Vlaanderen
is wetenschap

Capability of PlantCare Mini-Logger technology for monitoring of soil water content and temperature in forest soils

Test results of 2015

Bruno De Vos

Technical assistance by **Yvan De Bodt, Koen Vervaet** and **Koen Willems**
Eijkelkamp contacts: **Bregt Diependaele** and **Leon van Hamersveld**.

Report ID 12107469

INSTITUUT
NATUUR- EN BOSONDERZOEK

Preface

New technology always offers new perspectives for science. Accurate measurement of soil moisture is more difficult than it seems, especially if continuous measurements are required within for example monitoring programmes. Fortunately, one can always measure gravimetrical soil water content of a soil sample taken at a given time, location and depth which can act as the real reference (golden standard) for soil moisture measurements performed by other techniques and methods.

This report is the result of a parallel investigation on soil moisture monitoring on 5 selected UN/ECE ICP Forests intensive monitoring sites in Flanders, Belgium, which are part of the European Level II network. The main investigation aims at validation and –if necessary- in situ recalibration of soil water content reflectometers (FDR) installed and continuously operating since 2010 on the 5 test sites. The main goal is to determine status and trends of soil moisture evolution in forest soils since the start of the continuous measurements on these sites in the year 2000. Strongly linked with the climatic changes we observe, we want to see their impact on soil water balance and related hydrological and nutrient fluxes through these reference forest ecosystems.

The Eijkelkamp company (Giesbeek, The Netherlands) and PlantCare Ltd (Russikon, Switzerland) offered a set of 14 PlantCare Mini-Loggers that are using an innovative microthermic technique for measuring (plant available) soil water content and soil temperature in a single device. Each device contains a sensor, a soil specific felt material acting as an interface between soil and sensor, and a logger storing all data. The PlantCare Mini-Loggers have a high autonomy and can be easily inserted in the soil and are therefore of interest for use in remote areas as is often the case for research plots in forests and nature reserves.

Since the developers proclaim that these Mini-Loggers provide reliable results of soil moisture and temperature, are maintenance free, can store over 12000 records and that the recorded data can be easily logged using a simple USB-stick, we were triggered to test these statements under real-life conditions.

Therefore, 12 sensors were installed on 5 sites and 2 sensors were tested in the lab to check their performance. The results of PlantCare measurements during 2015 were compared with all other soil moisture and temperature data recorded at the test sites at the same locations and soil depths.

This report provides a discussion of the results and an evaluation of the performance of PlantCare Mini-Loggers during 9 months of operation.

We thank Bregt Diependaele and Leon van Hamersveld from Eijkelkamp NV for providing the Mini-Loggers, their technical assistance and useful suggestions. We especially appreciate their patience in waiting for this report, which took more time than initially planned. We acknowledge the manufacturers of this product, dr Walter Schmidt and colleagues, and hope they will continue to produce these stand-alone Mini-Loggers and make further improvements to them.

This report could not be realized without the work of our field technicians that monthly sampled all sites and logged the data. Special thanks to Yvan De Bodt who carefully processed the undisturbed soil samples for bulk density and reference soil moisture content and logged and elaborated the PlantCare readings. He was assisted by Koen Willems and Koen Vervaet for the field sampling on the Level II sites. Thanks for all your efforts !

English abstract

The Swiss company PlantCare Ltd. developed a new technique based on a heat-pulse to determine the relative soil moisture content of soils. At the same time the sensor is measuring soil temperature. Since 2004, several PlantCare systems were developed and successfully implemented in irrigation projects of crops.
Mini-Loggers that were developed in 2009 are autonomous devices consisting of a measuring unit (logger) and a sensor at the end of a stock that is inserted into the soil at a given depth. Temperature and moisture content are measured through a porous synthetic matrix (felt) that is in contact and equilibrium with the surrounding soil. The relative moisture measurement is based on the generation of a heat pulse and the time required to cool down, which is a function of moisture content and ambient temperature of the felt. Mini-Loggers can store a large amount of data in their memory and are easily programmed and logged using a standard USB memory-stick. Therefore they are convenient to use in eco-hydrological research in (remote) forest and nature areas.

In this study we tested from March to December 2015 a set of 14 Mini-Loggers. Twelve were installed on 5 Level II Intensive Monitoring sites in Flanders Region (Field observations) and two Mini-Loggers were tested under controlled lab conditions. The observations continued in 2016. The daily averaged results of soil temperature and relative moisture content of the PlantCare Mini-Loggers were compared to readings of Campbell T107 temperature probes and CS616 soil water reflectometers (FDR sensors) for the same depth and at short distance from each-other. Furthermore, monthly field sampling of undisturbed soil cores nearby the PlantCare sensors was conducted to determine gravimetrical moisture contents and bulk densities in order to quantify reference volumetric moisture contents.

The results of a nine months of observation show that soil temperature between nearby installed Mini-Loggers are correlating very well and show an identical temperature pattern. A good correlation exists with the data of the T107 probe, but on most sites a slightly higher temperature (mean: 0.69 °C, max: 1.08°C) was recorded by the Mini-Loggers. The systematic difference between these sensor types was varying over the year and was least when soils were wet (winter period). Over all, the Mini-Loggers were capable to produce accurate data of the soil temperature variation on all sites.

The evolution of soil moisture content recorded by the Mini-Loggers was different from the pattern of FDR readings . Mini-Loggers seem to respond more quickly and much stronger to soil moisture changes and the relative moisture percentages are clearly linked with rain events. Differences in response are partly explained by the fact that FDR sensors integrate their moisture measurement over a distance (e.g. 30 cm) whereas Mini-Loggers conduct point measurements. When neglecting the rain-peaks in the PlantCare response, the seasonal soil moisture pattern can be found between Mini-Logger and FDR data-series and this pattern is generally confirmed by the gravimetrical reference measurements.
Two types of felts were tested: (1) felts for natural soils (NS) and (2) for artificial substrates (AS). Both in the field as under lab conditions the AS felts were not performing adequately and were replaced by NS felts.

On sandy soils, the Mini-Loggers with NS felts showed a soil moisture response within a clear range, but on silt-loam and clay soils the relative soil moisture content is limited (saturated) upon water logging at a constant level of 100% providing no further information while FDR and gravimetrical moisture content still varies.
At the dry end, we observed the relative moisture content (NS felts) is never decreasing below 19 RelVol%.

It seemed hard to relate the relative moisture content to the absolute moisture content and hence with the conventional parameters field capacity and permanent wilting point used in eco-physiology. Therefore more research is needed to understand the ecological relevance of relative moisture content for the major plant species. The development of specific felt-types for major plant/soil combinations is worth-while. The PlantCare Mini-Loggers are robust, reliable and their data was easily logged and processed.

A practical draw-back was the short life-time (3 months) of the batteries. We recommend therefore equipping Mini-Loggers with rechargeable batteries that could be energized using the existing USB upload/download cable and a conventional powerbank.

PlantCare Mini-Loggers have high potential for ecological and climate research, provided felts could be manufactured that match specific soil-plant conditions. Ideally, the Mini-logger is simulating the plant while the felt is characterising the plant's root system.

Nederlandse samenvatting

Het Zwitsere bedrijf PlantCare Ltd. ontwikkelde een nieuwe techniek om op basis van een micro-hitte puls het relatieve vochtgehalte te bepalen in bodems. De ontwikkelde sensor meet tegelijk ook de bodemtemperatuur. Diverse systemen werden sinds 2004 ontwikkeld en zijn succesvol toegepast bij irrigatieprojecten van gewassen. De in 2009 ontwikkelde Mini-Loggers zijn autonome toestellen die bestaan uit een meeteenheid (logger) en een sensor aan het einde van een stick die op een bepaalde diepte in de bodem wordt gebracht. Temperatuur en vochtgehalte wordt gemeten via een poreus synthetisch medium (viltje) dat in contact en evenwicht staat met de bodem-matrix. De vochtmeting gebeurt door het genereren van een hitte puls en het meten van de tijd die nodig is om terug af te koelen, wat functie is van het vochtgehalte en temperatuur in het viltje. De Mini-Loggers kunnen een grote hoeveelheid data opslaan in het geheugen en worden geprogrammeerd en eenvoudig gelogd via een USB memorystick. Daardoor kunnen ze ingezet worden voor eco-hydrologisch onderzoek in (afgelegen) bos- en natuurgebieden.

In deze studie hebben we in de periode maart-december 2015 een set van 14 Mini-Loggers getest, waarvan 12 werden geïnstalleerd op 5 Level II Intensive Monitoring proefvlakken in Vlaanderen (veldwaarnemingen) en 2 Mini-Loggers onder gecontroleerde labocondities. De waarnemingen lopen door in 2016. De daggemiddelde resultaten van bodemtemperatuur en -vochtmetingen van de PlantCare Mini-Loggers werden vergeleken met de metingen van Campbell T107 temperatuursensoren en CS616 soil water reflectometers (FDR sensoren) voor dezelfde diepte en op een korte afstand van elkaar. Daarenboven werden maandelijkse ongestoorde bodemstaalnames vericht nabij de PlantCare sensoren voor het bepalen van een gravimetrisch vochtgehalte en de bulk densiteit, zodat het volumetrisch referentievochtgehalte kon worden berekend.

