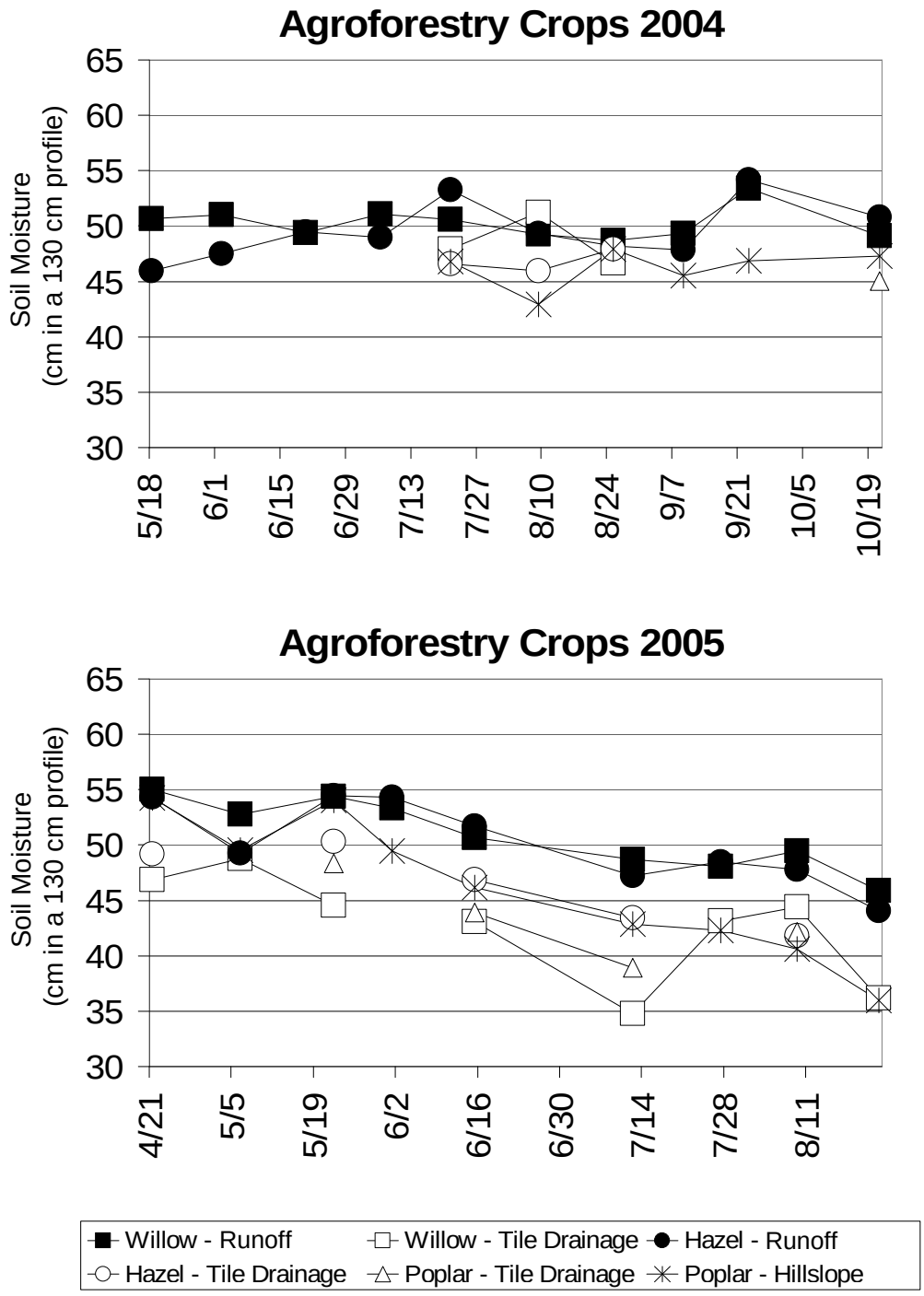


Figure 14: Comparison of soil moisture under agroforestry crops between sampling locations. Samples from tile drainage plots were taken on 4/23/2005 and 5/8/2005

increase water storage capacity on the land, and thus will not have the hydrologic benefits of drier soils created by increased crop use of water.

6.1.2.5 Further Discussion

Several factors may explain the lack of difference in soil moisture regimes among annual, perennial herbaceous and woody crops in the tile drain plots or the runoff plots. Foremost, in 2004 and early 2005, perennial crops were being established and would not have either sufficient rooting nor above ground biomass to transpire water at rates expected of mature trees. The woody crops in particular showed little growth over the course of the 2004 season, and the hazel were still underdeveloped at the end of the 2005 season. Given that the hazel biomass was so small as to be nearly inconsequential and that the sodgrass cover was influencing soil moisture on the hazel plots, these plots were in essence showing the influence of sod rather than hazel. In the case of willow and hybrid poplar, the trees were small, spaced at four-foot intervals and clean weeded; significant growth that resulted in crown closure did not occur until well into 2005. The data from the mature poplar stand and nearby cornfield support this idea, as the soil under the mature poplar was consistently drier than that in the cornfield during 2004. As discussed earlier, the lesser difference observed on the hillslope in 2005 might be the result of changes in weed management among the poplars. It is worth noting, however, that the poplar grove was significantly drier than the field in the earliest part of 2005, when the threat of flooding from runoff would be greatest. Fully mature annual crops do evapotranspire a considerable amount of water, making the convergence of soil moisture measurements in the hillslope area not unexpected either, especially given the weed removal in 2005.

In addition, in 2004, the lack of differences among perennial herbaceous and annual crops could be, in part, due to the high levels of rain during the summer and the proximity of sampling dates to precipitation events. In an average summer, the area receives 499 mm of rain between May and September. During the same period of 2004, 807 mm of rain fell. There was no period between sampling dates in which rain did not fall, and most periods experienced at least one reasonably sized storm (Figure 4). This frequent rainfall may have prevented any effects of differing water use to become manifested in soil moisture by keeping the soil continuously wet, as a longer dry period might be necessary for the effects of consumptive differences to become apparent. Norwood (2001) saw similar results in a study of soil water depletion under various management systems of dryland corn. In the study, soil water varied with management system, except during one year during which frequent rainfall replenished water in the soil profile throughout the season.

In 2005, there was less rainfall than in 2004. However, significant soil moisture differences were still not seen between crops on the two sets of experimental plots. During 2005 the woody crops began to add biomass, however they still remained below levels expected of mature bioenergy crops. Furthermore, soil

moisture carryover from 2004 was likely a factor as well, and 2005 was still wetter than average. Studies that have compared effects of changing tree cover on water yield have indicated that changes in water flow are often attributed in part to carryover effects of soil moisture from one year to the next (see, for example, results from watershed studies reported in Ice and Stednick, 2004). In this study, there was no effect on soil moisture the first year, and thus there was no chance for any carryover effect. When adding young trees to a bare soil we may not observe a carryover effect of drier soils until some threshold of biomass and rooting depth is reached.

It is also possible that the spatially variable nature of soil moisture combined with the small sample size meant that the measurements taken were not refined enough to pick up differences. This is an idea once again supported by the corn/poplar data, where larger sample sizes resulted in smaller margins of error.

Even if differences existed that would have been caught by more refined sampling methods, it is possible that they would have been of little practical importance. For example, in a two-year study of soil water under a variety of alternative cropping systems in western Canada, Izaurralde et al. (1994) observed consistently significantly drier soils under the studied perennial scenario than any of the studied annual cropping systems. This difference varied between 1.8 cm and a mere 0.2 cm of soil water in an 80 cm profile. It is worth noting, however, that the small sample size makes it impossible to determine conclusively if that is the case in the context of this study.

Thus, the data collected in this study do not support the hypothesis that perennial agroforestry crops will have higher consumptive water use resulting in increased water storage capacity during the establishment phase, as no significant differences in soil moisture were observed between crops on the experimental plots. However, significant differences in soil moisture beneath the mature poplar stand and corn/soy field in 2004 and the early months of the 2005 growing season indicate that mature agroforestry crops have the potential to provide hydrologic benefits through additional available water storage, although the reduced differences observed on the hillslope in 2005 reinforce the importance of overall management practices in taking advantage of this potential benefit. A better understanding of differences in the magnitude of potential ET between the crop types—in the spring in particular—will be key to quantifying the potential benefit.

6.1.3 Evapotranspiration

Calculated ET rates from the runoff plots were problematic (see Appendix E), as many unexpected and inconsistent results were seen. For example, in 2004, one of the highest ET rates in the corn was recorded in May when the corn had just barely been planted. Also, flax appeared to have negligible ET during early

July, when it was growing vigorously. These, and other results seemingly inconsistent with reality, indicate that something is amiss in the ET calculations. It is likely that such inconsistencies with probable reality arose from two main sources.

First, rainfall was not monitored directly at the runoff plots, but rather at the climatological station near the SROC main building (Figure 1). While this is reasonably near the runoff plots, it is far enough away that rainfall could have been different enough at the runoff plots to have a material effect on water balance calculations. It is worth noting, however, that even if the rainfall measurements were incorrect, the same ones were used for calculating ET of each of the crops, and the direction of the inconsistencies varied among crops for the same period, meaning that this could not have been the only factor at play.

