FUTMON PROTOCOL
Determination of the soil water retention characteristic

Version 1.2 (after FUTMON –D3 Soil moisture workshop, Freising 25-26 March 2009)

Soil water retention characteristic (pF analysis)	
Method sheet	SA14
Reference method	**ISO 11274**
Method suitable for	Mineral and organic soil horizons, undisturbed samples

1. Introduction

During the FutMon LIFE+ project 2009-2010, the demonstration action D3 aims at the assessment of forest water budgets. Data is collected on more than 100 D3 plots being a subset of the IM1 plots. For the parameterisation of various water balance models meteo data, stand characteristics and soil physical data are essential. For the validation of the models soil temperature, soil moisture and stand precipitation measurements are needed.

The soil water retention characteristic is a physical soil property depending mainly on soil texture, organic material and bulk density. Therefore it will vary both vertically (horizons/layers in the profile) and horizontally in each plot. Stratified sampling according to horizons or specific layers is a prerequisite to determine the overall hydrological behaviour of a soil profile.

Specific points on the soil water retention curve (SWRC), which is the relationship between volumetric soil water content and matric pressure, are required to (1) determine indices of the volume of plant-available water, (2) estimate the soils' pore size distribution and (3) predict other soil physical properties (e.g. hydraulic conductivity). The SWRC is an essential part in most water budget models.

This protocol describes the determination of the soil water retention characteristic in the laboratory, extending from saturated soil (no pressure or suction; 0 kPa) to oven-dry soil (about -10^6 kPa).

The format of this protocol is in line with the new standard structure for sub-manuals proposed by the QA committee (Quality objectives in FutMon).

2. Scope and application

This FutMon protocol conforms the ISO 11274 international standard for determination of the soil water retention characteristic based on measurements of the drying or desorption curve. All methods described by ISO 11274 are allowed, except method B, using a porous plate and burette apparatus for matric pressures from 0 to -20 kPa.

The volumetric soil water content at matric pressure 0 kPa is approximated by the total porosity of the soil.

In addition this protocol describes the mandatory and optional matric pressures to assess in the lab as adopted for FutMon action D3. This further standardisation is a prerequisite for facilitation and harmonisation of database handling.

The protocol outlines the general description of basic sampling and laboratory operation for soil water retention analysis at plot level. Definitions of variables and guidelines for method selection and sampling are applied as described in the ISO 11274:1998 method (ISO, 1998).

3. Operational objectives

The general operational objectives are:

- To determine on each plot the SWRC for specific soil layers of at least 3 profiles. The field matric potential for each layer will be inferred from the measured water content (WC) and its layer specific SWRC;
- To assess the SWRC at plot level only once. Just like texture, the SWRC is considered a constant soil property showing little change over time;
- To harmonise and standardize the field methods for sampling undisturbed soil samples and the determination of the SWRC in the lab;
- To quantify the accuracy (trueness and precision) of the results of SWRC determination, based on within lab analysis of replicate samples (e.g. twin field samples) and participation in interlaboratory physical soil comparisons using reference material;
- To assess the spatial variation of the SWRC within the plot;
- To use the SWRC for the parameterization of various water budget models (e.g. WATBAL, BROOK90, SIMPLE, COUP, THESEUS, WASIM-ETH, …). The prediction capacity of these models will be partly determined by the uncertainty of parameters derived from the SWRC.

The specific operational objectives described in this protocol are:

- adequate sampling of undisturbed soil in situ;
- correct handling of undisturbed soil cores prior to analysis;
- analysis of the soil water characteristic in the laboratory;
- standardised reporting of the SWR results.

4. Location of measurements and sampling

4.1 Sampling design at plot level

4.1.1. Sampling locations (profiles) within the plot

On each plot at least 3 profiles are sampled separately. The location of these profiles within the plot may be chosen freely, as long as their spatial design meets following requirements:

- the individual profiles are representative for the soil condition within the plot;
- the profiles are not located in one single profile pit (i.e. profiles are at least some meters apart);
- the profiles should be situated as close as possible to the location of the soil moisture measurement sensors;

The exact coordinates of each profile location should be determined.

