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Methods Used for Calculation of Plant Available Water in Nordic Till Soils

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This paper describes different methods used in the Nordic countries for calculation of the storage capacity of tills for water available for plant production. The purpose of the paper is to give an overall review of the state of art for calculating the plant available water in Nordic tills. The paper is therefore based on already published data and a comprehensive list of references is given.

Introduction

During the last ice age, the Nordic countries were covered with ice except for the southwest part of Denmark. Therefore the major part of the Nordic countries geologically consists of tills, but also glacifluvial and marine deposits cover huge areas. After the last ice age the humic climate has leached the soils and podzolization of sandy tills and clay illuviation in the loamy tills have taken place. This paper describes three different methods which have been used for determining the plant available water in Nordic tills. Because of the complexity of the glacial landscape most of the researches referred to do not only cover till soils but also soils on glacifluvial or marine deposits.

The storage capacity of the soil for water available for plant production also known as the root zone capacity, may be defined as the amount of soil water which can be utilized by the crop before wilting occurs due to water stress. The root zone capacity (*RZC*) represents only part of the total water available for plant production (*TAW*) during the growing season, which may be roughly calculated from the equation below.

$TAW = RZC + PR + CR - RO - DP$

In this equation, *PR* is the precipitation during the growing season, *CR* is the capillary rise of water into the root zone during the growing season, while *RO* and *DP* are surface runoff and water percolating to depth during the growing season. Evaporation from bare soil and interception in foliage are neglected.

RZC is dependent on two main factors, the available water capacity of the different soil layers *i.e.* the soil water retention curve and the root density.

Available Soil Water Capacity of Soil Horizons

The soil water retention curves for different tills have been determined in all the Nordic countries. The points on the soil water retention curve of greatest importance for determining the available soil water capacity are field capacity (*FC*) and permanent wilting point (*PWP*).

The concept of field capacity is not clearly defined in the literature (Andersson and Wiklert 1970), but it is ideally taken as the water remaining in the soil after saturation when water percolation has nearly ceased, and when precipitation and evapotranspiration has been negligible during the drainage period. *FC* may be determined in the field as the water content in the soil 2-10 days after water saturation (Skoglund 1973). Laboratory determination of the water content at *FC* is normally carried out in a pressure plate membrane apparatus or by suction in a sand box. In the Nordic countries FC is normally assumed to equal the soil water content at pF 2.0 (Ekeberg and Njøs 1970; Madsen 1983). Fig. 1 shows the relationship between the actual water content in soil samples collected at *FC* and the water content in the samples at pF 2.0. The samples are from Himmerland in North Jutland. The water content at pF 2.0 corresponds very well to field capacity for all soil samples except those with low water-holding capacity. These samples consist of coarse sand, and field capacity for this texture corresponds better to the water content at pF 1.7 (Madsen 1976). For loamy tills in south-eastern Norway, Riley (1986) found that measured *FC* equated well with the pF 2.0-value in both topsoil and subsoil. The relationship between soil properties and *FC* shows that the water content at *FC* increases with increasing clay, silt, fine sand, and organic matter content (Riley *et al.* 1990). In sandy tills the water content at *FC* will be about 5-15 vol %, in loamy tills about 25-35 vol %, and in clayey and silty tills up to more than 40 vol %.

The water content at *PWP* is the amount of water left in the soil when the rate of water supply is insufficient to prevent plants from wilting. Wiklert (1964) confirmed, in experiments with tomato plants, that wilting occurred at a soil water content corresponding to approximately pF 4.2, Fig. 1. This pF value is used in all Nordic countries as a measure for the water content at *PWP*. The relationship between soil characteristics and *PWP* shows an increasing water content with increasing clay, silt and organic matter content (Riley *et al.* 1990). In sandy tills the

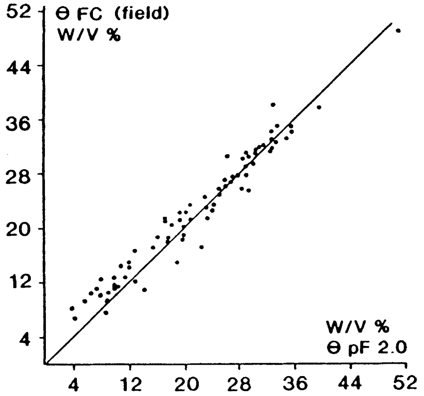

Fig. 1a.
The relationship between water content at pF 2.0 and field capacity determined as the water content at sampling time in November 1981. Results from well-drained soils only (Madsen 1983).