De resultaten van de eerste 9 maand geven aan dat de bodemtemperatuur tussen nabije Mini-Loggers onderling zeer goed correleren en hetzelfde temperatuurverloop aangeven. Ook bestaat een goede correlatie met data van de T107 probe, maar werd op de meeste sites een hogere bodemtemperatuur (gemiddeld 0.69 °C, maximum 1.08°C) waargenomen door de Mini-Loggers. Bovendien bleek het systematische verschil tussen deze sensoren te variëren doorheen het jaar en het kleinst wanneer de bodems nat waren (winterperiode). De Mini-Loggers waren in staat een accuraat beeld te geven van de variatie in bodemtemperatuur.

De evolutie van het bodemvochtgehalte gemeten door de Mini-Loggers verschilde van het patroon van de FDR vochtmetingen. Mini-Loggers blijken veel sneller en sterker te reageren op wijzigende bodemvochtcondities en de relatieve vochtpercentages zijn duidelijk te relateren aan neerslagpieken. Mogelijk is dit verschil in respons deels omdat FDR sensoren hun vochtmeting integreren over een afstand (bvb 30 cm) terwijl de Mini-Loggers puntmetingen uitvoeren. Abstractie makend van de pieken is er wel een overeenkomstig seizoenaal vochtpatroon, wat ook bevestigd wordt door de gravimetrische referentiemetingen.

Er werden twee soorten viltjes getest: (1) viltjes voor natuurlijke bodems (NS) en (2) voor artificiele substraten (AS). Zowel op het terrein als in labo-omstandigheden bleken de AS viltjes niet geschikt en werden vervangen door NS viltjes.

Op zandbodems geven de Mini-Loggers met NS viltjes een vochtverloop binnen een duidelijke bereik, maar op leem- en kleibodems wordt bij waterverzadiging constant een relatief vochtgehalte van 100% gemeten, waardoor geen extra informatie meer wordt gegeven terwijl FDR en gravimetrisch vochtgehalte wel varieert. In de droge range gaat het relatief vochtgehalte (NS viltjes) nooit onder de 19 RelVol%.

Het relatieve vochtgehalte blijkt moeilijk te relateren met het absoluut vochtgehalte en dus met de conventionle parameters veldcapaciteit en verwelkingspunt gebruikt in de ecofysiologie. Derhalve is bijkomend onderzoek nodig om de ecologische relevantie van “relatieve vochtgehaltes” aan te tonen voor de belangrijkste plantensoorten. Het ontwikkelen van specifieke vilt-types voor bepaalde plant/bodem combinaties lijkt dan ook zinvol. De PlantCare Mini-Loggers bleken robust, betrouwbaar en de data was makkelijk te loggen en te verwerken. Alleen de korte levensduur van de batterijen bleek een beperking, wat zou kunnen verholpen worden door herlaadbare batterijen via de bestaande USB kabel en met behulp van een power bank.

PlantCare Mini-Loggers hebben een hoge potentie voor ecologisch en klimaatsonderzoek, mits viltjes kunnen geproduceerd worden die matchen met de specifieke bodem-planteigenschappen.
In het ideale geval simuleert de Mini-Logger dan de plant en karakteriseert het viltje het wortelstelsel.

Content

1 Introduction

Accurate measurement of soil water content and soil temperature is crucial for ecosystem research and will become even more important with the further booming of climate change studies and experiments. Since long, soil scientists know that measuring soil temperature is not that difficult and conventional techniques provide precise and reliable results, but that numerous challenges remain for accurate soil moisture measurements, especially if continuous recording is required.

PlantCare Ltd. developed a new device for measuring plant available water based on a micro heat pulse technique and successfully implemented this in irrigation control for crop production. We wanted to test the performance of PlantCare sensors in environmental research, more specifically in natural and semi-natural ecosystems. Since these ecosystems are often located in remote areas, small, robust and independent devices can be very useful to provide these basic parameters of the soil environment.

By comparison of PlantCare's Mini-Logger readings with data generated by earlier installed FDR sensors on Long Term Ecosystem Research (LTER) sites along with monthly field sampling using undisturbed steel ring samples and gravimetrical soil moisture measurements to yield reference values, we evaluate the usefulness and added value of these innovative Mini-Loggers.

In this document we report on our findings of ten months of measurement (March-Dec 2015) with PlantCare Mini-Loggers installed on 5 intensively monitored forest sites. Data was logged monthly using a simple USB stick. The data was critically evaluated together with the overall performance of these devices.

Preliminary conclusions are drawn based on comparison of the datasets and suggestions for further research are formulated. The ambition is to run in situ tests with these PlantCare sensors during a period of at least two years (8 seasons) in order to come to final conclusions on their general applicability, accuracy and usefulness for our research and monitoring programmes.

2 Materials and Methods

2.1 Test sites

2.1.1. Site description

Five sites were selected from the international UN/ECE ICP Forests level II network consisting of intensively monitored forest plots all across Europe over the last 25 years. The initial goal of these plots was to assess the impact of air pollution on forest ecosystems, but since 2007 also research on climate change and biodiversity is conducted on them. The Flanders region (North of Belgium) is part of the ICP Forests network since the early 90-ties and continues until today to monitor five plots out of the ~800 European plots (Figure 2.1).

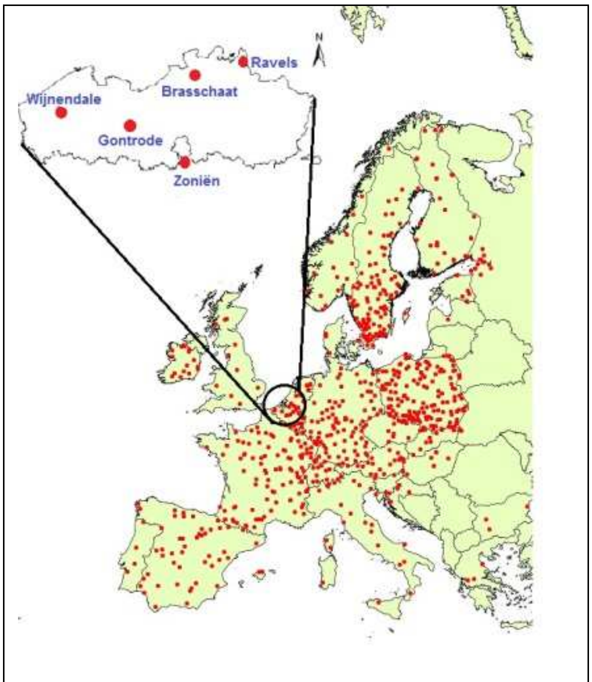


Figure 2.1. Selected level II sites in Flanders as part of the ICP-Forests level II network

The five selected sites represent the major soil-forest type combinations for the Flemish region. The sites Wijnendale, Gontrode and Zoniën are broadleaved forests on respectively Sandy, Silt Clay/loam and Silt loam soils, whereas the sites Brasschaat and Ravels are coniferous stands on Loamy sand and Sandy soils, typical for the Campine region in the North.

The major tree species on the sites are Beech (*Fagus sylvatica*) in Wijnendale, Oak (*Quercus robur*) in Gontrode, Beech in Zoniën, Scots Pine (*Pinus sylvestris*) in Brasschaat and Corsican pIne (*Pinus nigra subsp. laricio (Poiret) Maire*) in Ravels. Site code, Lat-Long coordinates and altitudes are provided in Table 2.1, and the location of the sites in Flanders region is mapped in Figure 2.1. All sites have a mean annual air temperature (MAT) between 10.4 and 11°C) and precipitation between 786 and 887 mm, a Mesic soil temperature regime and an Udic soil moisture regime according to Soil Taxonomy (Soil Survey Staff, 2003).

On the sites periodic surveys are conducted of (dry and wet) deposition, soil solution and soil condition. There is continuous monitoring of meteo, soil moisture and soil temperature. Growth and vitality of trees is recorded, foliar analysis of the trees is conducted every two years and ground vegetation is surveyed regularly. All information is stored in the ICP Forests database (more info: http://icp-forests.net/). Description of the ICP Forests data can be found in Cools and De Vos (2011).

Table 2.1. Plot coordinates, altitude, mean annual temperature and precipitation and soil climate characteristics for the selected 5 plots.

Site	Code	LAT	LONG	Altitude (m ASL)	MAT (°C)	MAP (mm)	Soil climate STR	Soil Climate SMR
Gontrode	201_16	50.975012	3.804330	22	10.6	786	Mesic	Udic
Ravels	201_14	51.403056	5.056941	31	10.4	887	Mesic	Udic
Brasschaat	201_15	51.307618	4.519817	16	10.8	882	Mesic	Udic
Wijnendale	201_11	51.069459	3.036118	20	11.0	867	Mesic	Udic
Zoniën	201_21	50.747222	4.414724	122	10.7	854	Mesic	Udic

2.1.2. Soil types

The soil types of the level II sites are well described (Mikkelsen et al., 2008) after comprehensive physico-chemical soil analysis and all soil data are stored in the ICP Forests soil condition databases (Cools and De Vos, 2011; Fleck et al., 2016) and the local central soil database (INBOdem) of our Institute.

Soils were classified according to World Reference Base 2006 (IUSS Working group WRB, 2007) and full classification names for soil and humus types are given in Table 2.2. Photos of topsoil profiles are given in Figure 2.2.

