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Soil hydrology at the Gunnarsholt experimental plantation: Measurement and results

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SUMMARY

The soil hydrological regime at the Gunnarsholt experimental plantation was studied in terms of surface and subsurface water content and subsurface water potential in 1994 and 1995. Surface water content ranged between 30–35% (39–45% saturation). Subsurface soil water content obtained by neutron scattering displayed spatial variation and vertical heterogeneity caused by the presence of volcanic depositional layers. The understorey cover was shown to influence near-surface readings using the neutron scattering technique. Profiles of soil water potential showed the characteristic response to wetting and drying events. The soil water potential reached a maximum (in absolute value) of 0.02 MPa after 12 consecutive days without rainfall and therefore no water stress was evident throughout the measurement period.

Key words: neutron scattering, soil water content, tensiometers, water potential.

YFIRLIT

Hringrás vatns í ungum asparskógi í Gunnarsholti

Vatnsbúskapur tilraunasvæðisins í Gunnarsholti var rannsakaður með mælingum á vatnsinnihaldi og vatnsspennu í jarðvegi sumrin 1994 og 1995. Vatnsinnihald yfirborðs var á milli 30 og 35% (39–45% vatnsmettun). Vatnsinnihald í jarðvegi, mælt með geislavirku endurkasti, var breytilegt bæði innan svæðisins og eftir dýpi. Hið síðarnefnda var einkum vegna öskulaga. Undirgróður hafði áhrif á mælingar með geislavirkni, væntanlega þar sem vetnisatóm í lífrænu efni bjöguðu mælingarnar. Vatnsspenna mæld á mismunandi dýpi breyttist í takt við hvort veður var þurrt eða úrkomusamt. Lægsta vatnsspenna í jarðvegi var aðeins 0.02 MPa eftir 12 úrkomulausa daga. Það varð því enginn merkjanlegur vatnsskortur á tilraunasvæðinu yfir tímabilið sem mælt var.

INTRODUCTION

The movement of water through the soil-plant-atmosphere system is the focus of the micrometeorological work at the Gunnarsholt experimental plantation. The growth and development of the plantation rely on the ability of the soil to absorb, move, and store water. It is therefore important to be able to characterise and quantify the soil water at the site. Prior to

1994, soil moisture data at this site, as for Icelandic soils in general, were limited. Given that the site is situated in a maritime climate with ample precipitation, it was assumed that water would not be limiting to tree growth throughout most of the growing season. The site is subject to infrequent dry periods with clear skies, relatively warm temperatures and increased atmospheric demand for water through evapotranspiration. It was uncertain how the soil-plant-atmosphere system would respond during these higher demand periods.

This paper reports on the introduction of routine measurement of soil moisture at the Gunnarsholt plantation forest between 1994 and 1996. Three measurement schemes are detailed: surface volumetric measurements, subsurface soil water profiles and soil water potential profiles. Spatial and temporal variability of soil water is discussed and the difficulties of measurement in a heterogeneous soil environment are highlighted. The site characteristics are described in detail in Strachan *et al.* (1998) and Sigurdsson *et al.* (1998).

METHODS

Subsurface soil moisture was measured with a neutron probe (model 3332, Troxler International Ltd, Research Triangle Park, NC). During May, 1994, eight aluminium access tubes, 2 m in length, were installed at the site. The base of each tube was sealed, thus providing permanent access for the neutron probe without the possibility of capillary rise of water into the base of the tube. Pairs of tubes were located in each quadrant of the site delineated by the central tower. Of each pair, one tube was located within a grass swath while its mate was located in close proximity (1–3 m), under moss cover, to sample the two dominant understorey cover types.

The radioactive source of high energy (‘fast’) neutrons and the detector of thermalized (‘slow’) neutrons are both contained in the probe. Soil water is the primary source of the thermalizing, but as well, organic matter content does affect the soil’s thermalizing ability. The count ratio, the ratio of the measured slow neutron count to a standard count, was recorded rather than the actual count because of the day-to-day variability in neutron emission from the source (Havercamp *et al.*, 1982). A linear relationship between the count ratio and soil water content can be determined by *in situ* gravimetric calibration. Often, field calibration is difficult in heterogeneous soils and depth-dependent calibrations must be used (Papakyriakou and McCaughey, 1991).