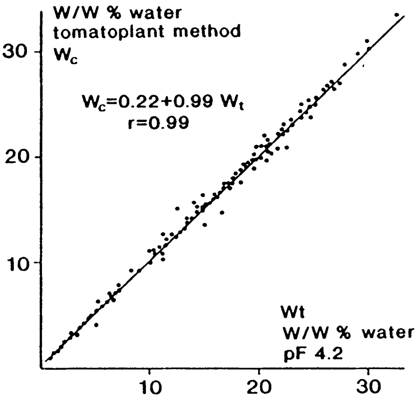

Fig. 1b.
The relationship between water content at wilting point for tomato plants and water content at pF 4.2 (Wiklert 1964).

water content at *PWP* may be close to zero, for loamy tills about 10 vol % and for clayey tills normally above 20 vol %.

The available water content (*AWC*) is the amount of water between pF 2.0 and pF 4.2. Madsen (1976) and Riley (1979) divide *AWC* into readily available water (pF 2.0-pF 3.0) and strongly held available water (pF 3.0-pF 4.2). In Sweden, *AWC* in soils is often calculated in realtion to ground water level by changing the upper limit of the available water content in the soil profile, *e.g.* pF 0.7 or pF 2.0 (Andersson and Wiklert 1970). The relationship between soil properties and AWC shows an increasing *AWC* with increasing silt, fine sand and in most cases organic matter content, while the clay content apparently plays a minor role. Table 1 shows, as an example, the calculated *AWC* of different Norwegian soils. Table 1 is based on samples from 62 profiles, approximately 3/4 of these are developed in tills.

Table 1 - Typical ranges of *AWC* calculated from regression equations for some Norwegian soil types (Riley 1986).

Norwegian name	Approx. equivalent	silt %	AWC vol %
sand	sand/loamy sand	0- 15	7-15
siltig sand	sandy loam	15- 45	15-25
lettleire	loam/silt loam	25- 47	20-30
sandig silt	sandy silt loam	45- 80	25-40
siltig lettl.	silty loam	47- 92	28-42
silt	silt	80-100	38-45

Root Development in Tills

In order to calculate the *RZC* it is necessary to have information on the root development of different crops and tree species. Very little information is available on this topic. On farmland Olsen (1958), Wiklert (1960, 1961) and Madsen (1979, 1983) have made comprehensive studies of the root development of crops in relation to soil type. These studies suggest that root development depends especially upon the following soil parameters: texture, organic matter content, soil structure, bulk density, air volume, and pH.

Pure sandy soils seem to impede root growth and only shallow root profiles are developed. Olsen (1958) pointed out that for the development of deep rooting, a soil should contain at least 2 % organic matter, or 6 % clay. Heinonen (1979) found shallow root profiles if less than 15 % of the soil material was finer than 0.1 mm. Madsen (1979, 1983) found that the root depth of barley was about 70 cm in pure sandy soils and up to 2 m in loamy tills. Stratified soils may impede root growth (Andersen 1962), as do soils with high bulk density (Madsen 1979, Stockholm 1977 and Andersen 1986) or low pH-values (Madsen 1979, Jessen 1982). Madsen (1983, 1985) showed that soils with low air volume have a shallow root profile, as did Wiklert (1961) for some gyttje soils. Table 2 gives some mean values for root profiles in sandy and loamy tills in Denmark.

