Classification of forest soils using dielectric and gamma-ray moisture detection

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Abstract

The present paper demonstrates that till soils in Lapland vary in hydraulic properties. Hydraulic site requirements are different between Scots pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* Karst) and tree species distribution follows the mosaic pattern tills. It was found that Scots pine tend to be adapted on dry tills, while Norway spruce has a larger tolerance for soil water content. The *in situ* dielectric determinaton of soil moisture, coupled with terrestial gamma radiation measurements, are reliable ground truth reference for the classification and interpretation of airborne radiometric data. The airborne gamma-ray data will provide necessary information to soil moisture and thus help in tree species selection when artificial regeneretion is applied.

1 Introduction

Forestry is practised over extensive, isolated areas under harsh climatic conditions in Finnish Lapland. Forest management intensified since the early 1950's when fellings increased greatly. Owing to the higher productivity and timber value of Scots pine compared with other species, the clear cutting, site preparation and artificial regeneration of pine have been the predominant forest regeneration activities during the last 40 years.

Serious cases of seedling dieback have occurred occasionally, the worst failures occurring in pine regeneration areas on fine-textured soils with a thick humus layer that have formerly been covered with spruce-dominated stands (Lähde 1974, Pohtila and Pohjola 1985). Even though some damage, such as frost heaving and fungus diseases, specially snow blight (*Phacidium infestans* Karst.) and Scleroderris canker (*Ascocalyx abietina* Lagerb.), could be observed in the field, the primary physiological reasons for the pine seedling dieback are still unclear.

The main problem has been the lack of techniques for classifying and mapping soils on the basis of their physical properties and for identifying the sites suitable for different tree species. Particle size distribution is the major factor determining the field capacity of soils (Hillel 1971, Viro 1962, Sepponen 1981), and the quantity and quality of the soil matrix govern the moisture content and hydraulic properities of soil materials. However, the conventional sedimentation techniques (hydrometer and pipette) used in standard particle size analysis have poor reproducibility and are too slow for practical soil classification and mapping. Furthermore, the conventional gravimetric techniques for measuring forest soil moisture cannot be used for areal mapping procedures. Therefore, rapid *in situ* techniques and remote sensing of the soil moisture content would be an enormous asset in forest regeneration work.

2 Materials and methods

Tills cover 75 % of the land area in Central Finnish Lapland. Due to the weak glacial erosion and deposition and presence of incorporated preglacial weathering products, tills are highly variable in hydraulic properties. A relatively thin layer of till (1–4 m) covers the bedrock in the study area. Limited proportion of stratified sandy and gravelly materials are found in the river valleys only. We studied hydraulic properities and tree species composition at 12 sites about 150–280 km north of the Arctic Circle. These sites, one hectar each, were surveyed in 1995 with terrestrial dielectric and gamma radiation measurement with 10-meter line separation and five-meter station separation. Since water content varies temporally, dielectric values of till soils monitored once a week from 1995 through 1997. In six sites gamma radiation was also monitored in order to acquire ground-truth reference for the airborne gamma radiation data such that half of the stations located on fine-grained tills and the other half on coarse-textured sandy tills. Registeration period was from the end of April to the begin of September at least once a week. Scots pine was a predominant tree species at five sites, rest of the sites were occupied by stands formed of Norway spruce or mixed Norway spruce and pubescent birch.

2.1 Dielectric properties

Dielectric properties (ε_r) of soils are predominantly dependent on the soil volumetric water content (Topp et al., 1980; Sutinen, 1992, Fig.1.). The dielectric properties of forest till soils *in situ* at each study site determined in grids using time domain reflectometry (TDR, Trase System 1, Soilmoisture Corp., Santa Barbara CA, USA). TDR provides information of the electromagnetic wave velocity and dielectric properties about the material along a parallel transmission line. For the grid measurements two parallel 15-cm-long steel probes with 5-cm-spacing inserted vertically into the soil. For the monitoring purposes probes installed horizontally into the soil layers and ε_r determined with TDR (1502B metallic cable tester, Tektronix, Beaverton OR, USA) on a weekly basis.