4.1.2. Sampling within the soil profile

At each location, adequate undisturbed soil sampling within the soil profile is done according to the sampling scheme in Table 1. At least one undisturbed core is taken within the fixed depth intervals 0 - 20, 20 - 40 and 40 - 80 cm, preferentially at the same depth as the soil moisture measurements (depth of TDR sensors). The exact depth range of the soil core (top to bottom of core) is reported, along with the ring ID information.

When forest floor thickness (OF + OH layer) is > 5 cm, the holorganic layer should be sampled also with a suitable cylinder. Optionally, extra soil layers or horizons could be sampled that are considered relevant for the hydrological regime of the soil profile.

Table 1. Soil profile sampling scheme

Matrix	**Depth interval (cm)**	**Minimum number of replicates**		**Requirements for D3**
		per profile	**per plot**	
Organic Layer	Forest floor > 5 cm thick Forest floor <= 5 cm thick	1 -	3 -	Mandatory not required
Mineral layer	0 - 20 cm 20 - 40 cm 40 - 80 cm > 80 cm Extra (specific) layer	1* 1* 1* - -	3 3 3 - -	Mandatory Mandatory Mandatory Optional Optional

(*) if the mineral layer is difficult to sample (e.g. caused by higher gravel content) a higher number of samples are strongly recommended).

Concluding from Table 1, on each plot at least 9 undisturbed and representative samples should be taken if the forest floor is less than 5 cm thick and 12 samples if the forest floor is more than 5 cm thick.

For each undisturbed sample, the pedogenetic horizon according to FAO (2006) designations, should be reported that contains the centre of the sampling cylinder. The pedogenetic horizon may be deduced from the soil profile description of the sampled plot.

Hence for each undisturbed core sample following information is reported:

- exact depth range of core cylinder in cm (e.g. 10 -15 cm for a cylinder of 5 cm in height);

- pedogenetic horizon containing centre of undisturbed sample (e.g. 12.5 cm is located in E horizon)

4.2. Sampling equipments

4.2.1. Sampling cylinders

Undisturbed soil cores are taken in dedicated metal cylinders (sleeves) with a volume between 100 and 400 cm³. Plastic cylinders are dissuaded. The same steel cylinders can be used as for determination of bulk density (method SA04). The sample ring dimensions should be representative of the natural soil variability and structure.

Recommended dimensions (height x diameter in mm) of cylinders for forest soil sampling are: 50 x 53, 40 x 76 and 50 x 100. It is important to verify that the laboratory that will process the undisturbed samples is equipped for the type of sample rings used.

The bottom of the sample ring should have a cutting edge. Plastic lids should perfectly fit to both ends of the steel cylinder.

4.2.2. Sampling material

In a soil profile pit, undisturbed samples can be taken directly using the sample ring, without extra material like an open or closed ring holder. In that case, after introduction, the soil sample ring should be dug out carefully.

Alternatively, an open ring holder may be used. In such a holder, the ring is locked by means of a rubber or lever. Over the ring some space headroom is left allowing for taking an oversize sample. This prevents the sample for compaction during sampling.
In hard soil layers, an impact absorbing hammer may be used for hammering the ring holder into the soil.

When sampling is done in a bore-hole, a closed ring holder is recommended. This type of ring holder holds the cylinder in a cutting shoe. The ring is clamped inside the cutting shoe and no water or soil can come into the ring from the top. Moreover, the sample ring is protected, the sample is oversized on both sides and there is no risk of losing or damaging the sample ring. In hard layers, an impact absorbing hammer may be used with care.

Trimming both ends of the cylinder is preferably done using a small frame saw. A spatula or knife may be used but care has to taken avoid smearing the surface (closing macro- and mesopores).

After closing the cylinders with plastic lids, the sample should be labeled and wrapped in plastic bags or plastic or aluminium foil to prevent drying.