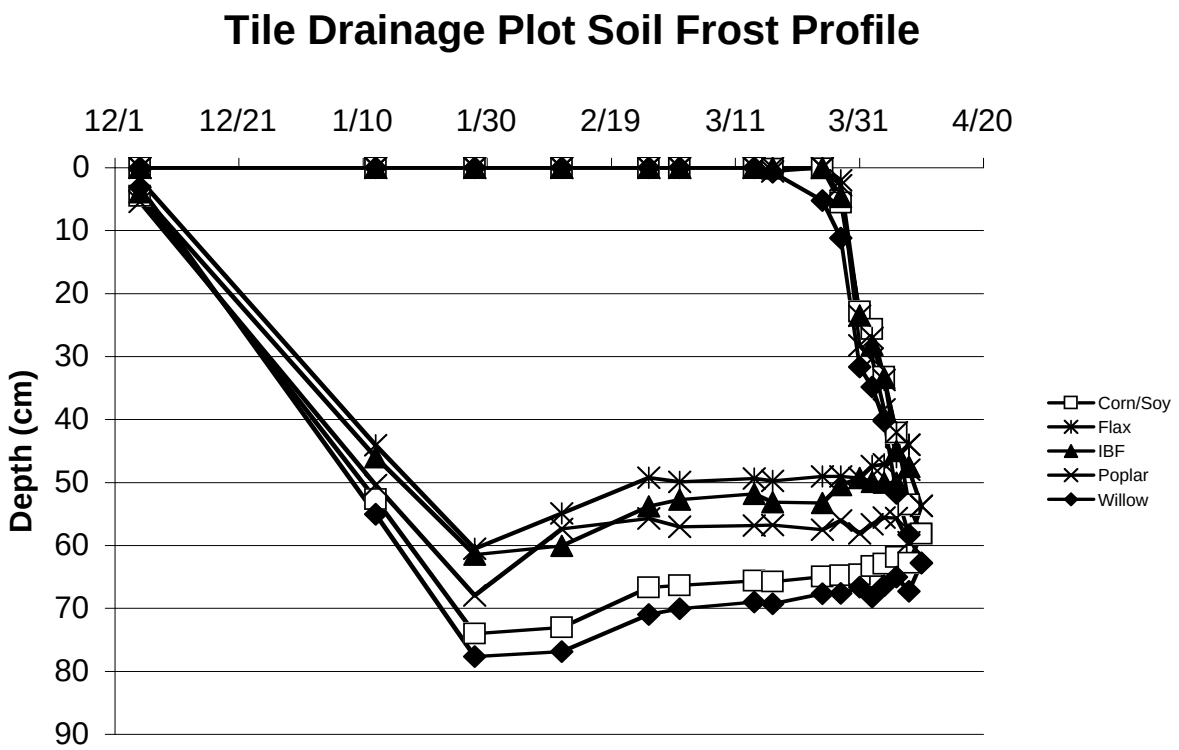
Second, and more importantly, the system used to monitor runoff on the plots was still undergoing refinement during both 2004 and 2005. It suffered numerous mechanical and calibration problems during both seasons. While an attempt was made to correct and account for the effect of these problems on the data, it is still likely that the runoff data had many errors of varying degree and direction, and that these errors in runoff measurement masked any reliable estimates of ET when calculated with a water budget. These issues led to significant changes in the runoff measurement system, which has subsequently been improved.

6.2 Soil Frost

6.2.1 Results

At the time of the first measurements (December 5), a thin (less than 10 cm) layer of frozen soil had begun to develop in all sampled locations (Figure 15). The maximum soil frost depth was measured in all locations on January 28 (Table 3), when average soil frost depth exceeded 60 cm in all sample locations, exceeding 80 cm in the landscape position willows. While the soil remained frozen to the surface for the next six weeks, the lower extent of soil frost retreated slightly, plateauing between 50 and 70 cm deep from the end of February through mid-March.

On March 17, the first signs of thawing at the surface were observed, and by March 25, soil frost under the willows in both locations and the young poplar on the landscape position plots had melted to a depth of more than 4.5 cm. After March 25, thawing proceeded rapidly in all sampled locations (Figure 16). In all cases, thawing was faster from the surface downward than from the bottom of the soil frost layer up. In fact, all locations showed minimal bottom-up thawing. All sampled locations showed similar rates of thawing.



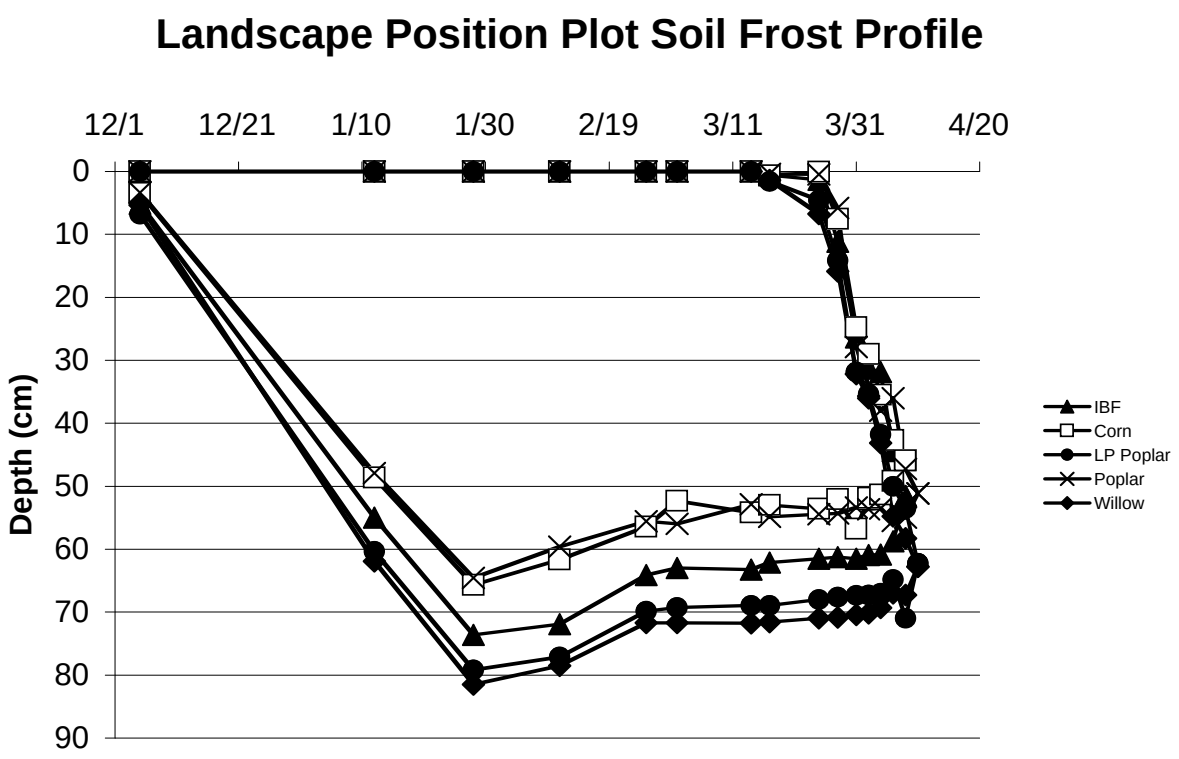


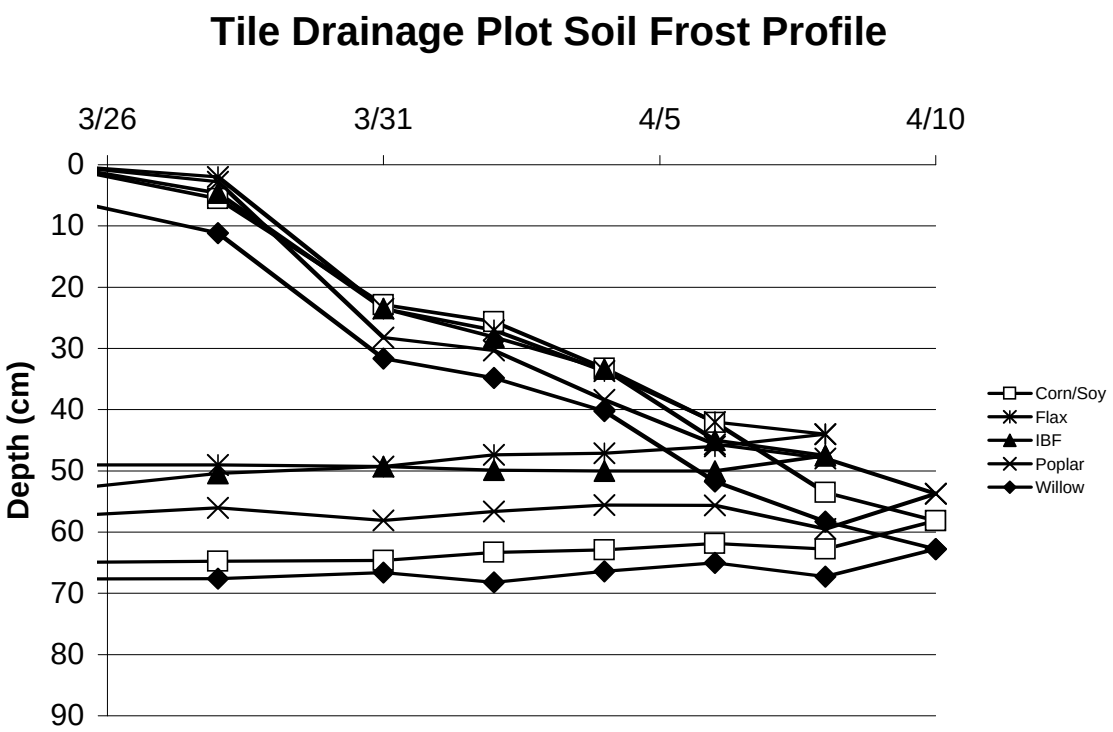
Figure 15: Soil frost profiles for the whole winter season. The mature poplar is indicated by "LP Poplar."