Fast neutrons emanate from the source in a spherical cloud whose volume varies inversely with soil moisture content. Ward and Robinson (1990) suggest that the sphere’s radius varies between 10 cm for wet soils to 25 cm for dry soils. Following protocols developed at Queen’s University (Papakyriakou, 1990; Papakyriakou and McCaughey, 1991), measurements were taken every 10 cm to a depth of 170 cm every three to four days during 1994 and 1995 with field calibration completed in both years.

Surface water content measurements were collected nearly daily during the 1995 summer field campaign approx. 10 m from the tensiometer array located on the west side of the site. After removing the moss layer, two soil samples were taken in tins of known volume (172.5 cm^3, determined by displacement), weighed to ±0.1 g and then dried for 48 hours at 105°C before re-weighing. An average surface bulk density of 0.50 g cm^{-3}, determined through field measurements, was used to convert the result to volumetric water content.

During the 1995 field campaign, a nest of six tensiometers was installed to record soil water potential at 30 cm depth intervals between 30 cm and 180 cm. The tensiometers were aligned in two rows of three with a 1 m separation between rows and 1 m between tensiometers within a row. Each tensiometer consisted of a PVC tube with a porous ceramic cup at the basal end and a septum stopper at top end. The portable monitoring device, a tensimeter (Soil Measurement Systems, Tucson, AZ) consisted of a side-port needle and display console. The tensiometers were installed to the appropriate depths and excavations were back-filled with a slurry of native soil. Soil water potential (bars=MPa ×10^{-1}) was recorded at approx. 0900 UTC during the 1995 and 1996 campaigns. Note that although water potential is always recorded as a negative pressure, potentials are presented here in absolute value for ease of explanation. Collectively, soil water content and water potential, provide a powerful descriptive combination giving changes in storage and direction of movement in the unsaturated soil profile.

RESULTS

Surface soil water

The soil 'surface' contained between 0.30 cm^3 cm^{-3} and 0.35 cm^3 cm^{-3} water for the majority of the 1995 season. Combining an average particle density of 2.12 g cm^{-3} and dry bulk density of 0.50 g cm^{-3} (Strachan *et al.*, 1998) yields a pore space of 76.4 cm^3 per 100 cm^3 total volume for the surface. Accordingly, 30–35% water by volume corresponds to >40% saturation. A drying period around day 200 reduced the surface water content by 15% to a low of 0.22 cm^3 cm^{-3} (29% saturation) on day 205 before a new frontal system came through and rains commenced to replenish the soil water.

Subsurface soil water

Gravimetric samples for calibration (n=35) were taken using a 2-cm-diameter auger coincident with neutron measurements at the northwest moss (NW-M) and southeast moss (SE-M) tubes to a depth of 90 cm (the length of the auger) over three days in each of the 1994 and 1995 seasons. The relationship (Figure 1) between gravimetric soil water content (q_{grav}) and count ratio (CR=measured count/standard count) is;

(1)

Gravimetric soil water (g g^{-1}) can then be converted to volumetric soil water (cm^3 cm^{-3}) by applying the average bulk density for the appropriate level (Strachan *et al.*, 1998).

The general shape of the soil water profile obtained by neutron probe is consistent with increasing soil water content with depth (Figure 2; tube location is designated by directional quadrant and understorey cover; e.g. NW-M = northwest quadrant, moss understorey). Layers with reduced soil water content can be seen in the soil moisture profile at 80 cm in the SW-G and SW-M profiles, at 60 cm in the NE-G profile, and at 100 cm in the SE-M profile. A second layer can be seen at 150 cm in the SE-M, NE-G, and SW-G profiles. Evapotranspiration from the surface reduces the water content at 20 cm by as much as 15% following the dry period (day 209). Data collected in 1994 and 1996 (not shown) indicate that very similar conditions persisted during each of these years.