Table 2 – The average depth (cm) of soil with more than 1.0 cm root/ccm soil, more than 0.1 cm root/ccm soil, and more than 0.01 cm root/ccm soil for different soil types in the Weichsel glaciation landscape. After Madsen (1983, 1985).

	root depth in cm			
	grass	spring-sown cereals	winter-sown cereals	cm root/ ccm soil
coarse sandy soils	30	30	35	>1.0
	50	50	50	>0.1
	60	60	70	>0.01
fine sandy soils	50	50	–	>1.0
	70	75	–	>0.1
	90	100	–	>0.01
loamy soils	30	40	40	>1.0
	70	90	110	>0.1
	110	130	170	>0.01

Calculation of the Root Zone Capacity

RZC may be determined by combining the *AWC* and the root density of different soil horizons. This has rarely been done and normally the *AWC* in the soil profile

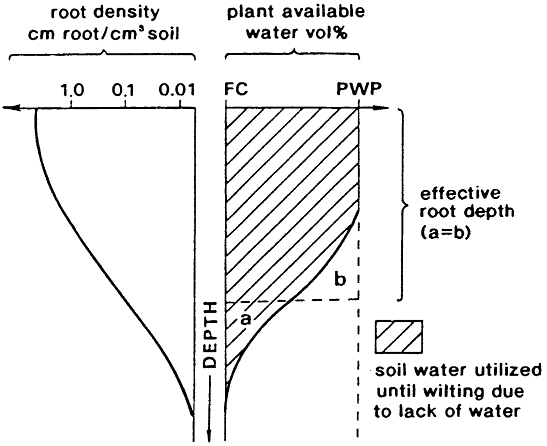

Fig. 2.
Schematic drawing showing the root density, the effective root depth, and the amount of soil water utilized in the soil layers when wilting occurs. (Madsen 1986).

has been calculated to an arbitrary depth, for instance 1 m. In the Nordic countries two different methods have been used for combining the information on soil water retention and root density at different depths. One is to simulate the water status and water transport within the soil-plant-atmosphere system during a severe drought period and thereby calculate the daily extraction of water from the soil layers until wilting occurs due to water stress. The summed transpiration is then a measure of the *RZC*. The other method is to define an effective root depth, Fig. 2, for crops in relation to soil type and then to sum the *AWC* of all soil layers within the effective root depth. A third method is to set up a relationship between root density or soil depth and the proportion of the theoretical *AWC* utilized by the plants.

Determination of RZC by Simulation

In a land quality assessment of an area in east Jutland (Madsen 1979), the *RZC* of 18 soil profiles was determined by the simulation model Heimdal (Hansen 1975). Half of the profiles were developed in tills, the other half in glacio-fluvial or aeolean deposits. The model is based on the assumption that the state of water in the soil-plant-atmosphere system can be quantitatively characterized at any moment and that changes in the system can be described by equations. The model is based on laboratory-determined soil-physical and plant-physiological parameters, and on climatic variables. Soil-physical and plant-physiological input parameters include soil moisture characteristics curves, soil hydraulic conductivity, root growth rate and distribution, plant resistance to water uptake, stomata resistance to vapour loss, crop growth and crop structure. Driving variables are global and net radiation, temperature, air humidity, wind velocity, and the rate and amount of precipitation. The soil profiles were divided into 10-cm thick compartments within