In conclusion, the sample material is:

- steel cylinders (sample rings) with lids
- open ring holder (optional)
- closed ring holder (needed when sampling in boreholes)
- spade and/or trowel for digging out the cylinder
- impact absorbing hammer (for hard soil layers only)
- small frame saw
- spatula or knife

- waterproof marker for labeling
- plastic bags or foil for wrapping the ring

4.3. Sample collection

Undisturbed samples should be collected during a wet period, preferentially when soil matric pressures are at or near field capacity. Do not sample the soils when it is freezing.

The sampling procedure for undisturbed soil sampling (core sampling in steel rings) is as follows:

- Take soil cores carefully to ensure minimal compaction and disturbance to the soil structure, either by hand pressure in suitable material or by using a suitable soil corer and/or core holder. Take one sample (preferentially 3) for each freshly exposed soil horizon or layer; more replicates are required in stoney soils;

- The ring sample is taken vertically with its cutting edge downwards;

- Dig out the cylinder carefully with a trowel, if necessary adjust the sample within the cylinder before trimming flush, trim roughly the two faces of the cylinder with a small frame saw or a knife and fit lids to each end;

- Record the sampling date, sample grid reference, horizon encompassing the centre of the core, and the exact sampling depths (depth of top and bottom of the cylinder with respect to the top of the mineral horizon).

- Label the cylinder on the lid clearly with the sample plot reference, the sampling date, the horizon code and the sample depth;

- Wrap the ring samples in plastic bags or a plastic or aluminium foil to prevent drying;

4.4. Sample storage and transport

The undisturbed samples are transported in plastic boxes or aluminium cases. They protect the samples from heat, humidity or dust. If transported in vehicles over long distances, shocking of samples should be avoided by using shockproof materials.

Prevent undisturbed soil samples from freezing. Store the samples at 1 to 2 ℃ to reduce water loss and to suppress biological activity until analysis. Samples with obvious macrofaunal activity should be treated with a suitable biocide, e.g. 0,05 % copper sulfate solution.

It is recommended to avoid weeks of storage of undisturbed soil samples. Ideally, undisturbed soil samples are analyzed in the lab immediately after sampling.

5. Measurements

5.1 Measurements to be done and reporting units.

In order to determine the SWRC, the volumetric water content (θ in volume fraction, $m^3\ m^{-3}$) is determined at predefined matric potentials (ψ, in kPa). As indicated in Table 2, six of these matric heads are mandatory to determine. Extra observations of the SWRC at pressures -10, -100 and -250 kPa are optional but they greatly improve fitting the SWRC.

Some matric heads immediately provide information on SWRC parameters: at 0 kPa the maximum water holding capacity (WHC) of the saturated soil sample is determined; depending on definitions and soil texture field capacity (FC) may be inferred from -5 till -100 kPa; permanent wilting point (PWP) is attained at a matric pressure of – 1500 kPa and dry bulk density (lowest pressure at about 10^{-6} kPa) derived in the oven at 105℃.
The standard instruments required for each determination are listed in Table 2.

Table 2. Overview of matric heads to assess for the determination of the SWRC. Mandatory pressures to determine are in bold, optional in italic.

Matric potential ψ		**Recommended Instrument**	**Estimator**
pF	**kPa**		
0.0	**0**	**Pycnometer**	**≈θsat=WHC= Total porosity**
1.0	**-1**	**Sand suction table**	
1.7	**-5**	**Sand suction table**	**FC**
2.0	*-10*	*Sand suction table*	*FC sand*
2.5	**-33**	**Kaolin suction table**	**FC siltloam**
3.0	*-100*	*Kaolin suction table*	*FC clay*
3.4	*-250*	*Ceramic plates*	
4.2	**-1500**	**Ceramic plates**	**PWP**
7.0	**-10^6**	**Oven**	**Dry BD**

Where:

1) the pF is the logarithm of the absolute value of the matric potential expressed by the graduation of the water column (cm).
2) 1 kPa = 10.22 cm H_2O or 1 cm H_2O column = 0.097885 kPa
3) 100 kPa = 1 bar

5.1.1. Determination of the soil water characteristic

The ISO 11274:1998 allows 4 methods to determine matric pressures within specific ranges:

A) method using sand, kaolin or ceramic suction tables for determination of matric pressures from 0 kPa to - 50 kPa;
B) method using a porous plate and burette apparatus for determination of matric pressures from 0 kPa to - 20 kPa; (single sample)
C) method using a pressurized gas and a pressure plate extractor for determination of matric pressures from - 5 kPa to - 1500 kPa;
D) method using a pressurized gas and pressure membrane cells for determination of matric pressures from - 33 kPa to - 1500 kPa.