Table 3: Summary of soil frost measurements. Letters indicate differences significant at α=0.10 within each location group.

	Date of Maximum Frost Depth	Maximum Frost Depth (cm)		Date of Maximum Snow Depth (cm)	Maximum Snow Depth (cm)	Date of Maximum Snow-Water Equivalent (SWE)	Max Snow-Water Equivalent (cm)		First Date with No Observed Frost In Crop Type	Average Number of Days from 1/28/05 to Complete Thaw
Landscape Position Plots										
Mature Poplar	1/28/05	64.6	ab		11.4		2.9	ab	4/10/05	67.5
Corn/Soy	1/28/05	65.7	c		8.4		1.5		4/8/05	67.7
Willow	1/28/05	81.5	ac		5.3		1.0	a	4/10/05	70.7
IBF	1/28/05	73.6			8.3		1.7		4/8/05	69.3
Young Poplar	1/28/05	79.2	b	2/22/05, 3/25/06, 3/2/06, 1/28/05*	4.8	3/25/05, 3/2/05, 1/28/05, 2/25/05 **	0.8	b	4/8/05	70.3
Tile Drainage Plots										
Flax	1/28/05	60.5	ab		14.4		6.8		4/8/05	67.8
IBF	1/28/05	62.3	cd		14.3		3.1		4/8/05	66.8
Poplar	1/28/05	67.9			20.6		4.2		4/10/05	67.5
Corn/Soy	1/28/05	74.1	ac		8.4		2.3		4/10/05	71.0
Willow	1/28/05	77.7	bd		7.6		1.3		4/10/05	70.3

* Date of maximum snow depth was not consistent among sample sites, and in fact, was nearly evenly distributed between the four listed dates, with no discernable pattern by location or crop type.

** Date of maxium SWE was not consistent among sample sites and often did not coordinate with date of maximum snow depth. Most maximum SWEs were achieved 3/25 or 2/25



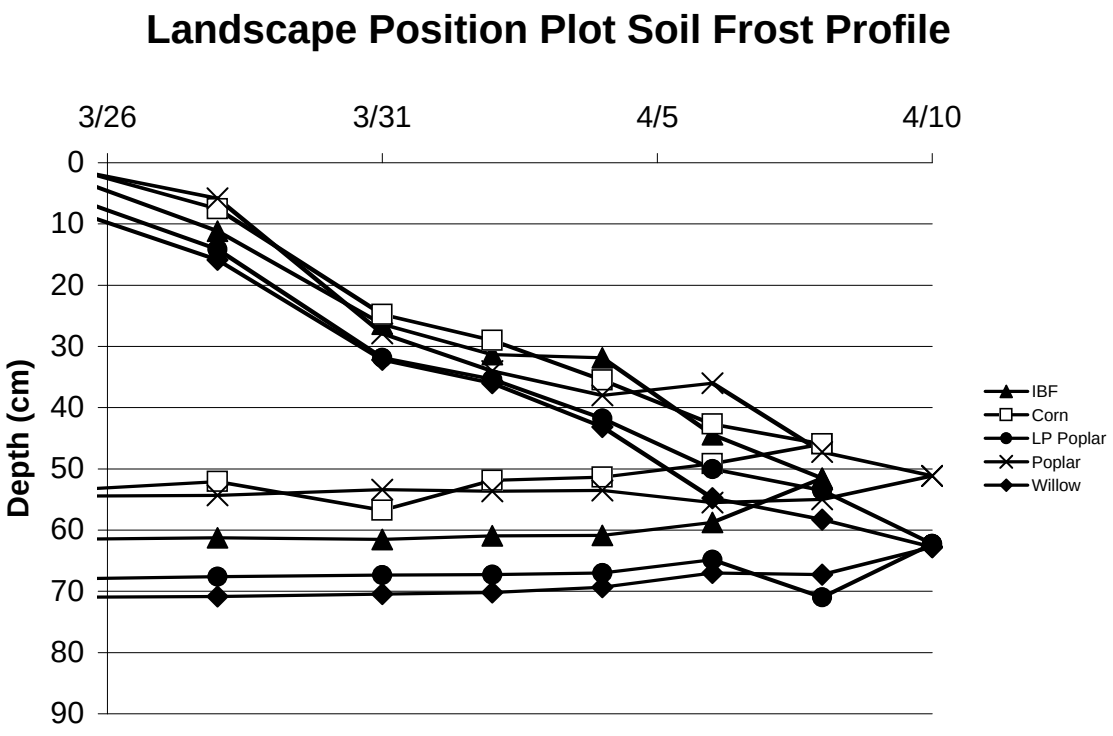


Figure 16: Soil frost profiles for the end of the season. The mature poplar is indicated by "LP Poplar."

On April 8, soil frost had disappeared from under the flax and IBF on the tile drainage plots, as well as from under the corn/soy field and IBF on the landscape position plots. On April 10, soil frost had disappeared everywhere.

When the data from the landscape position plots was separated by landscape position instead of crop type, a similar pattern was observed, with minimal differences between the landscape positions. Soil frost disappeared from all landscape positions on the same date.

Soil frost type was visually examined on March 17, and on all plots, concrete soil frost was observed.

As can be seen in Table 3, there were some significant differences in maximum frost depth within each location group. There were no significant differences in snow depth or average timing of thaw, and only one significant difference in maximum snow-water equivalent.

6.2.2 Discussion

The most striking characteristics of soil frost observed at the SROC during the 2004–2005 winter were the extremely deep penetration of soil frost, presence of concrete-type soil frost in all locations under all crop types, and closely timed disappearance of soil frost from under all crop types.

The deep penetration of soil frost and relative similarity in depth of penetration between crop types is likely explained by the lack of snow during November, December and early January, and especially during December when many days saw very cold temperatures. As discussed above, the depth of the snow layer has been shown to have the greatest effect on depth of soil frost. Differences in soil frost depth between crop covers are expected on the basis of the varying tendency of the different crop types to trap and retain snow cover. With minimal snow cover during the coldest part of the winter, snow conditions were essentially identical in all sample locations, making similar soil frost depth not unexpected. Given that differences in snow accumulation were observed on the two sampling dates when the greatest snow cover was observed, it seems likely that in a year with greater snowfall, crop cover would have more influence on depth of soil frost in Waseca.

The presence of concrete-type soil frost in all sample locations is likely a result of uniformly wet soil conditions prior to freezing, which, as discussed above, was likely the result of both late fall rain and the mid-winter thaw events.

As timing of frost disappearance might be considered the other most important factor in determining how much influence soil frost has on spring flooding, the similar timing of soil frost disappearance under all crops types is of particular interest. Christopherson (2001) saw differences in timing of soil frost disappearance of almost four weeks between a natural aspen stand and an open field in the first year of his study in northwestern Minnesota, and two weeks in the second. In this study, however, all locations thawed within a two-day period. While certain crops did thaw two days earlier than others, the importance of such a minor timing difference is questionable, especially since the crops that were not completely thawed on April 8 had very thin and fairly deep remaining layers of soil frost.

It seems likely that the similarly thick soil frost layers and uniformity of concrete-type soil frost contributed to this, as well as the sudden and dramatic increase in temperatures beginning March 28. Additionally, the snow cover that did exist at the end of March melted rapidly and completely from all sites in early April, minimizing the impact of snow cover on soil frost duration.

Lack of observed differences in soil frost depth or persistence between landscape positions in the landscape position plots is likely partially attributable to the lack of snow and consequent lack of difference in snow cover discussed above, partially attributable to the eastern aspect of the slope in question, and partially to the relatively gentle slope. Greater differences in landscape position might be expected with greater slope, southern aspect, or in examining locations of different aspect, such that solar radiation would vary more between landscape positions.

7. CONCLUSIONS

The data presented here imply that agroforestry and other perennial crops are likely to provide little hydrologic benefit during the establishment phase, although there is also no evidence that establishment-phase perennial and agroforestry crops would be more detrimental than annual row crops. It seems probable that agroforestry crops with mature woody components do have the potential to reduce soil moisture content in the soil, especially during early parts of the year when annual crops would not yet be fully established. This could, in turn, reduce water flow as either surface or subsurface flow from areas planted with agroforestry crops in contrast to annual crops. It is possible that differences among the various herbaceous and woody perennials may also be observed as crops mature. Continued monitoring of these sites will be essential to answering these questions, and understanding differences in the magnitude of potential ET during the spring months will be a key part of this.

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Appendix A: Site Descriptions

Table A1: Descriptions of sampling locations at the Waseca Southern Research and Outreach Center.

