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Water Availability to Some Arctic Ecosystems

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Water in permafrost areas is available to the organisms during a short time and in a restricted space. Models of soil water occurrence and flow are applicated as basis for analysis of moisture in the environment of organisms. Soil moisture, available for the transpiration process, has been calculated as to soil in permafrost. The seasonal variation of soil moisture is shown.

Water Budget Models

For the objectives of International Biological Programme's Tundra Biome the author has investigated water budget variables in two permafrost areas, i.e. the Stordalen (Abisko), Sweden, 1970-1975, and the Truelove Lowland, Devon Island, N.W.T., Canada in 1974.

Water occurrence in tundra soils is conveniently described in terms of functional zones distinguished by the significant levels traditionally accepted, i.e. the groundwater table, the capillary fringe which forms a very irregular boundary of saturation above the groundwater, the root depth and soil surface (Fig.1). Hydrological requests lead to the introduction of the thermocline level. Cf. Kristensen (1975).

The concept of a thermocline in the uppermost layer of the soil is derived from the experience that heating and cooling affect a thin upper layer, a »soil skin«. This is due

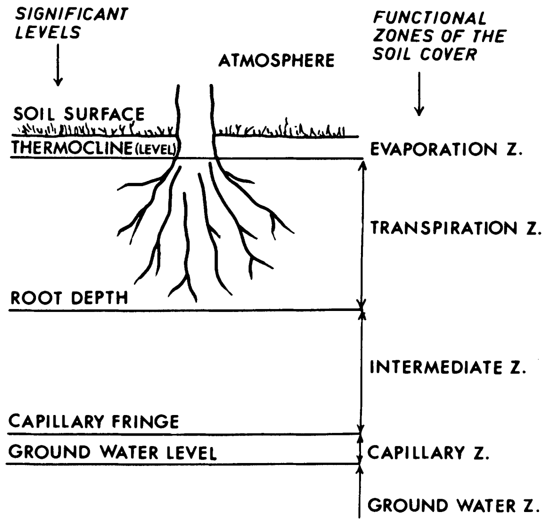

Fig. 1. Schematic representation of soil cover in terms of significant levels and functional zones as to water occurrence.

to low thermo-conductivity of most soils, creating both temperature and moisture gradients of strongest kind in the surface layers (Bjor 1972). The early and rapid thaw of tundras after snowmelt is also concentrated to a thin surface layer, while thaw of deeper layer of the soils is markedly slower (Rydén 1976).

Evaporation from moist soils is a process confined to this thin surface layer, thus defined as the evaporation zone. The energetic requisit for evaporation is often much better supported, than is the mass supply of upward capillary transport. Consequently, a dry soil skin can be found forming a crest above a still moist zone around the root systems, viz. the transpiration zone (Fig.1). Water for the transpiration process must have been transported into this zone, either by percolation or capillary transport. The intermediate zone shows a strongly varying extent in different soils; in tundra areas a variation according to the microtopography is apparent (Rydén, Fors, and Kostov, in manuscript).

Microtopographical considerations on the water balance parameters lead to models of water flow to and from the system of soil, water, and plants (Fig. 2). The elevated elements of the tundra are considered as inflow areas, whereas depressions act according to the outflow model. Slopes and intermediate elements are represented by the transition model. The sizes of these elements are of the magnitude of a few meters each. The calculations below concern an inflow system found in the field as a palsa of the Stordalen mire.

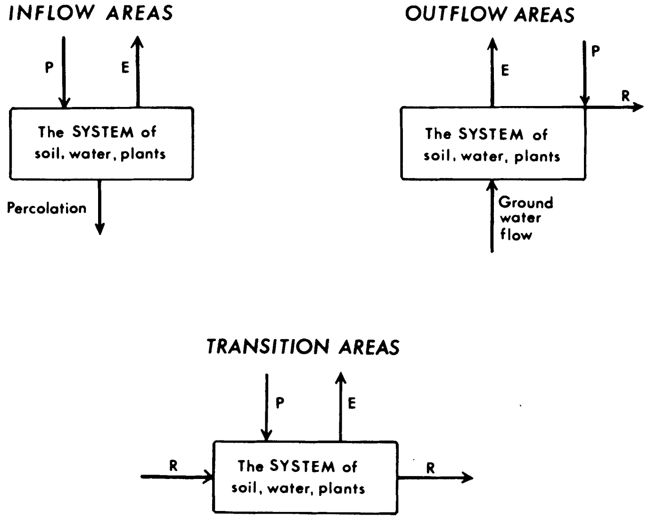

Fig. 2. Models of flow pattern in three different microsite types, i.e. elevated (inflow) areas, depressions (outflow areas), and transition forms between the other two types. - Note the vertical domination of water flow at inflow and outflow areas in contrast to a horizontal and ground water dependent flow pattern of the transition areas.