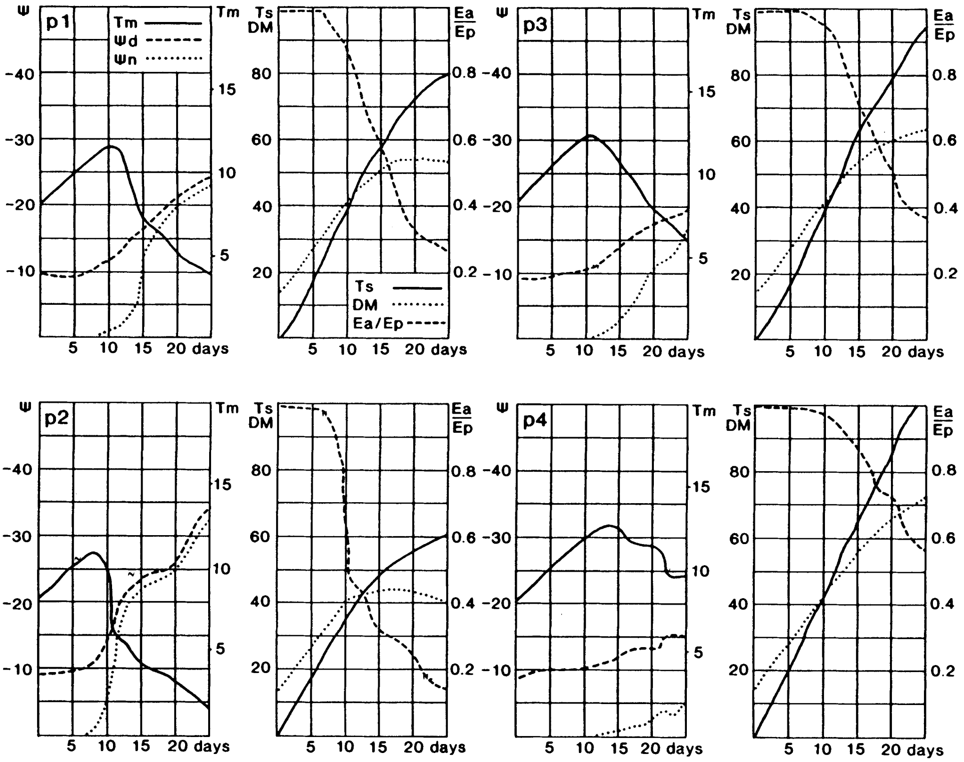

Fig. 3. Variation in max. transpiration rate (Tm), day- and night-time leaf water potential (ψd, ψn), accumulated transpiration (Ts), accumulated dry matter production (DM), and the ratio between actual and potential transpiration (Ea/Ep) over a drough period of 25 days. Tm indicated in mm/24h, ψ in bars, DM in hektokilos/hectare, and Ts in mm (Hansen and Madsen 1984).

which the soil was assumed to be homogeneous and the roots to be evenly distributed.

The possible outputs are many, the most relevant in this connection being the summed up transpiration and the soil water status at wilting. The model with laboratory determined parameters has been tested in the field, and simulated and measured data of evapotranspiration during a wet as well as a dry period agreed well, both on an accumulated basis and on a half hour basis (Hansen 1986).

For simulation with the model, soil moisture characteristics curves were determined to a depth of 150 cm. Unsaturated hydraulic conductivity was estimated according to Millington and Quirk (1961). The initial water content was assumed to be field capacity. From an initial distribution of barley roots, growth was assumed to occur progressively, until an upper root density was reached. This was taken as the root density determined after earing. The root density was determined in the

Table 3 – The quantity of water transpired (mm) and the number of days before the leaf water potential sank to below −20 bar. After Hansen and Madsen (1984).

	mm	days
P1, dune sand	73	19-21
P2, meltwater sand	44	12-13
P3, clayey till (acid)	105	26-30
P4, clayey till (neutral)	177	44-48

field at this stage at 10 cm intervals throughout the soil profile. The intial value of top dry matter of the crop was taken to be 1.5 t/ha.

Climatic conditions corresponding to a dry period in June in N. Europe were assumed. Diurnal mean values were: global radiation 30 MJ/m^2/day, net radiation 15 MJ/m^2/day, wind velocity 3m/sec, temperature 14°C, and vapor pressure 7 mb. Radiation and temperature were assumed to vary sinusoidaly during the photo period and 24 hours, respectively. The length of photo period was 17 hours. The duration of the simulation was a minimum of 25 days with time steps of 0.002 days. No precipitation was assumed during the simulation period. Fig. 3 shows the results with data from four soils situated in the Weichsel glaciation landscape (Hansen and Madsen 1984). Because leaf water potential directly affects plant growth, the amount of soil water transpired before the leaf water potential reaches -20 bar (L-20) may be chosen as a measure for *RZC*. L-20 is chosen because the dry matter production ceases or may even become negative at this or lower potentials. Table 3 shows the *RZC* of the four soils determined from Fig. 3.

Root Zone Capacity Determined as the Available Water Content within the Effective Root Depth

This method has been used in Norway (Samuelsen 1986) and in Denmark (Madsen 1979, Madsen and Platou 1983, Madsen and Holst 1987). In all cases *RZC* determinations were used for calculating the irrigation need at a regional scale.