Table 2.2. Soil type according to WRB 2006, USDA texture class of the topsoil (0-30 cm) and humus type (Zanella et al., 2011)

Site	Soil name	USDA Texture class	Humus Type
Gontrode	Luvic Folic Stagnosol (Albic, Ruptic, Dystric, Siltic, Clayic)	Silty Clay/Silt loam	Moder
Ravels	Endogleyic Hyperfolic Hypobrunic Albic Arenosol (Hyperdystric)	Sand/Loamy sand	Mor
Brasschaat	Endogleyic Hypobrunic Albic Hypoluvic Arenosol (Hyperdystric)	Loamy sand/sand	Mor
Wijnendale	Endogleyic Folic Umbrisol (Brunic, Humic, Alumic, Hyperdystric, Arenic)	Sandy loam	Mor
Zoniën	Glossalbic Hypocutanic Alisol (Fragic, Abruptic, Hyperalumic, Hyperdystric, Siltic)	Silt loam	Moder

Some basic soil characteristics are listed in Table 2.3. Soils are commonly deep and can be rooted by trees beyond 1.5 m of depth or are limited by the lowest groundwater table. Forest floors are quite thick and store a high amount of carbon, especially the mor types. Carbon stocks in mineral soil vary from rather low (93.7 t C ha^{-1} in Zoniën) to high (200 t C ha^{-1} in Wijnendale) predominantely due to higher hydromorphism of the latter site.

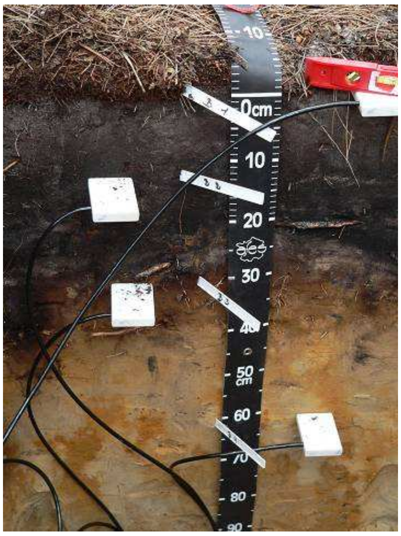
All sites are on non-calcareous, acidified soils evidenced by low potential pH-$CaCl_2$ (for pH-H_2O add about 0.7 units) and low base saturation in the topsoil. Cation exchange capacity is highest at the Gontrode site due to higher clay content, and lowest in Brasschaat (sandy site). Most sites have a rather low C/N, except for Ravels (C:N ratio > 20).

Table 2.3. Some soil characteristics of the test sites (Verstraeten et al., 2012)

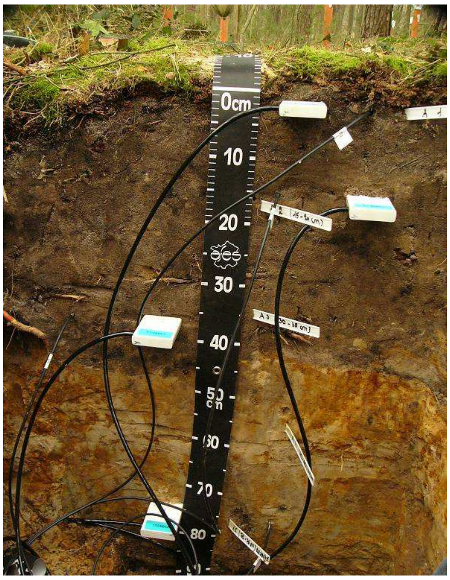
Site	Rooting depth (cm)	Groundwater range (m)	Forest Floor Carbon stock (ton C ha^{-1})	Mineral soil Carbon stock (ton C ha^{-1})	Soil layers within 0-20 cm depth			
					C:N	pH-$CaCl_2$	CEC ($cmol_c$ kg^{-1})	Base saturation (%)
Gontrode	180	1.5 - 1.8	40.3	132	17 - 20	2.9 – 3.0	12 - 17	15 - 23
Ravels	185	1.5 - 2.5	52.2	149	23 - 27	2.9 - 3.1	3.6 - 4.6	7.4 - 11
Brasschaat	160	1.2 - 2.3	38.7	82.5	15 - 18	3.1 – 3.3	1.7 – 2.2	15 - 18
Wijnendale	170	0.9 - 2.3	64.3	200	16 - 21	2.5 – 3.0	3.5 – 7.3	11 - 32
Zoniën	195	>30	20.4	93.7	14 - 17	3.3 – 3.8	3.8 - 6.3	11 - 16

Gontrode soil profile

Ravels soil profile



Brasschaat soil profile



Wijnendale soil profile

Zoniën soil profile

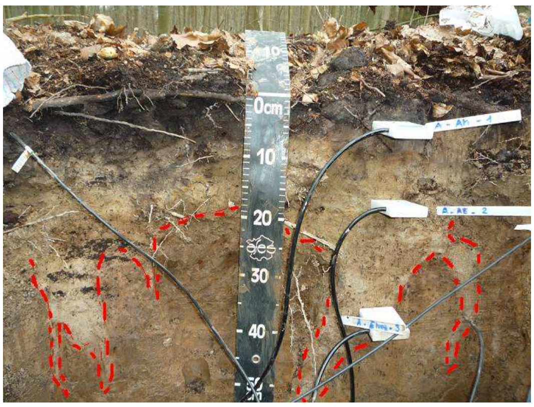


Figure 2.2. Soil profiles of the 5 test sites at the time the FDR and temperature sensors were installed. Photos by Frederic Vermeiren (April 2010).

2.2 Sensors

2.2.1. PlantCare Micro Heat Pulse (MHP) sensors

The PlantCare manual states the following: "*Different than all existing sensors on the market, PlantCare's MHP sensor "sees" respectively measures only the plant available water, the most crucial parameter in terms of moisture analyses or irrigation scheduling. Bound water or water in the roots of a plant is not measured. Another issue with existing sensor technologies is that their moisture values are misleading and distorted due to the salt or fertilizer content in the soil, whereas the PlantCare sensor readings are unaffected by any of these contents.*"

Matile et al. (2013) describes the PlantCare sensors as heat dissipation matric potential sensors, since they basically measure moisture content of a porous matrix ("the felt") that is in equilibrium with the surrounding soil matrix. Consequently the type and properties of the felt is important. The measurement of the water content of porous media is based on their thermal properties, i.e. predominantly heat conductivity. Consequently, ambient temperature can affect heat dissipation sensors which therefore require some type of correction for this effect.

We applied PlantCare Micro Heat Pulse Mini-Logger sensors with a stick that are inserted in the soil (Figure 2.3).

Figure 2.3. Design of PlantCare Mini-Loggers with stick (left) and detail of sensor tip (upper right) and tip's vertical section (lower right). Pictures taken from PlantCare documentation (PlantCare Ltd., Sennhof 13, CH-8332 Russikon, Switzerland)

Standard stick lengths are 18, 35, 60 or 100 cm. Also a cable version exists with standard lengths of 60 and 250 cm and optionally special extension cables up to 25 meters can be ordered.

On top of the Mini-Logger there is a box containing the electronics and battery holder (2 x AA cells). At the end of the stick there is the sensor (twice the size of a pen, Ø 15 mm) consisting of a yellow cap, a replaceable synthetic felt and the sensor tip.

Initially we applied two felts, one calibrated for natural soil (white colour) and one felt for artificial soil (green colour). The felts have high sensitivity in the 0 – 400 hPa range and are less sensitive in the 400 - 800 hPa range.

The sensor is inserted into the soil with the sensor tip at the required depth (Figure 2.4). The felt should make contact with the surrounding soil so that an equilibrium can be attained between felt and soil matrix for exchange of soil moisture. The PlantCare sensor remains inserted in the soil during the whole monitoring period. Read-out of data (and programming of device) is simply performed by means of a USB stick, allowing storage of read-outs of multiple plantcare sensors (one data-file per sensor is stored). The files on the USB stick are read on a standard computer for further data processing.

The sensors can be installed and removed easily and be installed from shallow depth (5 cm) to 100 cm or deeper when applying cables. Furthermore the soil temperature is measured along with the soil moisture. So no additional sensors are needed for soil temperature measurements.

Figure 2.4. Scheme of read-out process of PlantCare Mini-Logger. Small USB cable is connected to 5-pins connector on top of Mini-Logger. USB stick is inserted in USB port of cable. When data is logged on stick, stick is read on any computer for further processing of data. Pictures taken from PlantCare documentation (PlantCare Ltd., Sennhof 13, CH-8332 Russikon, Switzerland)

Measurement principle

The sensing principle of the PlantCare sensors is described well by Matile et al. (2013). Basically the sensor consists of a heat pulse generator and a temperature sensor embedded in a synthetic felt (Figure 2.3). In equilibrium with the surrounding soil, the water content of this felt is a function of the matric potential of the surrounding soil. The measurement of the PlantCare sensor consists of a heating pulse and a cooling phase (Figure 2.5). In the heating phase the sensor is warmed up during 20 s with 35 mW resulting in a temperature rise of 2–3 °C, mainly depending on the water content of the felt and the ambient soil temperature.