Available Water

In the environment of organisms water occur, both in soil and atmosphere, in all its three phases: solid, liquid, and gaseous. For the transpiration process water is taken only from the non-solid phases of the total soil moisture content.

The limit of uptake, however, is not identical with the isotherm of 0°C in the soil. Thermodynamics of soil water shows that an increase of suction causes a decrease of the freezing point of the soil water. The freezing point depression ΔT is determined from

$$\Delta T = \frac{V_w T}{{}_i L_w} (P - P_0) \tag{1}$$

where V_w is the volume of 1 g water, $T^0 K$ is the original freezing point, ${}_i L_w$ the latent heat of fusion of ice, and P and P_0 are hydrostatic and osmotic pressure, respectively (Childs 1969). Owing to the very low content of solved matter the osmotic pressure P_0 can be neglected. Soil water suction depends on the moisture content to the effect that a lower moisture content causes a greater suction. In the process of freezing the remaining moisture content is thus subject to a gradually decreased freezing point.

The suction $(P < 0)$ excerted by the roots may vary considerably but being limited at the wilting point, having a negative pressure of 15 atm. At least in the nearest vicinity of the root, the suction may reach this value. According to (1) the freezing point depression equals 1,24^{0}K. For comparison the corresponding values at 10 and 1 atm are 0,82^0 and 0,08^{0}K, respectively. The conclusion, however, is that calculations on the total available soil moisture content should be extended from 0^{0}C to -1,24^{0}C.

Soil moisture begins to be available during the gradual thaw of the root environment. In permafrost areas this process starts immediately after snowmelt and continues towards late summer when maximum thaw depth is achieved. The thaw (active) layer reaches at Stordalen Abisko 40-80 cm and at Truelove Lowland, Devon Island 30-50 cm in peat mire and sedge-moss meadow, respectively. The maximum thaw is in both cases well below the root depths.

A hydrodynamic model of the flow to the root is developed by Andersson (1972). The model makes it possible to establish a relationship between soil water tension, intensity of transpiration and root characteristics. Short term changes of soil water content within a horizon may thereby be calculated.

During a longer time scale the following approach will give the ecologist a possibility to quantify soil-water availability and transpiration. The available moisture storage and its variation within the growing season are defined by soil moisture measurements accompanied by assessment of soil physical parameters, in particular wilting point and field capacity. The wilting point is here considered to be the moisture content at 15-bar tension and the field capacity the greatest amount of water held under conditions of free drainage (see further Andersson 1962, and Danfors and Rydén 1975b). The available moisture is normally defined as the water portion held in the soil against tension between field capacity and wilting point. In the field studies of Stordalen and Truelove Lowland, however, it has not always been possible to distinguish between available water, as normally defined,and the total liquid content. The latter parameter is thus presented below.

The water budget is completed by precipitation as rain and snow and evapotranspiration. The net of these variables is assumed to infiltrate and recharge the root environment after moisture losses through evapotranspiration.

The peat at Stordalen is found to exhibit field capacity at a moisture content of approximately 30% by volume and wilting point around 13%. The physical properties refer to the root zone, approximately 0-25 cm. Full saturation followed by 24 hours of free drainage results in about 70% water content by volume. The actual variation in the surficial layer of 10 cm being 13.5% to 39% by volume (Rydén, Fors, and Kostov, in manuscript). Three types of soil moisture maximum are observed: one connected to snowmelt, a second during rains at early part of the growing season and the latest one immediately before freezing in the autumn. There is a decreasing trend throughout the summer until late August.

From the total content of soil moisture (W) we subtract the moisture content of the layers still frozen (W_f) and the water held in the soil against tension greater than that of the wilting point (W_w), or

$$W_{a'} = W - W_f - W_w \qquad (2)$$

where $W_{a'}$ indicates the water available to the root systems according to the modified definition applied in the present paper. Compare Hillel (1971) as to classical and newer concepts of soil-water availability to plants.

The calculated results are presented in Fig.3 as monthly values over the growing season at Stordalen. It is seen that the frost table is gradually lowered from end of snowmelt through the growing season and also after the first freezing has started at the soil surface. The diagram shows the conditions in an elevated area, a palsa of the mire. The permafrost table in the palsa is found at a maximum depth of 50-60 cm. The soil moisture movement shows a vertical drainage to the permafrost table; although the hydraulic gradient may be very great, horizontal transport of soil moisture is negligible (Rydén 1973).

The available moisture exhibits its regim in Fig.3. Following the downward movement of frost table during thaw, the liquid water content of the root zone markedly increases at the first part of the summer. A pronounced maximum occurs in June followed by a strong decrease towards September. The variation of evapotranspiration shows a similar regime, although its maximum seems to occur some weeks earlier. The evapotranspiration over Truelove Lowland has been found to follow the same variation (Rydén 1976), as do also the evapotranspiration of the sub-arctic area of Barrow, Alaska (Weller and Holmgren 1974).