The investigations in Norway were carried out in a small catchment area (Vigga), which covers 5,000 ha of arable land. Samuelsen (1986) defined *RZC* as the *AWC* within the effective root depth, which was defined as the depth of soil layers with a root density above 0.1 cm root/ccm soil. This is the same value as proposed by Madsen (1983) and used for mapping *RZC* in Denmark (Madsen and Platou 1983, Madsen and Holst 1987). Previously, Aslyng (1976) defined the effective root depth as the soil depth above which 80-90% of the evapotranspirated water was extracted.

The calculation and mapping of *RZC* in the Vigga catchment was as follows (Samuelsen 1986): Lines with an equidistance of 1 km were drawn on a map of the

Table 4 – *RZC* distribution for cereals in the Vigga catchment area. After Samuelsen (1986).

RZC (mm)	area (ha)	% of total area
200	485	9.5
175	690	13.5
150	815	16
125	1275	25
100	1325	26
75	355	7
50	155	3

watershed at scale 1:20,000. The *RZC* was calculated from soil investigations made at 100 or 200 metres intervals along these lines. Augerings, or excavations were carried out to a depth deeper than the root profile, and the following parameters were described: texture, horizon depth, humus content, stoniness, roots and vegetation. Samples were taken at selected sites for determination of soil water retention, root length and texture.

The profiles were divided into 7 *RZC*-classes 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm. The classes 200 mm, 175 mm and 150 mm were mainly situated on organic or silt-rich river and lake deposits or in depressions in the morainic areas, where the crops had deep root development. Such soils have a low irrigation need. The classes 125 mm and 100 mm have a higher irrigation need and are typical of moraine areas where the soils are low in humus but have a root depth greater than 50 cm. The classes 75 mm and 50 mm represent soils with high irrigation need. They are mainly situated in areas with a shallow soil layer overlying rock or in coarse sandy moraine deposits. Table 4 shows area statistics for the Vigga catchment area.

In 1986 the Danish Ministry of Environment initiated some investigations about marginal land, including a nation-wide mapping of potentially marginal land (Madsen and Holst 1987). This mapping included the elaboration of *RZC*-maps at a scale of 1:100,000 and 1:500,000 covering the entire country. The maps were compiled from soil data bases established at the Bureau of Land Data (Madsen 1986). The method used was as follows: All wetlands encircled on old topographic maps were excluded from the mapping because such areas normally have shallow groundwater. Within the non-wetland areas approximately 36,000 soil profiles were constructed with information on soil texture and organic matter content. The profiles were located at the sampling sites from the Danish soil classification (Mathiesen and Nørr 1976) and are based on analytical data from this classification and on information from geological maps. The soil profiles were divided into three layers 0-30 cm, 30-60 cm and 60-120 cm, and within each layer *AWC* was calculated by means of regression equations which relates the water content at pF 2.0 and pF 4.2 with texture and organic matter content. Based on the investigations of Wiklert

(1961), Vetter and Scharafat (1964), and Madsen (1979, 1983 and 1985), a mean effective root depth has been established for grass, spring-sown and winter-sown cereals in relation to the texture of top and subsoil (Madsen 1986). The analytical data of the 36,000 soil profiles was used to compute the mean *RZC*-values shown in Table 5.

Fig. 4 shows a root zone capacity map for barley production from the county Vejle in east Jutland. Each point represents a sampling site form the Danish soil classification.

Table 5 – *RZC* in mm for grass and spring-sown barley in relation to texture of topsoil and subsoil. Data from glaciation landscapes only. After Madsen and Holst (1987).

		grass		barley	
Topsoil	Subsoil:	sandy	loamy	sandy	loamy
coarse sand	(0-5 % clay)	75	75	75	75
fine sand	(0-5% clay)	110	115	120	150
loam	(15-25 % clay)	120	120	150	170
clay loam	(25-45 % clay)	140	140	170	190

