Report of Investigation 119

Investigation of Soil Moisture Variability Under Sod in East-Central Illinois

Robert W. Scott, Edward C. Krug, Stephen L. Burch, Charles R. Mitsdarfer, Paul Nelson

July 2010

Illinois State Water Survey
Institute of Natural Resource Sustainability
University of Illinois at Urbana-Champaign

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Abstract

Long-term data collection of volumetric soil moisture under sod has been conducted in Illinois for more than 25 years. These data have been used in numerous applied and modeling studies in which the results are often related to regional conditions under a variety of surface covers. The actual level of representation of these data to nearby areas with different surface covers, however, is unknown. In 2006–2007, the Soil Moisture Under Sod Experiment was conducted at Bondville, Illinois to increase understanding of soil moisture variability across a very small area of seemingly uniform surface and near-surface conditions. Ten locations were chosen at random within a 5.9-hectare sodded field for twice-weekly neutron probe soil moisture observations over a period of more than 13 months. Measurements were taken at the surface and at 20-centimeter intervals down to 2 meters, precisely matching the historic Illinois depth observations. A detailed surface terrain analysis was conducted to consider impacts of surface slope or ponding potential on soil moisture attributes at each monitoring location across the very low-relief surface. The near-surface water table level at the field location was monitored. At the end of observations, soil property heterogeneity (e.g., soil porosity, bulk density, and soil color) was determined by digging trenches and extracting soil cores immediately adjacent to each monitoring site at all observation levels within the predominantly loess soil.

Results indicate a strong temporal consistency at each site in trends of volumetric soil moisture at all depths throughout the experiment. However, inter-site spatial variability increased with depth, indicated by an average standard deviation of all temporal observations of 2.26% in the top 30 centimeters of soil and 5.19% in the 170- to 200-centimeter layer. Differences between the average field soil moisture at all primary randomly selected sites and the historic Bondville site was 2.39% and 6.51%, respectively. Variations in soil moisture in the lowest layers appear to be related to an intrusion of the water table. In addition, an apparent relationship was observed between soil moisture in deeper layers and surface terrain slope, and to a lesser extent with soil porosity and bulk density. Further, the near-surface soil moisture observations under sod in loess soils over one small region in Illinois are useful as ground truth for near-surface data observed with remote-sensing observations.

The question of representativeness of soil moisture under sod to moisture under crop surface covers was addressed in a cursory manner. Differences similar in magnitude to those found under sod were observed. Soil moisture variability measured across this seemingly uniform field suggests that proper use of the historic Illinois dataset by future researchers related to adjacent areas may need greater attention. Most of Illinois is under an agricultural cover, not sod, as are the surface covers at all of Illinois' soil moisture monitoring sites. Adequate data monitoring of terrain slope, soil profiles, and water table climatology under various major surface covers within a region is recommended prior to installing new soil moisture monitoring sites and before making useful assumptions concerning spatial representation that attribute individual soil moisture datasets to adjacent areas.

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Introduction

This document presents results from an experiment to understand the degree of soil moisture variability observed within a relatively small sod-covered area inside an agricultural region of Illinois. Soil moisture is a key component in the hydrologic cycle. It is useful in numerous settings, such as its relation to the magnitudes of localized floods and regional droughts, modeling research on watershed studies, and projected impacts due to climate change. Quality soil moisture assessments are becoming increasingly important to those involved in evaluating water resources via global satellite imagery. Perhaps as much as precipitation, soil moisture-holding capacities yield considerable information on the abilities of crops to withstand a dearth in rainfall, to project the timing of drought onset, longevity, and recovery, and to identify early and developing impacts that prolonged drying has on other water resources of a particular region.

Determining the representativeness of high quality, *in situ* soil moisture data is complicated, not only because of precipitation variability, but also because of unknown variability in soil characteristics where moisture observations are made. Often, these characteristics are poorly understood because (1) they are not observed easily without disturbing the soils in which moisture data are being collected, and (2) the breadth of the variability of local soil characteristics is similarly undefined.

One long-term source of soil moisture data in Illinois has been neutron probe observations collected since 1981 by the Illinois Soil Moisture Network (ISMN) of the Illinois State Water Survey (ISWS), Institute of Natural Resource Sustainability, University of Illinois. These volumetric data (fractional volume of water in the soil) have been employed by numerous researchers to represent soil moisture conditions under regional crop fields and other surface covers adjacent to monitoring sites. Adegoke and Carleton (2002) found weak correlations of vegetation indices for croplands and forests when comparing Advanced Very High Resolution Radiometer satellite data with Illinois soil moisture data. Vinnikov et al. (1999a) recognized a soil moisture signature over grass or crops by comparing Scanning Multichannel Microwave Radiometer data with Illinois soil moisture data. Brown and Arnold (1998) used Geostationary Operational Environmental Satellite imagery combined with computed evapotranspiration values from the ISMN data, concluding that significant convective cloud mass development occurs along agricultural, urban, and forest land cover boundaries.

Others have used ISMN data for various research studies. Findell and Eltahir (1997, 1999) quantified a positive correlation between soil moisture and subsequent summertime rainfall. Wu et al. (2002) related the soil moisture profile to long-term precipitation variability. Dirmeyer (2000) used average soil moisture in the top 1 meter (m) of soil to help evaluate the degree of climate drift in a land-atmospheric simulation. Gao and Dirmeyer (2006) used Illinois soil moisture data to help evaluate the performance of a combined land-surface and land-atmosphere model ensemble analysis that generated global soil wetness products. In addition, ISMN data have been employed in studies and simulations of the water balance in the Illinois River Basin (Niemann and Eltahir, 2004), the state of Illinois (Yeh et al., 1998; Rodell and Famiglietti, 2001; Yeh and Eltahir, 2005; Amenu et al., 2005), the Midwest U.S. (Zangvil et al., 2004), the conterminous U.S. (Maurer et al., 2002), and North America (Fan et al., 2006).

Many studies treated the Illinois *in situ* soil moisture observations, collected under sod, as representative of soil moisture in adjacent land cover areas of various types. Because of the uniqueness of the ISMN dataset, its use in this manner is clearly understandable. Nevertheless, the predominant surface cover in Illinois is not sod, but instead is row crops (primarily corn and soybeans) during the growing season, followed by a bare ground/low-tilled/no-tilled cover in the fallow season. Comparative extraction rates of sub-soil water and evapotranspiration by a perennial cover of sod in Illinois, operating on a different (longer) schedule than annual agricultural crops, have not been evaluated.

The validity of the ISMN data to provide high-quality soil moisture information is not contested here. However, questions are addressed relating to potential limitations of their representativeness to adjacent surfaces. The current study attempts to highlight limitations associated with the use of these data for the benefit of subsequent studies.

Background

The ISWS monitored soil moisture data at 18 locations in Illinois, beginning at most sites in 1981 (Figure 1). Soil moisture was initially measured using Troxler Neutron Depth Probes (model 3221) and Troxler Neutron Surface Probes (model 3411B; Troxler Electronics Laboratories, Research Triangle Park, North Carolina, 2008), until these tools were replaced by newer sensor technology during 2004–2008. Data were collected by Water Survey staff twice monthly during the growing season and monthly during the fallow season (19 observations a year) from the surface to a depth of 2 m at 20-centimeter (cm) intervals. All locations have a surface cover of sod.

The initial selection of neutron probe monitoring locations in the ISMN was determined by other monitoring efforts of the ISWS. Logistically, there was a desire to co-locate with the Illinois Climate Network (ICN), a weather mesonet initiated by the ISWS at the same time. No documented criteria exist from the installation period for locating neutron probe access tubes at monitoring sites (e.g., acceptance protocol for natural surface slopes, distances from different vegetation covers, buildings, roadways, and tiled areas).

Although all sites were installed and remain today under grass, actual surface covers vary substantially. Sod covers range from well maintained lawn-type grasses of a few centimeters in depth at locations in public areas to thick-matted sod, perhaps 25 cm deep, at more remote sites. Many sites are near agricultural fields. The potential impacts of different root zones on soil moisture at the various sites due to the various sod surface covers, and especially how they relate to conditions in adjacent bare soil/agricultural grounds, are unmeasured.

Gravimetric readings were obtained at each site in 1993 (Hollinger and Isard, 1994) to help define soil characteristics and to assess their water-holding potential. Most sites are characterized predominantly by loess, silt loam soils. Because of the apparent homogeneity of slope and soils, it was assumed that these data were representative of the general area. However, these data did not address the representativeness of neutron probe observations to adjacent areas typically covered with row crops.

Figure 1. Illinois Soil Moisture Network using neutron probe technology, 1981–2004

Due to the extensive travel that was required to manually collect the ISMN neutron probe soil moisture data every two or four weeks (along with data collections from several other ISWS monitoring efforts at the time on the same data run), no protocol was employed concerning data collections before or after precipitation events and the resulting temporal effects they would have on soil moisture data. In other words, because data collections occurred over a two- to three-day period, observations during some soil moisture data collection runs were taken both pre- and post-precipitation events at even adjacent ISMN sites, affecting observation sites during a different temporal period.

One of the long-term data collection locations is the Bondville Environmental and Atmospheric Research Site (BEARS), approximately 14 kilometers (km) southwest of Champaign, Illinois. The site is a highly instrumented rural field research area (http://www.isws.illinois.edu/atmos/bears/projects.asp) housing several research groups. The area measures roughly 256 x 232 meters (approximately 5.9 hectares). The land surface is typical of the general area: considerably flat and treeless, but conversely, it is totally covered in sod. It is surrounded by farm fields of corn and soybeans with only occasional farmsteads and their concomitant tree and shrub vegetation. Thus the site possesses near-perfect exposure conditions for meteorological observations and is the focal point of this study.

Soil Moisture Under Various Surface Covers

The potential impacts of different root zones on soil moisture at the ISMN sites and how they relate to conditions in adjacent bare soil/agricultural grounds generally have not been explored. During the summer of 2005, two sites in agricultural fields just adjacent to the BEARS field station were instrumented to measure soil moisture continuously at six depths, using Stevens-Vitel Hydra-20 soil moisture capacitance-measuring sensors: one under a crop of soybeans, and the other in corn. Data were compared with the long-term Bondville ISMN, which had been installed with a similar set of capacitance probes several years earlier. Site locations were separated by approximately 200 m. Hourly observations of soil moisture were collected at 5, 10, 20, 50, 100, and 150 cm of depth. Observations were initiated in mid-June and continued until April 2006 when seasonal planting operations began and sensors were removed.

Continuous soil moisture sensors produce a four-channel output of voltages used to obtain measurements of soil moisture, soil temperature, and salinity (Scott et al., 2010). Measurements yield information within a cylindrical volume approximately 2.5 cm in diameter and 6 cm in length, a volume of approximately 12 cubic centimeters (cm^3). These probes determine soil moisture by making high-frequency complex dielectric constant measurements. The measurement resolves the capacitive and conductive parts of a soil’s electrical response. The capacitive part is most indicative of soil moisture and the conductive part, salinity. Soil temperature is determined from a calibrated thermistor incorporated within the probe head.

Sensors were installed by digging a hole with a posthole digger or an auger, broad enough to reach down and insert probes horizontally into undisturbed soil at the appropriate level. This worked well for the top four levels, down to 50 cm. For 100 cm and 150 cm levels, a hole was augered and a device was fabricated to insert the probes at a 45º angle into undisturbed soil.

Sensors at the Bondville historic site were under an area totally covered by sod; sensors in crop areas were located under bare ground between rows of corn or soybeans. All cables were looped to avoid creating a path for rainfall or melting snow to be led from the surface down to the sensors.

Results at all levels for the three sites are shown in Figure 2. Conditions at 5 cm (Figure 2a) showed temporal trends in soil moisture that responded reasonably well to precipitation events and subsequent drying between events. Individual readings were spread apart initially until the first substantial rain event that occurred about two weeks after installation. Subsequently, values were similar through the remainder of the growing season. However, sensors at 5 cm in corn and soybean fields responded to heavy rainfall in mid-September, while the sensor under sod did not. From harvest time through mid-winter, the sensor under sod remained the lowest of the three sensors. It appeared to respond less than the sensors under crops to heavy rains in September, perhaps because the sod was still growing and actively removing water from the soil. Corn and soybean plants, on the other hand, had completed their seasonal growth cycle and had begun reducing their water use; thus heavy rains initiated seasonal recharge of soil moisture in these fields. Unfortunately, the sensor under corn, which appeared to mimic the sensor under soybeans at this level, failed in early November. During late winter, soil moisture values 5 cm under sod and in the former soybean field were nearly identical, except for two short episodes of high moisture late in the record observed under sod but not in the bare soybean field.

Capacitance-measuring sensors do not perform well in frozen soils. Periods of apparently frozen soils under sod (never less than -0.5ºC) were measured by the thermistor in the head of the soil moisture sensor at 5 cm at the sites under sod between December 8–26, 2005 and February 21–25, 2006. However, no periods of freezing temperatures were observed at 10 cm under corn and soybeans at 0000 Coordinated Universal Time (UTC) during the 2005-2006 winter.

Soil moisture values among sites at 10 cm (Figure 2b) broadly ranged from 20 to 50% during the summer and autumn 2005. The sensors under sod and soybeans appeared to respond to precipitation and dry periods more than the sensor in the corn field. By spring 2006, data from all sensors converged to 35 to 45%. A large, albeit short-lived, period of relatively low soil moisture was observed during February in the corn field with no explanation.

Data at 20 cm (Figure 2c) show considerable variability between sites. All values ranged from 20 to nearly 50% at installation. The sensor under sod showed considerable variability from June through October 2005 in direct conjunction with precipitation events and drying between events. The sensor under soybeans began and stayed considerably higher, with apparent muted response to rainfall. The sensor under corn began and stayed considerably lower with virtually no response to precipitation. Unfortunately, the sensor under corn at 20 m also failed in early October 2005. During winter and early spring, soil moisture measured under sod slowly increased, with values nearing that of the sensor under bare soil in the soybean field, whose values had remained rather static since October.

At 50 cm (Figure 2d), sensor values were largely identical throughout the period, generally ranging for the most part between 30 and 40%. Only the sensor under sod displayed a response to precipitation in August and September 2005, but not during other months. Although intra-site variability was occasionally high at the sites under sod and corn, the overall soil moisture levels were quite similar.

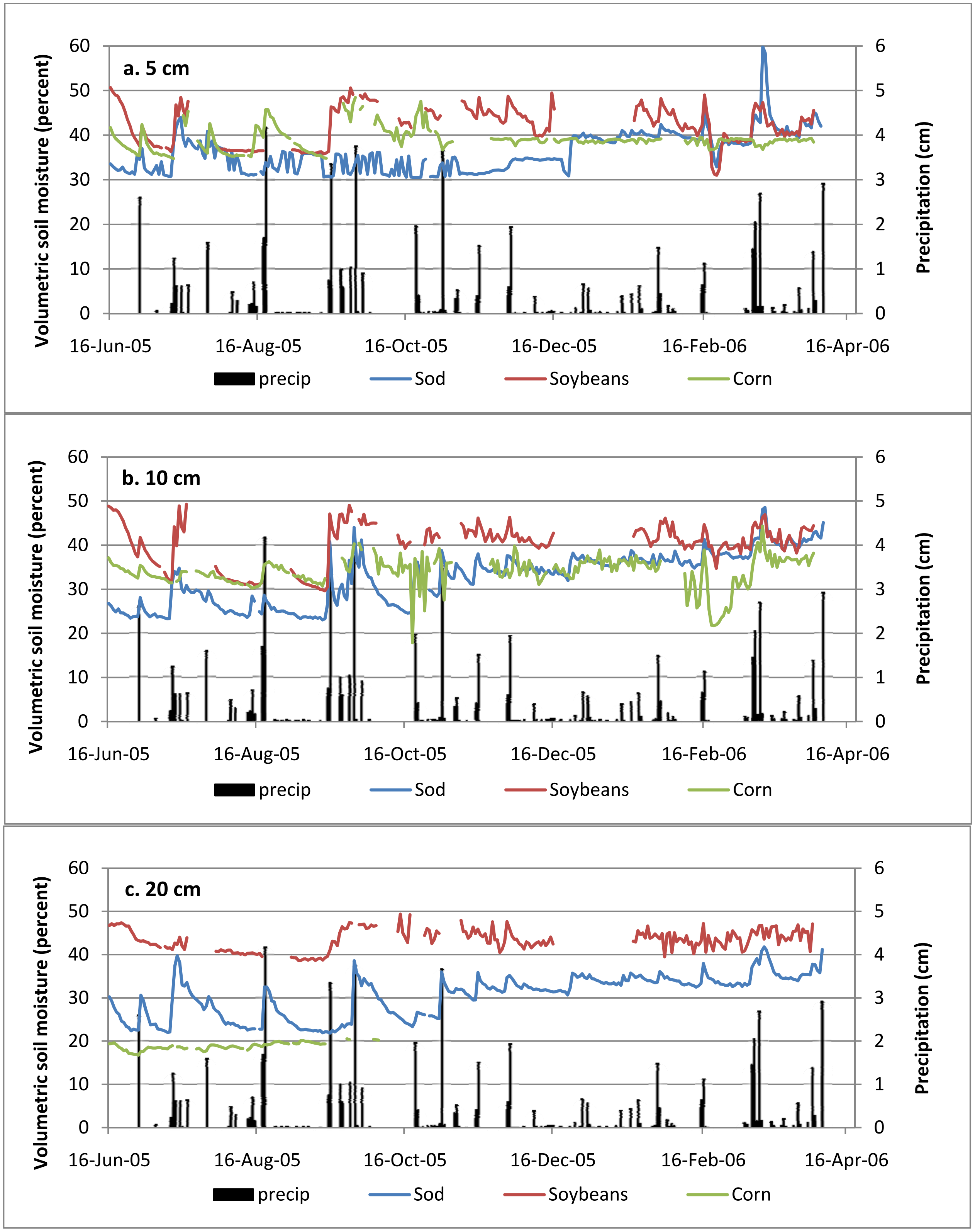


Figure 2. Volumetric soil moisture at 0000 UTC at Bondville, Illinois, June 2005–August 2006, under surface covers of sod, corn, and soybeans using capacitance soil moisture sensors at (a) 5, (b) 10, (c) 20, (d) 50, (e) 100, and (f) 150 cm. Daily precipitation totals are included.

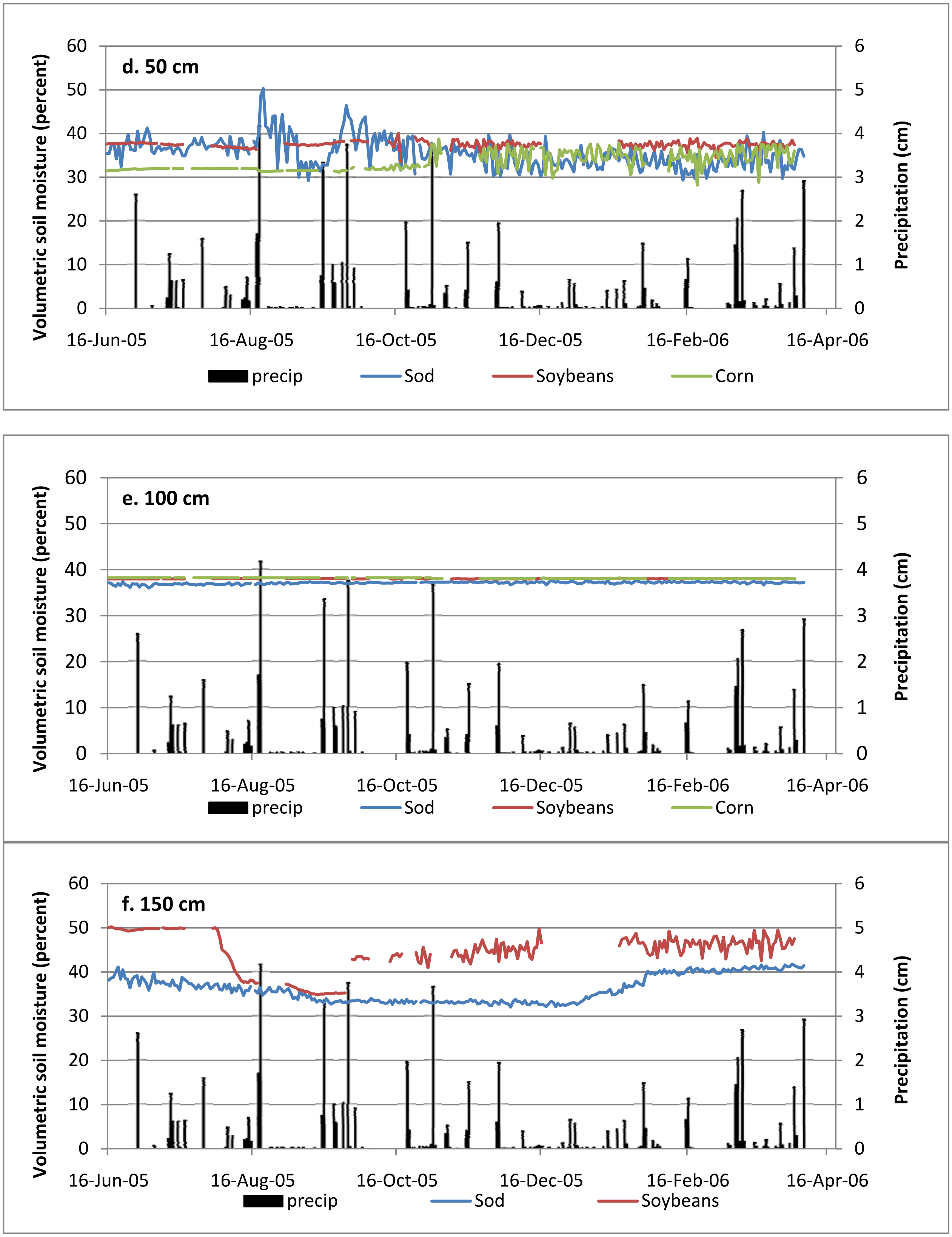


Figure 2. (Continued)

Data at 100 cm (Figure 2e) displayed trends that differed considerably from the other five levels. There was virtually no variability in data from the sensors under sod, soybeans, and corn, with all values lying at approximately 38%. No direct relationship to precipitation was observed at this level. Reasons for such a uniform soil moisture observation at all sites could be from a broad impervious layer at this level under the general area of the sites; however, there are no other facts to support this conjectural thought.

At 150 cm (Figure 2f), general drying was observed under soybeans and sod from June through September 2005, followed by moisture recharge. Drying occurred at different rates. Values at the end of the period were relatively close. (The corn sensor at 150 cm operated only intermittently and is not displayed.)

Figure 2 indicates that soil moisture can vary substantially among closely spaced sites with different surface covers. The data suggest that during the growing season, soybeans and corn tend to hold more water from 100 to 200 cm than does the soil under sod, and during other times of the year, soil moisture values for all ground cover types are similar. Whether or not this is a universal relationship within the study's environment is unknown. It is unclear what proportion of the differences was due to differences in surface covers. Also, the results raise speculation that large differences in soil moisture may exist due to highly variable and unobserved sub-surface soil conditions, controlling percolation and porosity.

From these results, it was concluded that large soil moisture variability may be quite common at closely spaced sites, even under the same surface cover. Information on the variability of subsurface soil conditions could help determine the representativeness of our historic soil moisture network data when used to relate those observations to soil moisture conditions in adjacent areas with a surface cover different from sod.

The current study was designed to better understand the magnitude of soil moisture variability over a small area under seemingly similar conditions to aid design and site selection protocols of future *in situ* soil moisture networks in order to achieve better regional data representation.

Moisture Variation Under Sod: Experimental Design

a. Soil Moisture Data Collection

In August 2006, eight sites at the BEARS field station were chosen at random for installation of neutron probe sensors to observe soil moisture variability across the field station, initiating the Soil Moisture Under Sod Experiment (SMUSE). Two additional sites were installed, each 1 m north and south from a random choice of one of the eight sites, to provide a site observation cluster of soil moisture variability over a very short distance. Neutron probe access tubes were inserted vertically to a depth of 2 m at each of these 10 locations, and observations commenced on a twice-weekly schedule. Measurements were also taken at the long-term Bondville soil moisture site.

Site locations are superimposed in Figure 3 on an aerial photograph of BEARS (Illinois State Geological Survey, 2007). In past decades, this entire site was used for crops and subject to the regular agricultural practices of the time. The site is classified with a mixture of Drummer or Elburn soils, quite typical of the silty loam or silty clay loam loess soils within the highly productive agricultural fields of central Illinois. To achieve conditions as pristine as currently possible, protocols were established to avoid selection of sites near existing BEARS equipment, adjacent crop fields, and access roadways and walkways, a process that resulted in all selected sites being placed in the northern and eastern portions of BEARS property. All sites were under an existing thick mat of sod, kept to a height of 10 cm or less surrounding each soil moisture monitoring location.