The PlantCare sensor measures the time needed to cool from the peak temperature to a threshold temperature of about 20 % of the temperature rise (Figure 2.5). The cooling time is a function of the thermal conductivity of the material around the sensor, that is mainly related to the water content of the felt material (0.56 $Wm^{-1} K^{-1}$ for water, 0.025 $Wm^{-1} K^{-1}$ for air and 0.2–0.3 $Wm^{-1} K^{-1}$ for the felt material) (Matile et al., 2013). The large range of soil thermal conductivity of 0.3–2 $Wm^{-1} K^{-1}$ influences the measurement as a second order effect especially under dry conditions.
In this type of Mini-Loggers, the strong temperature dependence of conventional heat dissipation sensors is suppressed by a new measuring procedure with the cooling time t that refers to a more normalized temperature change.

Sensor specifications and accuracy

PlantCare sensors operate within a normal soil temperature range from 2° C to +37° C. Soil temperature is given in °C and soil moisture in **relative % units (0-100%),** so not volumetric percentage. High sensitivity of relative soil moisture measurements is obtained between 0 – 400 hPa matric potential and lower sensitivity when > 400 hPa. It is documented that felt composition can be tailored to type of substrate/soil: High Matrix Potential (Felt Type A); Medium Matrix Potential (Felt Type B) and Low Matrix Potential (Felt Type C). Measuring accuracy for relative soil moisture is ± 3% and for soil temperature ± 0.3° C.
Reading accuracy is 1% for relative soil moisture and 0.1 °C for soil temperature.

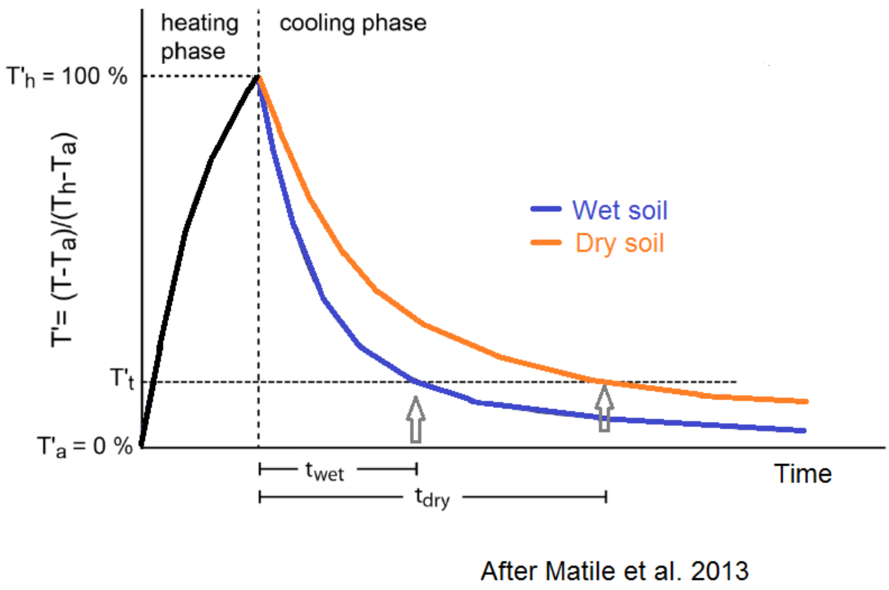


Figure 2.5. Relative Temperature T' = (T – Ta)/(Th – Ta) as a function of time during the measurement with a PlantCare heat dissipative sensor in a wet and a dry soil.

Sensor types

In total we investigated the performance of 14 PlantCare Mini-Logger sensors. Twelve sensors were installed on Level II forest sites (listed in Table 2.4) and 2 sensors were tested under laboratory conditions (Table 2.5).

We applied the PlantCare Mini-Loggers with a solid stick, two Mini-Loggers with maximum insertion depth of 18 cm and 12 Mini-Loggers with 35 cm insertion depth. The sensor tips were inserted at the same depth as the installed FDR and temperature sensors. At these depths also the Kopecky ring sampling was applied for monthly gravimetrical moisture measurements serving as the reference for soil moisture.

Sensor IDs were derived from the Sensor serial number, adding PC (PlantCare) as prefix. These IDs were also automatically stored in each data log file and helped to unambiguously identify the correct sensor. Initially sensors equipped with a natural soil felt (denoted as "NS") had numerical IDs starting with 143 whereas those equipped with green felt (artificial soil, denoted "AS") started with "155". However, after some months we discovered that the AS-felt was not appropriate for our measurements and then replaced these AS-felts with NS-felts for Period 2.
The sampling periods, identified by their day number (DN) in 2015, over which specific felts were used are indicated in Table 2.4. The location within the Level II plots where these PlantCare sensors were exactly installed together with other devices are described in section 2.3.

Sensor settings

The PlantCare Mini-Logger devices had firmware version 1.31 on board and consisted of hardware version C1.0.
The cycle time was set to 60 minutes, so measurements were recorded hourly.

Moisture results were given in rel %.
hPa settings were default set as: alpha = 0.014539999, n = 2.75799989 and K = 1

Table 2.4. Sensors installed in the field during testing periods 1 and 2. During Period 1 both natural soil felts (NS) and artificial soil felts (AS) where compared near Pit A. For testing Period 2, AS felts were replaced by NS felts.

	Level II Site	Sensor serial No	Sensor ID	Stick Length (cm)	Initial Felt Calibration type (Period 1)	Period 1 Day Number (Pit A)	Period 2 Day Number (Pit B)
1	Gontrode	143731/1.31/*/j	PC143731	40	Natural soil (white)	NS:70-365	
2	Gontrode	155087/1.31/*/j	PC155087	40	Artificial substrate (green)	AS:70-252	NS:313-365
3	Gontrode	143741/1.31/W/M	PC143741	15	Natural soil (white)	NS:71-365	
4	Gontrode	143758/1.31/W/M	PC143758	15	Natural soil (white)	NS:70-365	
5	Ravels	143784/1.31/*/j	PC143784	40	Natural soil (white)	NS:72-365	
6	Ravels	155086/1.31/*/j	PC155086	40	Artificial substrate (green)	AS:72-253	NS: 313-365
7	Brasschaat	143383/1.31/*/j	PC143383	40	Natural soil (white)	NS:72-365	
8	Brasschaat	155083/1.31/*/j	PC155083	40	Artificial substrate (green)	AS:65-253	NS:313-365
9	Wijnendale	143794/1.31/*/j	PC143794	40	Natural soil (white)	NS:70-363	
10	Wijnendale	155085/1.31/*/j	PC155085	40	Artificial substrate (green)	AS: 70-252	NS: 313-365
11	Hoeilaart	144783/1.31/*/J	PC144783	40	Natural soil (white)	NS:47-365	
12	Hoeilaart	155091/1.31/*/J	PC155091	40	Artificial substrate (green)	AS:97-251	NS: 313-365

Laboratory testing was performed with PlantCare sensors mentioned in Table 2.5.

Table 2.5. Sensors installed in the laboratory and garden trial.

	Lab testing	Sensor serial No	Sensor ID	Stick Length (cm)	Felt Calibration type
1	Laboratory	143504/1.31/*/J	PC143504	40	Natural soil (white)
2	Laboratory	155090/1.31/*/J	PC155090	40	Artificial substrate (green)

2.2.2. Campbell reference sensors

Temperature probe (model 107)

The Campbell model 107 Temperature probe is a BetaTherm 100K6A Thermistor with a measurement range between -35° and +50°C and with an interchangeability error of < ± 0.2 °C over 0-60 °C range. According to the manual and in a "worst case" situation, all errors add to an accuracy of ± 0.4°C over the range of -24° to 48°C and maximally ± 0.9°C over the range -38°C to 53°C.

The T107 was placed horizontally in the soil profile at the same depth of the FDR sensors and logged by a Campbell CR1000 datalogger.

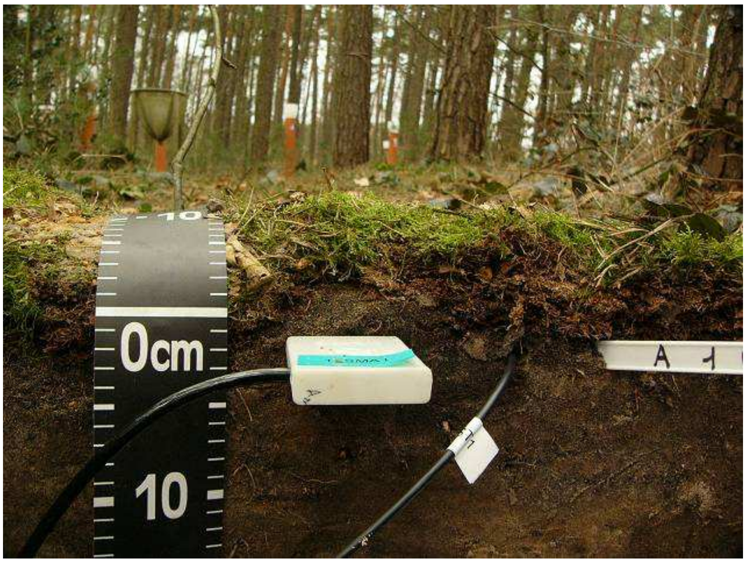


Figure 2.6. Campbell FDR soil water reflectometer (left) and temperature probe (right) just below the forest floor (Photo Frederik Vermeiren)

Measurement principle

The T107 probe applies a precise 2500 mV excitation voltage and measures the voltage drop across the 1K ohm resistor. The ratio of measured voltage (Vs) to the excitation Voltage (Vx) is related to the thermistor resistance (Rs), and the 1000 and 249K ohm fixed resistors as in the equation:

$$Vs/Vx=1000/(Rs+249000+1000)$$

T107 calculates Rs from the voltage ratio, and converts Rs to temperature using the Steinhart-Hart equation:

$$T= 1/(A+B(LnRs)+C(LnRs)^3 - 273.15$$

Where T is the (soil) temperature returned in degrees Celsius (°C), and A, B and C are coefficients provided by the manufacturer: i.e. A = 8.271111E-4; B=2.088020E-4 and C=8.059200E-8.