Subsurface soil water potential

The tensiometer nest provided a mechanism for determining the direction of water movement in the profile and three principal features can be seen in the 1995 results (Figure 3). First, the soil water potential is quite low (driest value at 30 cm is 0.019 MPa). Second, the direction of water movement is upward from 180 to 90 cm for the entire season; and third, the direction of water movement in the

Figure 1. Field calibration of the neutron probe completed in 1994 and 1995. Best-fit calibration line is significant (r^2=0.81, P<0.01, n=35).

1. mynd. Kvörðun mælinga á vatnsinnihaldi jarðvegs með geislavirku endurkasti sem gerðar voru 1994 og 1995. Aðhvarfslínan er hámarktæk (r^2=0.81, P<0,01, n=35).

Figure 2 . Subsurface water content profiles by neutron scattering for days 160 (June 9), 196 (July 15), 209 (July 28) and 229 (August 17) in 1995. Tube identification is given in the upper right corner (SW-M = southwest moss; NE-G = northeast grass and so on for the other directions).

2. mynd. Vatnsinnihald í jarðvegi mælt með geislavirku endurkasti, dagana 160, 196, 209 og 229, 1995, á átta mismunandi stöðum. Skammstafanir vísa til staðsetningar (sjá texta) .

upper 90 cm switches from downwards earlier in the season to upwards during the dry period and back to downwards following the resumption of rainy conditions after day 206 (cf. Figure 5). The water potential profile is almost linear during the dry period (Figure 3; Day 204), while water potential profiles earlier (Day 170) and later (Day 248) in the season show the split in the profile between upward and downward movement at 90 cm.

DISCUSSION

Spatial heterogeneity

In general, the effect of the grass understorey

Figure 3. Top. Soil water potential over six depths for the 1995 growing season. Bottom. Water potential profiles for three representative days in 1995: day 170 (June 19); day 204 (July 23); day 248 (September 5).

3. mynd. Vatnsspenna á sex mismunandi jarðvegsdýptum yfir sumarið 1995 (efri mynd). Vatnsspenna á mismunandi jarðvegsdýpi dagana 170, 204 og 248, 1995 (neðri mynd).

is to cause the upper soil profile to be wetter than profiles taken under moss (Figure 4). Competing mechanisms are present. Grass cover should lead to increased evaporation of intercepted rainfall and increased transpiration both leading to lower near-surface soil water content, however, evaporation directly from the soil surface is decreased beneath the grass swards due to the increased shading. It is suggested that the neutron count could be overestimated through a sensitivity to organic material. Where grass is present, the root density of the near surface profile will be increased. If significant non-soil water hydrogen is sensed by the neutron probe, the count (and therefore count ratio) will be overestimated leading to a fallacious increase in moisture content being recorded. This can be accounted for through calibration, however, the tubes used for calibration were situated in moss cover.

Spatial heterogeneity also influences the conversion of the soil water profiles to volumetric profiles. Given the difference between water profiles noted above, it is likely that the bulk density values calculated are also location-specific. One can, however, ascribe average values of 0.73 (±0.01) to measurements in the upper 90 cm and 0.58 (±0.02) to the lower 70 cm (100–170 cm) of the profile (Strachan *et al.*, 1998), each of which lie within the range of values given for Andisols by Maeda *et al.* (1977).

Figure 4. Soil water determined by neutron probe for paired tubes (SE-M, SE-G) showing the increase in near-surface water measured under grass compared with that measured under moss. Days 160 (June 9) and 196 (July 15) in 1995 are combined for this example. Numbers represent the depth at which the reading was taken.

4. mynd. Vatnsinnihald mælt með geislavirku endurkasti undir tvenns konar gróðurþekju (SE-M=mosaþekja og SE-G=grasþekja) dagana 150 og 196, 1995. Tölur standa fyrir jarðvegsdýpi sem mælingarnar voru gerðar á.

Vertical heterogeneity

Two key characteristics of the volcanic soils at Gunnarsholt are the numerous eruption layers and periodic erosion layers. The soil morphological profiles described by Strachan *et al.* (1998) contain layers identified as the 1947 eruption of Mt. Hekla and at least two regional erosional episodes (ca 1920 and 1880). Although most of these features are too thin (vertically) to be picked up uniquely by the neutron scattering technique, two events **can** be identified in the soil moisture record. Using tube SW-G as an example (Figure 2), a well-documented eruption of Mt. Hekla that started on July 25, 1510 (Hjartarson, 1995) can be seen at 80 cm while the layer at 150 cm is possibly an earlier eruption of Mt. Hekla.