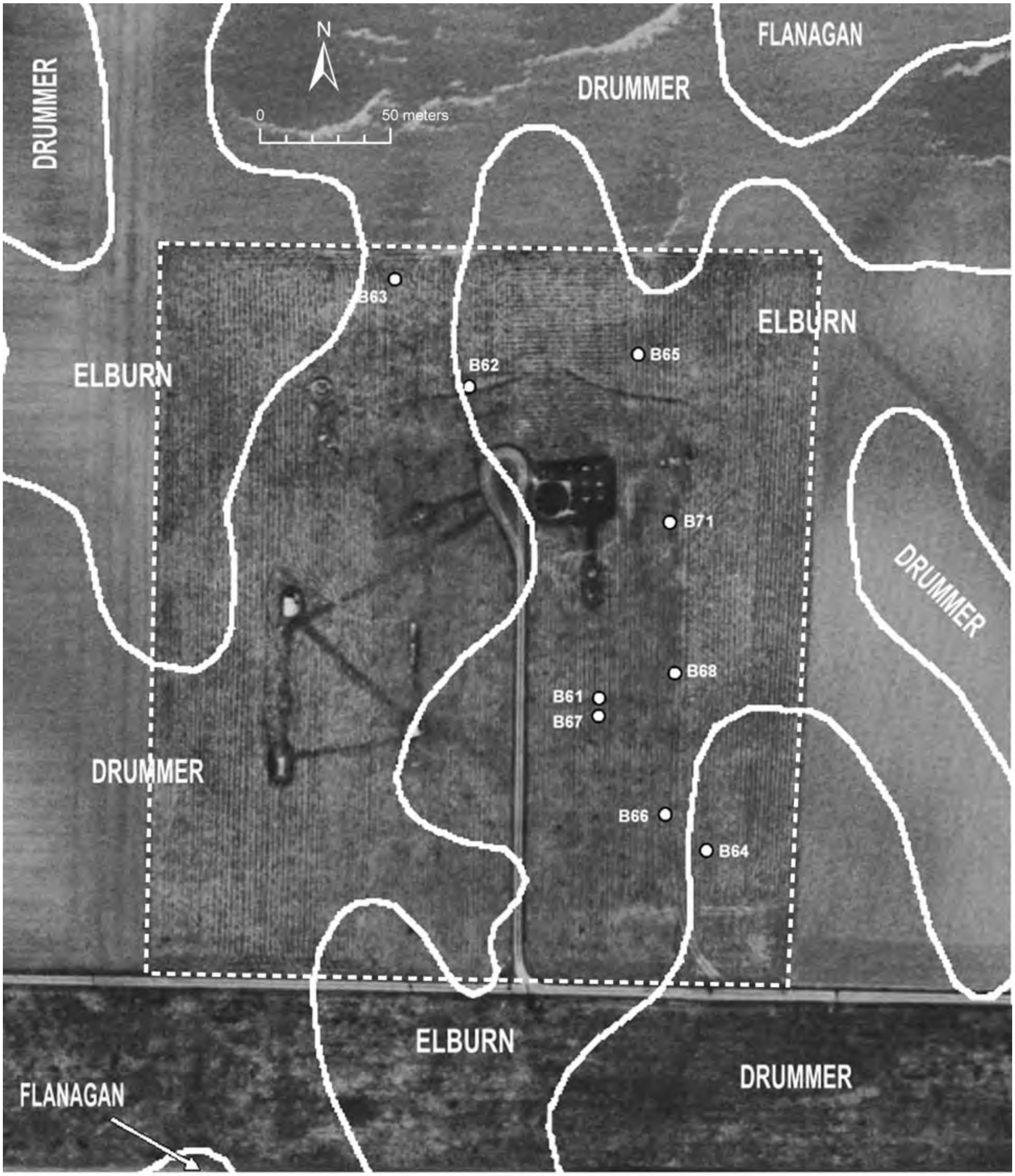
For consistency, soil moisture measuring equipment matched that used with the historic data. Observations were collected with a model 3221 Troxler Neutron Depth Probe and a model 3411B Troxler Neutron Surface Probe (Troxler Electronics Laboratories, Research Triangle Park, North Carolina, USA, 1980). The same pair of surface and depth sensors was used at all sites on each day of observation.

Soil moisture measurements during SMUSE were scheduled twice weekly at 11 sites during a three-hour period beginning at mid-day on Mondays and Thursdays. Observations began on August 8, 2006 and continued until September 17, 2007 (101 observation days). If precipitation was occurring and was expected to continue during the scheduled neutron probe operations, measurements were delayed for one day. On the next day, if precipitation was occurring during the designed period of observations, readings were postponed until the next scheduled date for measurements. This restriction, again only valid during the three-hour data collection window, likely caused an underestimation of soil moisture in the top layer of soil had collections been allowed during rain events. Regardless, the intent of the protocol was to balance days with observations to every three to four days, to take readings at the same time each day to avoid differences attributable to diurnal variations in the root extraction of moisture, and to avoid imbalanced readings among the sites due to precipitation occurring during an observation period, as well as to mitigate danger to staff from possible lightning strikes.

b. Topographical Observations

A detailed topographical elevation survey of the BEARS property was conducted to define regions of potential surface water runoff and accumulation from precipitation and their proximity to neutron probe locations. Typical local conditions within the very low relief topography show broad areas of standing water subsequent to heavy rain events. It is important to define the potential for surface ponding, which depends not only on the surface terrain, but also on the sub-surface strata, both of which ultimately impact soil moisture values.

A 210 x 240 meter rectangular grid was constructed over BEARS to measure land surface elevations. Determinations were made at regular 30-m intervals across the grid from differential leveling observations using a Lietz B1C Automatic Level. Observations were made optically on leveling rods to 0.003 m precision. Data were analyzed with Surfer 6 Terrain and Surface Modeling software (Golden Software, Inc., Golden, Colorado 80401) to generate contours of land surface elevation across BEARS.



Drummer	Silty clay loam	0–2% slopes	Photo source: ISGS
Flanagan	Silt loam	0–2% slopes	Soil information: NRCS
Elburn	Silt loam	0–2% slopes	Coords/Projection: NAD1983, UTM Zone16

Figure 3. Aerial photograph of the Bondville Environmental and Atmospheric Research Site (BEARS). Soil type boundaries are generated by the National Cooperative Soil Survey, National Resources Conservation Service, U.S. Department of Agriculture. Neutron probe monitoring locations during SMUSE are superimposed.

In addition, two 60-m transects were constructed diagonally (NW-SE and SW-NE), centered on seven of the eight primary neutron probe locations and the historic Bondville neutron probe site. Two selected sites (B61 and B67) were relatively close to one another. Only one set of transects was made at the midpoint of those sites, as well as only one at the cluster of three sites, B66. Height data were collected along each transect at 3-m intervals. In total, 401 elevations were taken across the regular grid and the expanded transects.

c. Soil Profiles

At the end of the experiment (the termination of soil moisture data collections), soil cores were extracted at each neutron probe location for a soil analysis throughout the depth of the soil moisture observation profile. Trenches were dug adjacent (within 0.2 m) to each neutron probe tube to provide access to a vertical wall of undisturbed soil at every tube location. Soil cores were taken in triplicate along a horizontal line 10 cm wide at each neutron probe observation depth, every 20 cm below grade, down to 200 cm. Samples were extracted using a hand corer with a diameter of 3.18 cm to a horizontal distance into the wall of 10.1 cm. Sealed soil tins were used for soil core storage and transportation to an ISWS lab for analysis, where they were weighed and placed into a 105°C ventilated oven for 48 hours. Subsequent final weights were taken and averaged by level. Analyses included soil bulk density (the mass of dry soil per unit volume of soil sample) and soil porosity (the amount of pore space), assuming that soil solids have an average particle density of 2.65 grams per cubic centimeter (g/cm^3) (Pierzynski et al., 2005).

Due to the thick mat of sod roots at BEARS, no soil cores were extracted at the surface to match with neutron surface probe data. It was noted empirically that surface cores would possess a substantial roots mass and insufficient soil for proper and equitable analyses compared to lower levels. Trenching and coring also was not performed at the Bondville neutron probe site in order to maintain a pristine soil environment for future observations at that historic location.

Within each trench at the other 10 sites, soil color was recorded as part of the visual analyses of soil profiles using Munsell Soil Color Charts (Munsell Color, 1976). Photographic records were taken of the vertical wall where soil cores were extracted to document the visible soil layers, color, and structure, which could add to the soil characterizations. Finally, data on the local shallow water table assisted in the timing of trenching operations. Automated shallow groundwater depths have been collected hourly at the Bondville ICN site (just south of the ICN tower) since 2001 (Illinois State Water Survey, 2008). Trenching and core extractions were scheduled when groundwater at the BEARS site was expected to be near its lowest seasonal level to permit core sampling as deeply as possible to lessen possibilities of soil compression due to high moisture content.

Results and Discussion

a. Topographical and Water Table Analyses

A contoured analysis of surface terrain heights across BEARS property is shown in Figure 4. The southwest corner of the field station served as the origin, and the 30-m observation intervals are indicated by labels along the ordinate and abscissa. The analysis displays the substantial flatness of the area common to east-central Illinois. However, albeit very small, variability in elevation was measured on the order of roughly 1 m across BEARS. Highest elevations were found in a band that stretched from the east-central boundary of the research area towards the northwest corner. Lowest elevations were observed where much of the other research at BEARS takes place, an area not randomly chosen for monitoring during SMUSE. A string of selected sites, from Site 61 southeastward to Site 64, were in relatively flat ground.

Evidence of potential ponding was important to determine at each site. This was attained by extracting the highest slope observed along a 12-m section of the 60-m NW-SE and SW-NE transects (shown as dots in Figure 5) centered at each site. These enhanced analyses found the highest topographical gradients at the historic site, B71, and experiment sites B68, B63, and B62 (0.0492, 0.0592, 0.0433, and 0.0408, respectively). Conversely, the clustered site, B66, and sites B65 and B64 showed lower slopes (0.0183, 0.0175, and 0.0150, respectively). The combined elevation measurements taken at sites B61 and B67 by far had the smallest slope (0.0050). Sites B66, B65, B64, B61, and B67 appeared to have the best opportunity for surface ponding due to very small slopes and occasional small depressions observed along site transects.

Historic shallow groundwater water table data (depth to water) from the ICN well (location shown in Figure 4) indicated that water table levels are never very far below the surface at the BEARS site. Proper soil core analyses require unsaturated soils to avoid compression during soil core extractions. The well data were evaluated to assess the timing for trenching and soil core analyses to a depth of 2 meters. From water levels during 2001 and 2006 and other empirical observations by Water Survey staff across east-central Illinois (personal communications), it is typical for water tables to be closest to the surface in late winter and early spring, followed by general drying throughout the subsequent summer and autumn. An analysis of these data indicate that dates for when water table levels fell below 2 m (the lowest planned level of soil moisture observations and core extractions) ranged from August 14 to November 7, averaging on September 26, with levels never falling to 2 m in autumn 2004.

Shallow water well depths in 2007 are shown in Figure 6. The depth to water fell below 2 m on September 1. With trenching and soil core operations waiting for this signal, delaying as long as possible to allow further drying, and keeping an attentive eye on weather forecasts for heavy rains, the date of trenching occurred on September 18 with a depth to water at the Bondville ICN site at 2.3 m.

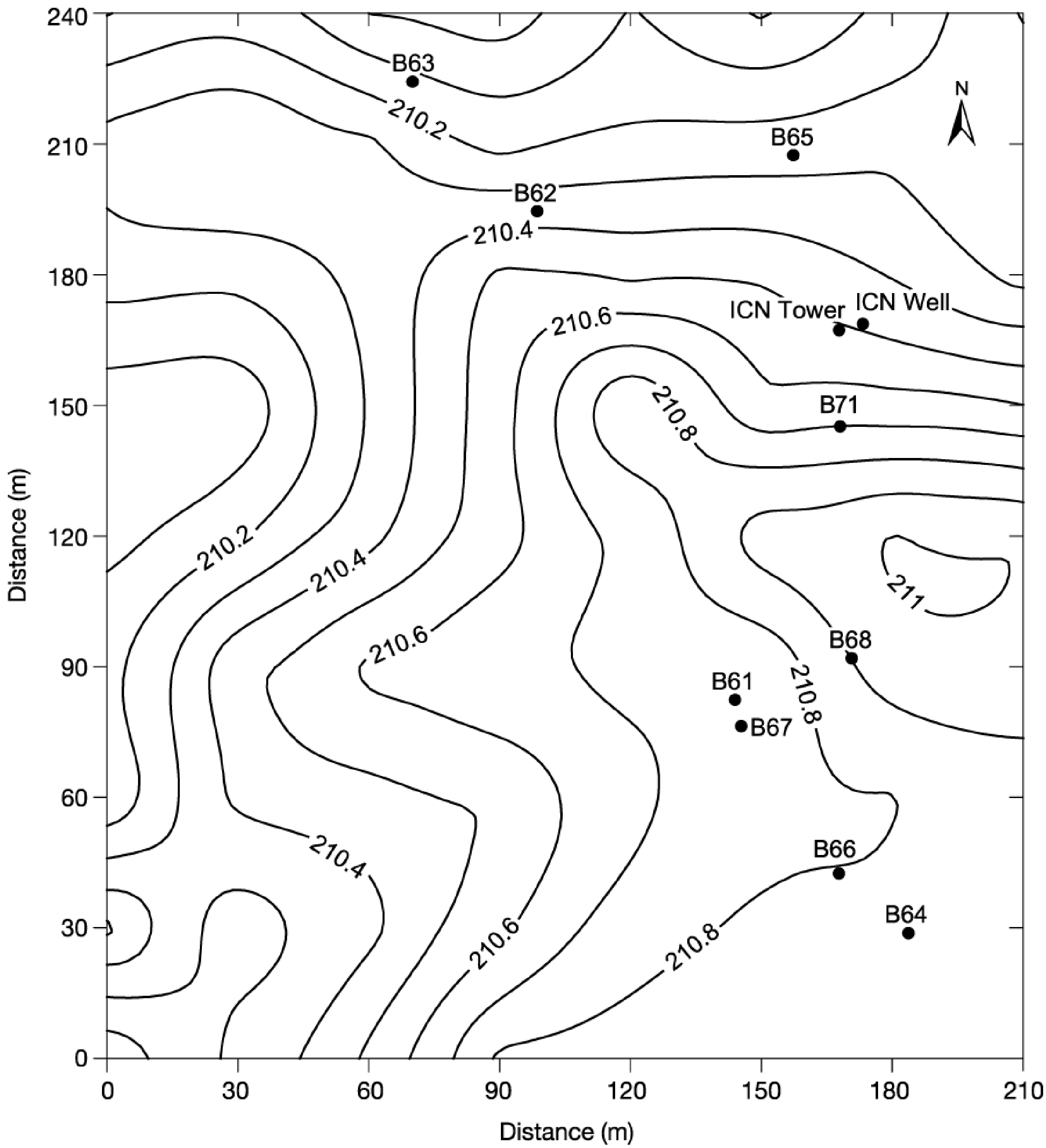
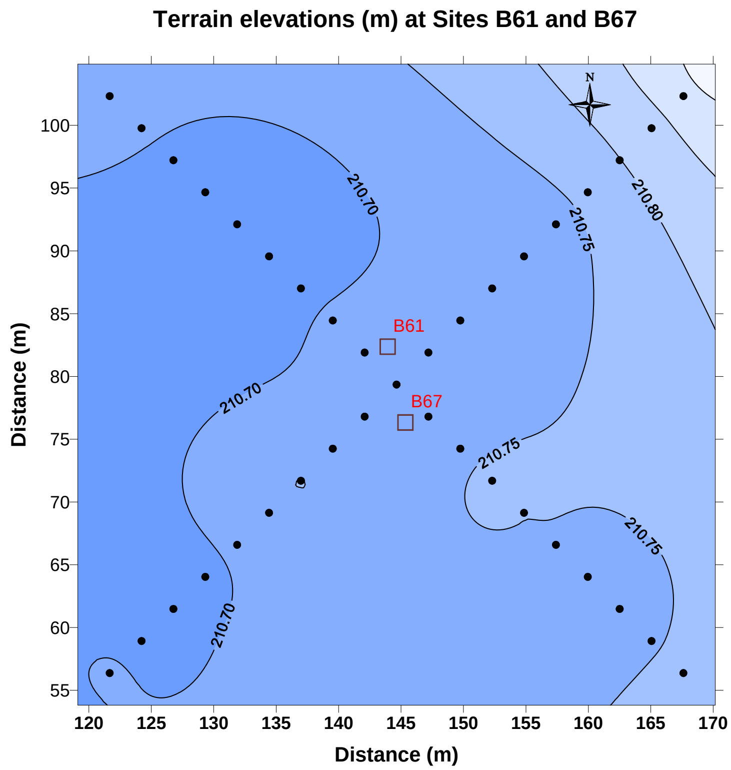


Figure 4. Surface elevations (m) across the BEARS site. Distances (m) are north and east of the southwestern corner of the field station. Locations of neutron probe sites, the ICN meteorological tower, and the ICN shallow groundwater well are included.



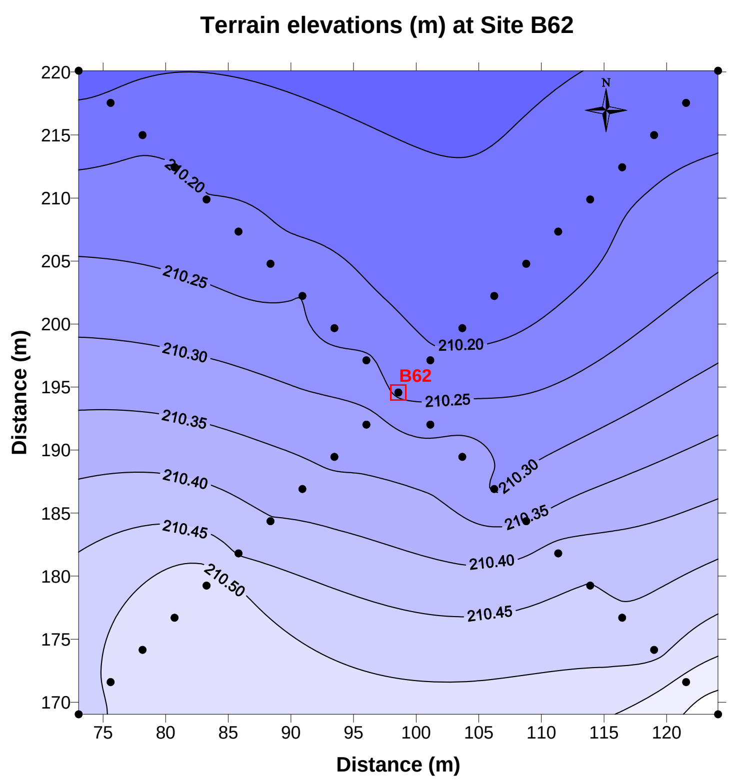
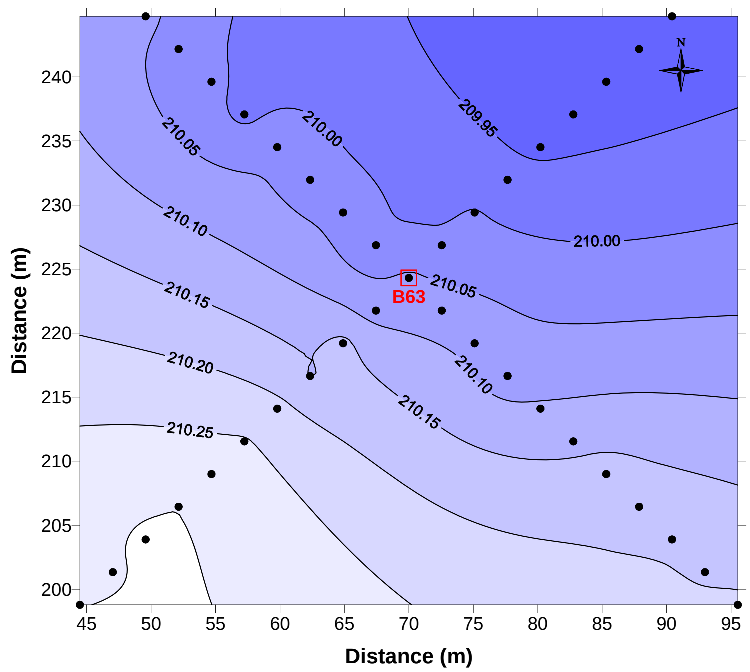


Figure 5. Surface elevations (m) at SMUSE neutron probe stations at the BEARS site. Distances (m) are north and east of the southwestern corner of the field station. Elevations were collected at 3-meter intervals (dots) along NW-SE/SW-NE cross sections near each site.

Terrain elevations (m) at Site B63



Terrain elevations (m) at Site B64

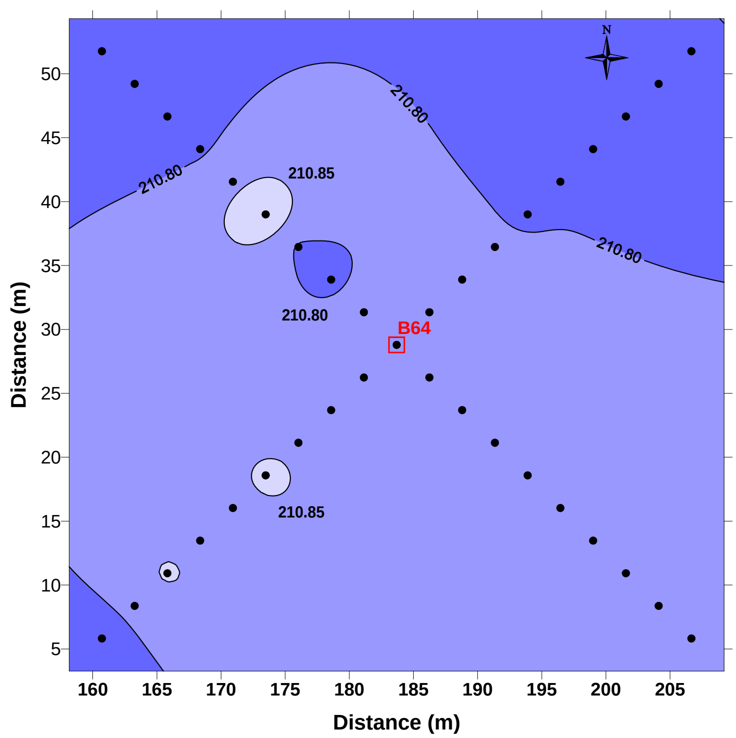
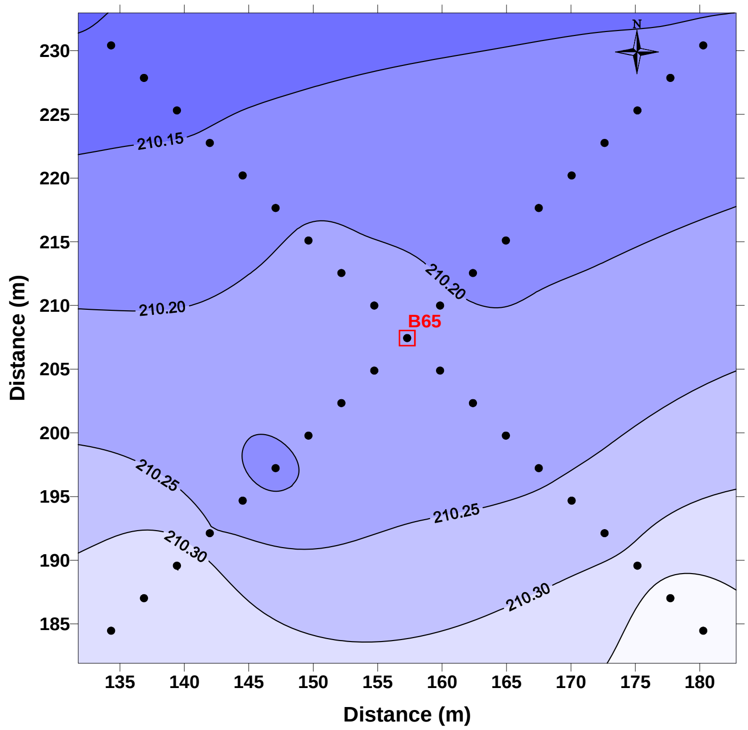


Figure 5. (Continued)

Terrain elevations (m) at Site B65



Terrain elevations (m) at Site B66

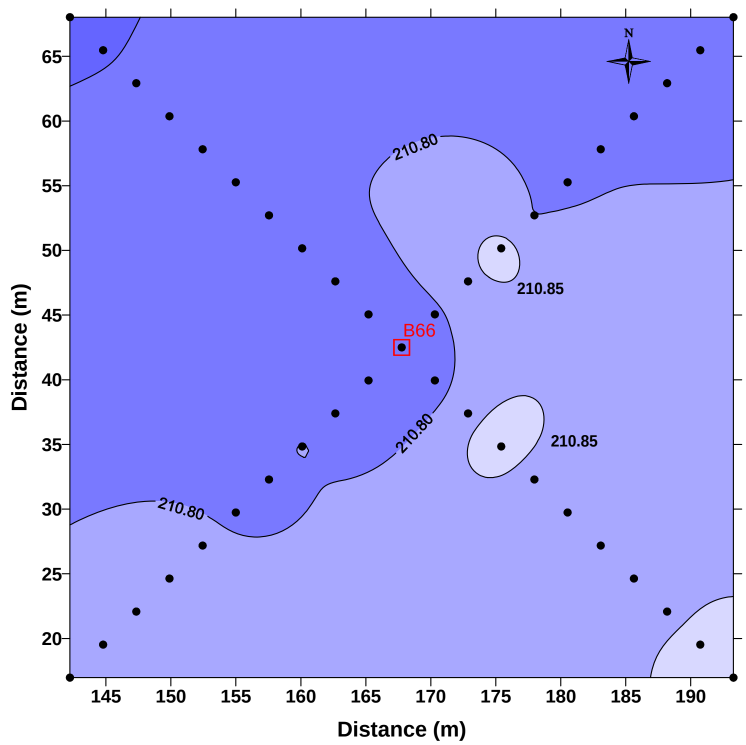
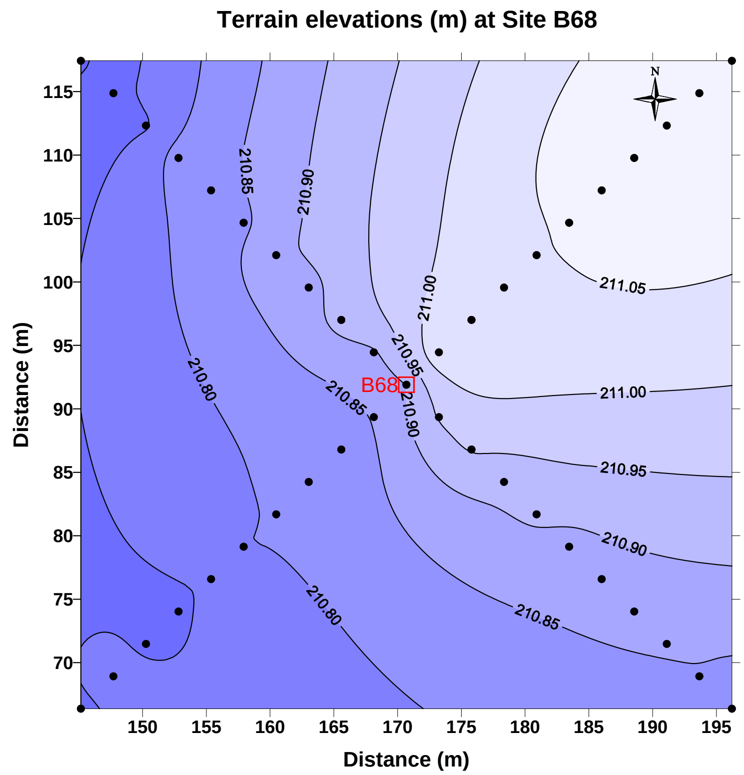