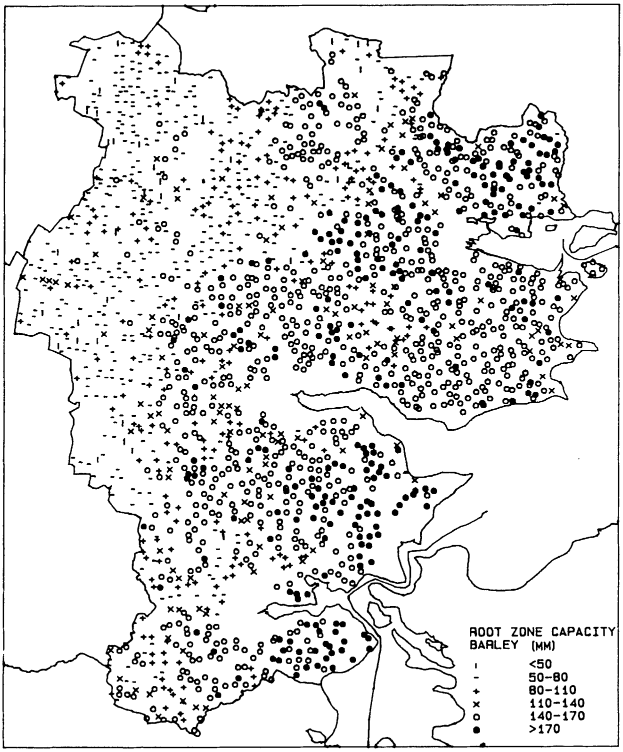

Fig. 4.
RZC-map covering Vejle county in East Jutland (Madsen & Holst 1987).

Root Zone Capacity Determined as the Sum of Available Water in the Different Soil Layers Actually Utilized by the Plants

A third alternative in the calculation of *RZC* is to make allowance for differences in the proportion of the theoretical *AWC* actually utilized by plants at different depths. Holst and Kristensen (1981) suggested factors ranging between 0,5 and 1. Madsen (1979) stated, in the above-mentioned simulation studies, that water potential values close to pF 3 were found at the point of wilting in soil layers with approximately 0,1 cm/ccm root densities. Andersen (1986) confirmed that plants extract at most about 20-25 % of the *AWC* at such root densities. This is equivalent to a water potential of pF 3 for many Norwegian loamy tills (Riley 1979). On the basis of observations of the maximum water extraction by field crops during drought periods, Riley (1989) has suggested that, for loamy tills in south-east Norway, the *RZC* comprises moisture held between pF 2,0 and pF 4,2 at 0-40 cm depth, and that held between pF 2,0 and pF 3,0 at 40-60 cm depth. Support for this hypothesis was gained from measurements of the decline in relative evapotranspiration rates with increasing soil moisture deficit. This method of calculation renders *RZC*-values ranging between 70 and 110 mm for loam soils in this region.

Conclusion

The paper describes three different methods for calculation of till's capacity for storing water for plant production: 1) the available water content within an effective root depth, 2) the sum of water actually utilized by plants from different soil layers, 3) a simulation model for determination of the storage capacity as water transpired from plants.

The first-mentioned method is a crude indicator of the plant-available water content in the root zone. Only two points on the soil-water retention curve are used to characterize the water content in each soil layer, and a mean effective root depth is then combined with these data. The method gives average *RZC*-values in relation to different soil types and is very useful for transforming soil maps into *RZC*-maps, because the data requirements are low and you operate with mean values. On the other hand the method is not good for calculating the *RZC* on single profiles.

For this purpose the second method is better, but more detailed data is then required, *e.g.* information on the whole soil-water retention curve. In the Nordic countries only few investigations using this method have been carried out and further are needed.

The third method is a very laborious and time-consuming one, and the data requirements for running the simulation model are enormous. Not only soil data are needed, but also plant- and climatic data. In return, it provides very detailed information about the uptake of water, *e.g.* the water status in the different soil layers when the plants are wilting due to water stress. The method is efficient for calculating the *RZC* in single profiles, but – as mentioned – huge amounts of data are needed.

A direct comparison between the three methods has not been made, but the definition of the effective root depth used in method 1) has been found as the thickness of soil layers with more than 0.1 cm root/cm^3 soil by means of simulation models (Madsen 1979).

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