Soil water content reflectometers (FDR)

On the five test sites volumetric soil water content is measured using Campbell CS616 soil water reflectometers (Figures 2.6 and 2.7). The water content information is derived from the probe sensitivity to the dielectric constant of the medium surrounding the probe rods. The CS616 output is a square wave output and is connected to a Campbell Scientific CR1000 datalogger. A special CS616 datalogger instruction is used to measure the probe output period which is converted to volumetric water content using calibration equations. Datalogger instructions for period averaging can also be used.

The Water Content Reflectometer consists of two stainless steel rods (300 mm long, 3.2 mm diameter, 32 mm spacing) (Figure 2.7) connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The circuit board is encapsulated in epoxy. High-speed electronic components on the circuit board are configured as a bistable multivibrator. The output of the multivibrator is connected to the probe rods which act as a wave guide. The travel time of the signal on the probe rods depends on the dielectric permittivity of the material surrounding the rods and the dielectric permittivity depends on the water content (Campbell Ltd., 2003). Therefore, the oscillation frequency of the multivibrator is dependent on the water content of the media being measured. Digital circuitry scales the multivibrator output to an appropriate frequency for measurement with a datalogger.

The Water Content Reflectometer output is essentially a 0.7 V square wave with frequency dependent on water content. The probe output period ranges from about 14 microseconds with rods in air to about 42 µS with the rods completely immersed in typical tap water. A calibration equation converts period to volumetric water content (Vol%).

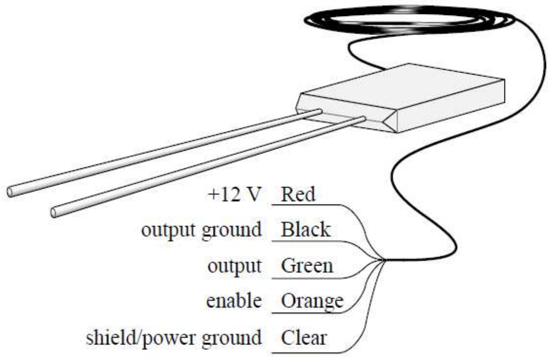


Figure 2.7. Campbell FDR soil water reflectometer design and horizontal installation in the soil horizons using an insertion guide and leveling device.

The FDR probes were horizontally inserted in the major soil horizons using a wooden guide and level, in order to determine vertical water fluxes. They are operational since April 2010. The maximum length of the cable is 305 m, but in our design max 10 m of cable was used between CS616 probe and CR1000 logger.

Sensor accuracy

The accuracy specification for the volumetric water content measurement using the CS616 probes is based on laboratory measurements in a variety of soils and over the water content range air dry to saturated. The soils were typically sandy loam and coarser. Silt and clay were present in some of the soils used to characterize accuracy. The Water Content Reflectometer accuracy is ± 2.5 Vol% using standard calibration with bulk electrical conductivity ≤ 0.5 deciSiemens meter^{-1} (dS m^{-1}) and bulk density ≤ 1.55 g cm^{-3} in measurement range 0 Vol% to 50 Vol%. Resolution is the minimum change in the dielectric permittivity that can reliably be detected by the Water Content Reflectometer. The CS616 is typically used to measure soil volumetric water content. The resolution of the CS616 is better than 0.1 % volumetric water content. Precision describes the repeatability of a measurement. It is determined for the CS616 by taking repeated measurements in the same material. The precision of the CS616 is better than 0.1 % volumetric water content. Probe-to-probe variability: ± 0.5 Vol% in dry soil and , ± 1.5 Vol% in a typical saturated soil (Campbell Ltd., 2003).

Measurement principle

The fundamental principle for CS616 operation is that an electromagnetic pulse will propagate along the probe rods at a velocity that is dependent on the dielectric permittivity of the material surrounding the line. As water content increases, the propagation velocity decreases because polarization of water molecules takes time. The travel time of the applied signal along 2 times the rod length is essentially measured. The applied signal travels the length of the probe rods and is reflected from the rod ends travelling back to the probe head. A part of the circuit detects the reflection and triggers the next pulse. The frequency of pulsing with the probe rods in free air is about 70 MHz. This frequency is scaled down in the Water Content Reflectometer circuit output stages to a frequency easily measured by a datalogger. The probe output frequency or period (PA in µS) is empirically related to water content using a linear or quadratic calibration equation. For example, an CS616 output period PA of 16 23 µS refers to about 2 Vol% and a PA = 32 µS to 47.3 Vol% moisture. The FDR response is affected by soil bulk density, clay and organic matter content, voids and also salts (electrical conductivity). Therefore we believe it is best that each sensor is calibrated in situ for the specific soil horizon it is located in. We also corrected the FDR output for soil temperature dependence using the temperature correction equation provided in the user manual by Campbell Ltd. (2003).

2.3 Installation and measurements

2.3.1. Field Monitoring and sampling design

PlantCare sensors are installed in the Level II plots, as close as possible to existing sensors without interfering with them or causing possible damage to their cabling. Figure 2.8 illustrates on a photo taken from the measuring tower on the Brasschaat site the overall design. Three sampling pits (A, B and C) are installed at 8 m distance from a central datalogger. Locations A, B and C were chosen depending on the configuration of tree locations on each plot. On each location a profile pit was dug and FDR sensors were installed in pedogenetic horizons within 4 fixed-depth intervals according to the scheme provided in Figure 2.9. Exclusively at location A also a temperature probe (T107) was installed at the same depth as the FDR sensors. The installation was done from February to April 2010.

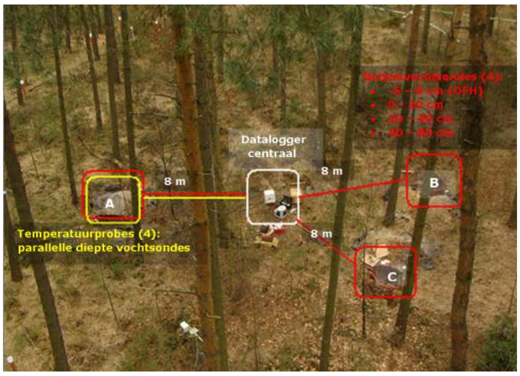


Figure 2.8 On field installation of probes in soil pits A, B and C according to a triangle around the central datalogger and considering the tree locations.

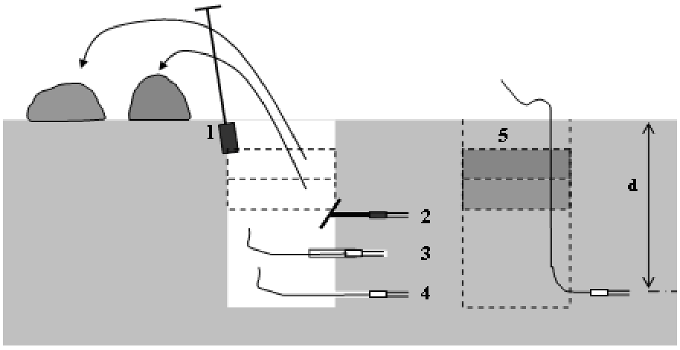


Figure 2.9 Installation of the sensors with following steps: preparation of the profile (1), fork hole with a dummy (2), installing the FDR and T107 sensor (3), refilling the wire hole (4) and layerwise refilling of the profile (5).

In February-March 2015 PlantCare sensors were installed 3 m north of pit A on each of the sites (Table 2.4. and Figure 2.10). Location A was selected because comparison could be made between soil temperature measurements of the PlantCare sensors with those of the T107 probes. In September 2015 PlantCare recording was terminated for those Mini-Loggers with a felt calibrated for artificial soil. The felt of these sensors was replaced by a natural soil felt and the Mini-Loggers were moved to location B (3 m north of pit B). On this B location the moisture measurements could still be compared with FDR and gravimetrical assessments from 18-20 November 2015 onwards, but not with (local) temperature recordings. On the other hand, data is gathered at the same depth but at another location within the plot providing limited information of within-plot variation.
The tip of the PlantCare sensors were installed at

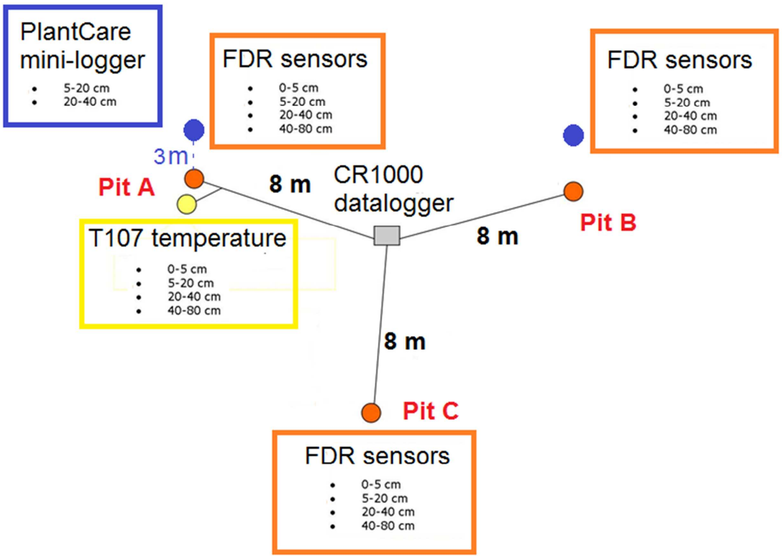


Figure 2.10. Schematic field layout of existing FDR and T107 sensors and cabling to central datalogger and addition of PlantCare Mini-Loggers at Pit A and (later) pit B locations within this design.

similar depth of the FDR sensors within the 20-40 cm depth interval (Table 2.6). This was convenient because stick length was about 40 cm. Additionally at the Gontrode site Mini-Loggers with 15 cm sticks were also installed in the 0-10 cm depth interval.