Figure 5. (Continued)



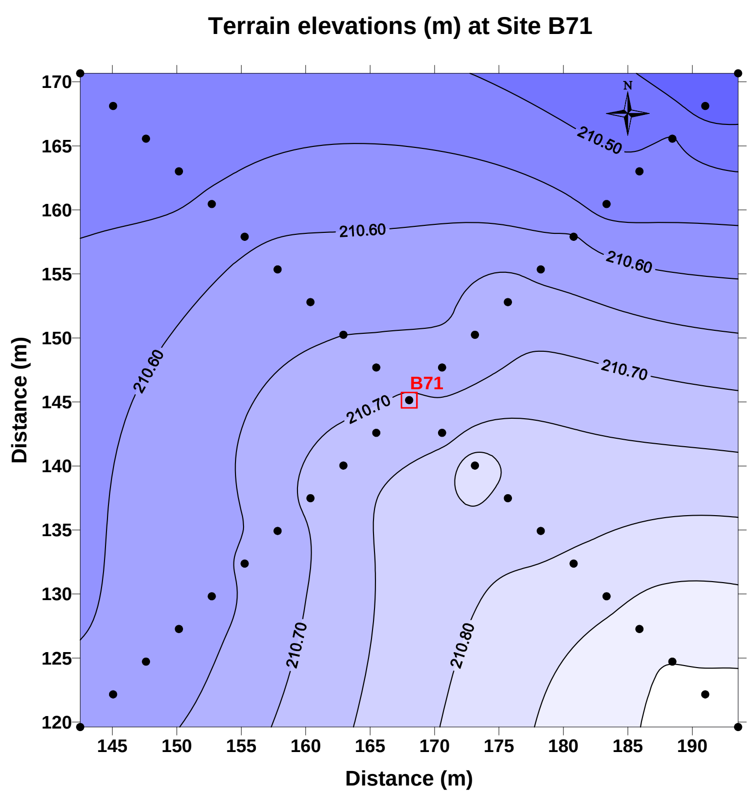


Figure 5. (Concluded)

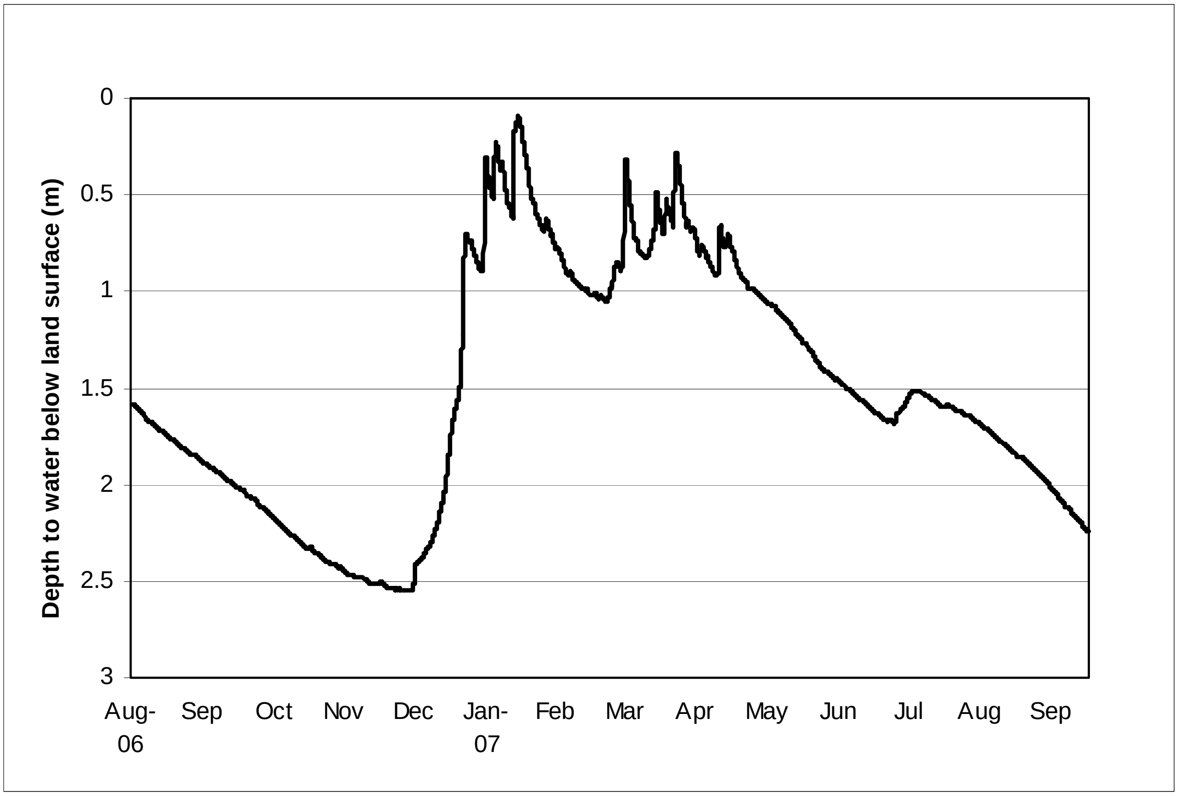


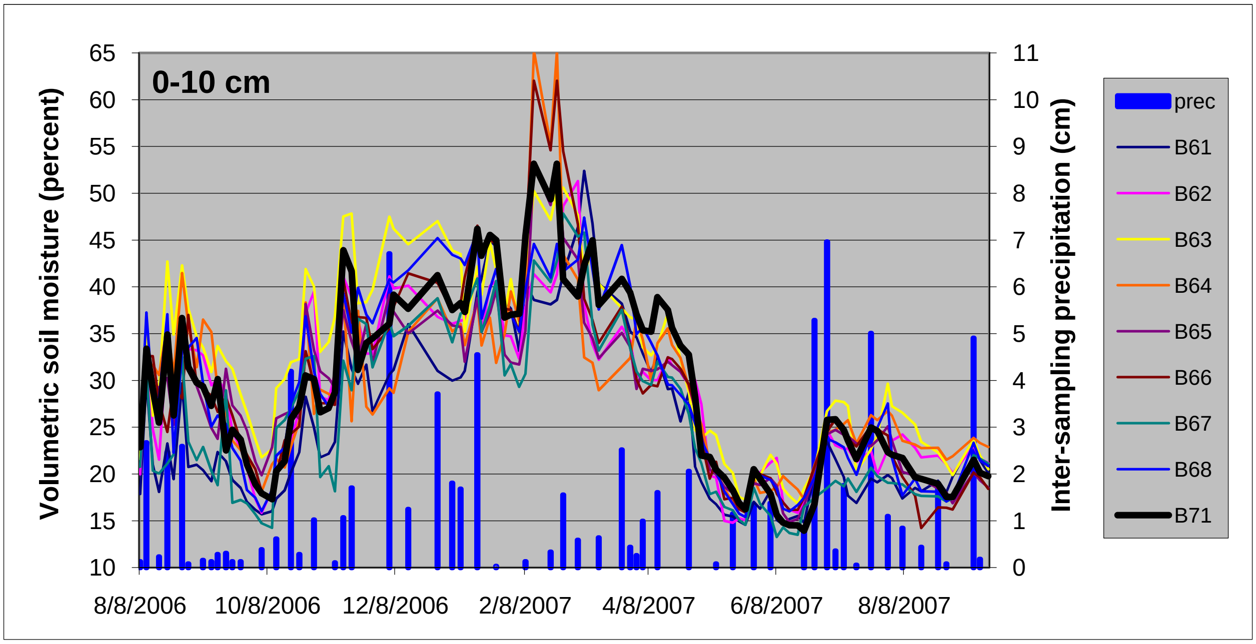
Figure 6. Hydrograph of the shallow water table at the Bondville, Illinois ICN site during SMUSE. [Data from: www.sws.uiuc.edu/warm/sgwdata/wells.aspx]

b. Soil Moisture Analyses

Figure 7 shows volumetric soil moisture (percent of volume) at nine neutron probe sites (B61-B68 and B71) within BEARS during SMUSE. Figures are arranged in 20-cm layers, except for the topmost and lowest layers, which have depths of 10 cm. Precipitation totals were included from daily (midnight-midnight, local time) data at the Bondville National Acid Deposition Program site (also located at BEARS), accumulated between successive soil moisture observation days.

1.0-10-cm Layer

Overall, in the 0-10 cm layer (Figure 7a), strong temporal consistencies in volumetric soil moisture were observed within each layer at each site. Large increases in moisture were evident near the surface related to rainfall, followed by decreases during periods when rain events were less frequent or with smaller totals. Volumetric soil moisture decreased at all sites during September 2006, a month with very low precipitation, but a time when the sod root zone continued to process near-surface moisture. The trend reversed in October with heavier precipitation, likely coincident with the end of the growing season for sod as near-surface water use and evapotranspiration waned. For the region, this time frame is typically the beginning of the near-surface, seasonal soil moisture recharge period.



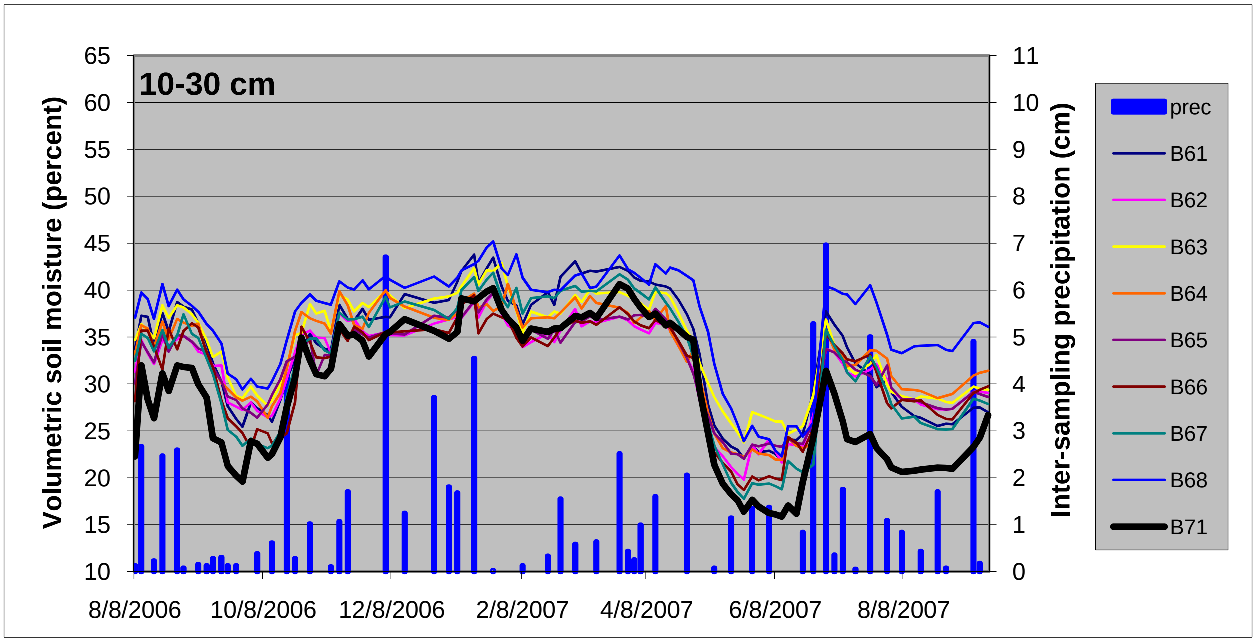
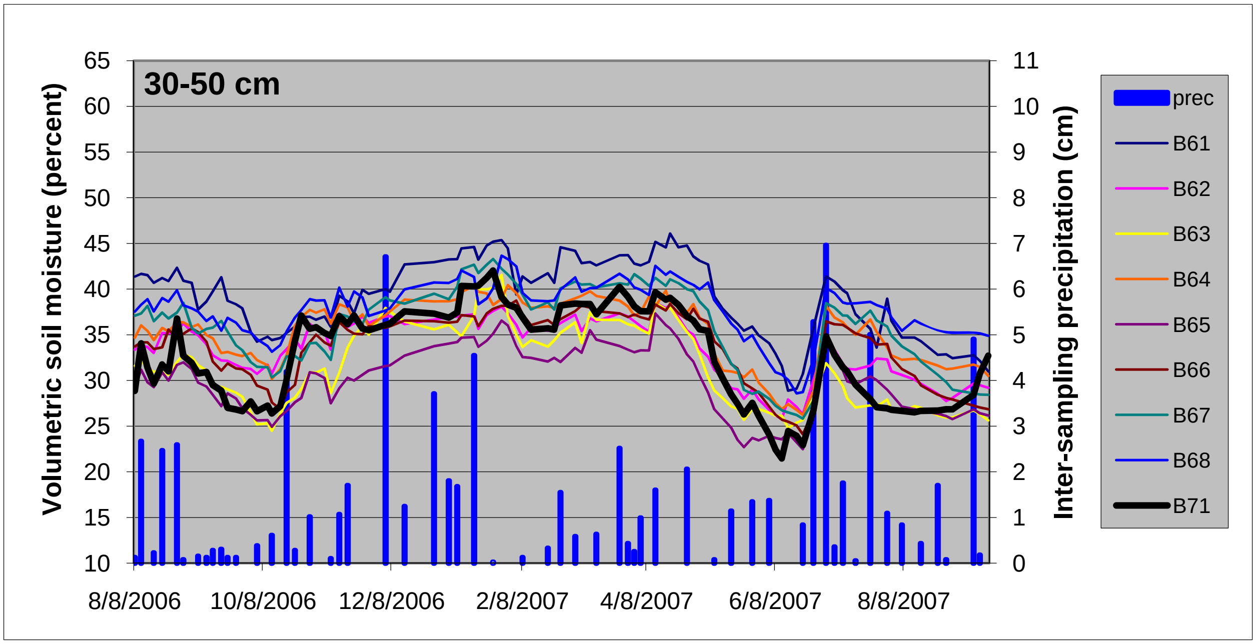


Figure 7. Volumetric soil moisture (percent) within 11 layers at eight neutron probe locations, plus the historic soil moisture site (B71), and precipitation totals (cm) between sampling dates during SMUSE.



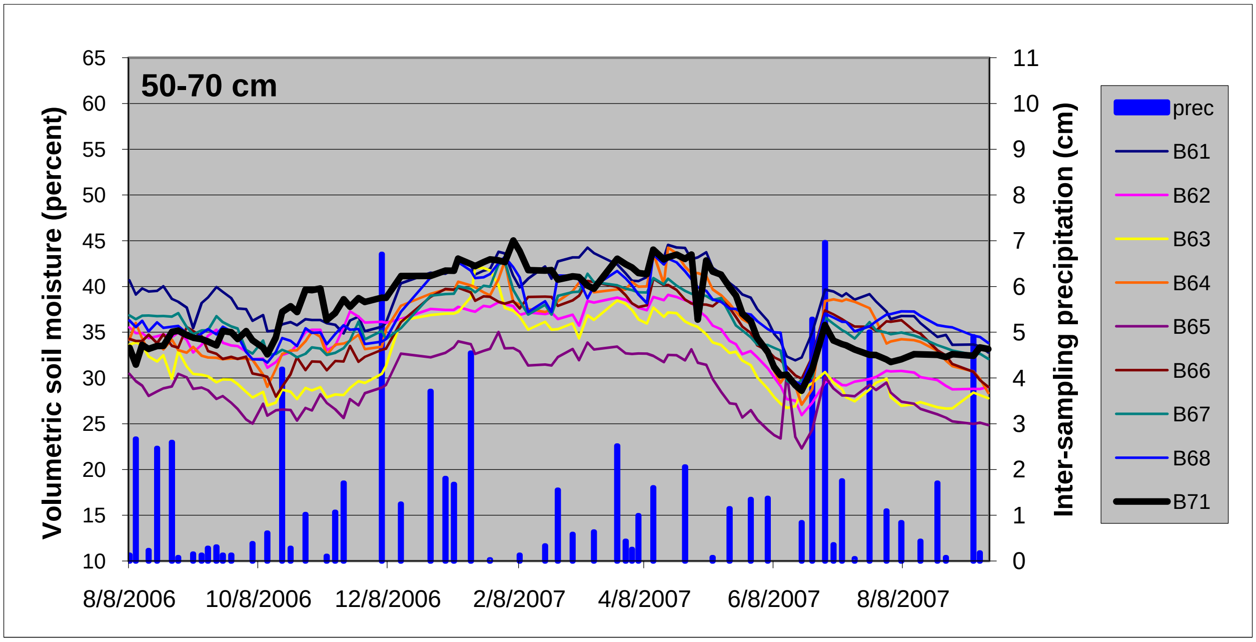
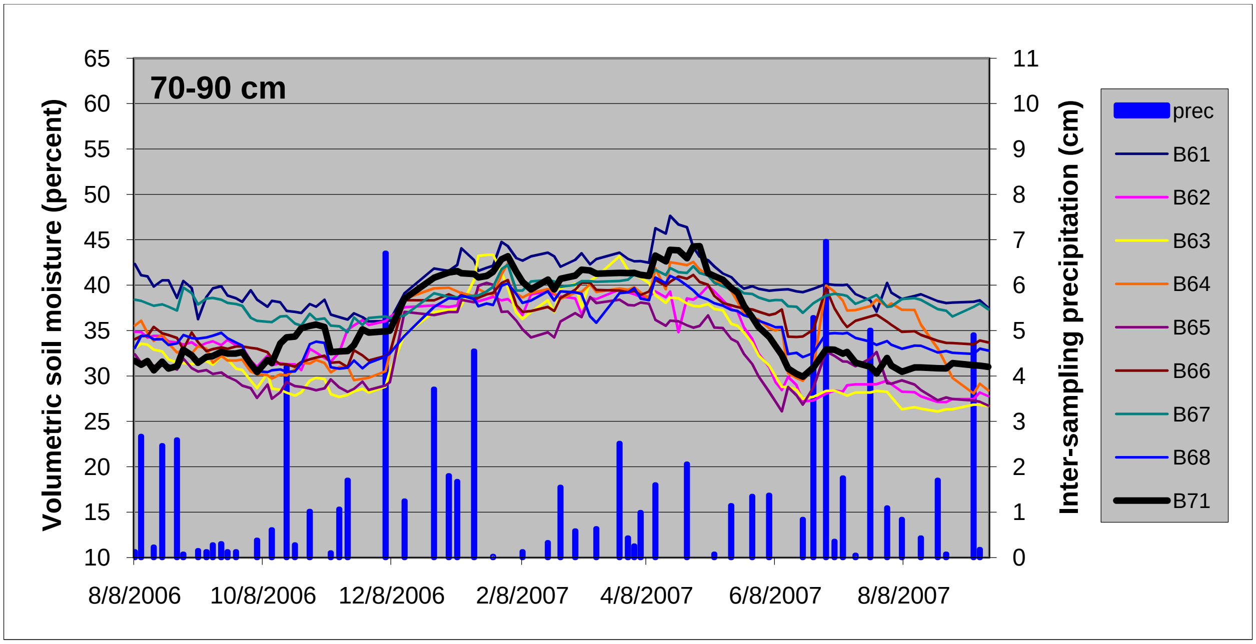


Figure 7. (continued)



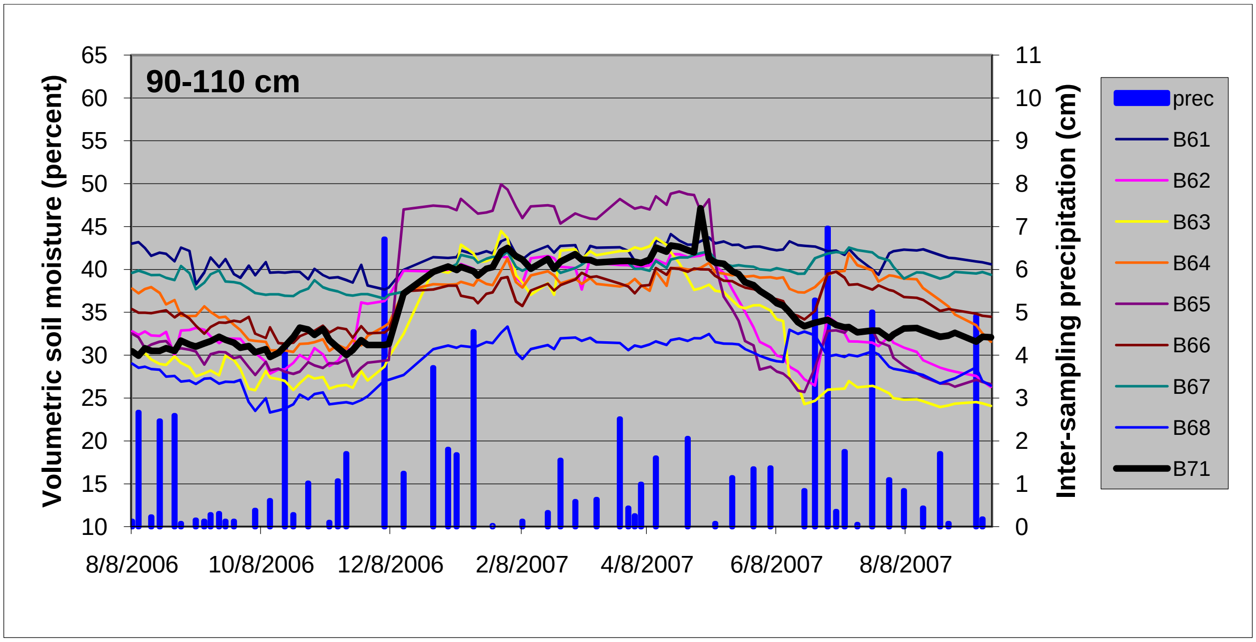
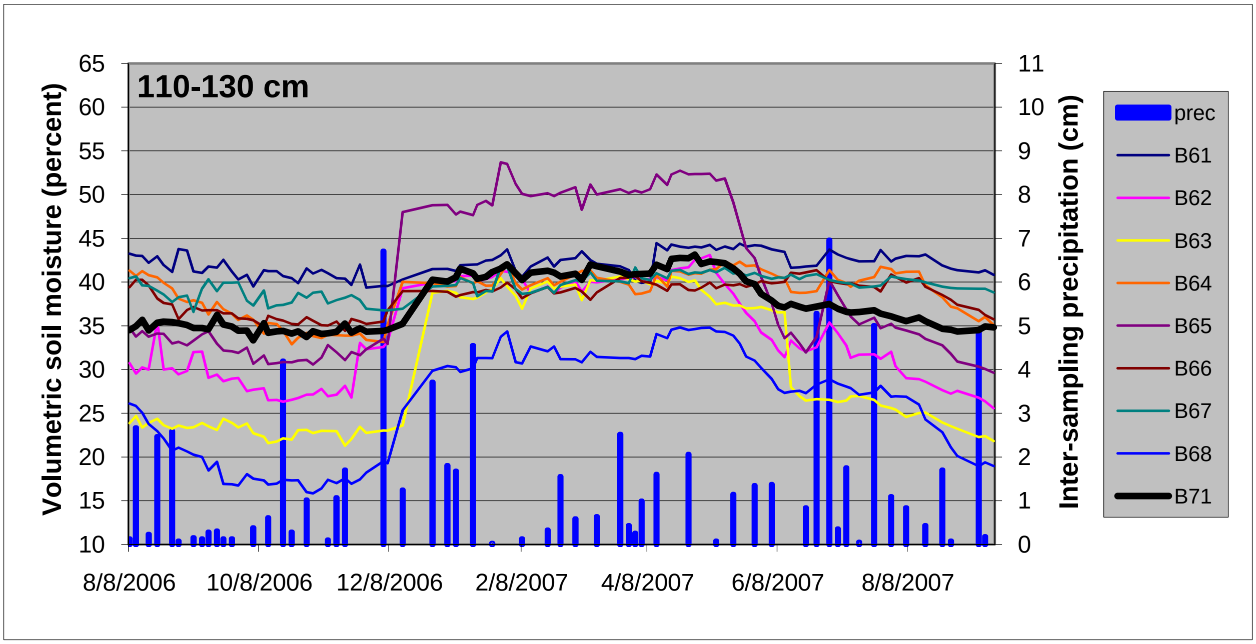


Figure 7. (continued)