Area	Crop	No. of Soil Moisture Samples	No. of Soil Frost Samples	2004 Soil Moisture Sampling Dates	2005 Soil Moisture Sampling Dates	2004/2005 Soil Frost Sampling Dates	Description of Area
Run off plots	Willow (no cover crop)	2 (5/19/04, 6/3/04, 6/21/04); 3 (all other dates)	--	5/19 (upper plots only), 6/3 (upper plots only), 6/21 (upper plots only), 7/7, 7/22, 8/10, 8/26, 9/10, 9/24	4/22, 5/6, 5/23, 6/2, 6/16, 7/13, 7/28, 8/10, 8/24	--	Three 20 meter-long repetitions of seven crops, arranged two in an upper row and one along the lower. Hybrid hazel and willow plots are 10 meters wide; all the others are 5 meters wide. Upper two repetitions are bounded by a plot-width plastic barrier.
	Illinois bundleflower	2 (5/19/04, 6/3/04, 6/21/04); 3 (all other dates)	--				
	Corn/soybean rotation (2004 in soybeans; 2005 in corn)	2 (5/19/04, 6/3/04, 6/21/04); 3 (all other dates)	--				
	Hybrid hazelnut (with turf grass)	2 (5/19/04, 6/3/04, 6/21/04); 3 (all other dates)	--				
	Perrennial flax	2 (5/19/04, 6/3/04, 6/21/04); 3 (all other dates)	--				
Tile drain plots	Willow (no cover crop)	3	8	7/22, 8/10, 8/26, 9/10 (soy only), 9/24 (soy and flax only)	4/23 (all except poplar), 5/7 (corn and willow only), 5/23, 6/16, 7/13, 7/28 (corn and willow only), 8/10, 8/24 (corn and willow only)	12/5, 1/12, 1/28, 2/11, 2/25, 3/2, 3/14, 3/17, 3/25, 3/28, 3/31, 4/2, 4/4, 4/6, 4/8, 4/10	22.9 meter by 27.4 meter plots. Tile drains installed about 1.2 meters below the surface.
	Illinois bundleflower	3	8				
	Corn/soybean rotation (2004 in soybeans; 2005 in corn)	3	8				
	Hybrid hazelnut (with turf grass)	3	8				
	Perrennial flax	3	8				
	Hybrid Poplar	3	8				
Hillslope	Hybrid Poplar	8	8	7/22, 8/10, 8/26, 9/10, 9/26	4/22, 5/6, 5/23, 6/2, 6/16, 7/13, 7/28, 8/10, 8/24	12/5, 1/12, 1/28, 2/11, 2/25, 3/2, 3/14, 3/17, 3/25, 3/28, 3/31, 4/2, 4/4, 4/6, 4/8, 4/10	Poplar stand is about 219.5 meters by 48.8 meters. Trees are planted on a 3 meter grid.
	Corn/soybean rotation (2004 in corn; 2005 in soybeans)	8	--				
Landscape Position Plots	Corn/soybean rotation (2004 in corn)	--	6	--	--	12/5, 1/12, 1/28, 2/11, 2/25, 3/2, 3/14, 3/17, 3/25, 3/28, 3/31, 4/2, 4/4, 4/6, 4/8, 4/10	Corn/Spy sample area is directly adjacent to other landscape position plots.
	Willow (no cover crop)	--	6				Crop strips are 6.1 meters wide.
	Illinois bundleflower	--	6				
	Hybrid Poplar	--	6				

Appendix B: Weather Data

Table B1: Temperature and precipitation at the Waseca SROC during the study period.

	Average Maximum Temperature (°C)	Departure from Normal (°C)	Average Minimum Temperature (°C)	Departure from Normal (°C)	Average Temperature (°C)	Departure from Normal (°C)	Precipitation (cm)	Departure from Normal	Snowfall (cm)	Departure from Normal
Apr-04	16.8	4.0	1.9	0.6	9.3	2.3	4.5	-3.1	0.0	-10.2
May-04	19.6	-1.1	8.3	0.4	13.9	-0.3	14.2	5.0	0.0	0.0
Jun-04	23.7	-2.1	12.8	-0.4	18.3	-1.2	16.3	5.9	0.0	0.0
Jul-04	26.3	-1.6	15.5	-0.2	20.9	-0.9	18.0	7.3	0.0	0.0
Aug-04	23.6	-2.8	12.3	-1.7	17.9	-2.2	14.6	3.9	0.0	0.0
Sep-04	24.8	2.9	12.7	3.7	18.7	3.3	17.6	8.7	0.0	0.0
Oct-04	15.3	0.3	3.9	1.4	9.6	0.8	6.2	0.0	0.0	-1.0
Nov-04	7.8	2.7	-2.1	2.7	2.8	2.7	3.0	-1.4	5.6	-9.9
Dec-04	-0.8	3.3	-10.3	3.6	-5.5	3.5	0.5	-2.8	2.5	-26.7
Jan-05	-5.9	0.7	-14.1	3.6	-10.0	2.1	2.7	0.2	18.8	-6.6
Feb-05	0.8	4.3	-8.8	5.5	-3.9	4.9	3.5	1.1	27.2	5.6
Mar-05	3.3	0.1	-6.2	0.4	-1.4	0.3	7.4	1.5	36.1	10.2
Apr-05	16.4	3.6	5.0	3.7	10.7	3.7	8.6	1.0	0.0	-10.2
May-05	17.7	-2.9	7.9	0.1	12.8	-1.5	15.1	5.9	0.0	0.0
Jun-05	28.0	2.2	17.1	3.9	22.6	3.1	14.5	4.1	0.0	0.0
Jul-05	28.5	0.6	17.8	2.1	23.1	1.3	7.8	-2.8	0.0	0.0
Aug-05	26.7	0.3	14.7	0.7	20.7	0.5	11.4	0.8	0.0	0.0
Sep-05	24.6	2.7	12.3	3.3	18.4	2.9	17.7	8.8	0.0	0.0

Appendix C: Snow Observations

Table C1: Snow cover observations from soil frost measurement dates.

Average Snow Depth (cm)

	LP Mature Poplar	LP Corn/Soy	LP Willow	LP IBF	LP Young Poplar	TD Flax	TD Willow	TD Poplar	TD IBF	TD Corn/Soy
12/5/04	0	0	0	0	0	0	0	0	0	0
1/12/05	1.75	2.50	1.00	1.00	0.75	2.44	0.75	1.56	2.81	0.63
1/28/05	8.63	0.25	0.10	2.00	0.50	11.13	0	15.50	10.38	0.88
2/11/05	3.13	3.83	2.60	3.25	3.92	4.94	4.94	5.50	4.94	4.50
2/25/05	8.00	8.42	5.00	7.67	4.42	8.00	7.00	7.56	7.44	7.19
3/2/05	8.00	4.75	5.30	7.92	4.42	8.19	7.38	8.38	7.94	6.63
3/14/05	0	0	0	0	0	0	0	0	0	0
3/17/05	0	0	0	0	0	0	0	0	0	0
3/25/05	5.19	1.17	1.00	2.25	0.50	13.13	0	15.63	11.31	6.81
3/28/05	0	0	0	0	0	0	0	0	0	0
3/31/05	0	0	0	0	0	0	0	0	0	0
4/2/05	0	0	0	0	0	0	0	0	0	0
4/4/05	0	0	0	0	0	0	0	0	0	0
4/6/05	0	0	0	0	0	0	0	0	0	0
4/8/05	0	0	0	0	0	0	0	0	0	0
4/10/05	0	0	0	0	0	0	0	0	0	0

Average Snow Water Equivalent (cm)

	LP Mature Poplar	LP Corn/Soy	LP Willow	LP IBF	LP Young Poplar	TD Flax	TD Willow	TD Poplar	TD IBF	TD Corn/Soy
12/5/04	0	0	0	0	0	0	0	0	0	0
1/12/05	0	0	0	0	0	0	0	0	0	0
1/28/05	1.99	0	0	0.48	0	5.70	0	3.25	2.38	0.19
2/11/05	0.49	0.61	0.33	0.44	0.48	0.52	0	0.70	0.54	0.50
2/25/05	1.43	1.44	1.00	1.37	0.80	1.22	0	1.35	1.31	1.26
3/2/05	0.93	0.78	0.65	0.99	0.59	0.87	0	1.09	0.86	0.80
3/14/05	0	0	0	0	0	0	0	0	0	0
3/17/05	0	0	0	0	0	0	0	0	0	0
3/25/05	1.69	0.27	0.16	0.36	0	3.93	0	3.65	3.41	2.38
3/28/05	0	0	0	0	0	0	0	0	0	0
3/31/05	0	0	0	0	0	0	0	0	0	0
4/2/05	0	0	0	0	0	0	0	0	0	0
4/4/05	0	0	0	0	0	0	0	0	0	0
4/6/05	0	0	0	0	0	0	0	0	0	0
4/8/05	0	0	0	0	0	0	0	0	0	0
4/10/05	0	0	0	0	0	0	0	0	0	0

**SWE was not measured for snow depth less than 2.54 cm.

Appendix D: Layer-by-Layer Soil Moisture Comparisons

Table D1a: Layer-by-layer soil moisture comparisons in 2004, with significant differences at α=0.10 (within the same set of experimental plots) shown.