Table 2.6. Monitoring depth of sensors and Kopecky sampling depth

Site	FDR sensor depth (cm)		Bulk density sampling depth (cm)		PlantCare tip depth (cm)	
Location	**A**	**B**	**A**	**B**	**A**	**B**
Gontrode	4	-3*	0-5	-5-0	5	5
	37	20	32-37	15-20	37	20
Ravels	30	31	25-30	26-31	30	30
Brasschaat	35	36	30-35	31-36	35	35
Wijnendale	36	31	31-36	26-31	36	36
Zoniën	39	45	34-39	40-45	39	39

(*) sensor installed in thick forest floor, 3 cm above mineral soil

FDR sensors and T107 temperature are logged automatically by the Campbell data logger of the plot. The Plantcare Mini-Loggers were downloaded each month at the same time of conducting the undisturbed sampling for reference moisture assessments.

2.3.2. Undisturbed sampling for bulk density and reference moisture content

Monthly sampling for bulk density and gravimetrical soil moisture was performed using Kopecky steel rings of 100 cc (53 mm diameter). Since none of the soils are stony nor contain coarse fragments in the sampled horizons this method is adequate for both the assessment of bulk density and gravimetric and volumetric moisture content. The samples are taken using a closed ring holder (Eijkelkamp, The Netherlands) loaded with the steel ring (Figure 2.11).

Figure 2.11. Kopecky steel rings with plastic cover for sampling of bulk density and soil moisture (left picture) and sample ring holder (right picture)

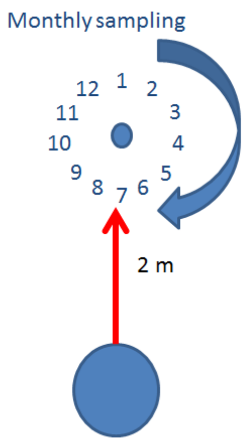


Figure 2.12. Scheme for monthly sampling 1 meter around Mini-logger.

First, using an Edelman- and Riverside auger soil material is removed until the required depth (top of soil layer to be sampled). Then the closed ring holder sampling device is employed to take an undisturbed sample from the soil profile. Immediately after sampling and recording of the ring ID, the Kopecky rings are sealed with plastic covers (top and bottom, Figure 2.11) to prevent moisture loss and stored in a plastic bag and curver box for transport.

Monthly sampling of the whole soil profile (4 sampling depths) is performed clockwise in a circle 1 m around the PlantCare Mini-Loggers (Figure 2.12). This means that sampling profiles are about 25 cm apart from each-other. A bamboo stick is left in the last sampled profile as an indication for the next sampling. Care was taken not to disturb (compact) the soil too much when sampling the soil, especially on the future sampling locations.

In the laboratory the undisturbed Kopecky samples were processed. Their wet/moist mass was determined prior to drying in a ventilated oven at 105 °C until constant mass, which was about one week for all soils. Then dry bulk density (BD) was determined as ovendry mass per unit volume and gravimetric moisture content quantified. Volumetric moisture content was computed by multiplying gravimetric moisture content with the fine earth bulk density of the sample.

2.3.3. Reference measurements for soil water retention characteristics

In 2010, soil water retention curves (SWRCs) were determined for all horizons where FDR sensors were installed. Determination of SWRC was perfomed using sand and kaolin/sand suction tables and pressure membrane plates (Eijkelkamp, The Netherlands). Volumetric water content at matric potential pF 0.0 (saturation), 1.0, 1.7, 2.0 (field capacity sand), 2.5 (Field capacity silt loam/clay), 3.0, 3.4 and 4.2 (permanent wilting point) was determined on triplicate samples in each horizon in each pit.

Figure 2.13. Suction table for determination of low pF range

Van Genuchten equations (Van Genuchten, 1980) were fitted to the mean values of the triplicate volumetric moisture measurements in each horizon, yielding the parameters: SWCr (residual soil water content; Θr), SWCs (saturated soil water content; Θs), alfa and n.

We reduced the number of Van Genuchten model parameters by imposing the constraint: $m = 1 - 1/n$ (Cornelis et al., 2001).

The relevant curves for this study are provided in Annex I.

Based on these modeled SWRCs, the Field Capacity for sand (at -20 kPa, pF=2) and silt/clay (-33 kPa, pF=2.5) and Permanent Wilting Point denoted PWP (-1585 kPa, pF=4.2) were derived and added to the plot (Annex I).

This information from the Van Genuchten models is used to interpret the dynamics of volumetric moisture content of each soil layer that are provided by FDR and gravimetrical assessments and the relative moisture content provided by the PlantCare Mini-Loggers.

2.4 Data processing

2.4.1. Data acquisition

PlantCare data

All PlantCare Mini-Loggers were logged once a month, simultaneously with the fortnightly collection of lysimeter water samples, which is typically planned before the 15th of each month. Data on USB memory sticks were logged on a personal computer and PVD data files (Ascii format) were read and checked in a simple editor.

The header of this PVD file provides useful information (Table 2.7) on alarms, system settings, firm- and hardware versions and info on date/time of operation. The PVD file structure is specifically designed for the PlantCare dataViewer software, which was not used by us since we encountered problems with version V1.3_28-07-2011 upon installation. However, data may be readily retrieved from the PVD file and imported in the statistical software or spreadsheets the user is familiar with.

We used the unique serial number from the file header information to rename the file as follows: prefix ‘PC’ (for PlantCare) and the serial number (e.g. PC143741) and stored the file in a folder of the site (e.g. Gontrode) and the subfolder for the month of logging.

So in each monthly folder the accumulated data is stored for each site.

Table 2.7. Typical header information of PlantCare PVD logfile

```
:Device: PlantCare Mini-Logger Version 1.31
:Device Name: PlantCare Mini-Logger

:Status:
Alarms            : none
Cycle time        : 60 minutes
Cycle start at    : Cycle time
Data memory free  : 84 %
Battery           : 2600 mV
Moisture in       : rel %
hPa value alpha   : 0.014539999
hPa value n       : 2.75799989
hPa value K       : 1
Device Name       : PlantCare Mini-Logger
Firmware          : Version 1.31
Hardware          : Version C1.0
Serial number     : 143758
Date/Time         : Thu, 07.05.2015 09:29:45
Power-on time     : 56d 20h 46m 30s (= 4913190 sec)
Additional Inform.: 6 20 76 18 42 22 122 0
```

Just below the header the data in the PVD file is stored line by line, with attributes Date_Time (Time stamp of measurement), S1M (Sensor 1 relative moisture content in RelVol%) and S1T (Sensor 1 soil temperature in °C) as illustrated in Table 2.8. As one can see in the example, first measurements were stored at 13h46 on March 11th, 2015 and each hour the measurement cycle was repeated and data was stored.

Table 2.8. Typical data section of PlantCare PVD logfile

```
:Data memory:
:Moisture: rel %
Date _ Time   Sensor 1 Moisture, Sensor 1 Temperature
:Sensor Name:         PlantCare Mini-Logger

   Date_Time          S1M       S1T
11.03.15_13:46:23     38        8.3
11.03.15_14:46:22     40        8.2
11.03.15_15:46:22     41        8.2
11.03.15_16:46:21     42        8.0
11.03.15_17:46:21     43        8.0
```

```
11.03.15_18:46:20    44    8.0
11.03.15_19:46:20    44    8.0
11.03.15_20:46:20    44    7.8
11.03.15_21:46:19    45    7.8
11.03.15_22:46:19    45    7.8
11.03.15_23:46:19    45    7.7
12.03.15_00:46:19    46    7.7
12.03.15_01:46:19    46    7.5
12.03.15_02:46:18    46    7.5
12.03.15_03:46:19    47    7.3
12.03.15_04:46:19    47    7.3
12.03.15_05:46:18    47    7.1
…

Finished.
:Data memory End
:End of file
```

For each site, the measurements were assembled for the whole year 2015 and stored in a CSV file named as follows: code of the site (e.g. GON for Gontrode) and sensor readings (PC143731), resulting in GON.PC143731.