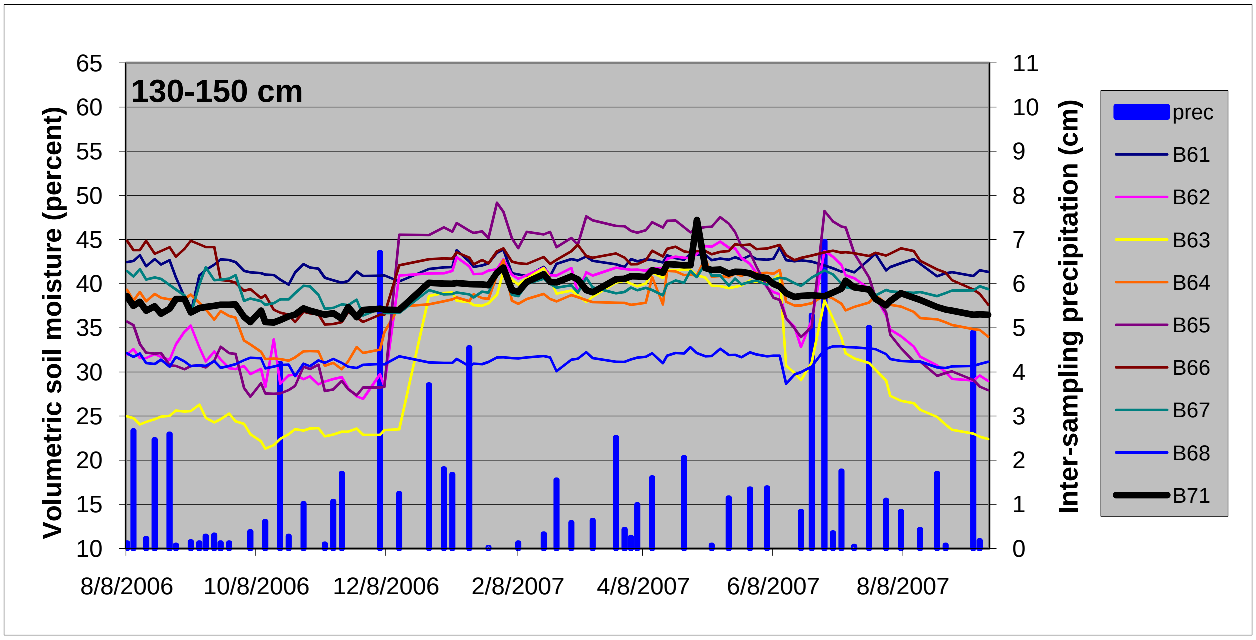
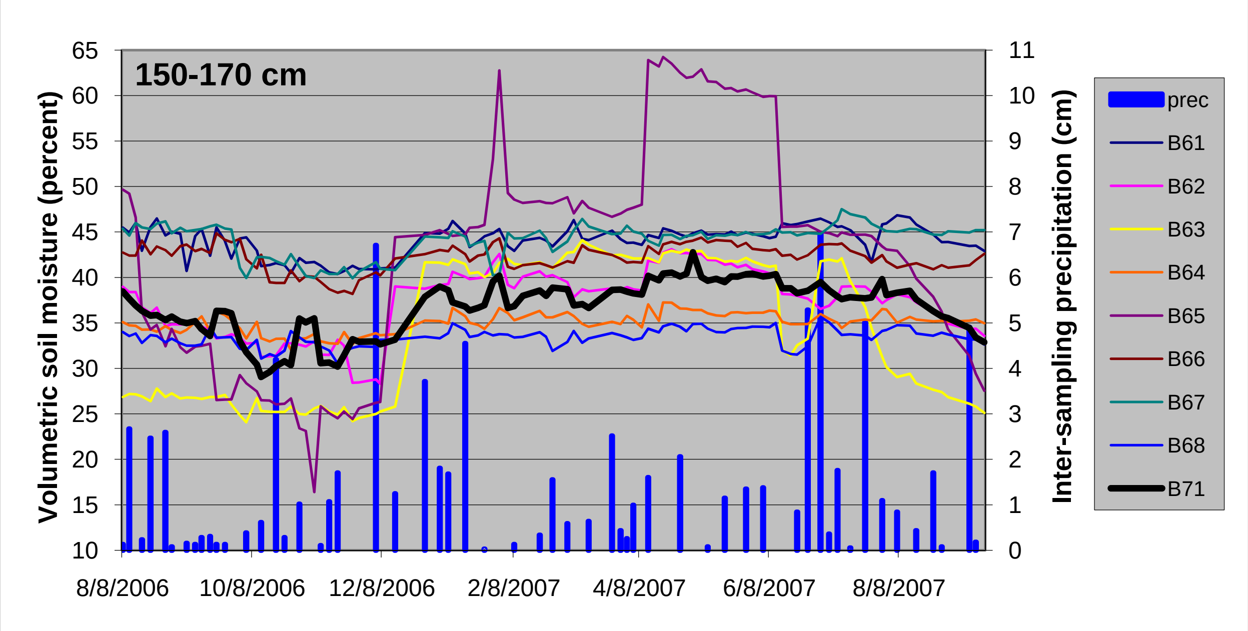


Figure 7. (continued)



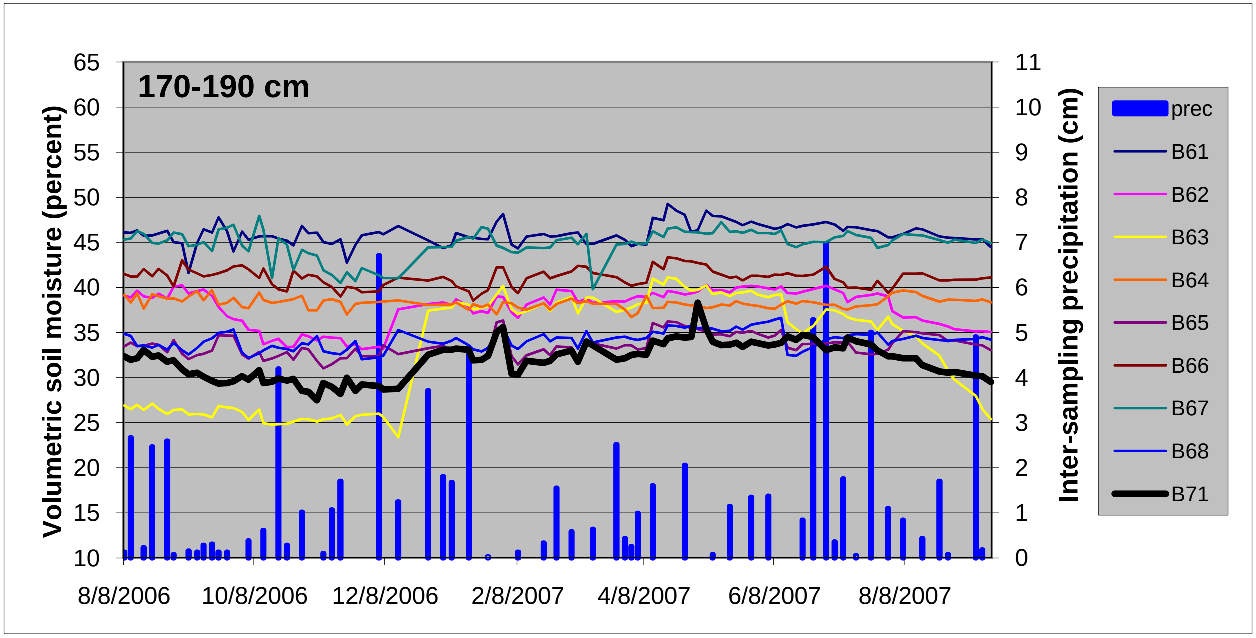


Figure 7. (continued)

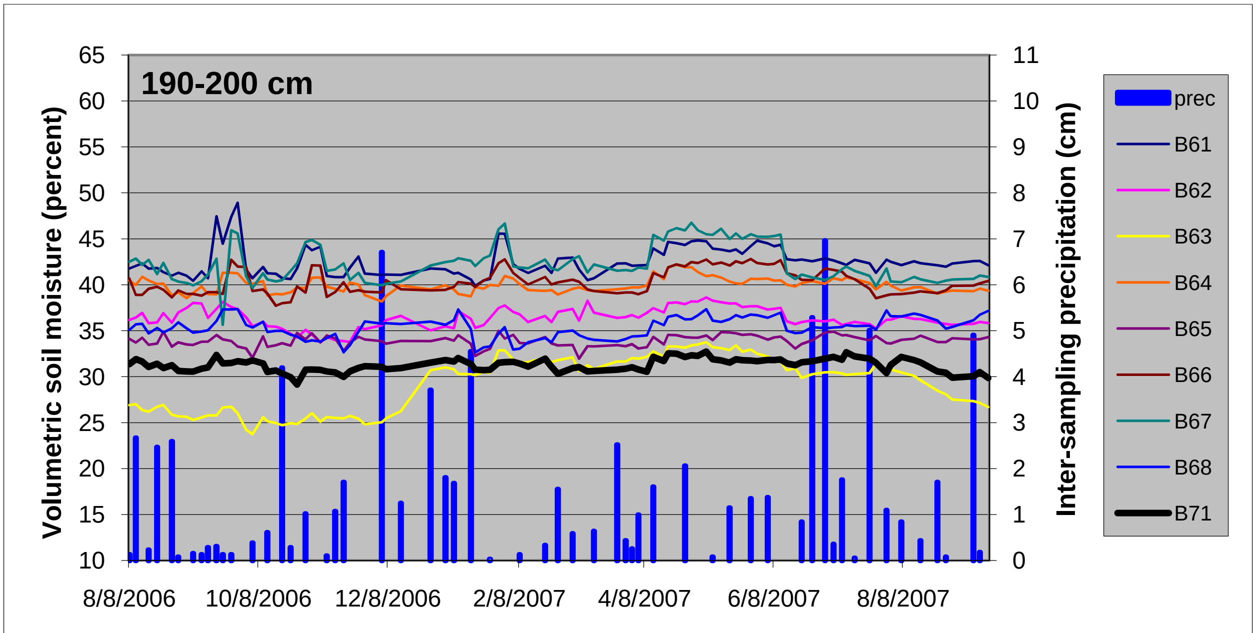


Figure 7. (concluded)

From November 2006 to the end of March 2007, soil moisture variability was relatively low at each site with values generally ranging from 30 to 45% by volume and was maintained by several substantial precipitation events from December to the middle of January. Surface soils were frozen at 10 cm of depth during January 30–March 12, effectively locking in moisture in the top soil layer and capping downward percolation below this level. Furthermore, much of the precipitation in this time period fell as snow and remained on the surface with considerable time to sublimate, melt, and evaporate, or blow into ditches before soils thawed, further limiting water movement into soils. A few sites reported a large increase in soil moisture from February into early March without concomitant precipitation. Values at two sites (B64 and B66) were exceptionally high (greater than 60%). Unfortunately, site-specific surface conditions were not taken during observations. Since it was late winter, melting of random snow drifts across the field could explain these localized moisture surges.

After soils thawed in mid-March 2007, the resumption of sod growth and lower than average seasonal precipitation caused volumetric soil moisture to fall sharply, but with consistently lower variability. The lowest near-surface values during the experiment were observed in mid-June (13 to 20%). Heavy rainfall events in late June and early July increased soil moisture quickly, followed by a slow decrease in moisture again at all sites through the end of the monitoring period as a result of average precipitation, high summertime moisture use by sod, and maximum evapotranspiration.

As stated previously, soil moisture variability among the sites was relatively high within this layer from August 2006 through February 2007, and then substantially smaller throughout the remainder of the experiment. Without other seasons of soil moisture observations at these locations over various precipitation settings, it is difficult to assess any significance in the drop in variability during the second half of the experiment. It must also be remembered that data from this near-surface layer were obtained from both the Troxler surface and depth probes, whereas below this layer, only the depth probe provided measurements.

The overall temporal consistency observed at all sites throughout the experiment provides a high level of sensor quality assurance. The same instrumentation was used at all sites on each day measurements were collected. Thus, the consistent reporting seen at each site from one observation to the next lends support to properly functioning units.

Table 1 displays the mean, range, and standard deviation values of volumetric soil moisture (in percent) at each site over all 101 neutron probe observation days for each of the 11 layers of measurements. It shows similar values of the average and standard deviation of each observation period over all nine “network” sites and over just the eight randomly-selected “field” sites. The table displays the overall difference in average soil moisture during the experiment between the field sites and the historic site (B71). Finally, Table 1 shows the coefficient of determination (R^2) between mean values of volumetric soil moisture at each field site versus the historic soil moisture station.

The strong seasonal variability in soil moisture in the top 10 cm of soil, shown graphically in Figure 7a, is quantified in Table 1 by comparing standard deviation values of the intra-site observations during the experiment. These ranged from 8.14% at B65 to 10.27% at B66. From the same data, it was observed that average volumetric soil moisture varied from 25.5% (B61) to 32.1% (B63). Thus, there was a relatively high level of variability at each site individually, which can be expected within the precipitation climate that is experienced in central Illinois. Intuitively, low variability in soil moisture might be expected throughout the experiment because all stations would have experienced the same precipitation events and, from a visual perusal of the field, appeared to possess similar surface conditions. However, differences between sites within the same sodded field on the same day were occasionally substantial. The average inter-site standard deviation of soil moisture for each observation day throughout the experiment was 3.41%, but varied on individual days from 0.91% (May 21) to 9.23% (February 12 and 23).

The lowest inter-site variation occurred near the end of a significant drying period when seasonal temperatures were increasing, evapotranspiration (from sod) was accelerating, and surface residual moisture was relatively low at all sites. On the higher inter-site deviation dates, soils below this level at 10 cm likely were frozen, causing reduced percolation, and melting from earlier snows (unverified) may have impacted surface soil moisture at some sites. Variability may have resulted from the influences of ponding at some sites and differences in percolation rates due to specific soil conditions under the various locations.

Table 1. Basic Site Statistics. Coefficient of Determination (R^2) in the Mean Values of Volumetric Soil Moisture (Percent) Within Each Layer at all Field Sites versus the Historic Soil Moisture Station, B71, During SMUSE (n=101). Average and Range of Bi-weekly Temporal Standard Deviation (All Sites) and Mean Difference Between the Field Average of Sites and B71.

	site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	*Average B61:B68*	*B71*	*Bi-weekly std.dev.*	*Difference: field-B71*
0-10 cm	mean	25.49	28.45	32.12	29.05	28.31	29.08	25.70	29.04	28.41	29.30	3.41	-0.90
	max	52.39	51.30	50.59	65.26	52.99	62.03	47.83	47.41	49.74	53.15	9.23	
	min	14.56	14.79	16.85	16.25	14.85	14.22	13.27	15.40	15.71	13.94	0.91	
	std. dev.	9.16	8.38	9.40	8.97	8.14	10.27	8.93	9.38	8.56	9.79		
	R^2	0.82611	0.81003	0.83810	0.73522	0.85839	0.86850	0.80180	0.87327	0.92899			
10-30 cm	mean	33.63	31.79	34.19	33.04	31.98	31.20	32.07	36.77	33.08	29.05	2.64	4.03
	max	43.78	39.65	42.90	40.66	39.71	39.46	41.86	45.18	40.89	40.63	4.30	
	min	21.77	19.81	23.77	21.90	22.02	18.70	17.76	22.28	21.28	15.86	1.40	
	std. dev.	6.44	4.96	5.18	5.34	4.73	5.65	7.07	5.77	5.52	7.43		
	R^2	0.91845	0.85943	0.90781	0.83605	0.88198	0.82327	0.90957	0.80275	0.90658			
30-50 cm	mean	39.03	33.47	31.36	35.25	29.88	33.60	35.80	37.78	34.52	32.69	3.26	1.83
	max	46.09	38.52	41.55	40.44	37.33	38.74	43.30	43.66	40.56	42.03	4.56	
	min	28.89	25.80	24.49	26.22	22.47	24.12	25.82	28.59	26.25	21.47	1.97	
	std. dev.	4.21	3.33	4.44	3.58	3.72	3.85	4.56	3.07	3.66	5.21		
	R^2	0.67881	0.81802	0.80607	0.83960	0.76984	0.72863	0.71652	0.73516	0.83779			
50-70 cm	mean	38.83	34.16	32.06	35.77	29.09	35.16	36.13	36.97	34.77	37.19	3.29	-2.42
	max	44.54	39.09	42.07	44.24	35.03	40.85	42.76	43.52	40.22	45.03	4.38	
	min	31.92	25.94	26.67	27.07	22.30	27.98	29.16	29.29	28.15	28.61	1.73	
	std. dev.	3.26	3.39	4.16	3.97	3.06	3.35	3.04	3.26	3.19	4.34		
	R^2	0.55439	0.76696	0.66162	0.64184	0.58471	0.49067	0.58193	0.63412	0.71539			
70-90 cm	mean	40.32	34.07	32.98	35.64	32.20	35.96	38.55	35.23	35.62	35.86	3.02	-0.24
	max	47.63	39.91	43.35	42.55	40.25	41.14	42.24	41.02	40.93	44.30	4.86	
	min	36.01	27.12	26.08	28.08	26.09	30.98	34.82	30.42	31.37	29.91	1.48	
	std. dev.	2.64	4.08	5.13	4.22	3.89	2.98	1.75	3.03	3.16	4.66		
	R^2	0.61526	0.73164	0.78627	0.59030	0.74245	0.62477	0.53942	0.75896	0.82566			
90-110 cm	mean	41.45	34.51	32.44	36.75	35.76	36.17	39.74	28.96	35.72	35.64	4.76	0.08
	max	44.11	41.97	44.47	41.88	49.93	40.17	42.56	33.33	41.72	47.13	6.33	
	min	37.66	26.31	23.95	30.39	25.71	31.34	36.60	23.31	30.70	29.79	3.28	
	std. dev.	1.51	4.99	6.71	3.20	8.64	2.51	1.54	2.69	3.49	4.58		
	R^2	0.33421	0.72937	0.82073	0.44479	0.78958	0.62361	0.39100	0.62438	0.87091			

Table 1. (Continued)

	site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	*average B61:B68*	*B71*	*network std.dev.*	*difference field-B71*
110-130 cm	mean	42.13	33.94	30.30	38.75	39.90	38.35	39.56	25.98	36.11	37.66	6.04	-1.54
	max	44.45	43.09	40.64	42.37	53.70	41.36	41.82	34.82	42.01	43.15	8.07	
	min	39.36	25.57	21.29	32.89	29.64	34.43	36.58	15.84	30.36	33.34	3.99	
	std. dev.	1.34	5.51	7.55	2.69	8.54	1.85	1.29	6.23	3.97	3.08		
	R^2	0.24266	0.88079	0.92757	0.45390	0.91665	0.34994	0.39850	0.85236	0.93753			
130-150 cm	mean	41.96	36.48	31.69	37.25	38.07	41.88	39.47	31.34	37.27	38.89	4.93	-1.62
	max	44.09	44.76	41.74	42.88	49.17	44.85	42.27	32.91	42.03	47.21	6.55	
	min	36.64	26.95	21.31	30.31	27.20	35.37	36.40	28.66	31.74	35.60	3.40	
	std. dev.	1.12	5.65	7.60	3.05	7.79	2.77	1.24	0.76	3.34	2.05		
	R^2	0.32817	0.74645	0.80111	0.61321	0.72488	0.38175	0.21429	0.22325	0.80501			
150-170 cm	mean	44.05	37.26	34.18	35.05	42.53	42.23	44.13	33.44	39.11	36.70	6.01	2.40
	max	46.83	43.11	44.08	37.25	64.23	44.85	47.51	35.67	44.43	42.76	8.42	
	min	40.38	28.30	24.07	32.03	16.40	38.18	39.91	30.53	32.66	29.06	4.07	
	std. dev.	1.68	3.70	7.64	1.12	12.58	1.50	1.83	0.99	3.42	3.06		
	R^2	0.50624	0.74426	0.58696	0.65610	0.74310	0.39357	0.27689	0.46150	0.80672			
170-190 cm	mean	45.99	37.77	33.11	38.29	33.57	41.11	44.89	34.16	38.61	31.97	5.52	6.64
	max	49.26	40.29	41.11	39.68	36.33	43.34	47.94	36.63	41.28	38.30	7.44	
	min	41.61	33.15	23.40	36.71	31.02	38.55	39.81	32.03	35.63	27.49	3.83	
	std. dev.	1.17	2.14	6.04	0.59	1.21	0.99	1.59	1.05	1.36	2.05		
	R^2	0.24085	0.60439	0.66412	0.05334	0.37324	0.11507	0.25647	0.26062	0.75442			
190-200 cm	mean	42.52	36.40	29.23	39.98	33.90	40.31	42.35	35.36	37.51	31.26	4.93	6.24
	max	48.92	38.62	33.75	42.21	34.98	42.80	46.75	37.35	39.76	32.72	7.15	
	min	39.88	33.74	23.73	38.16	31.95	37.72	35.65	32.63	35.80	29.14	3.64	
	std. dev.	1.62	1.13	3.01	0.81	0.61	1.34	2.10	1.14	1.08	0.70		
	R^2	0.23329	0.25229	0.26383	0.34018	0.14729	0.26787	0.18511	0.21128	0.43674			

A primary objective of this experiment was to test the representative nature of data collected from B71, the long-term historic site, compared with data collected across the field of observations. The average volumetric soil moisture throughout SMUSE in the 0- to 10-cm layer at the eight field sites was 28.41% compared with 29.30% at B71, a relatively small difference (0.90%). That is, during this experiment at least, the average soil moisture under sod in the top 10 cm of soil at the historic site, measured biweekly with neutron probe technology for more than 13 months, was within 1% of the average soil moisture across an array of eight stations within the same field. A more statistical analysis can be viewed with R^2 calculations between each site individually and B71. Table 1 shows that these ranged from 0.74 (B64) to 0.87 (B68). However, the field average of B71 possessed an R^2 of 0.93. These results suggest that soil moisture at the historic site (B71) may differ from other specific locations at BEARS, but may indeed be a good representative for volumetric soil moisture under sod in the near-surface layer for the BEARS site as a whole. These data, however, provide no information on the representativeness of soil moisture in adjacent crop areas.

2. 10-30-cm Layer

The most uniform network observations were observed in the next layer down, between 10 and 30 cm (Figure 7b). Once more, a high level of temporal consistency was observed at each site. There was a response due to precipitation in this layer during the growing seasons (but one more muted than observed near the surface) as well as to low precipitation totals, and presumably increased evapotranspiration in May 2007. Overall, a smaller range in intra-site standard deviations was observed among the sites than was seen in the layer above, between 4.73% (B65) and 7.43% (B71).

The inter-site by-weekly standard deviations were smaller as well, averaging 2.64% and ranging from 1.40 to 4.30%. Although soil moisture was slightly lower at B71 throughout the period compared to the other sites, R^2 values between the historic and field sites actually rose due to the overall closeness of values and more muted response to precipitation than was seen in the top soil layer. Individual R^2 values ranged from 0.80 to 0.92. The representativeness of the historic site to the field in the 10–30-cm layer was less than in the layer above, as it underestimated soil moisture by more than 4% compared to the field mean.

3. 30-90-cm Layers

Temporal variability also was relatively small at most sites from 30 to 90 cm deep (Figure 7c-e). Moisture levels became rather uniform at each site as the response to precipitation during SMUSE became muted to nearly undetectable with increasing depth through this layer. Thus, the range of intra-site standard deviations decreased from the layer just above, ranging 3.07–5.21%, 3.04–4.34%, and 1.75–5.13%, respectively (Table 1). Visually, average soil moisture values among the sites in Figure 7c-e were spread slightly further apart than near the surface as indicated by a slight increase in the average bi-weekly inter-site standard deviations (Table 1): 2.64% at 10–30 cm, and 3.26, 3.29, and 3.02%, respectively, within these three layers. However, the range of these values among the sites was slightly higher. Nevertheless, R^2 values between the field sites and the historic soil moisture site (B71) decreased to between 0.84 (B64) and 0.49 (B66) within these three layers.

Site B71 slightly underestimated soil moisture (1.83%) in the 30- to 50-cm layer, slightly overestimated (-2.34%) in the 50- to 70-cm layer, and was essentially the same (-0.24%) in the 70- to 90-cm layer compared to the average of the test sites. Some differences in average soil moisture throughout the experiment between B71 and other individual sites were quite large: 37.19% at B71 and 29.09% at B65 in the 50- to 70-cm layer, for example. These results suggest a reduction of confidence in relying on a single instrument site. For example, if B65 had been available for use historically instead of B71, different results may have been reported in earlier research.

4. 90-170-cm Layers

Soil moisture trends in middle layers, 90 to 110 cm through 150 to 170 cm, differed from the 0- to 70-cm layers (Figure 7f-i). Sudden rapid increases in soil moisture occurred at a few sites in December 2006 to moisture levels that remained high with a static trend until May 2007, and then fell to lower values once again late in the experiment. This was especially noted at Sites B65 and B63. Sites B64, B68, and B71 also showed some aspects of this trend. However, at other sites, such as B61 and B67, soil moisture remained relatively constant and relatively high throughout the entire 13 months of bi-weekly observations. These trends are reflected in the difference in standard deviations among the sites. Standard deviation values in these layers throughout SMUSE ranged between 7.79% and 12.58% at B65 (Table 1), but only from 1.12 to 1.68% at B61. The maximum bi-weekly inter-site standard deviations for these layers ranged from 6.33 to 8.42%, meaning a greater spread of site soil moisture values than observed in the layers above. R^2 values between each field site and the historic soil moisture site continued to decrease with depth at most sites, varying between 0.39–0.82 in the 90- to 110-cm layer to 0.28–0.74 in the 150- to 170-cm layer. However, two sites, B62 and B65, maintained R2 values above 0.72 throughout these layers, indicating that the historic site, B71, was partially impacted by this trend.

Figure 6 suggests that a seasonal intrusion by the local water table from below occurred at the sites in these layers with the extreme variability from December 2006 to May 2007. It is suggested that soil properties at other sites caused soil moisture to remain high throughout the experiment. Topographical and soil core analyses reported in the next section supports this contention. Sites with a low surface slope reported higher continuous soil moisture values in the middle layers, while sites with relatively higher slopes had periods of drier soils, but with an apparent seasonal intrusion of the water table. Soil attributes in addition to slope may play a part in these observations.

5. 170-200-cm Layers

Trends in the deepest layers (Figure 7j, k), were consistent with relatively flat temporal trends in volumetric soil moisture at nearly all sites. Standard deviation values at each were the lowest of all layers and varied between 0.59 and 2.14%, except for 6.04 and 3.01% at Site B63 at 170 to 190 cm and 190 to 200 cm, respectively (Table 1). Data at this site continued to show an apparent water table surge (and subsequent draining) during the experiment. However, the bi-weekly inter-site standard deviations of soil moisture values remained as high as in the middle layers, ranging between 7.15 and 7.44%. Comparison of the average volumetric soil moisture at the historic site to the rest of the network revealed an under measure of soil moisture during the experiment in these layers of 6.64 and 6.24%, respectively. Indeed, Figures 7j and 7k show soil moisture at B71 as one of the lowest plots on the chart. Lastly, in comparing data at B71 with the other experiment sites, R^2 values were between 0.05 and 0.66 in the 170- to 190-cm layer, dropping to a range of 0.15 and 0.34 in the 190- to 200-cm layer, suggesting a greater disconnection in data trends as the 2 m level is reached.

6. Mean Relative Differences

Earlier research by Vinnikov et al. (1999) using 14 of the Illinois soil moisture sites (Figure 1) over a 16-year period with 19 observations each year found a standard deviation by volume in the top 10 cm soil layer of 8.5%, and 4.0% in the top 1 m of soil. Corresponding values in these layers at all sites during SMUSE were 3.41 and 2.02%, respectively. Difference in the range of standard deviations is not surprising due to the large difference in temporal and spatial scales of the 14 ICN sites. Nevertheless, most of the Illinois long-term stations boast the same loess, silt loam soil texture, with total porosity in the top 1 m of soil ranging between 417 and 544 millimeters (mm, Hollinger and Isard, 1994). Thus, there are strong similarities between the Illinois sites, but as the results from SMUSE show, substantial differences can occur on a very localized scale.