The hummocky nature of the soil development is revealed in the heterogeneity of these subsurface soil water profiles. While SW-G contains both features mentioned above, its neighbour SW-M only contains the upper eruption layer and NE-M contains neither feature. Historical evidence suggests that the 1510 eruption of Mt. Hekla contained the coarsest ash to fall in the Gunnarsholt region since settlement in 874 AD (Hjartarson, 1995). It is probable that this layer exists across the site although its thickness and depth from the modern surface is variable. Where the layer thins, it may not be picked out uniquely by the neutron scattering technique. Indeed, soil coring performed for other concurrent experiments at Gunnarsholt always hit this layer in the first metre (approximately) of sample extracted.

This microscale spatial heterogeneity, over as little as a few metres horizontally, has implications for the measurement of soil water parameters. The major eruption layers each consist of sand-sized particles (Strachan *et al.*, 1998) and have a strikingly lower soil water content. These layers are potentially significant as they act to disconnect the local hydrology of the upper and lower portions of the profile; capillarity is reduced, and the upward movement of water from the layer 100–170 cm is interrupted. The upper 90 cm of soil is well-fed by rainfall and thus the dominant direction of water movement is downwards through gravity drainage. Only during the prolonged dry period did the direction of water movement in this layer change through the increased surface evaporation and continued transpiration from grass and trees.

Temporal variability

The effects of the periodic and frequent precipitation events are best illustrated in Figure 5. In this figure, the 24-hour rainfall (P) is indicated along with the changes in the soil surface volumetric soil water content (VC) and % saturation in the soil surface layer. The temporal and vertical distribution of soil water potential is given by isopleths of equal tension (MPa×10^{-1}).

VC is stable, ranging between 30–35% (39–45% saturation) corresponding with the frequent rainfall received at the site; the exception is the prolonged dry period where VC drops to 22%. The distribution of soil water potential with depth (shown in the middle figure)

Figure 5. Temporal patterns in (top) volumetric surface soil water content (VC), (centre) soil water potential with depth, and (bottom) precipitation (P). Soil water potential isopleths are in MPa×10^{-1}. Points a-e are discussed in the text.

5. mynd. Breytileiki í vatnsinnihaldi í yfirborðslagi (VSM) yfir sumarið 1995 (efsta mynd). Vatnsspenna í MPa×10^{-1}á mismunadi dýpi í jarðvegi (mið mynd). Punktar a til e vísa til umræðukafla. Úrkoma í mm (neðsta mynd).

illustrates a number of important features. The 0.12 isopleth bounds two pairs of dry and wet fronts (indicated by points a and b on Figure 5). In the two weeks prior to day 164, the site only received 2 mm rainfall with 0.5 mm occurring on day 160. The long dry period between days 193 and 204 (12 consecutive days without rain) clearly illustrates the lagged response of the soil system. The driest surface soil water reading occurred on day 205 at the end of the dry period. The wetting front represented by the 0.18 isopleth extends to day 215 and a depth of 50 cm, the wetting front represented by the 0.15 isopleth extends to day 220 and a depth of 90 cm, and the wetting front at represented by the 0.12 isopleth extends to approx. day 230 and 120 cm depth.

The region between the 0.09 and 0.12 isopleths (c), beyond the wetting front, represents a relative dry zone with wetter soil above and a wet base. The wetting from above this region is due to gravitational flow from rainfall (d). The depths below the 0.09 and 0.06 isopleths (e) are dominated by capillary rise from the water table (not shown).

Finally, it doesn't seem likely that plants having root systems reaching 30 cm depth will experience any significant water stress at the Gunnarsholt site even during prolonged periods without precipitation. The lowest water potential recorded in 1995 at 30 cm was 0.02 MPa after 12 days without rain (Figure 3). Salisbury and Ross (1992) indicate that mild water stress occurs when soil water potential reaches the range 0.3 to 0.8 MPa and that higher levels of stress occur at water potentials beyond 1 MPa.

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