Using R scripts the Date_Time stamp was converted in R date format, including a derived field for the day number (DN) of the year (1 to 365), along with the S1M (moisture) and S1T (temperature) data. In a next step, all data are aggregated by day number (DN) and hence the relative moisture and temperature data of each day are daily averaged.

FDR data

The Campbell CR1000 logger data are provided by the INBO data center in comma-separated-value (CSV) files, as illustrated in Table 2.9 . The first line provides information of device and site, the data logger and other technical information. The second line contains the attributes of the data-file and the third line attribute specifications.

Similarly as the PlantCare datafile, the sequence starts with the timestamp, a record number, all measured data channels, battery voltage and processor temperature. The data channels are coded as PA (Period average of FDR in µS) for location A (i.e. PA_A), B or C, and on each location according to the 4 layer depths (1), (2), (3), (4) as mentioned before. Soil temperature (only at location A) is provided by attributes ST(1) to ST(4) (see Table 2.9).

Table 2.9. Typical data section of Campbell CR1000 DAT logfile

```
"TOA5","TDR Wijnendale","CR1000","29167","CR1000.Std.17","CPU:TDR jan omgebouwd 1min scan.CR1","53589","PA_6h"
"TIMESTAMP","RECORD","loca","PA_A(1)","PA_A(2)","PA_A(3)","PA_A(4)","PA_B(1)","PA_B(2)","PA_B(3)","PA_B(4)","PA_C(1)","PA_C(2)","PA_C(3)","PA_C(4)"
,"ST(1)","ST(2)","ST(3)","ST(4)","batt_volt","PTemp"
"TS","RN","","","","","","","","","","","","","","","","","","","""","","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Smp","Sm
p","Smp","Smp","Smp","Smp","Smp"
"2015-01-01 00:00:00",5691,11,31.83,25.36,25.31,26.61,29.36,25.78,25.13,26.71,26.11,24.16,23.59,26.31,6.773,7.599,8.29,8.83,10.14,-0.33
"2015-01-01 06:00:00",5692,11,31.81,25.36,25.31,26.61,29.34,25.76,25.12,26.71,26.08,24.16,23.59,26.31,6.513,7.522,8.26,8.76,10.13,-0.969
"2015-01-01 12:00:00",5693,11,31.77,25.35,25.31,26.6,29.31,25.74,25.12,26.71,26.08,24.14,23.59,26.31,6.376,7.501,8.24,8.77,10.12,0.246
"2015-01-01 18:00:00",5694,11,31.74,25.34,25.32,26.61,29.28,25.73,25.12,26.71,26.04,24.13,23.6,26.3,6.406,7.385,8.22,8.77,10.14,3.635
"2015-01-02 00:00:00",5695,11,31.7,25.32,25.32,26.61,29.27,25.73,25.12,26.71,26.03,24.13,23.6,26.31,6.511,7.413,8.21,8.73,10.14,2.801
"2015-01-02 06:00:00",5696,11,31.67,25.31,25.32,26.61,29.24,25.72,25.12,26.69,26.03,24.1,23.6,26.31,6.576,7.429,8.12,8.71,10.15,5.96
"2015-01-02 12:00:00",5697,11,31.66,25.3,25.32,26.58,29.22,25.7,25.12,26.71,26.01,24.1,23.61,26.3,7.027,7.445,8.12,8.71,10.16,8.81
"2015-01-02 18:00:00",5698,11,31.67,25.3,25.31,26.54,29.22,25.69,25.12,26.71,26.01,24.1,23.61,26.29,7.224,7.574,8.09,8.7,10.17,6.482
"2015-01-03 00:00:00",5699,11,31.67,25.27,25.31,26.54,29.2,25.68,25.09,26.68,26.01,24.09,23.6,26.26,7.015,7.569,8.12,8.67,10.15,0.84
```

Note that FDR data are measured 4 times a day in a 6 hour cycle, starting at midnight and ending at 18h each day. For this study we averaged these 4 measurement events by day, and hence by day number in order to link daily averaged data to the PlantCare and other data.

The daily averaged soil temperature data can be directly used for comparison with PlantCare data for the same site and depth. The FDR data however are PA values which need transformation to soil moisture values using site and soil horizon specific FDR functions with PA and temperature as inputs and volumetric moisture content as output. These linear or quadratic functions were calibrated in situ and validated using field measured moisture contents (best performing function out of 4 calibration functions with highest index of agreement and lowest RMSPE was selected). The functions listed in Table 2.10 are the most advanced but may be revised in the future when longer reference datasets become available and recalibration is performed. Hence the database allows in that case simple recalculation of the PA values to predicted soil moisture levels.

Table 2.10. Applied site and horizon specific FDR functions for conversion of PA (in µS) to volumetric moisture content (MV in Vol%). PAC refers to temperature (REF.ST in °C) corrected PA values in case this was required (significant) for specific horizons.

Plot	Pit	Layer	Function
Gontrode	A	M12	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.A.M12=100*(-0.2104 + (0.0196*FDR.PAC))
	A	M24	MV.FDR.A.M24<-100*((0.8896 - (0.0833*FDR.PA) + (0.0024*(FDR.PA^2))))
	B	M24	MV.FDR.B.M24=100*((30.6646 - (1.7827*FDR.PA) + (0.0262*(FDR.PA^2))))
Ravels	A	M24	MV.FDR.A.M24=100*((-0.3316 + (0.0251*FDR.PA)))
	B	M24	MV.FDR.B.M24=100*((-0.3316 + (0.0251*FDR.PA)))
Brasschaat	A	M24	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.A.M24= 100*((-0.4521 + (0.0301*FDR.PAC)))
	B	M24	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.B.M24=100*((0.6115 - (0.0796*FDR.PAC)+ (0.0028*(FDR.PAC^2))))
Wijnendale	A	M24	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.A.M24= 100*((-0.1284 + (0.0166*FDR.PAC)))
	B	M24	MV.FDR.B.M24=100*((-0.2904 + (0.0228*FDR.PA)))
Zoniën	A	M24	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.A.M24= 100*((-1.0750 + (0.0467*FDR.PAC)))
	B	M24	FDR.PAC= FDR.PA + (20-REF.ST)*(0.526 - (0.052*FDR.PA) + (0.00136*(FDR.PA^2))) MV.FDR.B.M24=100*((-0.7474 + (0.0361*FDR.PAC)))

The resulting moisture contents are denoted further as for example FDR.A.M24, indicating FDR response for location A and mineral layer M24 (from 20 to 40 cm).

Field sampling

In contrast to the high sampling frequency of the PlantCare (hourly) and FDR sensors (each 6-hours), the reference field sampling could only be conducted once a month, since it is laborious and destructive (sample extracted).

Though on each location 4 samples are taken in each depth interval (12 per site), only the sample taken in the M24 layer at locations A and, at the end of 2015 also for locations B, could be used for this study. There is also just one sample that is considered representative for the soil moisture conditions during that day.

The samples are taken and transported to the lab, and processed there as explained in section 2.3.2. The resulting data is stored in a dataset with attributes: Plot, Sampling date, Pit, Layer, TDR.Depth, Kopecky.Depth.Top, Kopecky.Id, Moisture.Mass, BD, and Moisture.Volume. Based on the sampling date a day number is generated and added. The dataset was split according to Plot (or Site) and ranked by day number (DN).

2.4.2. Ancillary data

Rainfall data was derived from VMM meteo stations stored in the databases of the Flemish Government, freely available from the website with URL: http://www.waterinfo.be/default.aspx?path=NL/Thema/Neerslag

The nearest meteo-stations from which the daily precipitation sum for the whole year of 2015 was derived for each of the sites is given in Table 2.11. Although distance between sites and meteo stations is limited (< 16 km), specific rainfall events may occur at the meteo station, but not at the observation site and vice versa. Moreover, through interception by the tree crowns, small rain events may be missed or delayed below canopy. However, systematic data of 2015 of throughfall water was not available yet for all sites at the time of this study. In future, effective daily precipitation under canopy can be related to the soil moisture measurements.

Table 2.11. Meteo stations that recorded the daily precipitation sum (mm)

Plot	Meteo station	Owner	LB72X (m)	LB72Y (m)	LAT Degrees	LONG Degrees	Distance to plot (km)
Gontrode	Massemen	VMM	115584	185349	50.97738	3.878706	5.2
Ravels	Vosselaar	VMM	187754	220718	51.29507	4.910016	15.8
Brasschaat	Kapellen	VMM	158181	226446	51.34773	4.486184	5.0
Wijnendale	Zarren	VMM	51907	191193	51.02264	2.970586	6.9
Zoniën	St-Pieters-Leeuw	VMM	144952	166549	50.80937	4.297131	10.8

2.4.3. Assembling all data

All data were assembled and analysed by means of the statistical language R version 3.2.2 (R Core Team, 2014), employing various packages. Using R scripts the final working datasets for this study were generated as 5 data matrices, one for each site (i.e. GON.2015, RAV.2015, BRAS.2015, WIJN.2015 and ZON.2015) consisting of 365 rows and 61 columns. Each row is a day of the year 2015 (Day Number, DN) and each column an attribute (variable).

The data matrices stored data for all layers in a consistent way, not only the soil layers used in this study. The columns are day number and sampling date, 12 columns with FDR response (PA), 4 columns T107 soil temperature (ST), 6 columns PlantCare measurements (2 sensors with relative moisture and temperature on location A and 2 on location B in November-December), 36 columns with field measured data (BD, moisture by mass and moisture by volume of reference samples for each of the 12 layers on each location) and finally a column with daily precipitation.