One method to assess representativeness of sites to the analysis domain is with temporal stability analyses developed by Vachaud et al. (1985). This analysis compares fractional volumetric soil moisture data from each experiment site to the average soil moisture across BEARS, normalized by the average and summed over the whole experiment, using the formula:

$$MRD_i = \frac{1}{t}\sum_{j=1}^{t}\frac{S_{ij} - \overline{S}_j}{\overline{S}_j}$$

where t is time, $\overline{S}_j$ is the computed average at all sites, and $S_{i,j}$ represents the j^{th} sample of the i^{th} site. Results are shown in Figure 8. As described by Cosh et al. (2008), sites with small mean relative differences (MRD) reflect the field average, while sites with relatively small standard deviations can be good candidates as regional representative sites.

An examination of results in the near-surface layer shows that many sites matched the network average quite well (Figure 8a). Certainly, this layer would be expected to have greater soil moisture variability than other layers due to residual moisture from heavy rainfall, direct surface evaporation, higher plant root mass and transpiration, and percolation, which over a period of time varies the soil moisture from saturation to being significantly dry.

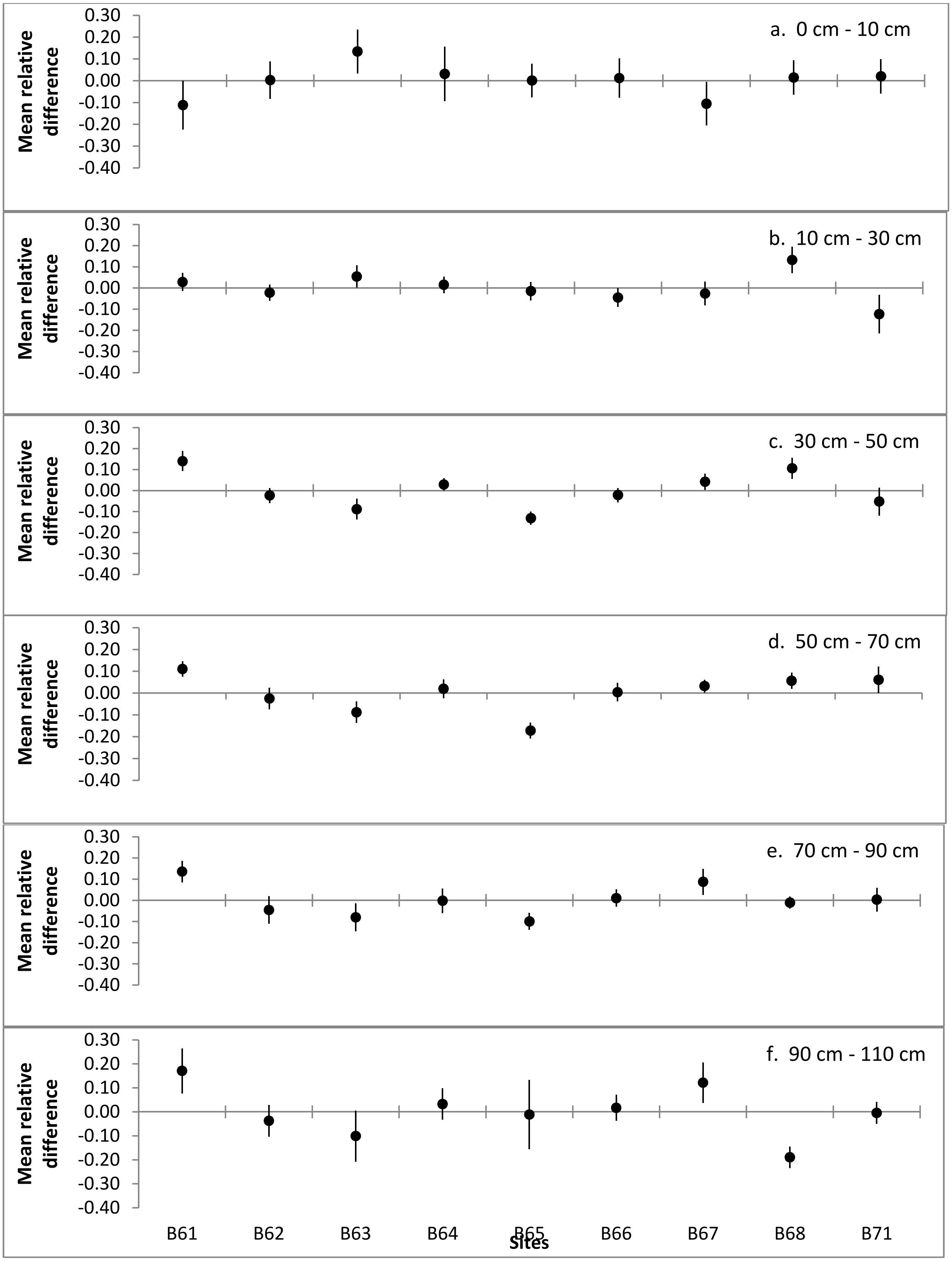


Figure 8. Mean relative difference plots during SMUSE. Error bars are one standard deviation.

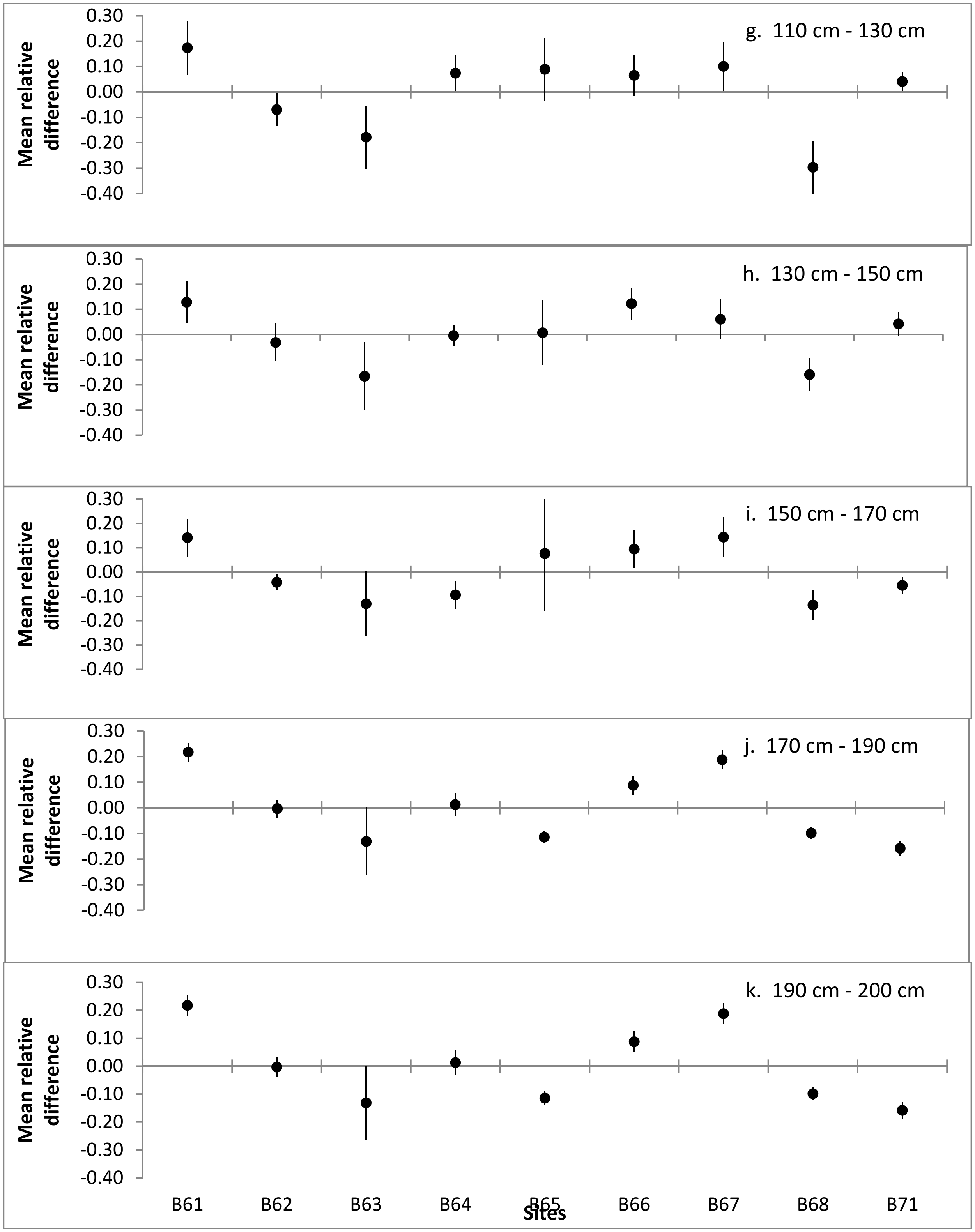


Figure 8. (Continued)

During SMUSE, the historic data set at B71 appeared to be representative of the near surface layer. Conversely, data from B61 and B67 under measured average network soil moisture, while data from B63 over measured the data. The similarities among sites in the near surface layer suggest that these data provide excellent ground truth for comparisons with satellite imagery observations, which generally examine the top 5 cm of soil. Five of the nine sites in the experiment reported near zero MRD values and very similar standard deviations. Thus, these five sites, including the historic site, would be equally representative of the field soil moisture observations.

Similar analyses are presented for each successive layer in Figure 8b-k. Data from nearly all sites in the 10- to 30-cm layer were close to the network average as well as having relatively low standard deviation values. Exceptions occurred at the long-term site (B71) and its nearest neighbor, B68. Compared to other sites, those two locations over measured and under measured soil moisture within the layer, respectively, but gave quantification to their differences observed in Figure 7b.

Data in deeper layers reveal gradual departures of MRD values away from the network mean at many sites. For example, high soil moisture was observed at B61 from 30 cm to 2 m (Figure 8c-k). This was supported in most layers by high values at nearby site B67. Likewise, large MRD standard deviation values were observed at some sites in deeper layers from the probable invasion (and subsequent drainage) of the water table. This was most notable at Sites B63 and B65, resulting in a poor representation (high standard deviation values) of the data domain, Figure 8f-i at B63 and Figure 8f-k at B65. An analysis of all sites indicates that the best representative sites for soil moisture data throughout all layers during SMUSE may have been B62 and B64. These data were closest to the network average with the smallest standard deviation values.

A matrix of spatial correlation coefficients for each layer (Table 2) provides similar information. Correlations in the 0- to 10-cm layer, in accordance with moderate variance observed in earlier figures, were 0.7 or higher at all sites. Similarly, soil moisture values showed much less intra-site variability in the 10- to 30-cm layer and generated correlations that were 0.9 or higher. Subsequently, correlations decreased with depth, and became especially poor in the lowest layer. In relative terms, it appears Site B65 reported the highest correlations across all layers. For example, taking B65 in the 150–170-cm layer, the highest correlation values occurred at B62, B63, and B71. At these site traces within this layer in Figure 7, B65 shows a high change due to the water table and B62, B63, and B71 show similar changes, just not as pronounced. Thus, these sites have the highest correlations, meaning that high correlations quantify the level of similarity in the traces among sites within each level.

From this analysis, B64 was poorly correlated to all sites in the two lowest layers, while data from the historic site indicate that as a whole it may be a less worthy representative of the sod-covered region than other sites, at least during this short 13-month experiment.

Table 2. Correlation Coefficient Matrix of Volumetric Soil Moisture at all Sites and the Average of all Sites During SMUSE

0 to 10 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.85659	0.82475	0.71777	0.82368	0.84771	0.90891	0.89283	0.90890	0.91452
B62	0.85659	1.00000	0.94032	0.80106	0.91076	0.89123	0.89996	0.92263	0.90002	0.95287
B63	0.82475	0.94032	1.00000	0.80868	0.93588	0.88690	0.87652	0.91984	0.91548	0.95176
B64	0.71777	0.80106	0.80868	1.00000	0.88503	0.89150	0.76677	0.79210	0.85745	0.88327
B65	0.82368	0.91076	0.93588	0.88503	1.00000	0.95246	0.90135	0.90617	0.92650	0.96742
B66	0.84771	0.89123	0.88690	0.89150	0.95246	1.00000	0.89354	0.89581	0.93193	0.96282
B67	0.90891	0.89996	0.87652	0.76677	0.90135	0.89354	1.00000	0.92634	0.89544	0.94727
B68	0.89283	0.92263	0.91984	0.79210	0.90617	0.89581	0.92634	1.00000	0.93449	0.96208
B71	0.90890	0.90002	0.91548	0.85745	0.92650	0.93193	0.89544	0.93449	1.00000	0.97221
Net. Avg.	0.91452	0.95287	0.95176	0.88327	0.96742	0.96282	0.94727	0.96208	0.97221	1.00000

10 – 30 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.94952	0.96409	0.92794	0.96227	0.94351	0.97605	0.90972	0.95836	0.97941
B62	0.94952	1.00000	0.96645	0.97404	0.97871	0.95804	0.96980	0.93163	0.92705	0.98317
B63	0.96409	0.96645	1.00000	0.94990	0.96197	0.92989	0.96572	0.90748	0.95279	0.97843
B64	0.92794	0.97404	0.94990	1.00000	0.95894	0.95124	0.96807	0.93912	0.91436	0.97518
B65	0.96227	0.97871	0.96197	0.95894	1.00000	0.94708	0.97212	0.92971	0.93914	0.98330
B66	0.94351	0.95804	0.92989	0.95124	0.94708	1.00000	0.96598	0.93808	0.90734	0.97134
B67	0.97605	0.96980	0.96572	0.96807	0.97212	0.96598	1.00000	0.95300	0.95372	0.99358
B68	0.90972	0.93163	0.90748	0.93912	0.92971	0.93808	0.95300	1.00000	0.89597	0.95613
B71	0.95836	0.92705	0.95279	0.91436	0.93914	0.90734	0.95372	0.89597	1.00000	0.96475
Net. Avg.	0.97941	0.98317	0.97843	0.97518	0.98330	0.97134	0.99358	0.95613	0.96475	1.00000

30 – 50 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.84135	0.87356	0.84746	0.87274	0.89531	0.93183	0.86533	0.82390	0.93296
B62	0.84135	1.00000	0.89125	0.92841	0.90532	0.87446	0.88507	0.85754	0.90444	0.94623
B63	0.87356	0.89125	1.00000	0.85356	0.90357	0.84382	0.87950	0.79096	0.89781	0.93448
B64	0.84746	0.92841	0.85356	1.00000	0.92931	0.93618	0.91742	0.92468	0.91630	0.96436
B65	0.87274	0.90532	0.90357	0.92931	1.00000	0.90231	0.93224	0.89515	0.87741	0.96158
B66	0.89531	0.87446	0.84382	0.93618	0.90231	1.00000	0.94641	0.93171	0.85360	0.95622
B67	0.93183	0.88507	0.87950	0.91742	0.93224	0.94641	1.00000	0.90601	0.84647	0.96541
B68	0.86533	0.85754	0.79096	0.92468	0.89515	0.93171	0.90601	1.00000	0.85742	0.93561
B71	0.82390	0.90444	0.89781	0.91630	0.87741	0.85360	0.84647	0.85742	1.00000	0.93834
Net. Avg.	0.93296	0.94623	0.93448	0.96436	0.96158	0.95622	0.96541	0.93561	0.93834	1.00000

50 – 70 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.78395	0.84976	0.89576	0.84772	0.88123	0.93839	0.86423	0.74458	0.93849
B62	0.78395	1.00000	0.82169	0.72200	0.79219	0.65670	0.81658	0.73580	0.87576	0.87287
B63	0.84976	0.82169	1.00000	0.79496	0.87533	0.82344	0.88631	0.84560	0.81340	0.93282
B64	0.89576	0.72200	0.79496	1.00000	0.83035	0.90062	0.87436	0.89281	0.80115	0.93137
B65	0.84772	0.79219	0.87533	0.83035	1.00000	0.83788	0.88599	0.82244	0.76466	0.92106
B66	0.88123	0.65670	0.82344	0.90062	0.83788	1.00000	0.87793	0.88378	0.70048	0.90933
B67	0.93839	0.81658	0.88631	0.87436	0.88599	0.87793	1.00000	0.91215	0.76284	0.95577
B68	0.86423	0.73580	0.84560	0.89281	0.82244	0.88378	0.91215	1.00000	0.79632	0.93452
B71	0.74458	0.87576	0.81340	0.80115	0.76466	0.70048	0.76284	0.79632	1.00000	0.88538
Net. Avg.	0.93849	0.87287	0.93282	0.93137	0.92106	0.90933	0.95577	0.93452	0.88538	1.00000

Table 2. (Continued)

70 to 90 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.64863	0.81047	0.81824	0.78378	0.85451	0.87962	0.90083	0.78438	0.89274
B62	0.64863	1.00000	0.88920	0.60153	0.81656	0.58410	0.58418	0.72662	0.85536	0.84539
B63	0.81047	0.88920	1.00000	0.75167	0.93489	0.79259	0.76357	0.87095	0.88672	0.95209
B64	0.81824	0.60153	0.75167	1.00000	0.83589	0.92092	0.85085	0.87836	0.76831	0.89274
B65	0.78378	0.81656	0.93489	0.83589	1.00000	0.83264	0.75602	0.84324	0.86166	0.94577
B66	0.85451	0.58410	0.79259	0.92092	0.83264	1.00000	0.88163	0.90646	0.79042	0.90513
B67	0.87962	0.58418	0.76357	0.85085	0.75602	0.88163	1.00000	0.90779	0.73445	0.86870
B68	0.90083	0.72662	0.87095	0.87836	0.84324	0.90646	0.90779	1.00000	0.87118	0.95222
B71	0.78438	0.85536	0.88672	0.76831	0.86166	0.79042	0.73445	0.87118	1.00000	0.93413
Net. Avg.	0.89274	0.84539	0.95209	0.89274	0.94577	0.90513	0.86870	0.95222	0.93413	1.00000

90 – 110 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.39300	0.47371	0.76862	0.43093	0.71358	0.74665	0.75034	0.57811	0.63319
B62	0.39300	1.00000	0.89161	0.57331	0.93521	0.69100	0.48876	0.64673	0.85403	0.91759
B63	0.47371	0.89161	1.00000	0.55915	0.90900	0.65673	0.49298	0.69033	0.90594	0.92727
B64	0.76862	0.57331	0.55915	1.00000	0.58073	0.88526	0.86925	0.88677	0.66693	0.77423
B65	0.43093	0.93521	0.90900	0.58073	1.00000	0.71058	0.55668	0.68066	0.88858	0.94354
B66	0.71358	0.69100	0.65673	0.88526	0.71058	1.00000	0.85514	0.83720	0.78969	0.85506
B67	0.74665	0.48876	0.49298	0.86925	0.55668	0.85514	1.00000	0.83429	0.62530	0.72062
B68	0.75034	0.64673	0.69033	0.88677	0.68066	0.83720	0.83429	1.00000	0.79018	0.84905
B71	0.57811	0.85403	0.90594	0.66693	0.88858	0.78969	0.62530	0.79018	1.00000	0.95033
Net. Avg.	0.63319	0.91759	0.92727	0.77423	0.94354	0.85506	0.72062	0.84905	0.95033	1.00000

110 – 130 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.38280	0.44506	0.75788	0.39240	0.56808	0.66581	0.61803	0.49261	0.56041
B62	0.38280	1.00000	0.91350	0.64740	0.96379	0.57369	0.49917	0.88616	0.93851	0.94988
B63	0.44506	0.91350	1.00000	0.64341	0.93457	0.57975	0.59243	0.89283	0.96310	0.95703
B64	0.75788	0.64740	0.64341	1.00000	0.63129	0.86847	0.70695	0.85597	0.67372	0.78977
B65	0.39240	0.96379	0.93457	0.63129	1.00000	0.52861	0.51753	0.88336	0.95742	0.95620
B66	0.56808	0.57369	0.57975	0.86847	0.52861	1.00000	0.72828	0.81698	0.59156	0.71502
B67	0.66581	0.49917	0.59243	0.70695	0.51753	0.72828	1.00000	0.70966	0.63127	0.67442
B68	0.61803	0.88616	0.89283	0.85597	0.88336	0.81698	0.70966	1.00000	0.92323	0.97256
B71	0.49261	0.93851	0.96310	0.67372	0.95742	0.59156	0.63127	0.92323	1.00000	0.97356
Net. Avg.	0.56041	0.94988	0.95703	0.78977	0.95620	0.71502	0.67442	0.97256	0.97356	1.00000

130 – 150 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.45521	0.51999	0.57672	0.49171	0.45450	0.66110	0.27929	0.57286	0.58393
B62	0.45521	1.00000	0.93444	0.78590	0.96747	0.68262	0.38574	0.55255	0.86397	0.97075
B63	0.51999	0.93444	1.00000	0.76067	0.92669	0.60407	0.39971	0.44884	0.89505	0.95640
B64	0.57672	0.78590	0.76067	1.00000	0.73715	0.89804	0.65110	0.47241	0.78308	0.87159
B65	0.49171	0.96747	0.92669	0.73715	1.00000	0.62721	0.39466	0.53844	0.85140	0.96108
B66	0.45450	0.68262	0.60407	0.89804	0.62721	1.00000	0.59562	0.41028	0.61786	0.75796
B67	0.66110	0.38574	0.39971	0.65110	0.39466	0.59562	1.00000	0.31238	0.46292	0.52790
B68	0.27929	0.55255	0.44884	0.47241	0.53844	0.41028	0.31238	1.00000	0.47250	0.55018
B71	0.57286	0.86397	0.89505	0.78308	0.85140	0.61786	0.46292	0.47250	1.00000	0.91075
Net. Avg.	0.58393	0.97075	0.95640	0.87159	0.96108	0.75796	0.52790	0.55018	0.91075	1.00000

Table 2. (Concluded)

150 to 170 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.62126	0.46919	0.65917	0.56808	0.62820	0.62425	0.54589	0.71150	0.67202
B62	0.62126	1.00000	0.84117	0.76677	0.93888	0.61018	0.46784	0.61508	0.86271	0.95780
B63	0.46919	0.84117	1.00000	0.66976	0.84482	0.47373	0.37753	0.56126	0.76613	0.90336
B64	0.65917	0.76677	0.66976	1.00000	0.75900	0.63490	0.54028	0.66011	0.81000	0.82313
B65	0.56808	0.93888	0.84482	0.75900	1.00000	0.58117	0.39902	0.62442	0.86203	0.96810
B66	0.62820	0.61018	0.47373	0.63490	0.58117	1.00000	0.57850	0.52341	0.62735	0.66213
B67	0.62425	0.46784	0.37753	0.54028	0.39902	0.57850	1.00000	0.46753	0.52621	0.53294
B68	0.54589	0.61508	0.56126	0.66011	0.62442	0.52341	0.46753	1.00000	0.67934	0.68974
B71	0.71150	0.86271	0.76613	0.81000	0.86203	0.62735	0.52621	0.67934	1.00000	0.91691
Net. Avg.	0.67202	0.95780	0.90336	0.82313	0.96810	0.66213	0.53294	0.68974	0.91691	1.00000

170 – 190 cm

site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.41300	0.41490	-0.09013	0.63255	0.39567	0.36786	0.51901	0.49077	0.61441
B62	0.41300	1.00000	0.64192	-0.09007	0.47240	0.38732	0.54192	0.52479	0.77742	0.82030
B63	0.41490	0.64192	1.00000	-0.36849	0.51257	0.14509	0.40714	0.54566	0.81494	0.89329
B64	-0.09013	-0.09007	-0.36849	1.00000	-0.04494	0.05755	0.02679	-0.19248	-0.23096	-0.20214
B65	0.63255	0.47240	0.51257	-0.04494	1.00000	0.52694	0.49891	0.74018	0.61093	0.73861
B66	0.39567	0.38732	0.14509	0.05755	0.52694	1.00000	0.33514	0.39019	0.33922	0.43102
B67	0.36786	0.54192	0.40714	0.02679	0.49891	0.33514	1.00000	0.46190	0.50643	0.63950
B68	0.51901	0.52479	0.54566	-0.19248	0.74018	0.39019	0.46190	1.00000	0.51051	0.71102
B71	0.49077	0.77742	0.81494	-0.23096	0.61093	0.33922	0.50643	0.51051	1.00000	0.90545
Net. Avg.	0.61441	0.82030	0.89329	-0.20214	0.73861	0.43102	0.63950	0.71102	0.90545	1.00000

190 – 200 cm

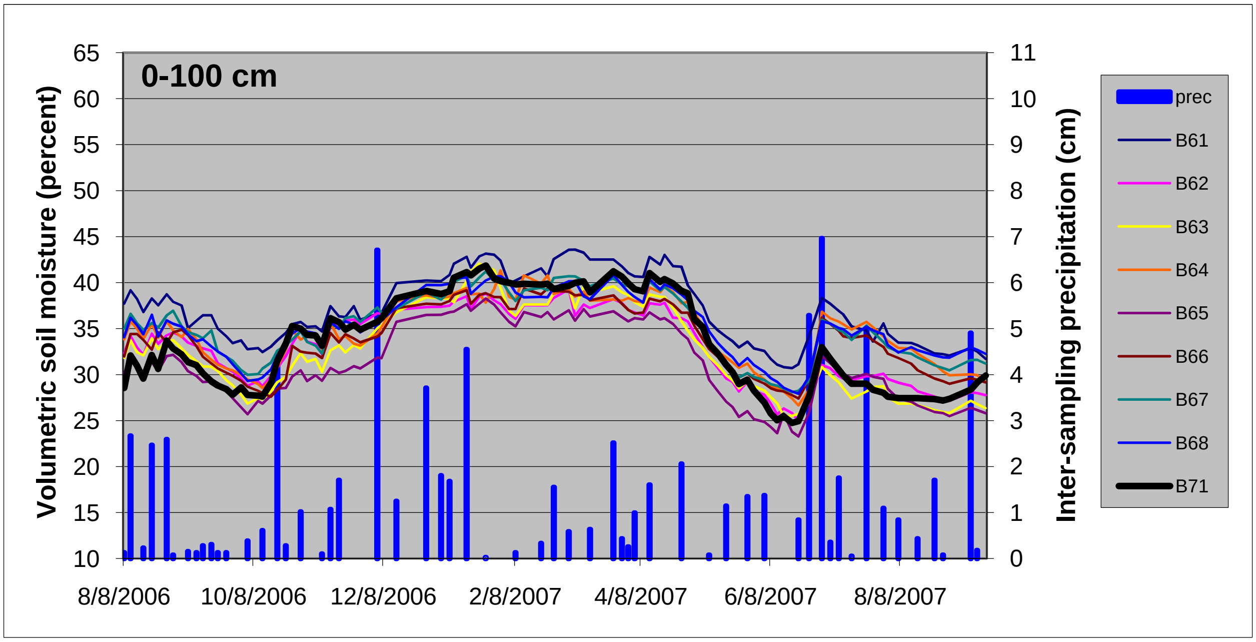
site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	***B71***	*Net. Avg.*
B61	1.00000	0.48849	0.32041	0.63212	0.41637	0.64504	0.64200	0.50349	0.48300	0.76912
B62	0.48849	1.00000	0.54719	0.41546	0.23390	0.47535	0.44409	0.47130	0.50228	0.71183
B63	0.32041	0.54719	1.00000	0.41602	0.22775	0.53739	0.53250	0.14776	0.51364	0.76469
B64	0.63212	0.41546	0.41602	1.00000	0.34678	0.65895	0.59755	0.30760	0.58325	0.72917
B65	0.41637	0.23390	0.22775	0.34678	1.00000	0.38516	0.31820	0.42088	0.38378	0.48655
B66	0.64504	0.47535	0.53739	0.65895	0.38516	1.00000	0.76550	0.28848	0.51756	0.83261
B67	0.64200	0.44409	0.53250	0.59755	0.31820	0.76550	1.00000	0.20536	0.43025	0.81896
B68	0.50349	0.47130	0.14776	0.30760	0.42088	0.28848	0.20536	1.00000	0.45965	0.50126
B71	0.48300	0.50228	0.51364	0.58325	0.38378	0.51756	0.43025	0.45965	1.00000	0.70287
Net. Avg.	0.76912	0.71183	0.76469	0.72917	0.48655	0.83261	0.81896	0.50126	0.70287	1.00000

c. Upper vs. Lower Root Zone Analysis

One further analysis was made with these data: a subjective division of output into upper and lower root zones as used in some previous studies (e.g., Hollinger and Isard, 1994): 0–100 cm and 100–200 cm, respectively (Figure 9). Volumetric soil moisture appeared relatively similar at all sites in the upper root zone (Figure 9a) with an overall inter-site (bi-weekly) average standard deviation of 2.02%, and a range of 1.13 and 3.12% (Table 3). Intra-site standard deviation also was quite similar between the sites. The historic site (B71) showed the greatest value, 5.17%, meaning it had the highest variability. As observed in the individual layers of Figure 7, large differences between sites at depths below 90 cm were confirmed in the lower root zone (Figure 9b), generating an average bi-weekly standard deviation of 4.57% and ranging between 3.19 and 6.16%. Differences again were likely caused by the intrusion of the water table. This condition may have been semi-permanent through a greater depth at B61 and B67, revealing high soil moisture values continuously, while at other sites, the intrusion was seasonal or perhaps did not occur at all (e.g., B68). The intra-site standard deviation values yield support for this conclusion at B61 and B67, with values of approximately 1.1%. Strong variability was evident at B63 and B65, where the water table purportedly came in and then drained out, reported soil moisture standard deviation values in excess of 6%.