The reason for increasing availability during May, June, and July is the lowering of the thaw depth, that does not reach the dominant root depth until late July. At Stordalen the root depth of 25 cm is found to be valid for about 80% of the roots. During August and September the recharge of soil moisture is little and the decrease of available moisture within the evaporation and transpiration zones is pronounced. The soil moisture available in the beginning of the growing season is of the same order of magnitude as that of the situation before freezing, or about 35 mm. The maximum amount is roughly twice this value.

The moisture available to the root systems is considered to equal the maximum amount of evapotranspiration. The comparisons possible from Fig.3 prove this statement, on a monthly basis. The differences between input to the system from precipitation and the output through evapotranspiration is assumed to run off from the elevated areas. It should be kept in mind that Fig.3 refers to elevated areas which are exposed and thus different from depressions as to drainage (Rydén, Fors, and Kostov, in manuscript). The depressions accumulate soil-water and create an environment of abundant water supply all through the summer. Evapotranspiration may thereby be damped as shown by Addison (1975).

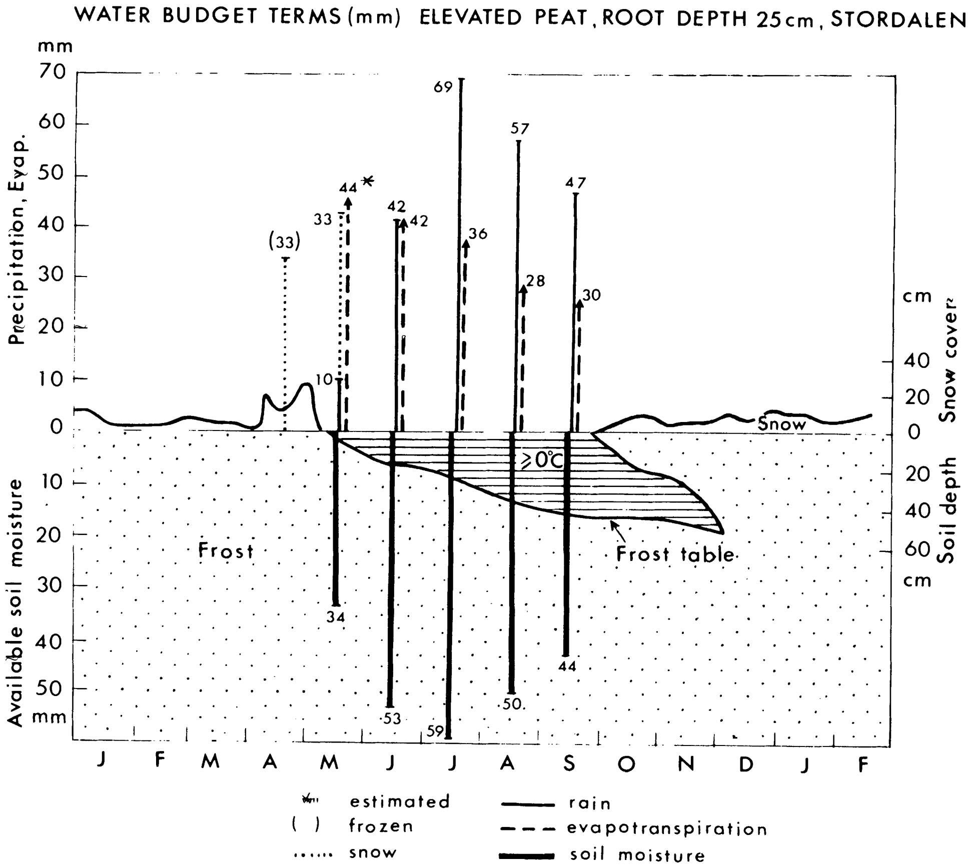

Fig. 3. Seasonal distribution of water budget variables at Stordalen, Abisko, Sweden, during 14 months from one winter to the following. The upward directed arrows depict precipitation, evapotranspiration, snow cover and the downward directed arrows show the available soil moisture (see text for definition). The underlying figure illustrates in the soil part the observed thawing and freezing of the peat, having a maximum thaw depth of 50-60 cm. The frost cycle diagram type originates with the research by Andersson (1964).

The results above are, however, most problably valid also for transition areas that cover the greatest portion of the Stordalen mire and wide areas of Truelove Lowland. The flow of transition areas (Danfors and Rydén, 1975a) give, however, a better connection to neighbouring soil, partly through a relatively high groundwater level, partly through flow along inclined permafrost tables.

Summary

Within the limit of actual thaw depth, evaporation and transpiration zones of the soil cover define the soil moisture available to the root system. The variation through the growing season of this parameter shows a maximum (about 60 mm) during July and minima (approximately equal, or 35 mm) in connection to snowmelt and start of freezing in the autumn. The upper limit of evapotranspiration is set by this amount of soil moisture, which is proved on a monthly basis.

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