	5/19	6/3	6/21	7/7	7/22	8/10	8/26	9/10	9/24
RO Willow (s)	0.22	0.23	0.20	0.34 a	0.20 abcd	0.23 ab	0.23 ab	0.28	0.34
RO (Corn)/Soy (s)	0.27	0.31	0.14	0.40	0.30 a	0.28	0.35 a	0.29	0.41
RO IBF (s)	0.19	0.27	0.21	0.40 a	0.35 b	0.33 a	0.33	0.28	0.37
RO Hazel (s)	0.19	0.33	0.18	0.39	0.31 c	0.26	0.31	0.25	0.37
RO Flax (s)	0.25	0.32	0.16	0.38	0.32 d	0.32 b	0.37 b	0.23	0.37
RO Willow (30 cm)	0.35	0.37	0.35	0.37	0.34	0.35	0.34	0.36	0.37
RO (Corn)/Soy (30 cm	0.38	0.38	0.38	0.37	0.39	0.31	0.34	0.36	0.40
RO IBF (30 cm)	0.36	0.34	0.35	0.37	0.35	0.33	0.37	0.38	0.41
RO Hazel (30 cm)	0.35	0.36	0.35	0.37	0.38	0.35	0.36	0.36	0.39
RO Flax (30 cm)	0.37	0.36	0.30	0.32	0.35	0.33	0.36	0.36	0.38
RO Willow (75 cm)	0.39	0.41	0.39	0.42	0.40	0.39	0.40	0.40	0.43
RO Corn/(Soy) (75 cm	0.37	0.37	0.40	0.37	0.41	0.35	0.35	0.32	0.43
RO IBF (75 cm)	0.36	0.39	0.40	0.35	0.42	0.34	0.37	0.38	0.42
RO Hazel (75 cm)	0.34	0.38	0.40	0.38	0.41	0.40	0.36	0.38	0.43
RO Flax (75 cm)	0.36	0.34	0.39	0.34	0.40	0.36	0.37	0.36	0.43
RO Willow (120 cm)	0.45	0.42	0.44	0.40	0.48	0.42	0.43	0.40	0.45
RO Corn/Soy (120 cm	0.38	0.38	0.40	0.32	0.44	0.42	0.37	0.41	0.46
RO IBF (120 cm)	0.43	0.37	0.43	0.41	0.42	0.42	0.43	0.42	0.45
RO Hazel (120 cm)	0.39	0.36	0.43	0.39	0.47	0.42	0.41	0.39	0.45
RO Flax (120 cm)	0.37	0.38	0.41	0.37	0.43	0.40	0.40	0.41	0.44
					7/22	**8/10**	**8/26**		**9/24**
TD Willow (s)					0.25	0.30	0.26		
TD Soy (s)					0.31	0.34	0.39		0.43 a
TD IBF (s)									
TD Hazel (s)					0.26	0.26	0.28		
TD Flax (s)					0.24	0.25	0.31		0.34 a
TD Poplar (s)									
TD Willow (30 cm)					0.35	0.39	0.38		
TD Soy (30 cm)					0.36	0.33	0.35		0.36
TD IBF (30 cm)									
TD Hazel (30 cm)					0.37	0.37	0.36		
TD Flax (30 cm)					0.38	0.36	0.38		0.39
TD Poplar (30 cm)									
TD Willow (75 cm)					0.38	0.37	0.34 a		
TD Soy (75 cm)					0.41	0.28	0.31 b		0.38
TD IBF (75 cm)									
TD Hazel (75 cm)					0.35	0.33	0.41 ab		
TD Flax (75 cm)					0.35	0.39	0.35		0.37
TD Poplar (75 cm)									
TD Willow (120 cm)					0.40	0.44 a	0.38		
TD Soy (120 cm)					0.41	0.26 a	0.32		0.38
TD IBF (120 cm)									
TD Hazel (120 cm)					0.36	0.37	0.35		
TD Flax (120 cm)					0.36	0.40	0.38		0.39
TD Poplar (120 cm)									
					7/22	**8/10**	**8/26**	**9/10**	**9/26**
HS Corn/(Soy) (s)					0.41 a	0.35 a	0.42 a	0.38 a	0.39 a
HS Mature Poplar (s)					0.33 a	0.28 a	0.35 a	0.29 a	0.26 a
HS Corn/(Soy) (30 cm)					0.40 a	0.39 a	0.40 a	0.39 a	0.38 a
HS Mature Poplar (30 cm)					0.34 a	0.31 a	0.34 a	0.33 a	0.33 a
HS Corn/(Soy) (75 cm)					0.41 a	0.42 a	0.42 a	0.42 a	0.44 a
HS Mature Poplar (75 cm)					0.36 a	0.35 a	0.39 a	0.36 a	0.37 a
HS Corn/Soy (120 cm)					0.51 a	0.46 a	0.42	0.44 a	0.42
HS Mature Poplar (120 cm)					0.38 a	0.34 a	0.39	0.38 a	0.40

Table D1b: Layer-by-layer soil moisture comparisons, with significant differences at α=0.05 and α=0.10 (within the same set of experimental plots) shown.

	4/22		5/6		5/23		6/2		6/16		7/13		7/28		8/10		8/24	
RO Willow (s)	0.32		0.32		0.32		0.28		0.25		0.10		0.20	ab	0.35		0.11	a
RO (Corn)/Soy (s)	0.27		0.33		0.29		0.21		0.30		0.20		0.21	cd	0.33		0.16	
RO IBF (s)	0.32		0.35		0.32		0.24		0.38		0.19		0.32	ac	0.38		0.23	
RO Hazel (s)	0.40		0.33		0.43		0.33		0.40		0.23		0.32	bd	0.36		0.26	a
RO Flax (s)	0.40		0.33		0.35		0.28		0.36		0.20		0.25		0.34		0.17	
RO Willow (30 cm)	0.41		0.37		0.39		0.37		0.37		0.32		0.33		0.35		0.32	
RO (Corn)/Soy (30 cm	0.40		0.36		0.38		0.40		0.38		0.30		0.29		0.30		0.25	
RO IBF (30 cm)	0.40		0.37		0.40		0.41		0.39		0.34		0.37		0.34		0.31	
RO Hazel (30 cm)	0.39		0.35		0.40		0.40		0.38		0.32		0.35		0.35		0.30	
RO Flax (30 cm)	0.40		0.36		0.39		0.37		0.38		0.33		0.34		0.32		0.29	
RO Willow (75 cm)	0.42		0.42		0.44		0.44		0.38		0.41		0.37		0.40		0.37	
RO Corn/(Soy) (75 cm	0.42		0.42		0.43		0.44		0.44		0.36		0.34		0.33		0.29	
RO IBF (75 cm)	0.41		0.39		0.46		0.41		0.42		0.40		0.36		0.36		0.29	
RO Hazel (75 cm)	0.43		0.40		0.41		0.43		0.37		0.38		0.37		0.35		0.35	
RO Flax (75 cm)	0.42		0.40		0.42		0.43		0.41		0.39		0.35		0.34		0.34	
RO Willow (120 cm)	0.46		0.46		0.46		0.45		0.46		0.45		0.45		0.42		0.42	
RO Corn/Soy (120 cm	0.45		0.44		0.45		0.50		0.41		0.42		0.40		0.37		0.39	
RO IBF (120 cm)	0.45		0.44		0.49		0.41		0.48		0.41		0.43		0.43		0.37	
RO Hazel (120 cm)	0.45		0.41		0.46		0.45		0.46		0.44		0.42		0.41		0.40	
RO Flax (120 cm)	0.44		0.46		0.46		0.54		0.43		0.43		0.39		0.39		0.39	
	4/23		**5/7**		**5/23**				**6/16**		**7/13**		**7/28**		**8/10**		**8/24**	
TD Willow (s)	0.32	cd	0.34	a	0.22	bc			0.18	b	0.13		0.28		0.39		0.20	
TD Soy (s)	0.39	d	0.37	a	0.24	a			0.26		0.18		0.28		0.37		0.25	
TD IBF (s)	0.28	b			0.26				0.21	c	0.09				0.38			
TD Hazel (s)	0.37	abc			0.31	c			0.23		0.17				0.37			
TD Flax (s)	0.37	a			0.33	ab			0.34	abc	0.16				0.40			
TD Poplar (s)					0.27				0.18	a	0.17				0.38			
TD Willow (30 cm)	0.38		0.35		0.37				0.36		0.27		0.34	a	0.36		0.28	
TD Soy (30 cm)	0.40		0.37		0.39				0.39		0.27		0.26	a	0.31		0.27	
TD IBF (30 cm)	0.38				0.39				0.37		0.33				0.36			
TD Hazel (30 cm)	0.41				0.40				0.37		0.32				0.33			
TD Flax (30 cm)	0.43				0.37				0.36		0.29				0.39			
TD Poplar (30 cm)					0.39				0.31		0.27				0.36			
TD Willow (75 cm)	0.34		0.39		0.37				0.32		0.28	a	0.31		0.30		0.28	
TD Soy (75 cm)	0.36		0.35		0.37				0.33		0.32		0.28		0.28		0.27	
TD IBF (75 cm)	0.36				0.36				0.33		0.34				0.31			
TD Hazel (75 cm)	0.37				0.38				0.36		0.36	a			0.31			
TD Flax (75 cm)	0.40				0.31				0.37		0.36				0.32			
TD Poplar (75 cm)					0.38				0.35		0.31				0.27			
TD Willow (120 cm)	0.36	a	0.39		0.29				0.33		0.26		0.35		0.36		0.29	
TD Soy (120 cm)	0.30		0.38		0.40				0.32		0.32		0.32		0.37		0.33	
TD IBF (120 cm)	0.37	a			0.36				0.33		0.34				0.35			
TD Hazel (120 cm)	0.35				0.40				0.37		0.35				0.31			
TD Flax (120 cm)	0.43				0.34				0.37		0.36				0.32			
TD Poplar (120 cm)					0.35				0.38		0.35				0.33			
	4/22		**5/6**		**5/23**		**6/2**		**6/16**		**7/13**		**7/28**		**8/10**		**8/24**	
HS Corn/(Soy) (s)	0.41	a	0.26	a	0.38		0.17	a	0.22	a	0.14		0.25		0.35	a	0.22	a
HS Mature Poplar (s)	0.48	a	0.37	a	0.42		0.36	a	0.36	a	0.18		0.24		0.30	a	0.16	a
HS Corn/(Soy) (30 cm	0.46	a	0.40	a	0.47	a	0.38	a	0.37	a	0.31		0.28		0.34		0.29	
HS Mature Poplar (3(	0.38	a	0.35	a	0.39	a	0.34	a	0.34	a	0.30		0.31		0.31		0.26	
HS Corn/(Soy) (75 cm	0.46		0.43		0.46		0.40		0.41	a	0.39	a	0.33		0.29		0.27	
HS Mature Poplar (7!	0.42		0.41		0.42		0.39		0.37	a	0.36	a	0.34		0.30		0.29	
HS Corn/Soy (120 cm	0.51		0.41		0.47		0.45		0.40		0.40		0.32		0.33		0.28	
HS Mature Poplar (1:	0.47		0.40		0.44		0.43		0.35		0.36		0.43		0.33		0.30	