As suggested earlier in deeper layers, sites appeared to be stratified with the smallest terrain slopes possessing the highest moisture and nearly static moisture trends throughout the experiment: B61, B66, and B67. Conversely, those with a greater terrain slope displayed periods of both relatively high and low soil moisture: B63, B68, and B71. A large difference between some sites was quite noticeable. During parts of the experiment, the level of soil moisture observed at Site B61 (43%) in the lower root zone was 80% higher than the value measured at Site B63 (24%).

The coefficient of determination (R^2) between each field site and B71 is better than 0.80 at all sites in the 0- to 100-cm layer and at most sites in the 100- to 200-cm layer. However, values at B61 and B67 were only 0.53, indicating a larger difference likely due to the high continuous moisture levels at these sites, which was not observed at B71. Data from B71 were located roughly in the middle of the set of sites seen visually in Figure 9, but overall it slightly under measured soil moisture in these two layers by 0.56 and 1.81% (Table 3), respectively. However, if the two sites most continuously affected by the water table intrusion (B61 and B67) were excluded, the remaining values were much closer. Although some values are not considered largely different from many of the other sites, the question remains concerning the impacts these revelations would have on previous research if either of the extremes observed in B61 or B63 had been selected as the location of our original neutron probe.



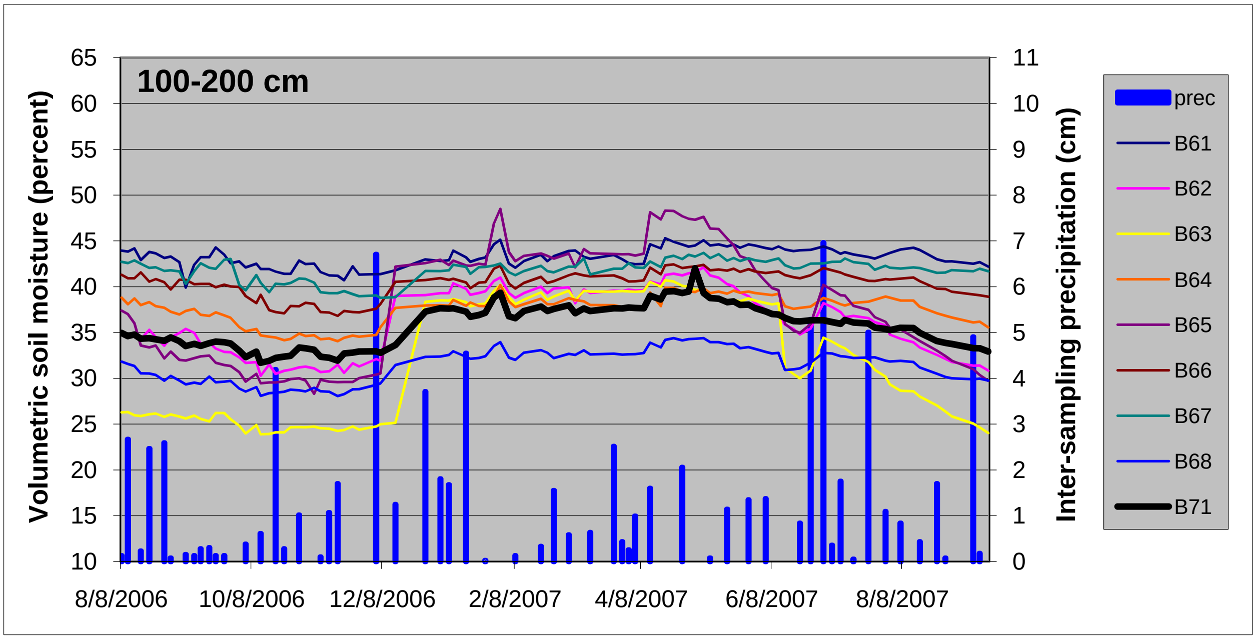


Figure 9. Volumetric soil moisture (percent) within the upper and lower root zones at eight neutron probe locations, plus the historic site, and precipitation totals (cm) between sampling dates at the BEARS field station during SMUSE.

Table 3. Same as Table 1, Except for the 0- to 100- and 100- to 200-cm Layers

	site	*B61*	*B62*	*B63*	*B64*	*B65*	*B66*	*B67*	*B68*	*Average B61:B68*	*B71*	*Bi-weekly std.dev.*	*Difference: field-B71*
0-100 cm	mean	37.06	32.99	32.58	34.52	31.04	33.71	35.05	35.15	34.01	33.45	2.02	0.56
	max	43.58	39.27	42.06	41.33	38.26	39.36	41.20	40.83	40.01	41.86	3.12	
	min	30.71	24.97	25.49	26.64	23.28	27.39	28.09	27.92	26.91	24.75	1.13	
	std. dev.	3.74	3.93	4.70	3.67	4.20	3.61	3.71	3.49	3.79	5.17		
	R^2	0.85163	0.89922	0.90872	0.80559	0.89167	0.81890	0.85598	0.87444	0.90726			
100-200 cm	mean	43.22	36.18	32.02	37.54	37.78	40.36	41.82	31.42	37.54	35.73	4.57	1.81
	max	45.31	42.10	40.71	40.17	48.50	42.45	43.69	34.39	41.91	42.01	6.16	
	min	39.91	30.28	23.88	34.05	28.32	36.81	38.80	28.06	33.09	31.69	3.19	
	std. dev.	1.08	3.61	6.49	1.63	6.28	1.46	1.19	1.85	2.76	2.32		
	R^2	0.53273	0.89736	0.89679	0.73151	0.91462	0.67753	0.52844	0.92211	0.95592			

d. Clustered Station Analysis

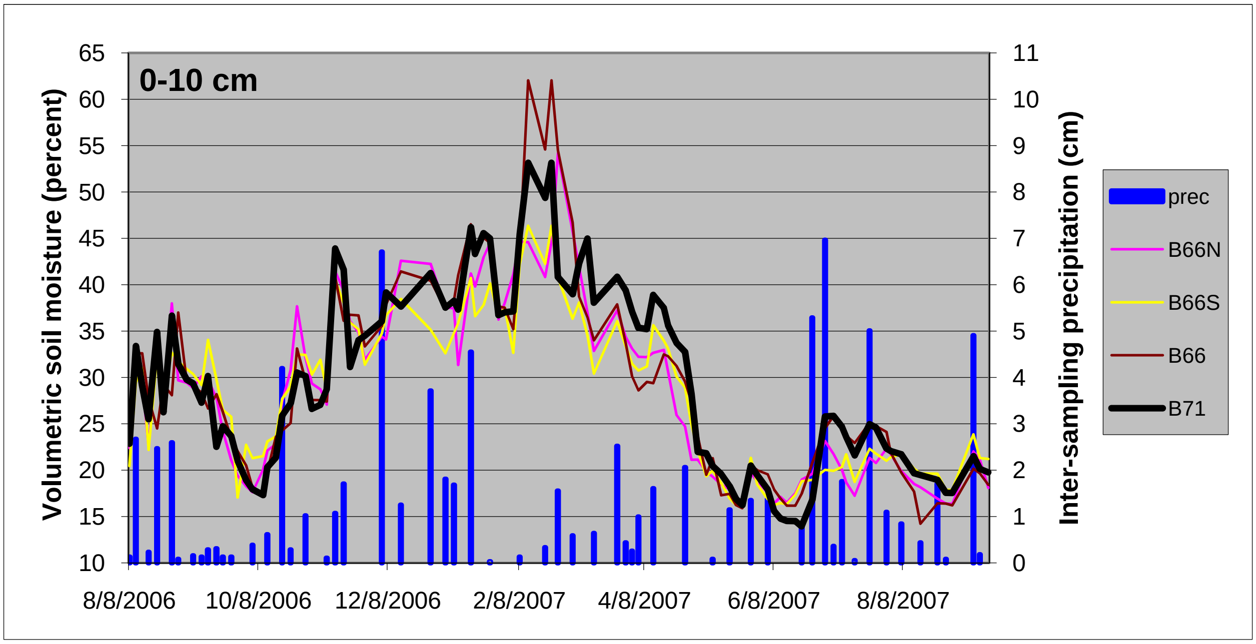
Collection of data from the clustered site, B66, was designed to observe changes in soil moisture over a very short distance (Figure 10). As described earlier, two additional neutron probe tubes were installed along a 2-m north-south line centered at B66. The historic monitoring site was included for comparison. Observations were collected on the same schedule used at all other sites.

Outputs show similar results to that observed at other sites. In the near surface layers (Figures 10a-d), volumetric soil moisture values at B66N, B66S, and B66 generally were close to one another. Figure 10a at the surface shows expected variability as was observed in Figure 7a with increases and decreases due to impacts from precipitation and drier periods. Data from all three clustered sites were reasonably close in value, except for a short period in the middle of February at B66, when a temporary increase in soil moisture was measured. This rather large exception was mirrored at the historic site (approximately 105 meters away), but was not observed in the two other cluster sites 1 meter to the north and south. The event is unexplained. It likely is not coincidental, because it was observed also at B64 and B63. It may represent some particular undetermined surface attributes, or perhaps could have resulted from melting of random snow drifts above these sites. Snow observations during SMUSE were not made.

From 10 cm to 70 cm deep (Figure 10b-d), soil moisture at all three cluster sites were very similar to each other. The spread of values was generally around 5%, much smaller than the 10–15% observed in Figure 7b-d. With few exceptions, traces were similar in comparison to B71.

Beginning in the 70- to 90-cm layer (Figure 10e) and continuing through the 150- to 170-cm layer, a large variability in soil moisture was observed at the southern site of the cluster that was not measured at the other two sites. Values at B66S were the lowest of the three stations in early December, highest in winter and early spring, then lowest again at the end of the experiment. All sites observed increases on the same schedule, but not with the magnitude observed at B66S. Its trends closely match trends at B63 and B65, purportedly due to a rising water table. The concurrent soil moisture patterns at B66 and B66N closely paralleled Site 71 and other sites not strongly impacted by the varying water table.

In the two lowest layers (Figure 10j, k), soil moisture patterns paralleled trends observed among other sites in this layer (Figure 7j, k), relatively flat temporal trends, but with a moderate spatial variability among the three sites just two meters apart. Soil moisture at Sites B66N and B66 measured roughly 33 and 41%, respectively. If the differences observed in the lower two layers at the site cluster were due to soil properties, results here suggest that choices of representative sites for future regional soil moisture networks could be complex. Overall, volumetric soil moisture observed at the clustered sites, 1 m apart, were not as consistent with each other as may have been surmised prior to the experiment. Individually, they showed some surprising similarities to other network sites, not observed to the same scale with each other. This highlights interest in the succeeding section on soil attributes to discover if observed differences provide an explanation for the unexpected varied results at the clustered sites.



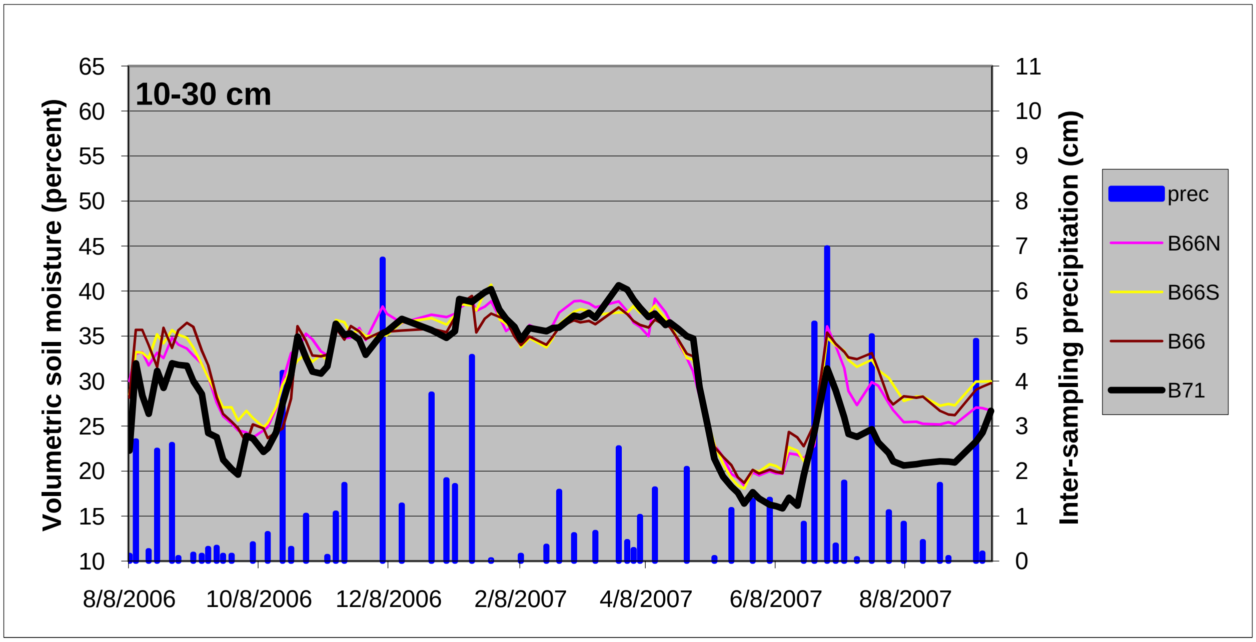
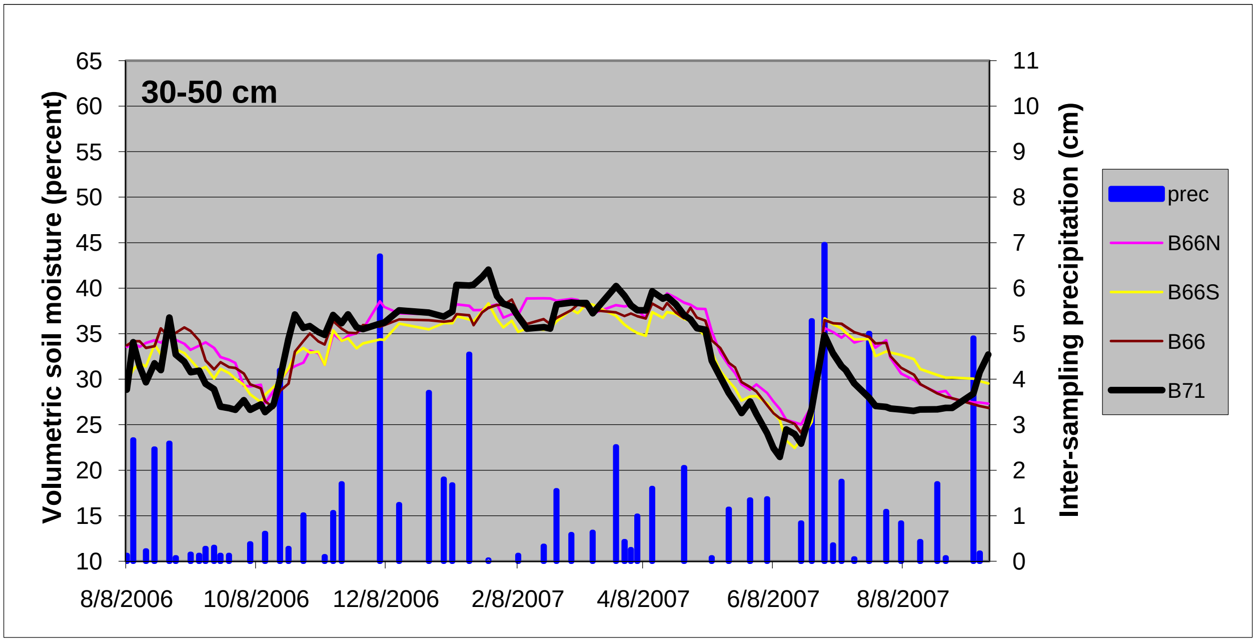


Figure 10. Volumetric soil moisture (percent) within 11 layers at the clustered site location, plus the historic soil moisture site (B71), and precipitation totals (cm) between sampling dates during SMUSE.



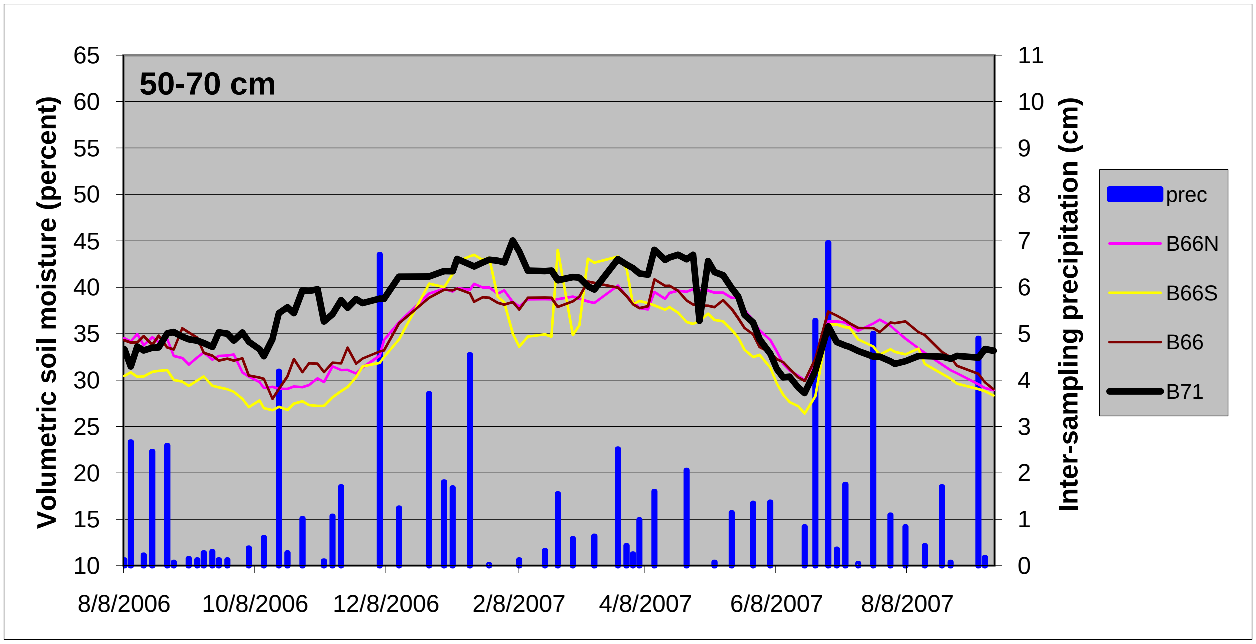
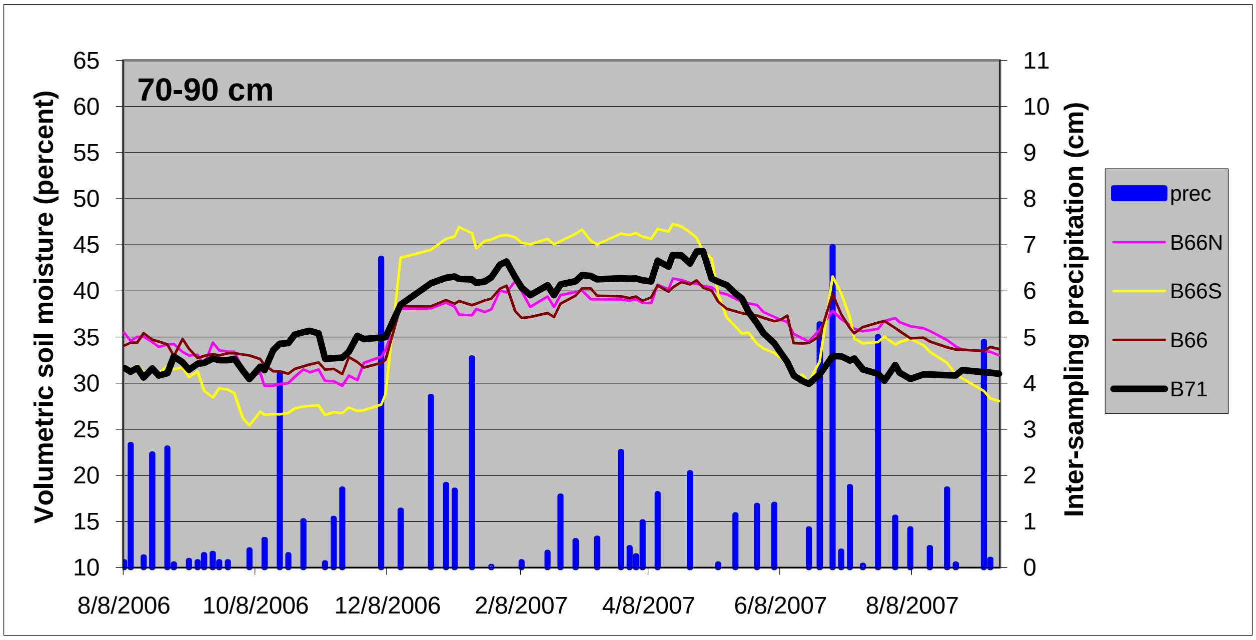


Figure 10. (continued)