Since method B allows only processing a single sample at the time, use of this method is not recommended. Laboratories are free to apply methods A, C and D according to the ISO 11274 standard.
Guidelines for choosing the most appropriate method for specific soil types are given in ISO 11274, chapter 3.

Before applying methods A, C or D, general recommendations for sample preparation are:

- For measurements at pressures from 0 to -50 kPa, use a nylon mesh to retain the soil sample in the sleeve and secure it with an elastic band or tape;

- Ensure maximum contact between the soil core, mesh and the porous contact medium of the suction tables, plates or membranes; remove any small projecting stones if necessary;

- Avoid smearing the surface of (clayey) soils, especially when water saturated;

- Inspect the sample for bioturbation (worms, isopods) or germination of seeds during analysis; the use of a biocide is discouraged;

- Report the temperature at which the water-retention measurements are made;

- Ideally, measurements start with field-moist samples [i.e. do not dry the undisturbed samples first (hysteresis effect)]. Then, samples are saturated with water.

- Respect wetting times before starting measurements to obtain a saturated sample. General guidelines for wetting times according to ISO 11274 are:
  - sand 1 to 5 days
  - loam 5 to 10 days
  - clay 5 to 14 days or longer
  - peat 5 to 20 days.

5.1.2. Method A (recommended method for matric pressures 0, -1, -5, -10 and -33 kPa)

Determination of the soil water characteristic using sand, kaolin and ceramic suction tables

Apparatus

- Suction table (watertight, rigid container with outlet in base and close fitting cover)
- Drainage system for suction table, enabling to maintain suction at specific matric pressures
- Sand, silt or kaolin packing material, appropriate for use in suction tables (homogenous, sieved, graded and washed, free of organic material or salts). Material should achieve the required air entry values (see ISO 11274 for details)
- Drying oven capable of maintaining temperature of 105 ± 2 °C
- Balance (accuracy 0.1% of measured value)

Procedure

- Weigh the cores and then place them on a suction table at the desired matric pressure with table cover closed. The reference 0 cm height for setting the suction level is the middle of the core;
- Leave the cores for 7 days (minimum equilibration time). Equilibrium is reached if daily change in mass of the core is less than 0,02 %;
- If equilibrium is reached, weigh the cores, if not, replace cores firmly onto the suction table and wait until equilibrium is reached.

Calculation

ISO 11274 describes two procedures:

1. Procedure for soils containing less than 20 % coarse material (diameter greater than 2 mm)
2. Procedure for stony soils; conversion of results to a fine earth basis

For soils with less than 20% coarse material:

- Calculate the water content mass ratio at matric pressure ψ_i using the formula:

$$WC\psi_i = (M\psi_i - M_{dry}) / M_{dry}$$

where
$WC\psi_i$ is the water content mass ratio at a matric pressure ψ_i, in grams;
$M\psi_i$ is the mass of the soil sample at matric pressure ψ_i, in grams;
M_{dry} is the mass of the oven-dried soil sample, in grams.

- Calculate the volumetric water content at matric pressure ψ_i using the formula:

$$\theta\psi_i = [(M\psi_i - M_{dry}) / (V \times \rho_w)] \times 10^{-3}$$

alternatively

$$\theta\psi_i = WC\psi_i \times (\rho_b / \rho_w)$$

where
$\theta\psi_i$ is the water content volume fraction at matric pressure ψ_i, expressed in $m^3\ m^{-3}$ (volume of water per volume of soil);
$M\psi_i$ is the mass of the soil sample at matric pressure ψ_i, in grams;
M_{dry} is the mass of oven dried soil sample, in grams;
V is the volume of the soil sample in m^3
ρ_w is the density of water, in kg m^{-3}
ρ_b is the bulk density of oven dried soil at 105℃, in kg m^{-3}.