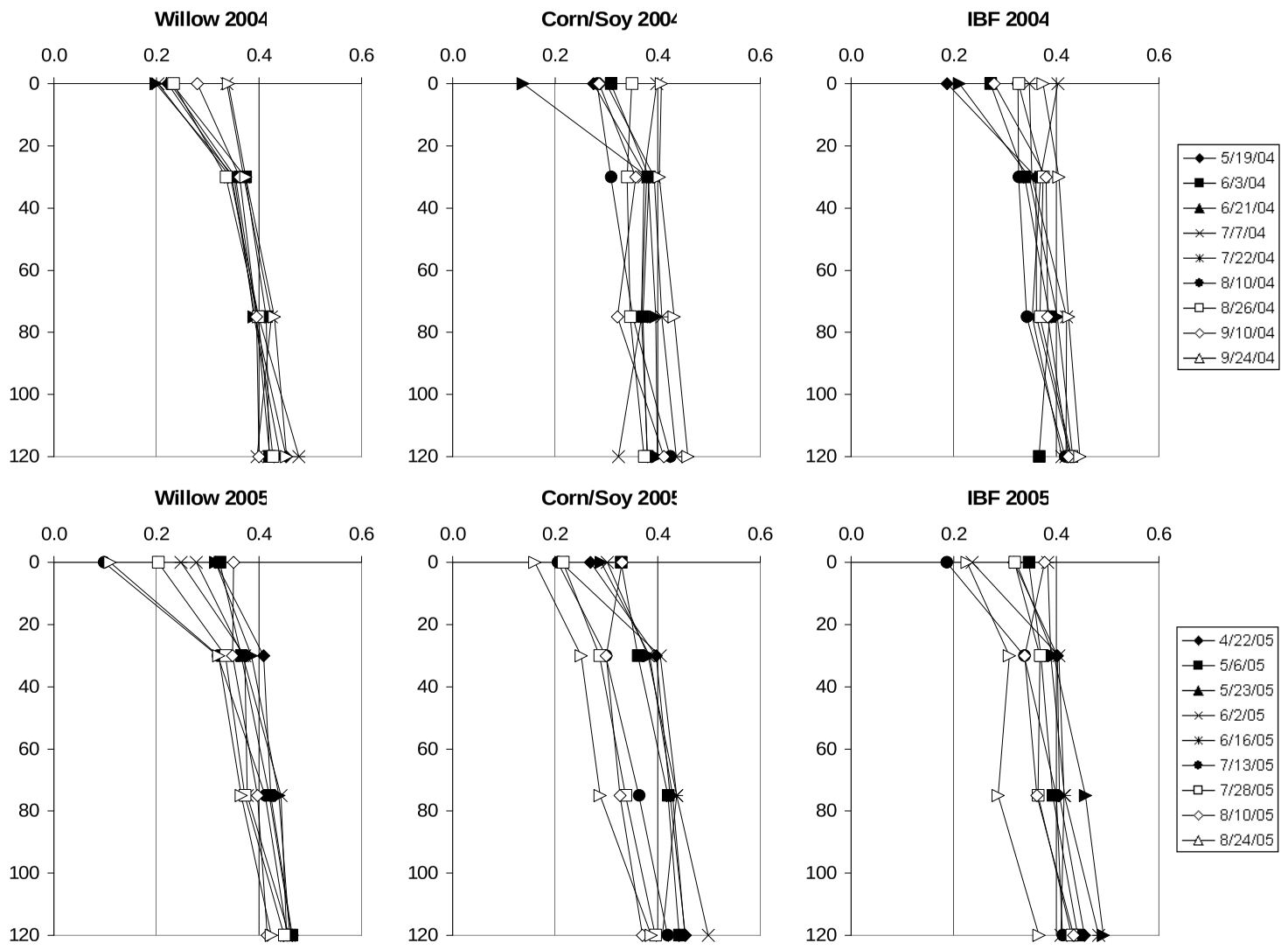

Figure D1: Soil moisture profiles for the runoff plots. Depth in cm is along the y axis; volumetric water content(cm/cm) is along the x axis.

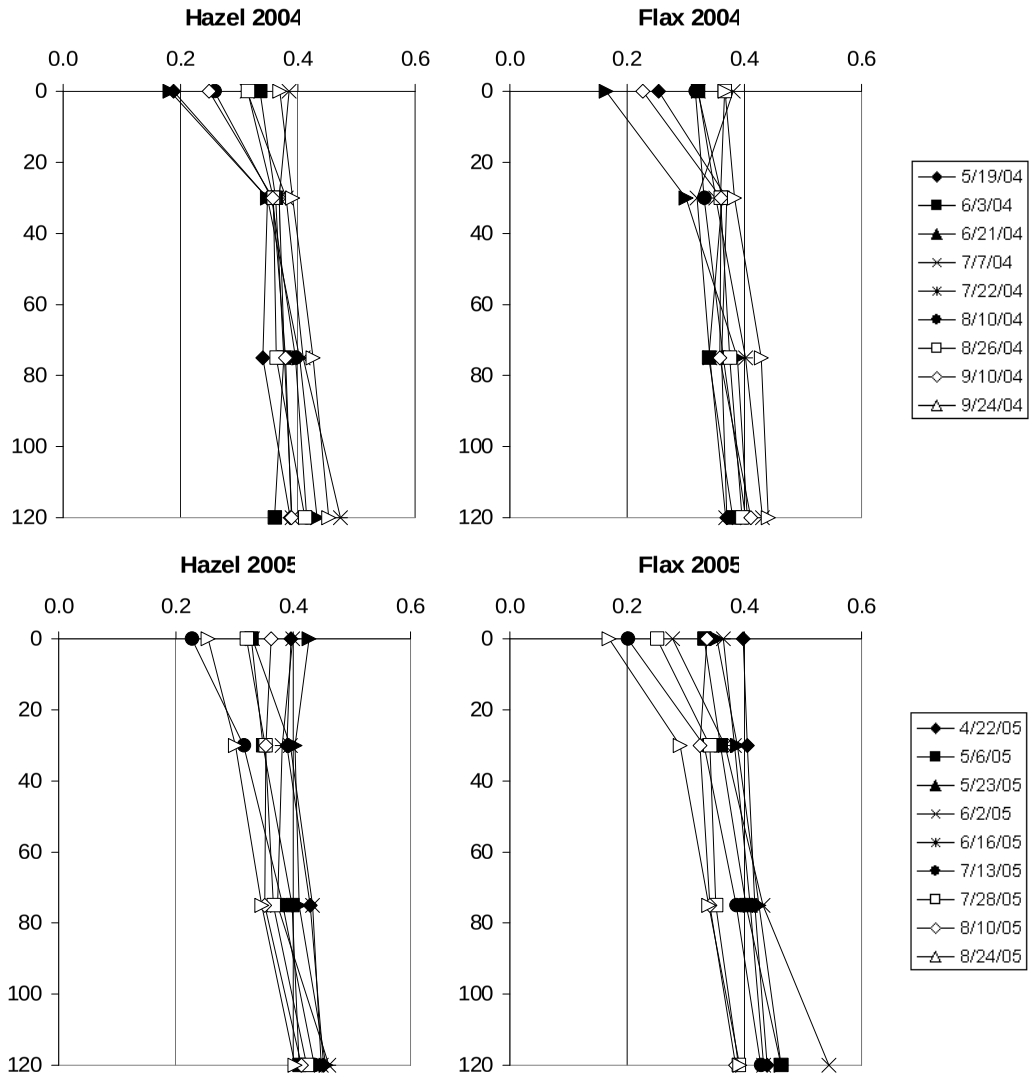

Figure D2: Soil moisture profiles for the runoff plots. Depth in cm is along the y axis; volumetric water content(cm/cm) is along the x axis.