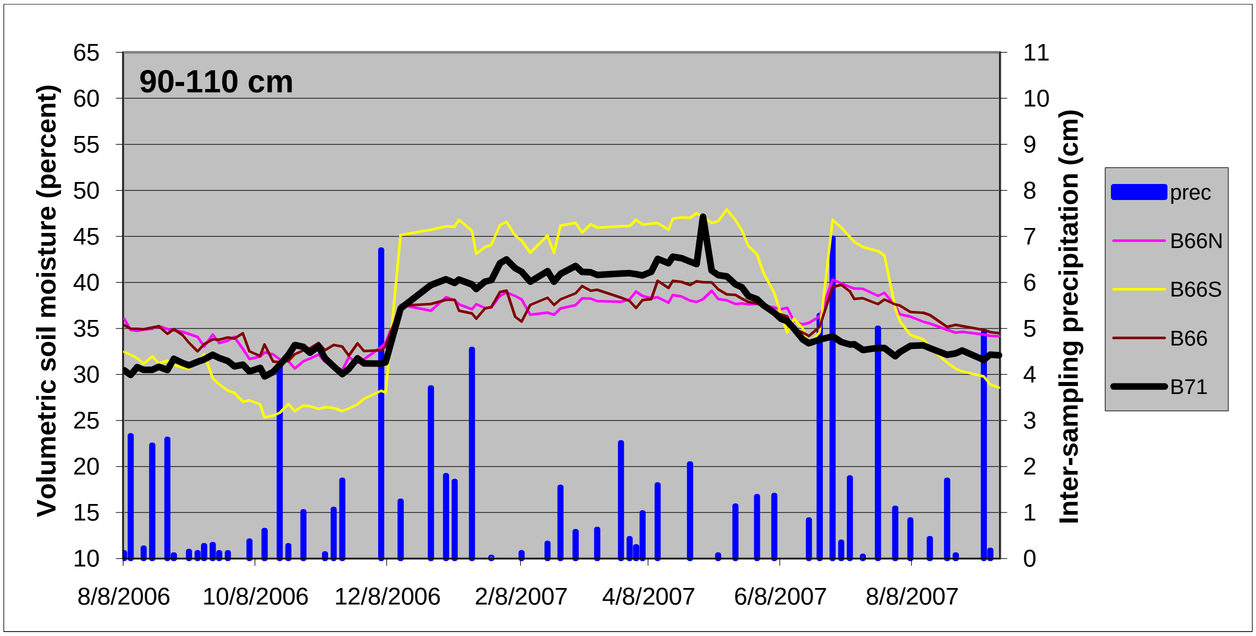
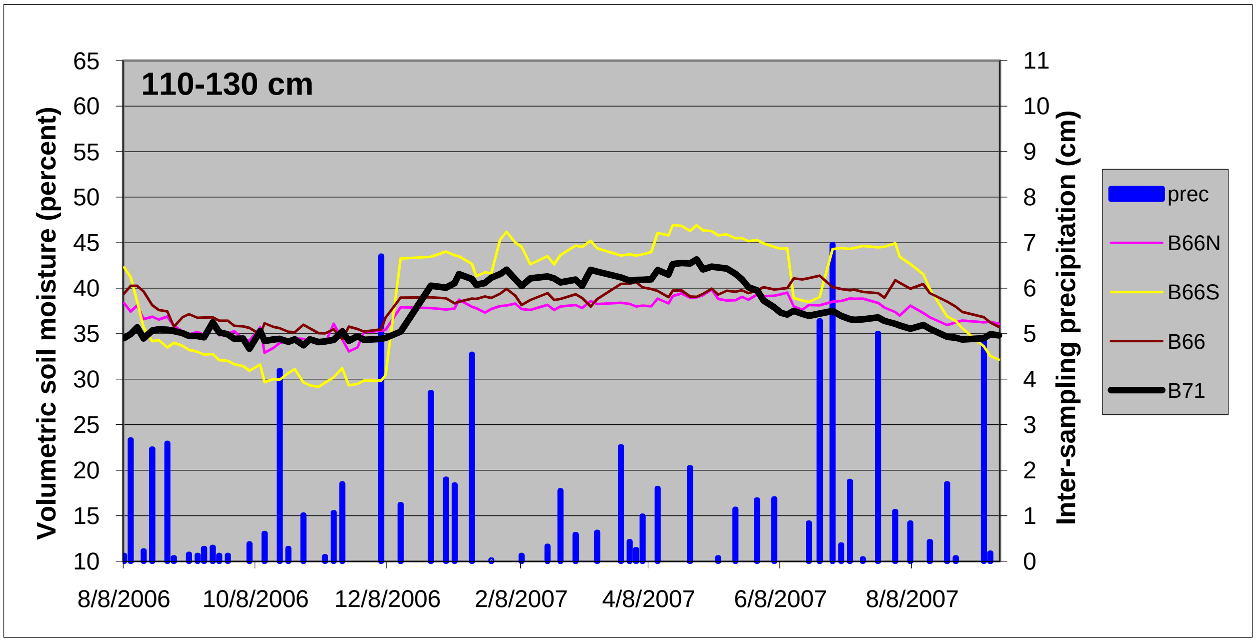


Figure 10. (continued)



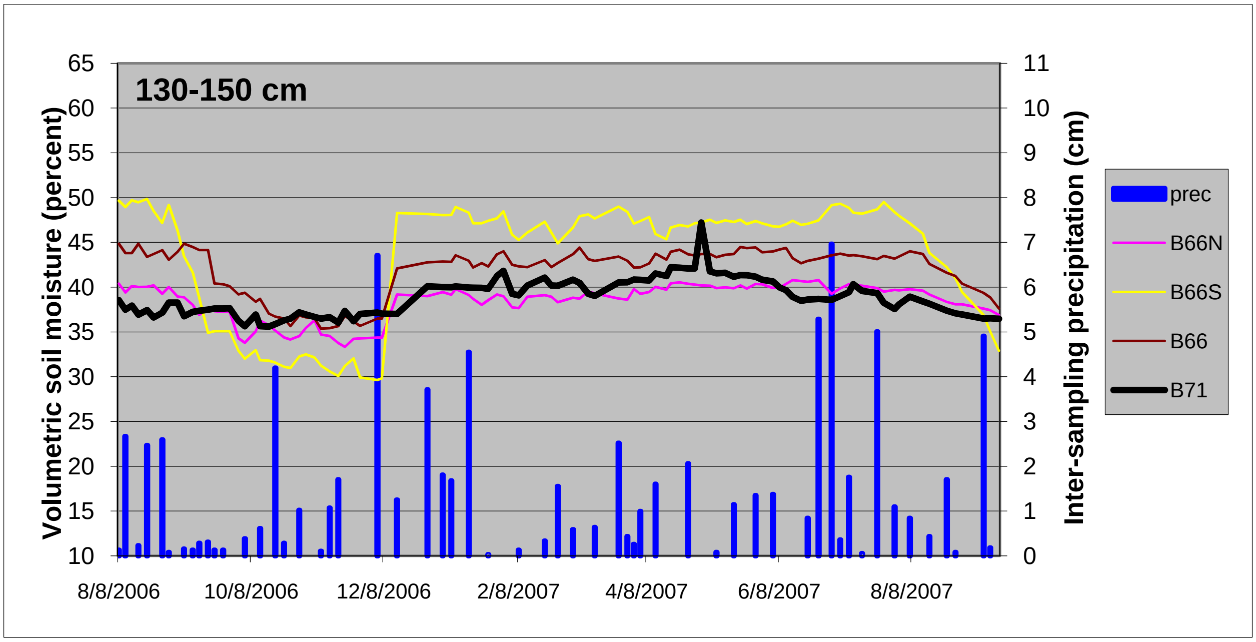
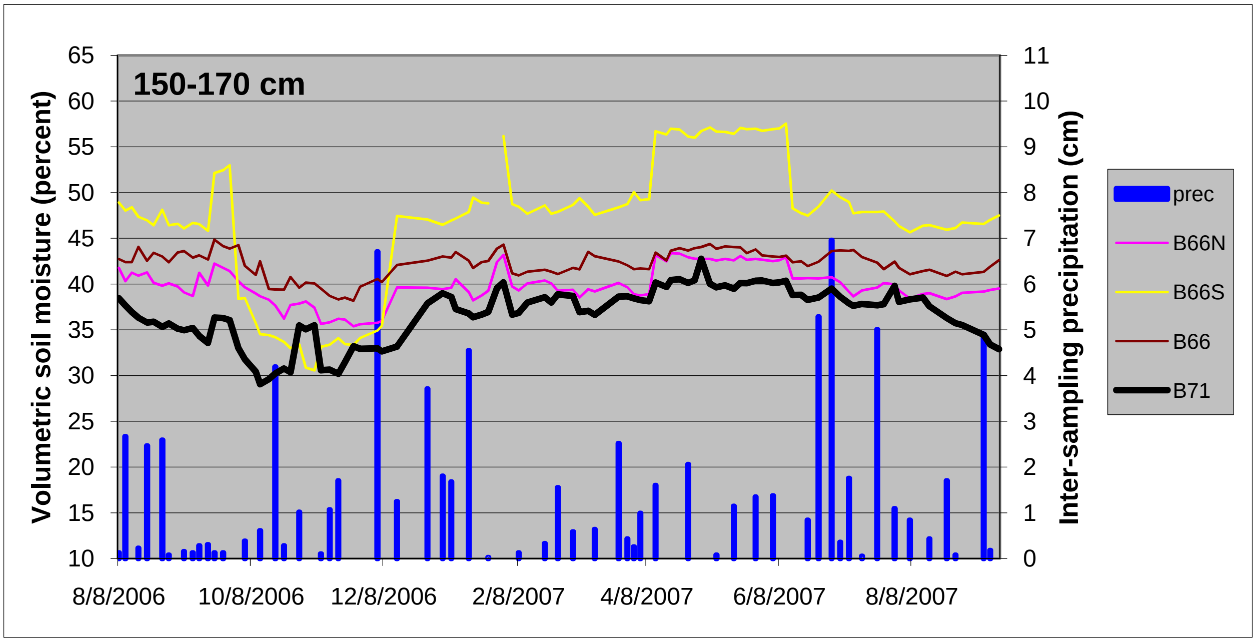


Figure 10. (continued)



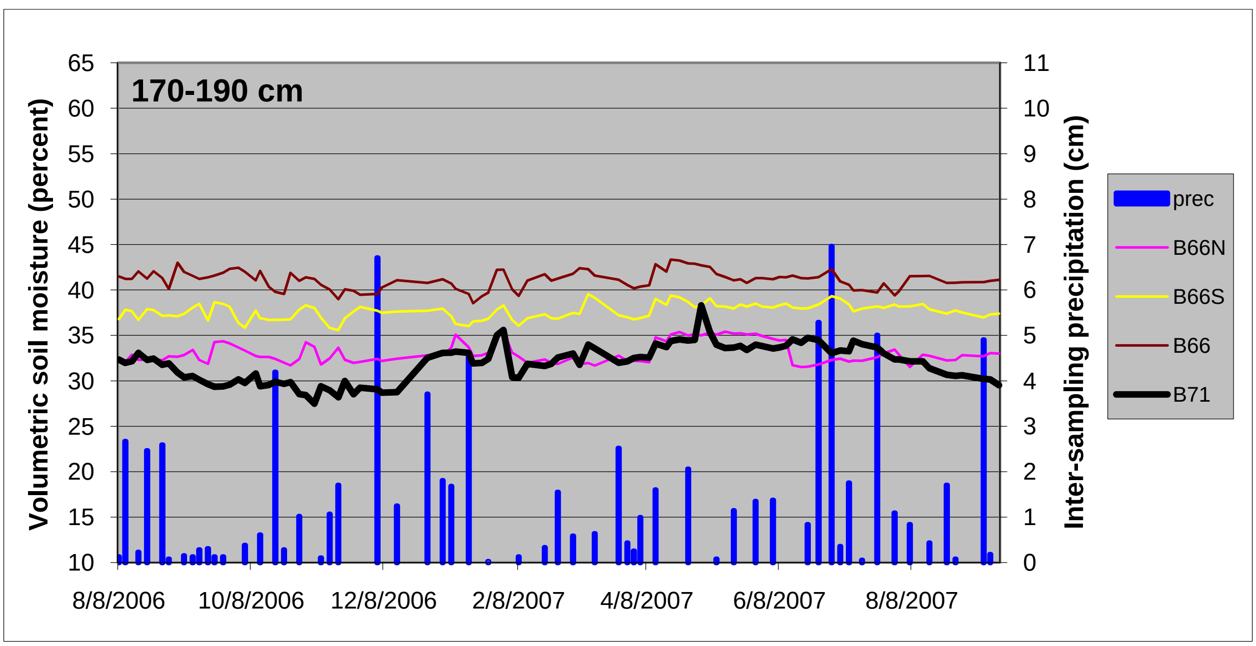


Figure 10. (continued)

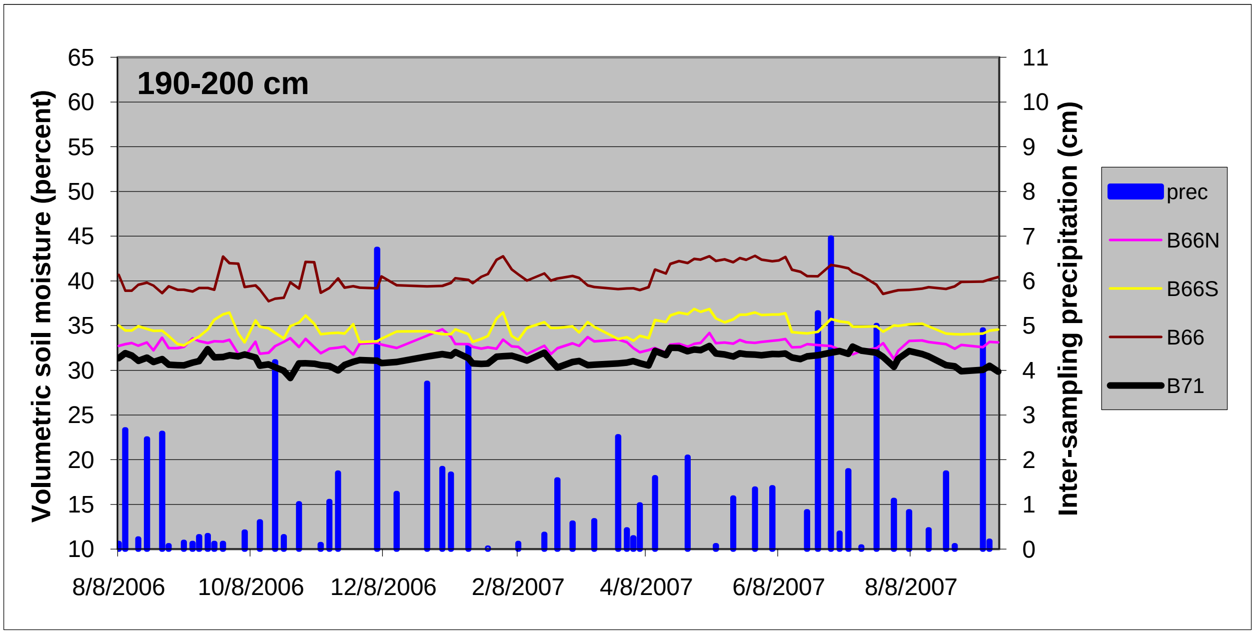


Figure 10. (concluded)

e. Soil Core Analyses

On September 17–18, 2007, trenching was performed at all randomly selected neutron probe sites to provide a bare wall, 2.1 meters deep, from which core samples could be extracted at all neutron probe observation levels. Core samples were collected, documented, and placed in soil tins. A soil color analysis was performed of the soils at each observation level, and photographic records were taken of all walls (Figure 11). Subsequently, trenches were refilled. It was attempted to replace soil to the same level as before trenching began. A safety officer was selected from ISWS staff, and defined safety protocols, developed prior to trenching activities, were followed to mitigate the danger of these activities to staff.

Although the observed water table level from the site shallow water well on the day of core extractions was at 2.3 m below the surface, 0.3 m below our deepest planned core sampling, soil core compression due to soil wetness occurred in lower levels at four sites, B61, B64, B66, and B67. Perhaps only coincidentally, these four sites were also sites with the lowest terrain slopes. As stated in earlier sections, it is suggested that these conditions could have resulted from a water table intrusion into the lower levels of observations, and that the water table height possessed substantial variability across the field of measurements, causing the level of observed wetness in the different trenches.

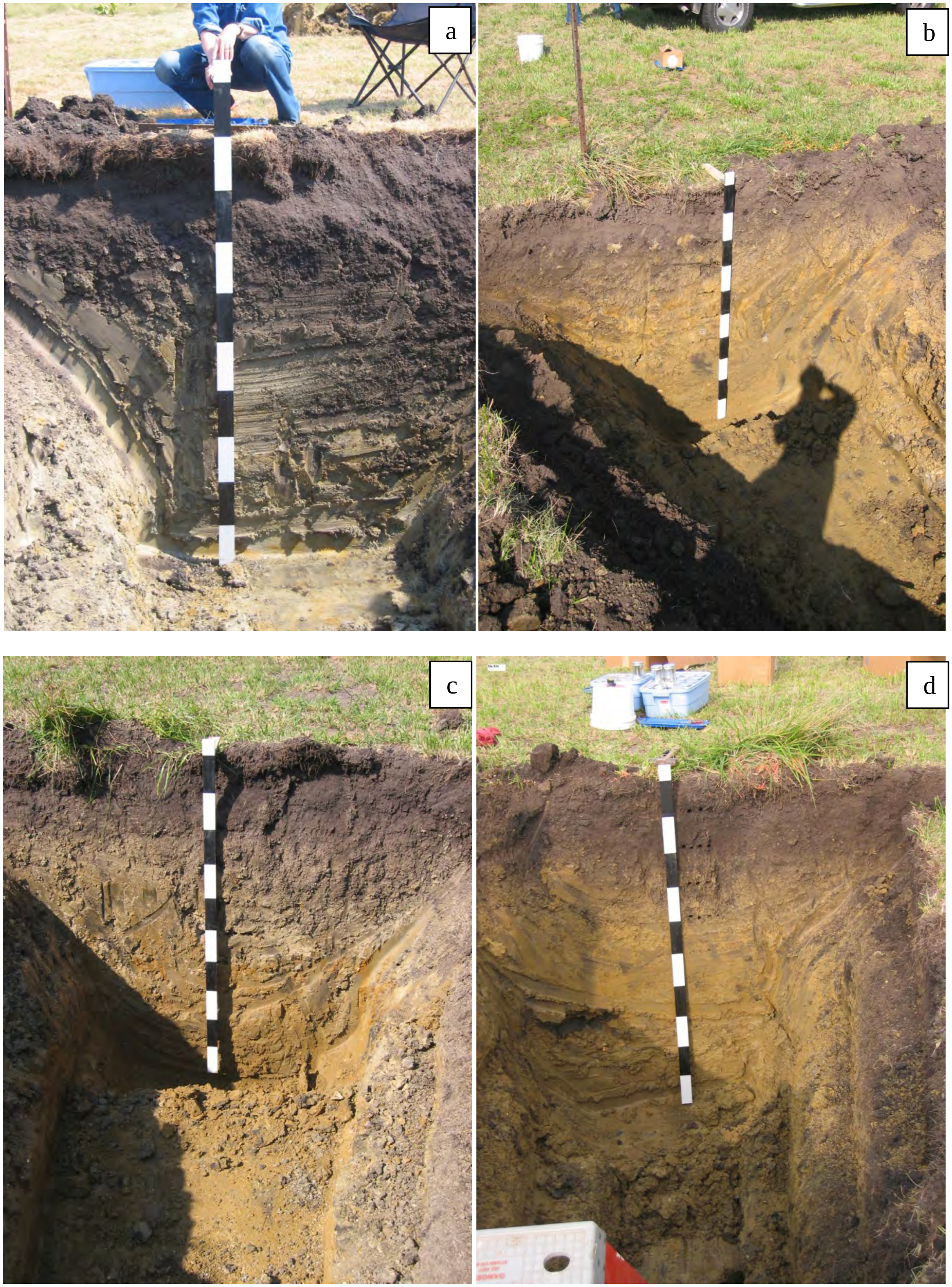


Figure 11. Photograph records of trenched walls during SMUSE at sites: a. B61, b. B62, c. B63, d. B64, e. B65, f. B66, g. B67, and h. B68. Markings on stick show 20-cm intervals to match soil moisture observations and coring levels. (Photo credit: R. W. Scott)

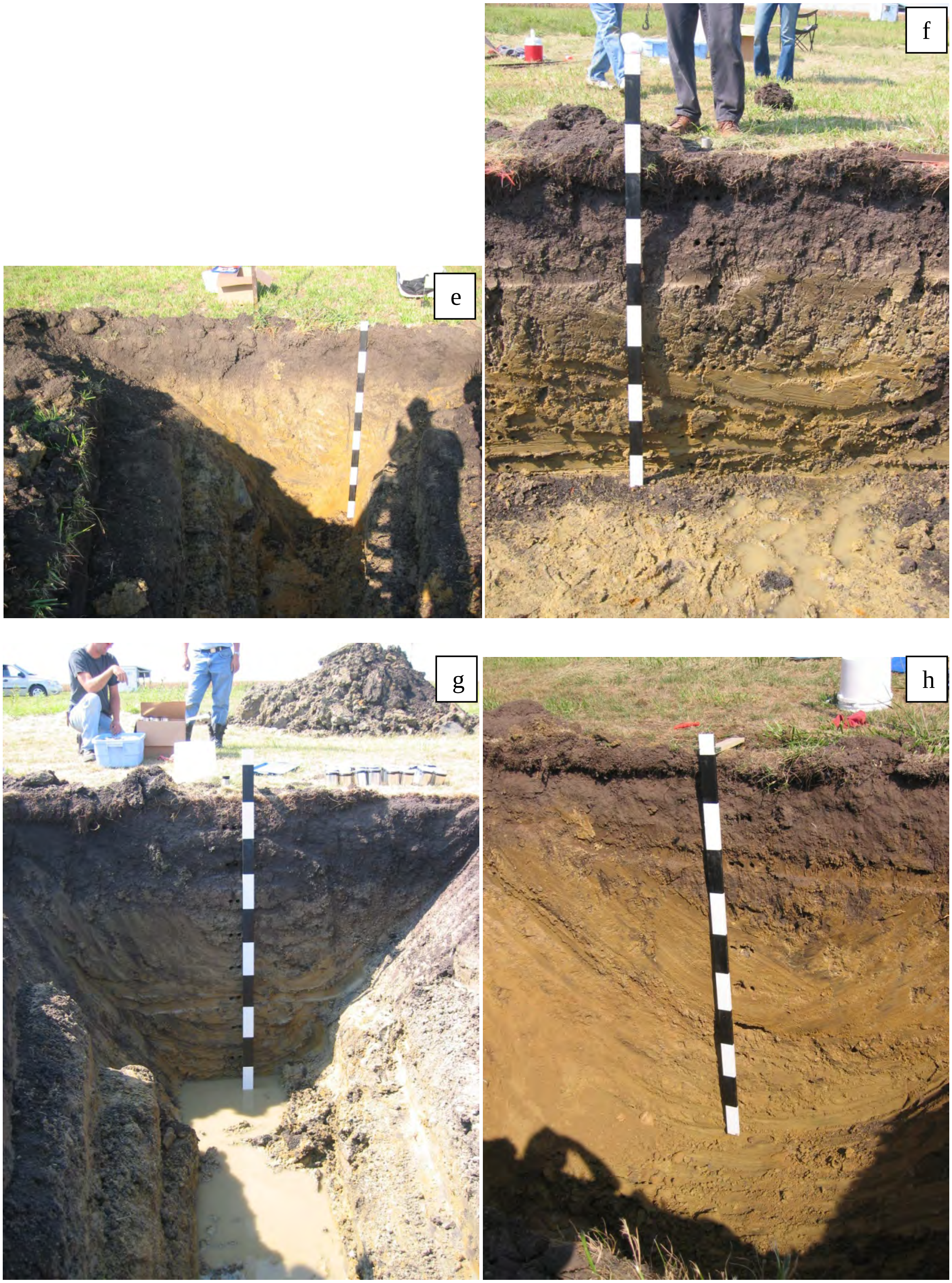


Figure 11. (Continued)

Most trenches displayed muddy conditions at 2 m. Saturated conditions were observed at the base of the trench at B61 (Figure 11a) and B66 (Figure 11f). B67 had standing water at 1.7 m (Figure 11g). At B64 (Figure 11d), water pulsed out of a core hole at 1.4 m deep with each strike on the soil corer, attempting to extract a core at 1.6 m. This suggested there was a trapped water lens within the particular soil profile at this station. Core compression occurred at all of these sites, beginning as high as 1.6 m. Soil cores were not collected at levels below where compression occurred. The remaining sites were relatively dry at all levels with no compression, except at 180 cm at B65. The base at B68 was exceptionally dry (Figure 11h).

Results of the soil core lab analyses are presented in Table 4. The data indicate an apparent relationship with surface slope suggested earlier. Even though the variability in slopes across the entire 5.9 hectare field area may be considered slight (only 1 m of total relief), locations with lowest terrain slopes were also sites that: (1) reported the most consistent and relatively high soil moisture values in the deeper layers throughout the experiment, (2) generally did not have seasonal low soil moisture conditions in summer and autumn, and (3) generally reported the highest soil porosity and lowest bulk density values (Table 4). Sites with greater terrain slopes generally reported lower soil porosity and higher bulk densities, as well as higher temporal soil moisture variability.

Soil moisture was identified in soil cores and along the trench walls by their color via Munsell Color (1976) with results shown in Table 5. Descriptions from this source are as follows. “The hue notation of a color indicates its relation to a visually equally-spaced scale of 100 hues. The value notation indicates the lightness or darkness of a color in relation to a neutral grey scale. The chroma notation indicates the degree of divergence of a given hue from a neutral gray of the same value.” Full descriptions of hue, value, and chroma are provided from various Internet sources and at Munsell Color (1976). An excellent description of soil color related to soil moisture can be found at the U.S. Department of Agriculture (2009) Natural Resources Conservation Service Web site.

Field and lab soil analyses indicated that animal burrows, crotovinas (former burrows filled with A horizon material), partially filled burrows, and mottling (varying soil colors due to the presence of water) existed in all soil profiles (Table 5). The mottling, created by the fluctuating water table, is indicative of heterogeneity of soils processing moisture. The parent materials here are 2+ m of loess soil. Despite these heterogeneities, some general trends are present. Soils tended to become more compressed (more dense, less pore space) with depth, with one profile (B65) having a density maximum in the B horizon at 80–100-cm depth (Table 4). The sites with very low surface slope profiles had thicker A horizons and yellower subsoils, features diagnostic of being wetter than the other soil profiles with greater surface slopes. In general, water content in cores tended to increase with depth (Table 4). However, in three drier profiles (B62, B63, B65), this trend was interrupted deep in the profile. This latter trend is consistent with rewetting of previously dried soil profiles. Overall, these differences in soil genesis may suggest that the topographic differences impacting soil moisture were retained from pre-settlement prairie conditions.