For soils with more than 20% coarse material, data needs conversion to a fine earth basis as follows:

The volumetric water content of the fine earth (θf) equals:

$$\theta f = \theta t / (1 - \theta s)$$

where:
θf water content of the fine earth, expressed as a volume fraction ($m^3\ m^{-3}$);

θs volume of non-porous stones, expressed as a fraction of total core volume ($m^3\ m^{-3}$);

θt is the water content of the total earth, expressed as a fraction of total core volume ($m^3\ m^{-3}$);

For porous stones, a different correction should be applied as described in ISO 11274.

If volumetric water content is reported on fine earth basis, this should be clearly reported along with the volume of non-porous stones in the sample.

5.1.3. Method C (recommended method for matric pressures -250 and -1500 kPa)

Determination of soil water characteristic by pressure plate extractor

Apparatus

- Pressure plate extractor with porous ceramic plate
- Sample retaining rings/soil cores with discs and/or lids

- Air compressor (1700-2000 kPa), nitrogen cylinder or other pressurized gas)
- Pressure regulator and test gauge
- Drying oven capable of maintaining temperature of 105 ± 2 ℃
- Balance (accuracy 0.1% of measured value)

Follow the manufacturer's instruction to assemble and operate the apparatus.

Procedure

- Take small subsamples from the undisturbed sample: soil cores of approximately 5 cm diameter and between 5 mm and 10 mm in height; smaller samples for lower pressures are used in order to avoid long equilibration times;
- It is acceptable to use disturbed samples at pressures lower than - 100 kPa, providing that the disturbance consists only in breaking off small pieces of soil and not in compressing or remoulding the soil.
- Use at least three replicate samples of each sample and place them on a presaturated plate;
- Wet the samples by immersing the plate and the samples until a thin film of water can be seen on the surface of the samples;
- Create a saturated atmosphere in the extractor;
- Apply the desired gas pressure and keep to a constant level, check for leaks;
- Record on a daily basis the evacuated water from the samples, when no change are observed (volume in a burette remains static) the samples have come to an equilibrium;
- At equilibrium status, soil samples are weighed, oven-dried and reweighed to determine the water content at the predetermined pressures

Calculation

The same calculation procedure as in 5.1.2 is applied, for samples without or with coarse fragments.

5.1.4. Method D (recommended method for matric pressures -250 and -1500 kPa)

Determination of soil water characteristic using pressure membrane cells

Apparatus

- Pressure cells with porous baseplates
- Cellulose acetate membrane
- Pressure regulator
- Air compressor (1700-2000 kPa, nitrogen cylinder or other pressurized gas)
- Drying oven capable of maintaining temperature of 105 ± 2 ℃
- Balance (accuracy 0.1% of measured value)

Follow the manufacturer's instruction to assemble and operate the apparatus.

Procedure

- Soil subsamples are placed on a porous cellulose acetate membrane
- Equilibrium status is attained when water outflow from the pressure cell ceases and soil water content is determined by weighing, oven-drying and reweighing the sample.
- Gas pressure methods are only suited to determine matric pressures below - 33 kPa

Calculation

The same calculation procedure as in 5.1.2 is applied, for samples without or with coarse fragments

5.1.5 Determination of the total porosity

A value for porosity can be calculated from the bulk density ρ_{bulk} and particle density $\rho_{particle}$:

$$\phi = 1 - \frac{\rho_{\mathrm{bulk}}}{\rho_{\mathrm{particle}}}$$

Often the **particle density or true density** of soil is approximated by 2650 kg.m^{-3} (mineral density of quartz). But the direct measurement of the particle density is strongly recommended to be done by the means of a pycnometer.

5.1.6. Determination of dry bulk density

Determination of dry bulk density is also done according to method SA04 (submanual IIIa) The dry bulk density (BD) is recorded in kg m^{-3} with no decimal places.