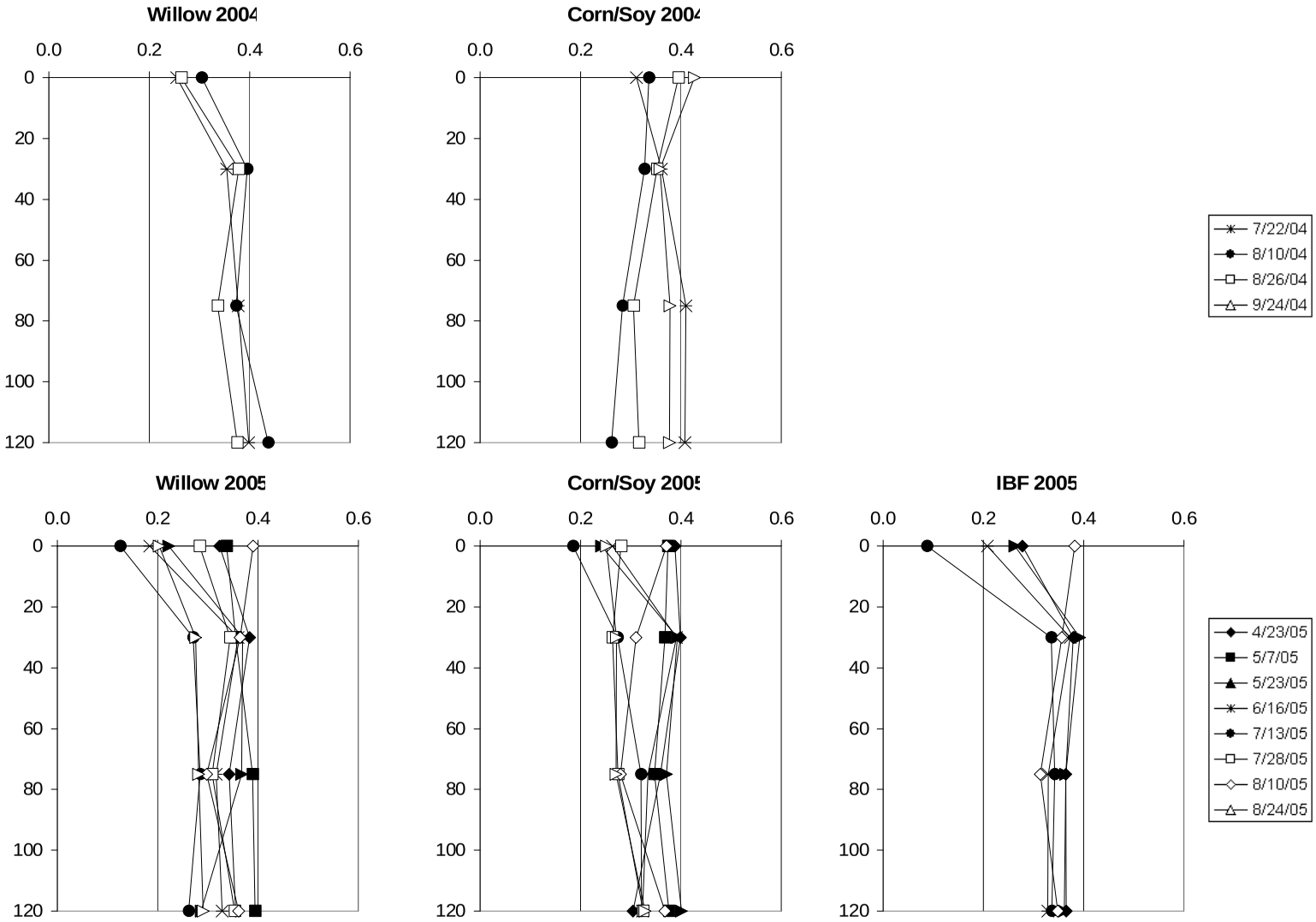

Figure D3: Soil moisture profiles for the tile drainage plots. Depth in cm is along the y axis; volumetric water content(cm/cm) is along the x axis.

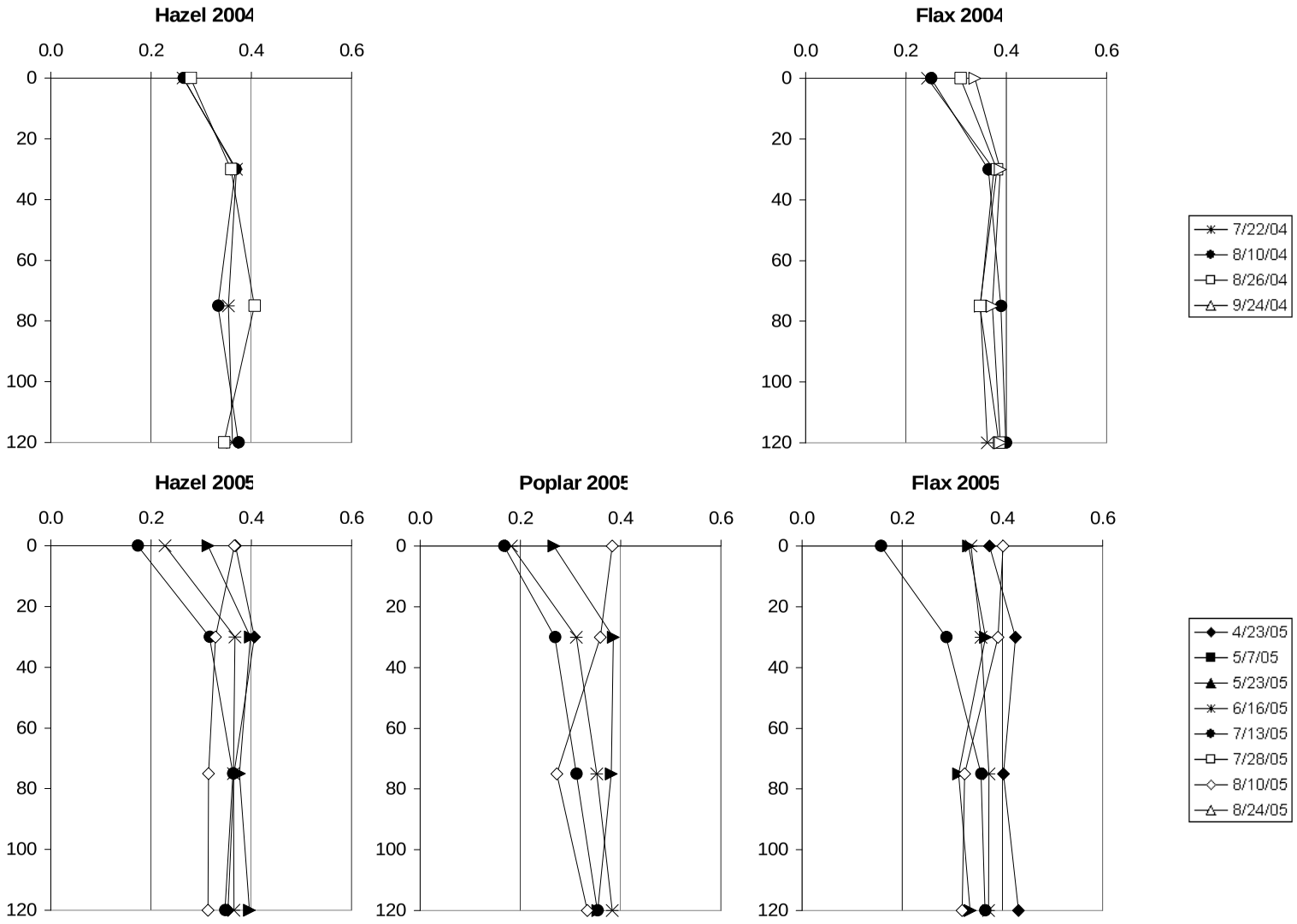

Figure D4: Soil moisture profiles for the tile drainage plots. Depth in cm is along the y axis; volumetric water content(cm/cm) is along the x axis.