2.2 Gamma ray spectrometry

All minerals and consequently till soils are radioactive to some extent. The attenuation of gamma radiation is dependent on the quantity and quality of the absorbant medium and the energy content of the gamma radiation. Natural gamma radiation is effectively attenuated by water, and variations in soil moisture can be detected by terrestrial gamma-ray spectrometry (Zotimov 1971). For example, 50 % attenuation of the radiation in the potassium energy window occurs in about 100 m of air, 10 cm of water and 5 cm of rock.

The low-altitude airborne geophysical surveys carried out by the Geological Survey of Finland consist of the recording of the total magnetic field, in-phase and out-of-phase components of the electromagnetic field, as well as gamma radiation.

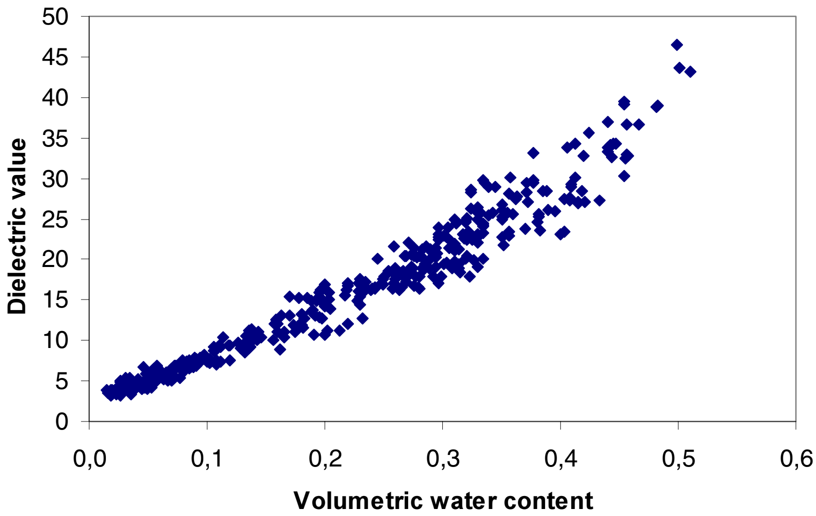

Figure. 1. A plot showing correlation (r_s =0.98, P<0.01, n=425) between the soil dielectric values and volumetric water contents according to Sutinen (1992). An empirical relationship $\varepsilon_r = 3.2 + 35.4 * \theta_v + 101.7 * \theta_v^2 - 63 * \theta_v^3$ is obtained.

These airborne surveys have been conducted since 1972. The flight altitude varies from 30 to 50 m with a flight line separation of approximately 200 m. The data recording speed, 1–4 times per second, and a flight speed of 50 m/s permits a data-recording spacing of 10-50 m. The airborne gamma ray data are recorded by a gamma spectrometer equipped with six NaJ(Tl) sensors with a volume of 25 l. The gamma spectrum of 0.3–3.0 MeV consists of 120 channels with 24 keV. The measuring range is divided into four windows: total, potassium, uranium, thorium (Table 1). This is the most common distribution because the 42 % of gamma radiation of the rocks is derived from K^{40} isotope, 32 % from Th^{232} and 25 % from U^{238} isotopes (Grasty 1977).

The terrestrial gamma radiation data were obtained using a 256-channel gamma spectrometer (GS-256, Geofyzika Brno). The volume of the NaJ(Tl) sensor of the instrument is 0.35 l and a four window division, analogous to the airborne data was used (Table 1). The detector diameter is 3.5 cm, thus allowing point-wise radiation detection.

Table 1. Energy contents of the airborne and terrestrial gamma-ray spectrometers.