Table 4. Site Surface Slopes and Average Soil Core Attributes at Each Sampling Level

Site	*Surface Slope*	*Level (cm)*	*Dry soil (g)*	*Water mass (g)*	*Water by volume (%)*	*Soil bulk density (g/cm^3)*	*Porosity (%)*	*Site*	*Surface Slope*	*Level (cm)*	*Dry soil (g)*	*Water mass (g)*	*Water by volume (%)*	*Soil bulk density (g/cm^3)*	*Porosity (%)*
B61	0.0050	20	29.69	5.44	22.36	1.22	54.0	B65	0.0175	20	30.51	5.97	24.55	1.25	52.7
		40	28.08	6.93	28.47	1.15	56.5			40	31.47	5.86	24.08	1.29	51.2
		60	30.68	6.37	26.18	1.26	52.4			60	32.12	4.92	20.22	1.32	50.2
		80	34.71	8.27	34.00	1.43	46.2			80	42.90	5.78	23.75	1.76	33.5
		100	34.22	9.34	38.37	1.41	46.9			100	41.87	6.07	24.96	1.72	35.1
		120	34.13	9.46	38.89	1.40	47.1			120	35.08	7.69	31.60	1.44	45.6
		140	33.69	9.67	39.74	1.38	47.8			140	35.18	8.21	33.74	1.45	45.4
		160	35.09	10.13	41.62	1.44	45.6			160	34.44	9.15	37.60	1.42	46.6
		180	NA	NA	NA	NA	NA			180	NA	NA	NA	NA	NA
		200	NA	NA	NA	NA	NA			200	39.75	6.35	26.11	1.63	38.4
B62	0.0408	20	36.22	5.36	22.04	1.49	43.8	B66	0.0183	20	29.85	5.23	21.51	1.23	53.7
		40	30.60	5.41	22.22	1.26	52.6			40	31.09	5.94	24.40	1.28	51.8
		60	34.37	6.28	25.82	1.41	46.7			60	32.06	5.65	23.22	1.32	50.3
		80	30.51	5.51	22.66	1.25	52.7			80	33.39	6.50	26.71	1.37	48.2
		100	34.22	6.46	26.53	1.41	46.9			100	33.95	7.56	31.06	1.40	47.4
		120	36.84	6.66	27.36	1.51	42.9			120	34.98	8.21	33.73	1.44	45.7
		140	38.70	7.48	30.74	1.59	40.0			140	35.95	8.77	36.03	1.48	44.2
		160	41.14	8.09	33.26	1.69	36.2			160	34.60	9.25	38.03	1.42	46.3
		180	41.14	6.74	27.71	1.69	36.2			180	NA	NA	NA	NA	NA
		200	42.41	5.85	24.06	1.74	34.2			200	NA	NA	NA	NA	NA
B63	0.0433	20	29.85	6.06	24.90	1.23	53.7	B67	0.0050	20	29.08	5.03	20.69	1.20	54.9
		40	31.74	5.12	21.04	1.30	50.8			40	29.73	5.31	21.84	1.22	53.9
		60	34.37	5.76	23.69	1.41	46.7			60	33.03	5.62	23.08	1.36	48.8
		80	32.87	6.25	25.70	1.35	49.0			80	33.54	5.97	24.55	1.38	48.0
		100	35.40	6.76	27.79	1.45	45.1			100	35.30	8.87	36.45	1.45	45.3
		120	42.21	4.78	19.63	1.73	34.5			120	35.00	9.14	37.58	1.44	45.7
		140	40.31	4.77	19.60	1.66	37.5			140	34.59	9.11	37.44	1.42	46.4
		160	40.98	4.39	18.04	1.68	36.4			160	33.53	9.99	41.06	1.38	48.0
		180	42.07	5.27	21.66	1.73	34.8			180	NA	NA	NA	NA	NA
		200	43.99	5.45	22.41	1.81	31.8			200	NA	NA	NA	NA	NA
B64	0.0150	20	33.53	4.88	20.06	1.38	48.0	B68	0.0592	20	28.52	5.07	20.85	1.17	55.8
		40	32.81	5.93	24.38	1.35	49.1			40	30.08	7.58	31.16	1.24	53.3
		60	34.14	5.71	23.45	1.40	47.1			60	32.62	8.21	33.73	1.34	49.4
		80	36.28	5.92	24.32	1.49	43.7			80	35.63	7.83	32.19	1.46	44.7
		100	34.76	6.15	25.29	1.43	46.1			100	40.37	5.58	22.93	1.66	37.4
		120	35.53	7.78	31.99	1.46	44.9			120	39.58	4.75	19.51	1.63	38.6
		140	37.18	8.30	34.11	1.53	42.3			140	43.99	8.02	32.95	1.81	31.8
		160	27.48	5.77	23.70	1.13	57.4			160	39.03	7.01	28.82	1.60	39.5
		180	NA	NA	NA	NA	NA			180	39.59	6.99	28.71	1.63	38.6
		200	NA	NA	NA	NA	NA			200	42.14	7.82	32.15	1.73	34.6

Note: NA = Data not available due to compression during soil sampling.

Table 5. Munsell Soil Color Chart Analysis

Site B61

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	black	5YR	2.5/1
60	grayish brown	10YR	5/2
80	gray	10YR	6/1
100	gray	10YR	6/1
120	gray	10YR	6/1
140	light brownish gray	10YR	6/2
160	light brownish gray	10YR	6/2
180	compression (no sample)		
200	compression (no sample)		

Site B62

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	very dark gray	5YR	3/1
40	dark reddish gray, some mottling	5YR	4/2
60	dark reddish gray, some mottling	5YR	4/2
80	mottled		
100	reddish yellow, mottled	5YR	6/6
120	yellowish red, mottled	7.5YR	5/6
140	reddish yellow, mottled	5YR	6/6
160	reddish gray, mottled	5YR	5/2
180	reddish brown, mottled, rocks in pit	5YR	5/3
200	reddish gray, some mottling	5YR	5/2

Site B63

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	dark reddish brown	5YR	3/2
60	reddish brown	5YR	4/3
80	reddish brown, mottled	5YR	4/3
100	gray, mottled	5YR	5/1
120	reddish gray, mottled	7.5YR	5/2
140	reddish brown, heavily mottled	5YR	5/3
160	reddish gray, heavily mottled, stones in pit, black-filled holes	5YR	5/2
180	reddish gray mottled	5YR	5/2
200	reddish brown mottling	5YR	4/4

Table 5. (Continued)

Site B64

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	very dark gray	5YR	2.5/1
60	variegated with dense root channels, mix of above/below colors		
80	variegated with dense root channels, mix of above/below colors		
100	yellowish brown	10YR	5/4
120	pinkish gray, crotovina	7.5YR	6/2
140	pinkish gray, crotovina	10YR	5/2
160	pale brown, crotovina	10YR	6/3
180	light yellowish brown, crotovina, compression	10YR	6/4
200	light yellowish brown, crotovina, compression	10YR	6/2

Site B65

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	very dark gray	5YR	3/1
60	dark reddish gray	5YR	4/2
80	dark reddish gray, mottled	5YR	4/2
100	brown, mottled	7.5YR	5/2
120	dark brown, mottled	7.5YR	4/2
140	strong brown, mottled	7.5YR	5/6
160	dark brown, mottled	7.5YR	4/2
180	compression (no sample)		
200	mottled, some sand (degraded rock?)		

Site B66

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	very dark gray	5YR	3/1
60	mottled		
80	mottled		
100	dark grayish brown	10YR	4/2
120	dark grayish brown	10YR	4/2
140	yellowish brown	10YR	5/4
160	dark brown	10YR	3/3
180	compression (no sample)		
200	compression (no sample)		

Table 5. (Continued)

Site B66N

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	2.5YR	2.5/0
40	very dark gray	5YR	3/1
60	mottled		
80	grayish brown	10YR	5/2
100	dark brown	10YR	3/3
120	yellowish brown	10YR	5/4
140	yellowish brown	10YR	5/4
160	compression (no sample)		
180	compression (no sample)		
200	compression (no sample)		

Site B66S

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	very dark gray	5YR	3/1
60	mottled		
80	grayish brown	10YR	5/2
100	mottled		
120	mottled		
140	dark yellowish brown	10YR	4/4
160	compression (no sample)		
180	compression (no sample)		
200	compression (no sample)		

Site B67

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	black	5YR	2.5/1
60	dark gray	5YR	4/1
80	grayish brown	10YR	5/2
100	grayish brown	10YR	4/2
120	gray	5YR	5/1
140	gray, mottling	5YR	5/1
160	dark gray	5YR	4/1
180	compression (no sample)		
200	compression (no sample)		

Table 5. (Concluded)

Site B68

Level (cm)	*Color, comments*	*Hue*	Value/Chroma
20	black	5YR	2.5/1
40	dark gray	7.5YR	4/2
60	dark brown	7.5YR	5/2
80	yellowish brown	10YR	5/4
100	yellowish brown	10YR	5/4
120	yellowish brown	10YR	5/4
140	yellowish brown	10YR	5/4
160	pale brown	10YR	6/3
180	light yellowish brown; rocks, stones, strands of sand; degraded rock	10YR	6/4
200	pale brown	10YR	6/3

f. Soil Moisture Analysis Incorporating Slope

Results from this study have shown similar near-surface volumetric soil moisture at each monitoring site during SMUSE and growing levels of variability among sites in deeper layers with empirical connections to site terrain slope. This variability is summarized in Figure 12 where monitoring sites are arranged in order of terrain slope at each location. Those sites with a relatively low surface terrain slope are shown using dotted columns, and those with larger slopes are striped. The historic Bondville site was characterized by the highest slope and is the solid black column. Layers are combined into broader layers with similar apparent traces observed in Figure 7: 0–30 cm, 30–90 cm, 90–170 cm, and 170–200 cm.

Soil moisture in the 0–30-cm layer was quite similar at all sites, showing an approximate range of soil moisture from 29 to 34%. In this layer, no obvious impact was evident from surface ponding at sites with lower slopes. Average soil moisture was essentially identical from 31% at low-sloped sites and 32% at the moderate-to-high sloped sites. The experiment protocol restricting measurements during precipitation events, as well as the thick mat of sod cover everywhere at the surface, may have given sufficient opportunity for uniform water levels at all sites in this layer subsequent to precipitation events.

Data from deeper layers, however, revealed a record of progressively higher moisture values from sites with low surface slope and lower levels of soil moisture at sites with the highest slope. Average volumetric soil moisture at high- versus low-sloped locations was 34% and 37% in the 30- to 90-cm layer, 35 and 40% in the 90- to 170-cm layer, and 34 and 42% in the 170- to 200-cm layer, respectively. High moisture values at the sites with lowest slopes may suggest the occurrence of surface water ponding, yielding more available water to percolate downward. It may also suggest a variety of soil layering just below the surface allowing rapid flow of subsurface water with a coincidental relationship to surface slopes.

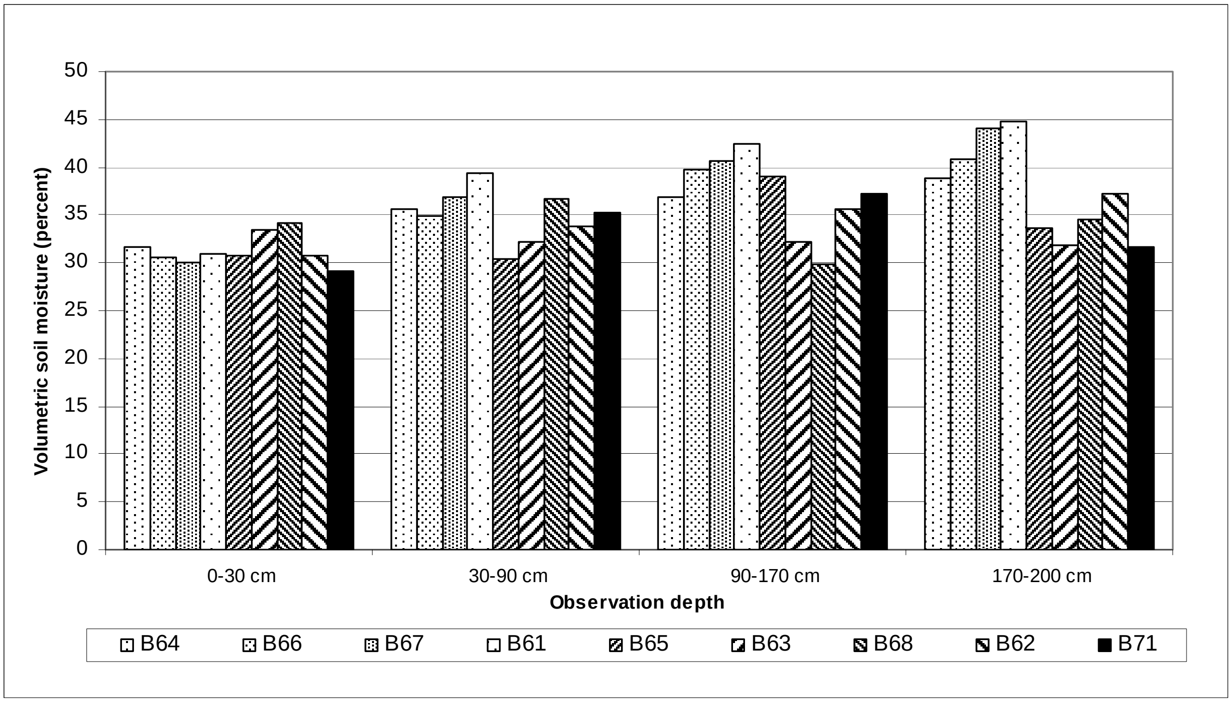


Figure 12. Average volumetric soil moisture (percent) at nine sites during SMUSE at 0-30, 30-90, 90-170, and 170-200 cm deep. Dotted columns are sites with the lowest surface terrain slopes; striped columns have higher slopes. The long-term Bondville soil moisture station (B71, black) has the highest surface terrain slope.

From a strict "best representative" standpoint assessing the location of the historic Bondville soil moisture site, Figure 12 suggests that from this 13-month period alone, B62, whose data lies closest to the middle of all sites in each layer, may have been a better selection, whereas B61 would have resulted in high continuous values within the 2-m profile. The actual long-term Bondville site location (B71) reported the lowest averaged moisture values in the 0–30 and 170–200 cm layers, and was in the middle to upper range in the 30–90 and 90–170 cm layers. However, since it generally agrees with the other sites without lesser evidence of ponding, maintaining this site as a pristine research location seems advisable.

g. Neutron Probe vs. Stevens-Vitel Hydra Soil Moisture Measurements

Lastly, a contemporary indication of soil moisture variability at the Bondville site can be presented. During 2000–2004, all ICN sites were converted to Stevens-Vitel Hydra continuous soil moisture sensors. The temporal schedule between data obtained by the new instrumentation and those of the neutron probe are substantial. In addition, the difference in the volume of soil monitored between the two probes needs to be considered before direct observations can be made.

As described in a previous section, these new instruments were buried under sod at depths of 5, 10, 20, 50, 100, and 150 cm. They measure soil moisture within a set of sensor prongs forming a regular triangle, 2.2 cm on a side and 5.7 cm long, yielding a volume from which soil moisture data are measured of approximately 12 cubic centimeters (cm^3). Neutron probe observations are taken within a spherical volume of soil around the sensor with a diameter of at least 10 cm (which varies in size with moisture content), yielding approximately 4,189 cm^3, or about 350 times larger. Data from the continuous sensors are measured hourly. Neutron probe observations were collected twice weekly during the field experiment, but 19 times a year within the historic dataset. For these reasons, neutron probe observations would be expected to display a highly smoothed temporal and spatial soil moisture dataset with a substantially muted reaction to singular event precipitation, depending upon the time between the event and measurement. Depending upon the season, it could pass unnoticed, while maintaining "base" soil moisture levels.

Both soil moisture observation platforms collected during SMUSE are shown in Figure 13. The Bondville neutron probe site (B71) is located approximately 21.5 m south of the ICN tower (Figure 5). The continuous sensors, attached to the ICN data logger, are located about 3.7 m south-southeast of the tower. Soil moisture is presented for each dataset at a depth of 10 cm. Hourly precipitation observations from a Belfort weighing bucket rain gauge, hooked directly to the ICN data logger, have been superimposed.

Again, it should be noted that the experiment protocol did not allow neutron probe readings on days with precipitation that occurred during the observation window, reducing the opportunity for neutron probe sensors to observe the same impacts of rainfall as was allowed with the continuous probes. In addition, output from the capacitance sensors were unusable during times of frozen soils at this level (February–mid-March) and were removed from the figure.

Seasonal trends in Figure 13 are noteworthy with heavier rainfall events in summer being concomitant with high sinks of soil moisture (root extraction and evapotranspiration) compared to the winter season, a time of lower precipitation amounts and minimal root extraction of moisture when much of the rain that falls is available for soil recharge. Soil moisture values from both the continuous and neutron probe data sources are fairly similar between rain events within a few percent. However, the continuous data reveal substantially higher soil moisture values during rain events, and show the speed at which water moves through the soil profile at the Bondville ICN site at the 10-cm depth, returning soil moisture values to a seasonal "base" amount. The observational structure applied by the experiment protocol caused the neutron probe observations to miss these events directly; however, the authors contend that the restriction as described earlier was necessary to maintain consistency of observations between precipitation events.

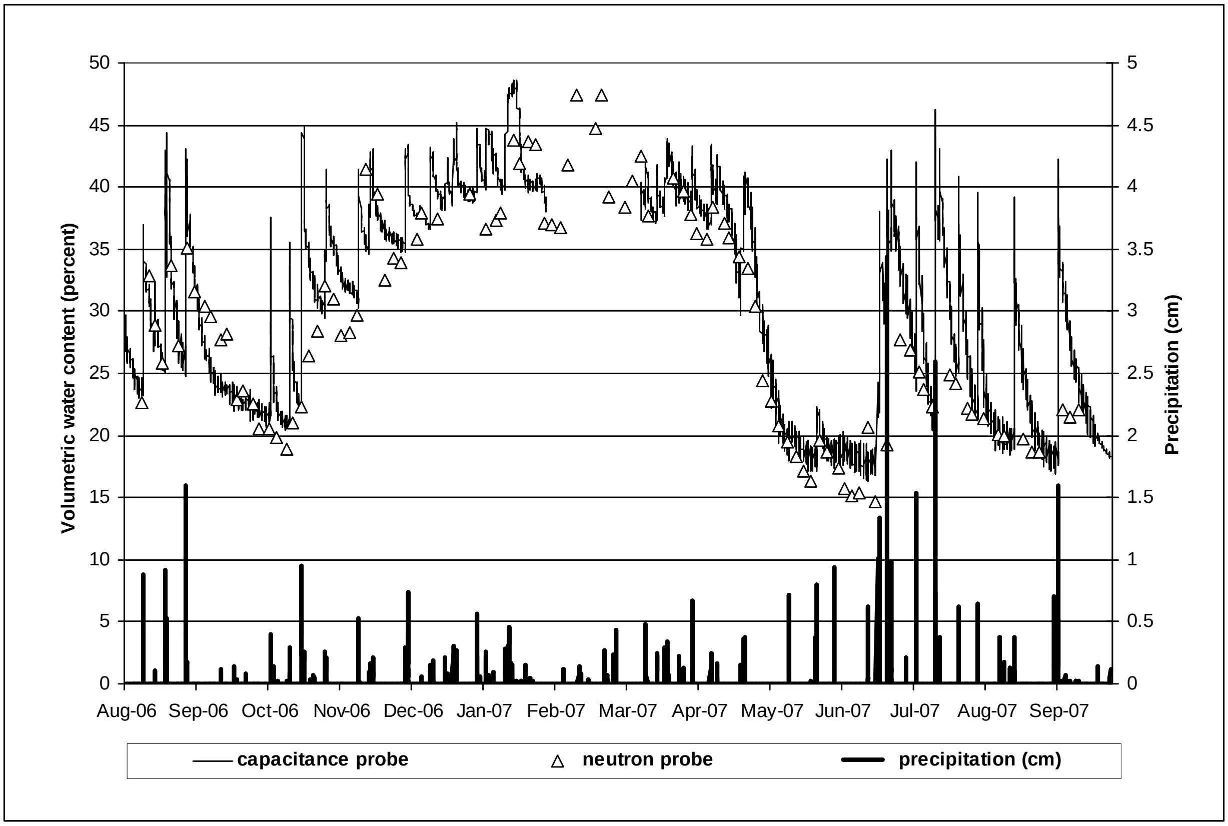


Figure 13. Hourly soil moisture (capacitance probe) observations 10 cm below ground, twice-weekly 10-cm neutron probe observations and hourly precipitation at the long-term Bondville ICN monitoring site during SMUSE

Summary and Conclusions

Long-term data collections of volumetric soil moisture under sod have been conducted in Illinois for more than 25 years by the Illinois State Water Survey's Illinois Soil Moisture Network, primarily using neutron probe observations. Numerous prior studies have applied these data to various regional scenarios. However, true representativeness of these soil moisture data to adjacent areas of various surface covers is unknown. This work indicates that care needs to be taken with how these *in situ* data are applied.

A 13-month field study, the Soil Moisture Under Sod Experiment, was conducted at the ISMN site at Bondville, Illinois to increase understanding of soil moisture variability across a relatively small area under seemingly uniform conditions. Eight locations for neutron probe observations were chosen at random for monitoring across a 5.9-hectare sodded field, as well as two additional stations near one of these random sites for a cluster site analysis.

Observations of soil moisture were taken twice weekly at these 10 sites and the Bondville ISMN station from the surface and at 20-cm intervals to 2 m below ground using neutron technology on days without afternoon precipitation from August 2006 to September 2007. A detailed surface terrain analysis was conducted across the field site to determine the potential for ponding near each monitoring site from rainfall runoff. At the end of the period, trenches were dug adjacent to the randomly selected stations to extract soil cores at the same levels of the neutron probe observations in order to conduct analyses on soil porosity, bulk density, and soil color, and to determine the heterogeneity of soil conditions.

Results indicate (1) strong, intra-site, temporal consistencies in volumetric soil moisture at all levels, and (2) increasing inter-site soil moisture variability with depth. Values in the top 90 cm of soil responded to rainfall and subsequent drying with slowing impact from these events with depth through this layer. In layers below 90 cm, precipitation appeared to have a lesser immediate impact, while a continuous moisture level within the soil or rising and falling sub-surface water became dominant. Inter-site soil moisture variability on a given observation day during the experiment in the 10–30-cm layer was relatively uniform, with a standard deviation of 2.64%, but increased to just over 6% in the 110–130 and 150–170-cm layers. Although surface topography varied by only 1 m across the entire 5.9-hectare field, a connection was observed in deeper layers at sites with low surface terrain slope having high soil moisture content, and vice versa. Variability in soil porosity and bulk density supported a similar relationship between site terrain slope and soil moisture. A noticeable level of mottling was observed visually and in soil cores, indicative of heterogeneity in the soils' processing of moisture. Data from the clustered group of stations, with a separation of just 1 m, revealed larger than expected and inconsistent soil moisture variability at such closely spaced locations.

Results suggest a high level of soil moisture variability, typically undetected without a measure of soil profiling. An apparent water lens observed in the 140–160 cm region at Site 67, a large seasonal fluctuation of water at Sites B63 and B65 apparently due to water table intrusion, a high continuous amount of soil moisture with very low variability at Sites B61 and B67, and conflicting results observed in the clustered site data (Site B66), all are indicative of the existence of localized soil conditions in this field location, creating a wide variety of water flow patterns under a sodded surface condition that visually appears to be quite uniform. Sites with driest conditions in trenches at 2 m were also generally sites with lowest soil porosity. Perhaps the lower porosities at Sites B63 and B65 forced a higher water table in their site profiles. Likewise, the larger porosity of soils at Sites B61 and B67 allowed more water to be stored in the middle soil moisture layers and thus, not invade to the levels closer to the surface. Unmeasured was permeability, which surely impacted all sites, allowing surface water to percolate differently as well as impacting upward water movement from below. Furthermore, soil characteristics below 2 m of depth are unknown anywhere across the region, as well as their impacts on the soil layers above. These data indicate the importance of soil characteristics to the results of this experiment and add further to the complexity of proper interpretation of soil moisture trends as well as the selection process of future sites.

The experiment raises concerns that use of just one site to monitor soil moisture within a broad area, without additional analyses for its selection, may have less regional or even local representation than previously accepted. Vinnikov et al. (1999b) used root-mean-square errors to conclude that 10 monitoring stations would be sufficient to determine average soil moisture within the top 1 m of soil for the state of Illinois. Famiglietti et al. (2008) suggested that "a maximum of 18 samples would be required to measure the 800-m mean soil moisture to within 3%." Our conclusions add to these statements, suggesting from temporal stability analyses that to obtain soil moisture in deeper levels, a small number of sites may be needed at each regional location to properly define local soil moisture conditions and select the most representative monitoring site in a given area. Multiple site monitoring was not conducted during the siting-selection process of the current ISMN sites. It is anticipated that similarly strong soil moisture variability exists at all ISMN sites as those observed at Bondville during SMUSE.

Nevertheless, since the beginning of our network, especially with its limited historic observation schedule, and collections of data without regards to on-going precipitation events, our advice on the best use of the ISMN data has been with (1) observed changes between successive observations and (2) departures from developed normals. We took this position due to the unknown association between our data collected under sod, and the soil moisture community's greater interest: soil moisture under adjacent areas with different ground covers. The current work, finding high variability across a single sodded field, verifies this conservative viewpoint.

The future of near-surface soil moisture data collection is moving largely in the direction of satellite imagery and numerical simulation to monitor and predict soil moisture globally, a plan with substantial current efforts by the International Soil Moisture Working Group of the Global Energy and Water Cycle Experiment (Leese et al., 2001). One of our results here is that near-surface soil moisture observations all under sod in loess soils over one small region in Illinois are useful as ground truth for near-surface remote-sensing observations. But similar analyses as was done here may be required at each ISMN site to determine the local representativeness of *in situ* data for adequate data validation and model parameterization. This is even more important for quality soil moisture observations in deeper layers. The relationship between the historic Illinois soil moisture data under sod versus that in adjacent areas under different surface covers was not addressed here, except to point out that arbitrary acceptance of such representation without additional analyses may be unwarranted.

Protocols for high-quality soil moisture data are needed that require multiple data analyses within a region prior to installation of permanent sensors, including measurements within all major surface covers, in order to determine a representative location for soil moisture monitoring. Adequate soil core analyses at numerous locations within a small area, a surface slope analysis and a climatology of the near-surface water table, precipitation, and perhaps evapotranspiration are advisable. Pitfalls will include, among other items, an impact assessment of local land use, e.g., attempting to define a representative soil moisture environment in agricultural areas that are traversed constantly by agricultural vehicles and the magnitude of tiling. Construction of universal protocols of soil moisture data collections and a unified global development strategy for monitoring could address many issues noted here as they apply to current and future soil moisture networks.

Work Assignments

Robert Scott was PI for the experiment and was responsible for its design and operations. He conducted the soil moisture analyses and was the lead in its documentation. Edward Krug was responsible for soil color analyses. Stephen Burch conducted the surface topographical elevations and analyses. Charles Mitdarfer collected and reduced the neutron probe observations and performed soil core moisture analysis. Paul Nelson provided training for neutron probe data collections as well as mechanical and technical expertise in numerous aspects of the experiment.

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