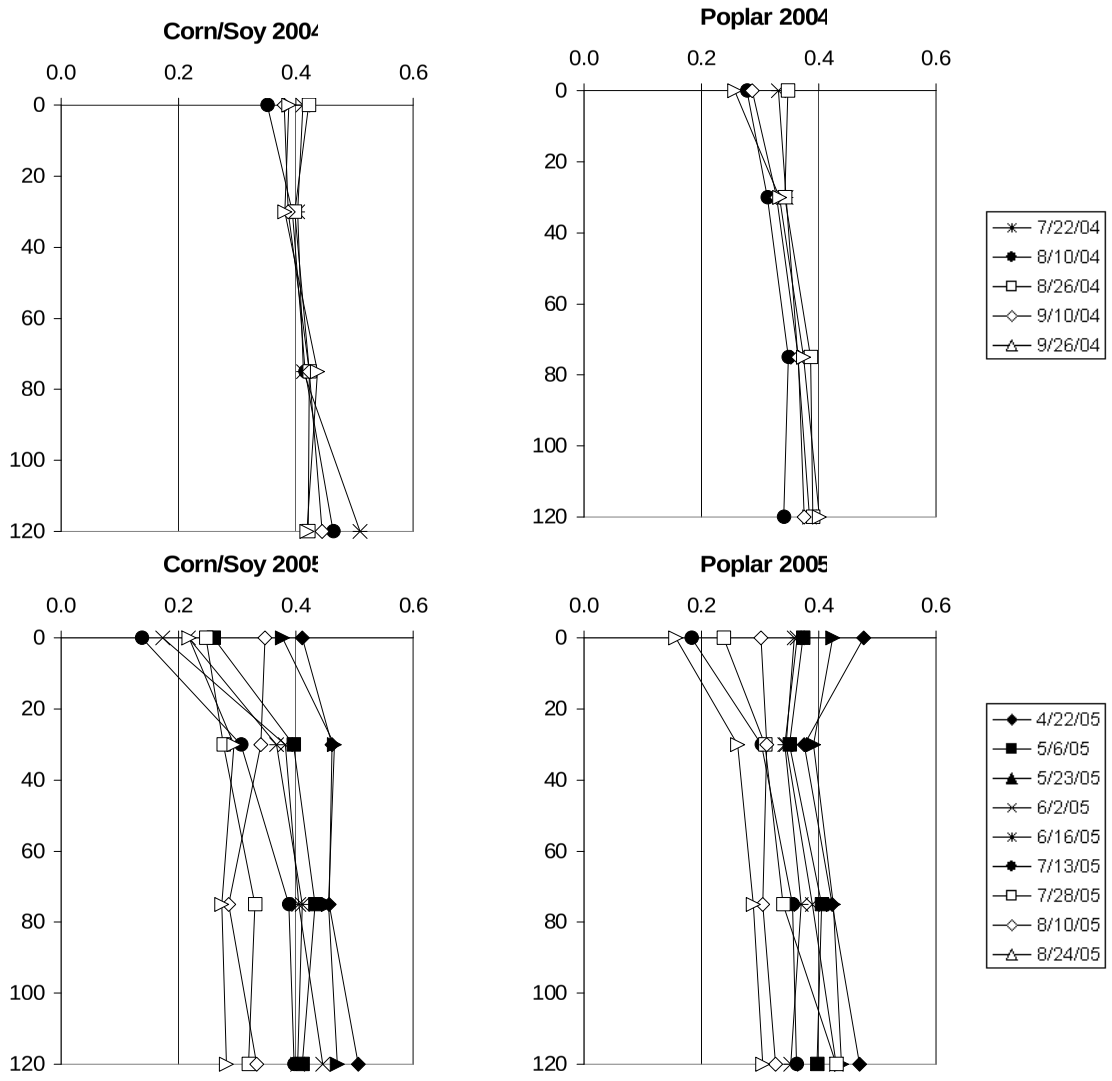

Figure D5: Soil moisture profiles for the hillslope. Depth in cm is along the y axis; volumetric water content(cm/cm) is along the x axis.

Appendix E: Evapotranspiration Calculations

Table E1: Calculated evapotranspiration (cm) and average ET rate (cm/day) from runoff plots. Dates designate the beginning of the calculation period. A blank entry indicates ET could not be calculated for the period due to missing runoff data.

Total Calculated ET for Period (cm)

	2004									2005								
	5/19	6/3	6/21	7/7	7/22	8/10	8/26	9/10	9/24	4/22	5/6	5/23	6/2	6/16	7/13	7/28	8/10	8/24
Corn/Soy	9.5	11.1	8.5	3.6	8.5	6.9	4.7	2.3	--	2.3	10.1	0.9	6.2			5.2	5.5	--
Flax	11.0	14.6	9.9	0.4	10.2	4.6	7.8	4.9	--	8.5		1.1	8.7	13.6	9.9	5.7	5.6	--
Hazel	8.0	11.9	6.7	6.9	7.4	6.5	6.9	7.0	--	6.4	4.3	1.9	9.1	16.8	4.4	5.3	4.9	--
IBF	12.3	9.0	9.3	5.5	10.6	2.8	1.5	7.9	--	4.3	3.9	5.5	2.4		5.7	7.0	7.3	--
Willow	9.8	13.9	5.2	4.9	3.2	4.2	1.8	5.1	--	1.5	11.0	2.0	7.7		7.6	3.1	5.2	--

Average Daily Calculated ET for Period (cm)

	2004									2005								
	5/19	6/3	6/21	7/7	7/22	8/10	8/26	9/10	9/24	4/22	5/6	5/23	6/2	6/16	7/13	7/28	8/10	8/24
Corn/Soy	0.6	0.6	0.5	0.2	0.4	0.4	0.3	0.2	--	0.2	0.6	0.1	0.4			0.4	0.4	--
Flax	0.7	0.8	0.6	0.0	0.5	0.3	0.5	0.3	--	0.6		0.1	0.6	0.5	0.7	0.4	0.4	--
Hazel	0.5	0.7	0.4	0.5	0.4	0.4	0.5	0.5	--	0.5	0.3	0.2	0.6	0.6	0.3	0.4	0.3	--
IBF	0.8	0.5	0.6	0.4	0.6	0.2	0.1	0.6	--	0.3	0.2	0.6	0.2		0.4	0.5	0.5	--
Willow	0.7	0.8	0.3	0.3	0.2	0.3	0.1	0.4	--	0.1	0.6	0.2	0.5		0.5	0.2	0.4	--

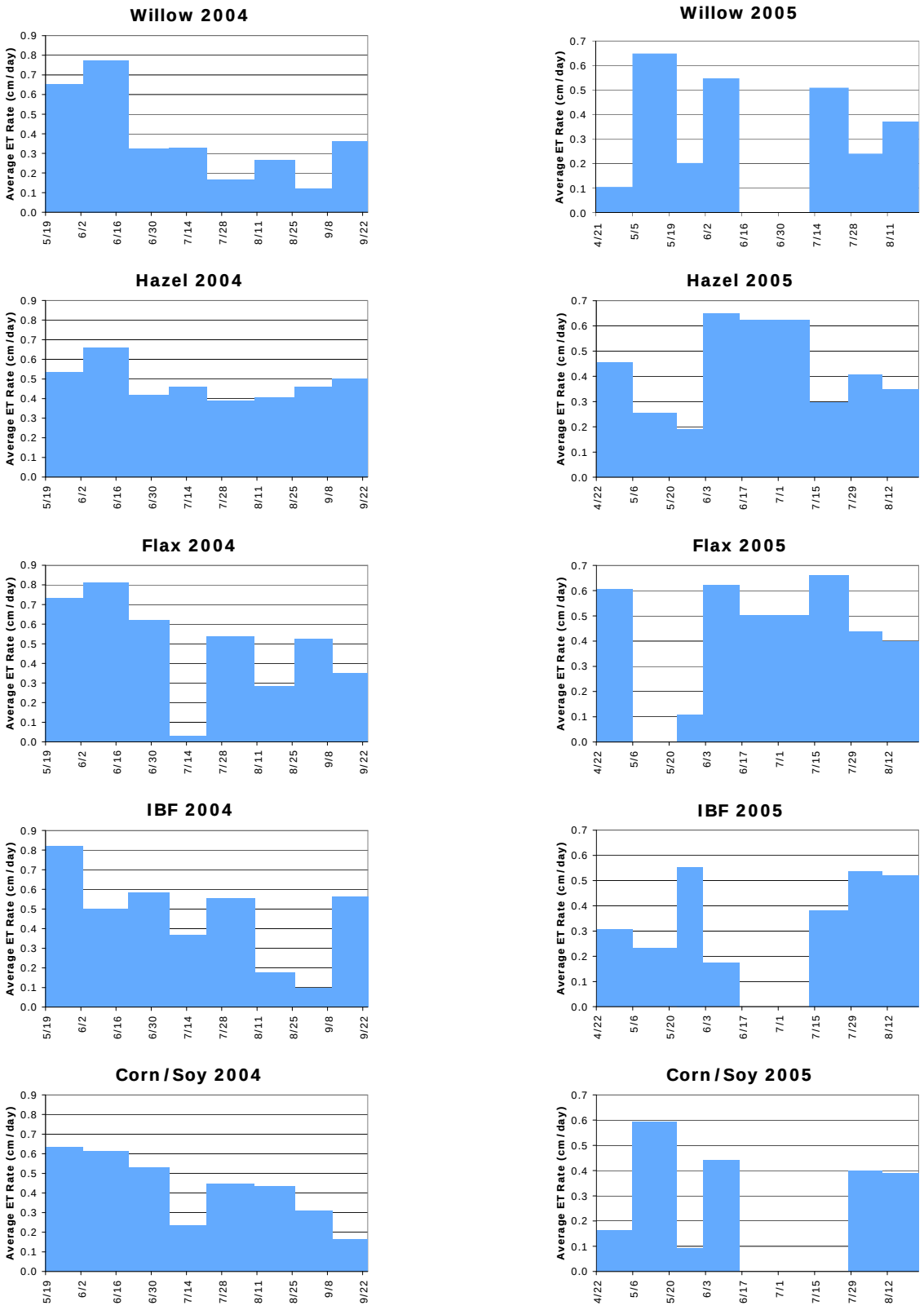

Figure E1: Average ET rate (cm/day) in the runoff plots in 2004 and 2005. A zero value indicates that ET could not be calculated due to missing runoff data.