Window	Airborne (MeV)	Terrestrial (MeV)
Total count	0.30–3.0	0.83–3.0
Potassium	1.36–1.56	1.36–1.53
Uranium	1.66–1.86	1.65–1.86
Thorium	2.41–2.81	2.48–2.74

2.3 Hydraulic conductivity

The vadose zone hydraulic conductivity (K) was determined using a constant head infiltration along with automatic dielectric measurements with TDR (CS-615 probes with CR10 dataloggers by Campbell Scientific Inc., Logan, UT, USA). K-values calculated by Darcy's law by deriving the pressure potential gradient from the water pressure and the soil suction. Darcy's law originally conceived for saturated flow only was extended by Richards (1931) to unsaturated flow. The unsaturated conductivity is a function of the matric suction head, $K=K(\psi)$, and Darcy's flux, $q=Q/A=- K(\psi)\Lambda H$, where ΛH is the hydraulic head gradient, which may include both the suction and the gravitional components.

3 Results

3.1 Spatial variability

Dielectric and gamma data from the twelve sites show the water status to be significantly different between the sites (Fig. 2). Low mean dielectric values $\varepsilon<13$ and high mean gamma values $\gamma>1$ (potassium window) were observed at the sites naturally occupied by Scots pine stands. In contrast, high mean dielectric values $13<\varepsilon<30$ and low mean gamma values $\gamma<1$ were typical to sites occupied naturally by Norway spruce stands. The spatial variability of the sites, according to semivariogram models, ranges from 20 to 150 m (Hänninen 1997).

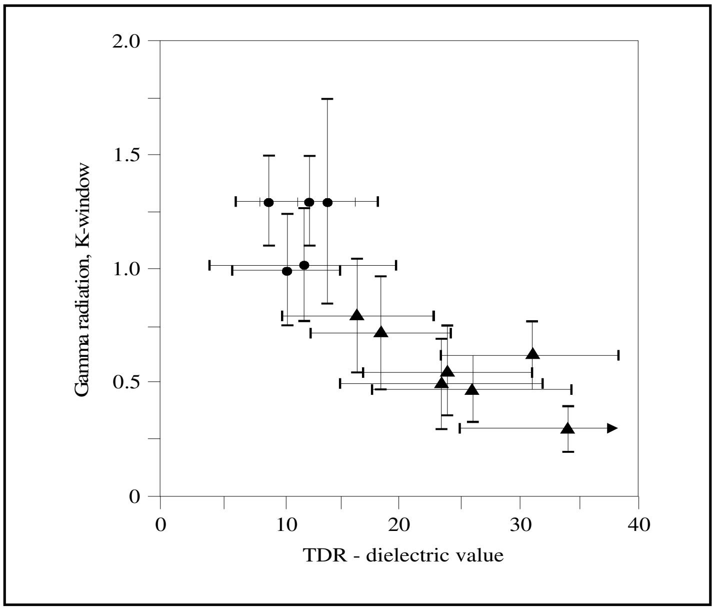

Figure 2.A plot of the terrestrial gamma radiation vs.TDR dielectric data of forest till soils in Central Lapland. For each site 220 TDR measurements and 110 gamma spectrometer measurements were made. Dots indicate sites occupied by Scots pine stands, triangles sites occupied by Norway spruce stands.

The dielectric data indicate hydraulic conditions at the soil surface such that dielectric information is from the top 15 cm. Also, most of the gamma radiation is resulted from till soil and radiation intensity is depending on the concenration of radioactive emitters in the soil, texture and soil water content. Natural gamma radiation is effectively attenuated by water. Previous experiments (Zotimov 1971) have indicated that the water content in soil to a depth of 50 cm can be determined by measuring the gamma field of the earth. It is suggested that increase in a 10 % soil moisture causes a reduction of 3–5 % in ^{40}K counts. The radon effect is most insignificant in ^{40}K channel.