In the case of stony or gravely soils the bulk density of the fine earth fraction (< 2 mm) should be reported. Furthermore, the bulk density of the coarse fragments should be known, but this may be approximated as 2650 kg.m^{-3}.

5.1.7. Reported data, their units and numerical precision

Based on the SWRC measurement in the lab, data reported for each undisturbed soil sample are listed in Table 3.

Table 3. Raw SWRC data: measurement, unit and numerical precision to be reported for each sample. Data in bold are mandatory to report.

Matric pressure (kPa) ψ	**Volumetric water content (VWC) = θ**	**unit**	**Numerical Precision**
0	**0.xxxx**	$m^3 m^{-3}$	0.0001
-1	**0.xxxx**	$m^3 m^{-3}$	0.0001
-5	**0.xxxx**	$m^3 m^{-3}$	0.0001
-10	0.xxxx	$m^3 m^{-3}$	0.0001
-33	**0.xxxx**	$m^3 m^{-3}$	0.0001
-100	0.xxxx	$m^3 m^{-3}$	0.0001
-250	0.xxxx	$m^3 m^{-3}$	0.0001
-1500	**0.xxxx**	$m^3 m^{-3}$	0.0001
Matric pressure (kPa) ψ	**Dry bulk density (BD)**	**unit**	**Numerical Precision**
-10^6	**xxxx**	kg m^{-3}	0

5.2. Data Quality Requirements

Plausibility limits for SWRC of mineral forest soils and organic layers will be developed in the future; partly based on the results of Action D3 in FutMon.

Tolerable limits for laboratory performance will be derived from the reproducibility data gained by performing the interlaboratory physical soil ringtest during FutMon.

Soil water retention data are considered complete if volumetric water content for all six mandatory matric heads (bold in Table 3) is determined. For scientific reasons analysing the optional matric heads also is strongly recommended.

Interpolation of volumetric water content between matric pressures is not allowed. All reported values should have been measured according to the methods described in this protocol.

6. Data handling

6.1. Data storage forms

Forms for storing the SWRC data in the FutMon databases will be developed under FutMon. Basically following data should be stored:

- the undisturbed sample metadata:
    - sample ID
    - plot ID
    - profile ID
    - fixed depth layer
    - horizon designation
    - sample ring depth (top) in cm below top of mineral soil
    - sample ring depth (bottom) in cm

- the raw volumetric water content (θ = VWC in $m^3\ m^{-3}$) data mentioned in Table 3:
    - VWC0
    - VWC-1
    - VWC-5
    - VWC-10
    - VWC-33
    - VWC-100
    - VWC-250
    - VWC-1500

- derived data from SWRC
    - bulk density (kg m^{-3})
    - moisture content at field capacity ($m^3\ m^{-3}$)
    - moisture content at permanent wilting point ($m^3\ m^{-3}$)
    - Van Genuchten model parameters θ_r, θ_s, α, n
    - Predicted Ksat (cm day^{-1})

- Data quality indicators
    - Lab ID (laboratory that analysed SWRC)
    - Lab quality indices (to be defined)

6.2. Plausibility limits, data completeness

To be defined.

6.3. Transmission to co-ordinating centres, with timetable and rules

To be defined.

6.4. Data processing guidelines

Soil water retention curve models will be fitted to the raw data (Table 3). For forest soils, one of the best performing functions is the Van Genuchten equation defined by its empirical parameters θr, θs and empirical constants α, n and $m = 1\text{-}1/n$.

Calculation of these parameters can be done using the public domain RETC programme which may be downloaded from: http://www.pc-progress.cz/Pg_RetC.htm.
This software enables to predict Ksat from the SWRC measurements.

The Van Genuchten model parameters are also stored in the FutMon soil physical databases.

6.5. Reporting guidelines

Data will be reported as foreseen in the data storage forms. See Annex x.

7. References

ISO 11274:1998(E). Soil Quality – Determination of the water-retention characteristic – Laboratory methods. International Organization for Standardization. Geneva, Switzerland. 20 p. (available at www.iso.ch)