The terrestrial gamma radiation data are related to the dielectric properties of the soils on the studied sites. The plot (Fig. 2) clearly indicates that soils with a high dielectric values and consequently a high water content have low gamma values due to strong attenuation. Consistently, soils with a low dielectric values and low water content have larger gamma radiation values. The till soils with high water content in Central Lapland are typically derived from fine-grained schistous rocks of the Central Laplands Greenstone Belt. The matrix of these tills contain silt and clay size particles enough to effectly resists water percolation through the soil sequences. Precipitation water presumably pass directly into the streams and rivers via surface run-off. The tills on the sites occupied by stands formed by Scots pine are coarse-textured and sandy in matrix. These tills are dominantly derived from coarse-textured granitoids.

3.2 Temporal variation

Our monitoring results showed that 40K counts were more than 1 %K on sites dominantly occupied by Scots pine (Fig. 3) where as the counts were less than 1 %K on sites occupied by Norway spurce (Fig. 4). In similar way, dielectric values were low on the pine sites, such that mean dielectric was ε<13 through the growing seasons (from June through September) 1995 and 1996. In contrast, the sites occupied by Norway spruce were high in soil water content during the growing seasons. The most pronounced feature was several weeks long saturation following snowmelt The greatest variations in gamma radiation intensity were observed in fine-grained tills in the early summer due to frost and snow melting. Gradual soil warming and drying results in increasing levels of the gamma radiation. The maximum values simultaneously with maximum soil temperature reached in mid-August. The difference between the minimum and maximum values of ^{40}K counts was at least double of the minimum value at every station. Heavy rainfalls caused reduction of 10–20 % in ^{40}K counts. The second critical period in the gamma radiation is in autumn when soil cools, evaporation reduces and probability of rainfall increases.

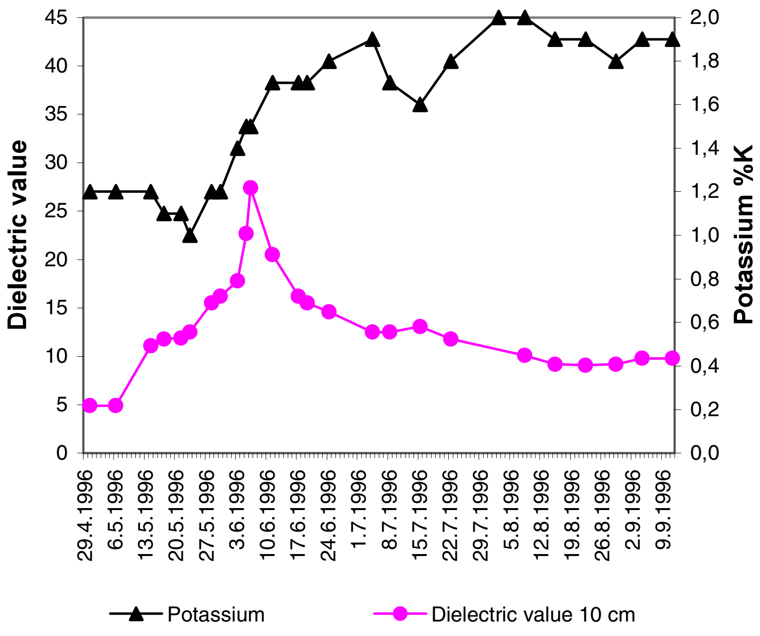

Figure 3. An example of temporal variation of gamma radiation (potassium window) and dielectric values at the till site established naturally by Scots pine stands.

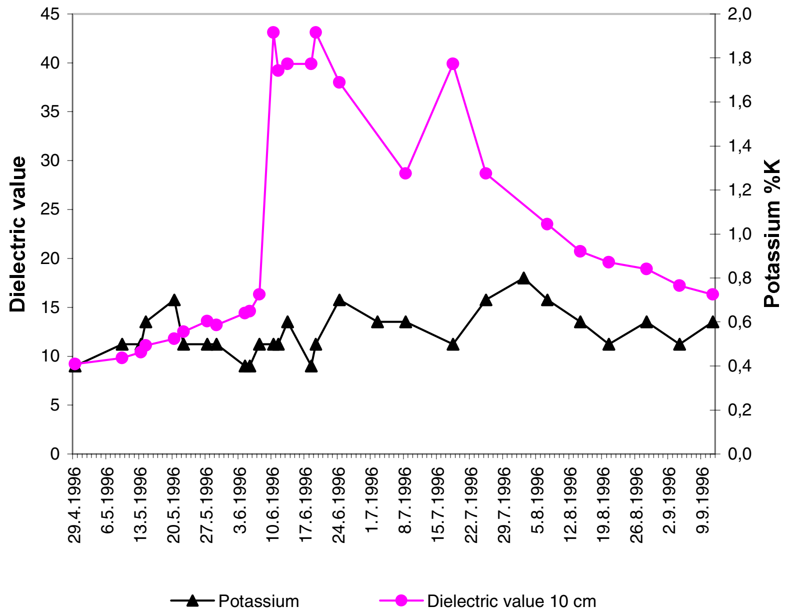

Figure 4. An example of temporal variation of gamma radiation (potassium window) and dielectric values at the till site occupied naturally by Norway spruce.

These data showed that for the interpretation of airborne gamma radiation data it is necessary to know the basic level of the gamma radiation in the research area. Dielectric detection was found to be reliable ground-truth reference and the quantity of ground measurements varies from one lithology to the other. An other important factor is the flight date. The airborne surveys in Finland date back to 1970's and the basic level of radiation has been varied annually. Therefore most reliable results will be obtained when flight data from each year will be processed and classified separately. From this standpoint the areal mapping of moisture content of forest soils is possible on the basis of airborne gamma radiation data.

3.3 Hydraulic classification

Water content, matric potential, gamma radiation and dielectric values are temporally changing features, but are controlled by the texture and structure of tills. The measured matric potentials, however, were significantly different between the till sites occupied by Scots pine ($5<\psi_p <17$) and Norway spruce ($0.5<\psi_p <8$) (Siira 1988).

Hydraulic conductivity is a property determining how rapid the changes in water contents are after rainfalls and snowmelt. Under the field conditions the maximum value of hydraulic conductivity may only be about half of the saturated hydraulic conductivity (Stephens 1996). Good correlations were found between the unsaturated hydraulic conductivity and soil dielectrics (r_s =0.80, P<0.01, n=16, Fig. 5) and between hydraulic conductivity and gamma radiation (r_s =0.79, P<0.01, n=12; Fig. 6). Regression line goodness in both cases are good R^2=0.79 and R^2_γ=0.82, respectively. The highest hydraulic conductivity values (10^{-5} <K<10^{-7} m/s) were observed to be typical of coarse-grained sandy tills where Scots pine stands are dominating. Lowest K-values (10^{-7} <K<10^{-10} m/s) recorded from fine-grained tills. Scots pine is lacking on these till soils, but are covered by Norway spruce and/or mixed spruce-pubescent birch.

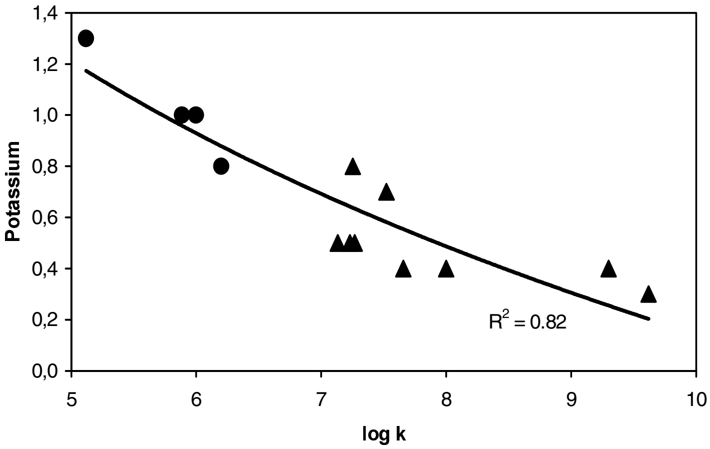

Figure 5. Relationship between in situ dielectric values and vadose zone conductivity (log scale). Symbols are same as in figure 2.

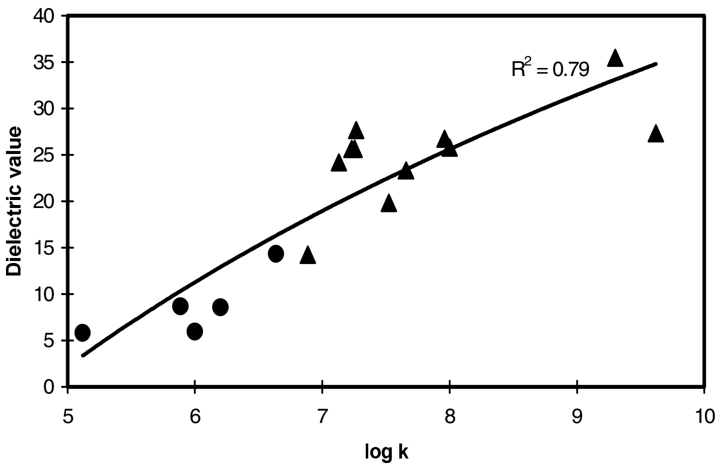

Figure 6. Relationship berween in situ gamma radiation (potassium window) and vadose zone hydraulic conductivity. Symbols are same as in figure 2.

4 Discussion

Terrestrial dielectric moisture detection is a rapid and reliable technique for the detailed surveys of forest soils. Even if laboratory tests with frequencies higher than 1 GHz indicate slightly different texture dependent relationships between the dielectric properites and the volumetric water content (Ulaby et al. 1986), our *in situ* results obtained from Central Lapland and also elsewhere (Sutinen 1992) suggest that dielectric variations and respective variations in soil water content between different types of till soils are large enough for the classification of forest soils.

The main part of the gamma radiation is derived from the top half meter of soil (Grasty 1977) and the radiation is dependent on density of the rock and unconsolidated earth materials. The density of till in Central Lapland varies between 1.4–2.1 g/cm^3 (Nieminen, 1985) so 90 % of the radiation is derived from the top 35–45 cm. Therefore, better correlation would be achieved between the dielectric and gamma data if the dielectric logging averages of the top 40 cm are used. However, the airborne surveys averages gamma values from an oval area 110 m in longitudinal diameter, while the terrestrial measurements are only points. The interpolated airborne imagery is only feasible for general-scale overviewing of the variations in forest soil moisture (Sutinen et al. 1994). Gamma radiation and dielectrics are both temporal variables and therefore best results will be obtained if flight data for each year will be prossed and classified separately.

The present paper shows that till soils derived from fine-textured schistous rocks in Central Lapland have a high water content, that is indicated by high dielectric values (ε_r>15), low gamma radiation values (^{40}K counts less than 1 %K) and low hydraulic conductivity (K<10^{-7}) values. These tills are generally occupied naturally by Norway spruce and/or mixed spruce pubescent birch stands. In contrast, Scots pine is naturally growing on till sites with low dielectric values (ε<13, Sutinen et al. 1997), high gamma radiation values (^{40}K counts more than 1 %K) and low hydraulic conductivity (K>10^{-7}).

The site requirements of Scots pine and Norway spruce are different. Therefore some of the failures in artificial regeneration by pine might be attributed to high soil water content. The rate of seedling mortality in the early stages seem to increase along with an increasing soil water content (Sutinen et al. 1994). From a physiological point of view, the roots of pine seedlings may suffer from a lack of oxygen in silty till and hypoxia is suspected to be one reason for the damage. Hydraulic conductivity of silty till in Central Finnish Lapland seems to be very low, and much of the excess of rain water is lost through surface run-off. This might partly increase the hypoxia effect during the early stages. Presumably the moisture content in ploughed tilts increases as a result of compaction and the realignment of the capillary pathways in the tilts. This may explain the cases of pine seedling dieback after 10–20 years after ploughing.

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