These data matrices where the basis for all calculations in this report. For each type of statistical analysis and graphical work (plots) specific scripts were developed which could be easily adapted according to the datasets of the sites.

2.4.4. Linking relative to absolute moisture content

The output of the moisture measurements of the PlantCare sensors is in relative units, denoted further as RelVol%. In order to compare the absolute volumetric moisture content determined by gravimetric analysis and FDR sensors with the outcome of the PlantCare sensors, 100 RelVol% of the PlantCare was set equal to the Vol% of a water saturated soil (Θs) as determined during empirical soil water retention analysis in the lab (Annex I). We therefore hypothesise that in a water saturated soil, 100% of the water is available to plants, and the PlantCare sensor responds similarly as when it was calibrated in pure water.

Though the samples for the soil water retention analysis (three replicates) were taken from the same locations and layers (depths) where the PlantCare sensor tips are located, small deviances may occur due to local variations in organic matter and physical properties (cracks, roots, biogaleries, etc) inherent to natural field conditions.

2.5 Laboratory testing

A simple laboratory test was conducted with two PlantCare sensors in a plastic container (dimensions 20x28x40 cm) filled with exactly 11200 cm³ (11.2 L) oven-dry silt loam soil (Figure 2.14), originating from the INBO nursery The felt of the sensors were exacly between 11 and 12 cm depth below the surface. The two PC sensors had following characteristics:

- ID=143504/1.31/*/J, 40 cm stick, Felt for Natural soil (white)
- ID=155090/1.31/*/J, 40 cm stick, Felt for Artificial substrates (green)

Figure 2.14. Basic setup of PlantCare sensor in container with Delta-T HH2 moisture meter

Reference soil moisture was monitored using a 4 pin Delta-T HH2 moisture meter with soil type = “mineral” setting (Figure 2.14). Volumetric soil moisture was measured at regular intervals in the four corners of the container, with pins 6 cm inserted in the soil.

Initially soil moisture as recorded by the HH2 meter was 1.20 ± 0.29 Vol% (mean ± SD), indicating the soil was very dry. Prior to installation of the PlantCare sensors to test their performance, the soil was wetted using 1120 ml of tap-water in order to bring the soil volume to 10 Vol% of moisture content. Then the calibrated sensors with moist tips were installed and recording was initiated. Several consecutive test runs were performed under these controlled conditions as listed in Table 2.12. The drying out of the soil was simple evaporation at room temperature (18-25°C).

Basically the aim was to analyse the response of the PlantCare sensors in a drying out trajectory starting from a known added volume of water to a known volume of soil. The responses of both sensors were compared to analyse the effect of the felts (natural soil versus artificial substrate), both for soil moisture and temperature recordings. Furthermore the RelVol% readings of the PlantCare sensors were compared with the added water volume and the HH2 meter measurements, to see their relationship.

Table 2.12. Different runs to analyse the PlantCare responses under controlled conditions.

Run	From	To	Evaluation/testing	Observations
1	16.03.2015_13:40	25.03.2015_11:00	Redistribution of soil moisture	PlantCare (Rel Moisture + Temperature hourly), HH2
2	25.03.2015_11:15	13.05.2015_15:15	Drying out traject after addition of 2240 ml of water (~20 Vol%)	PlantCare (Rel Moisture + Temperature hourly), HH2
3	13.05.2015_15:30	25.09.2015_16:00	Drying out traject after addition of 2240 ml of water (~20 Vol%)	PlantCare (Rel Moisture + Temperature hourly), HH2
4	28.09.2015_11:55	23.11.2015_14:55	Drying out traject after addition of 2240 ml of water (~20 Vol%)	PlantCare (Rel Moisture + Temperature hourly), HH2
5	23.11.2015_15:00	14.01.2016_09:00	Drying out traject after addition of 1120 ml of water (~10 Vol%)	PlantCare (Rel Moisture + Temperature hourly), HH2

3 Results and discussion

3.1 Temperature measurements

Soil temperature measured with the PlantCare sensors are compared with soil temperature measured with the Campbell T107 sensors operational on the sites since 2010.

3.1.1. Gontrode

On the Gontrode site, soil temperature was measured using four nearby located PlantCare sensors, with 2 sensors (replicates) in each of the two depth layers i.e. 10-20 cm and 20-40 cm. In the 10-20 cm layer (Figure 3.1), the PlantCare temperatures were on average 1°C higher than the T107 temperature (bias in Table 3.1), but this deviance appeared to decline slightly from May to December (Figures 3.1 and 3.2). This deviance may be partially explained by the lateral distance (2-2.5 m) between the PlantCare sensors on the one hand and the T107 probe (reference) on the other, but other factors may play a role as well, since the deviance varies over time while the distance remains constant.

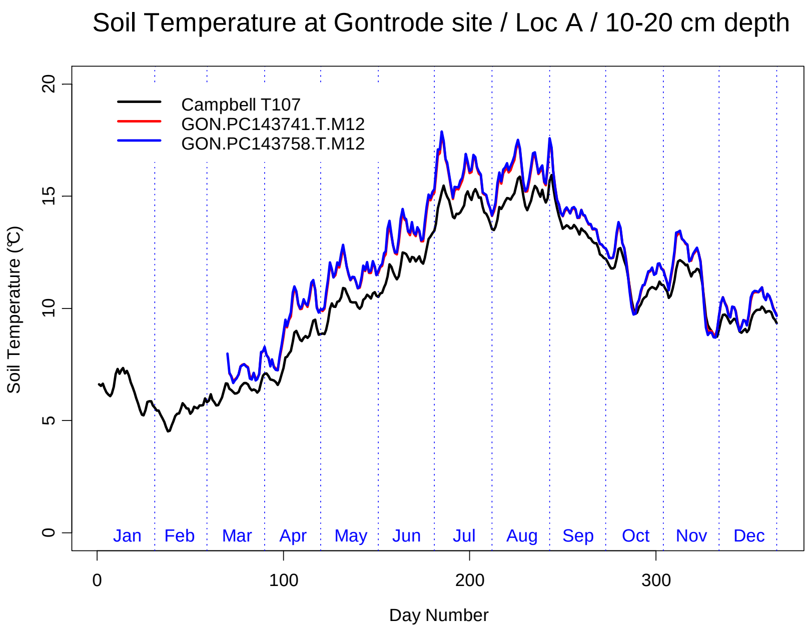


Figure 3.1. Pattern of daily averaged soil temperature of the 10-20 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

As shown in Figure 3.1, the temperature response of both PlantCare sensors is identical and in perfect agreement (d=1), evidenced by a negligible difference (0.05 °C) and variation (SD=0.081 °C) between the readings (Table 3.1).

Table 3.1. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	Trueness Error (%)	Precision Error (%)	Index of agreement (d)
T107	**PC143741.T.M12**	**295**	**0.949**	**0.485**	**1.065**	**0.985**	**79**	**21**	**0.96**
T107	**PC143741.T.M12**	**296**	**1.000**	**0.553**	**1.143**	**0.982**	**76**	**24**	**0.96**
PC143741.T.M12	**PC143741.T.M12**	**295**	**0.050**	**0.081**	**0.095**	**1**	**27**	**72**	**1**

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott (1981).

Daily temperature variations were recorded similarly by both sensor types, as indicated by the high correlation (R=0.98). Hence, PlantCare sensors could reliably replace the T107 measurements in the 10-20 cm layer.

In Figure 3.3. both PlantCare temperatures are plotted against the T107 reference temperature and compared to the 1:1 line. Note that in the range 9-12 °C some readings are closest to the 1:1 line (i.e. same as reference temperatures), but others show a high bias in the same temperature range. When the delta Temperature (Temp. difference between PlantCare and Reference T107 Temp.) is plotted against Moisture content as observed by the FDR sensors (Figure 3.4.), it is clear that under wet conditions Delta Temp. is smallest and increases when the soil desiccates. The same conclusion is drawn based on the relative soil moisture content of the PlantCare sensors, (Figure 3.4.). When the soil is saturated (100%) delta temperature is low and vice versa.

Since the Gontrode site has a clay-sand substrate at limited depth (<80 cm) with a low hydraulic conductivity, the profile gets easily saturated with water during wintertime. Lateral water flow is conducting energy and soil temperature is expected to become spatially homogenized. Hence, differences between temperatures measurered at different locations decline, which is a reasonable explanation for our findings.

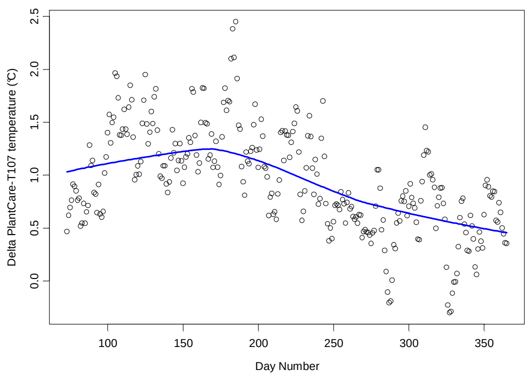


Figure 3.2. Temperature difference between PlantCare sensors and T107 over time – Lowess curve in blue.

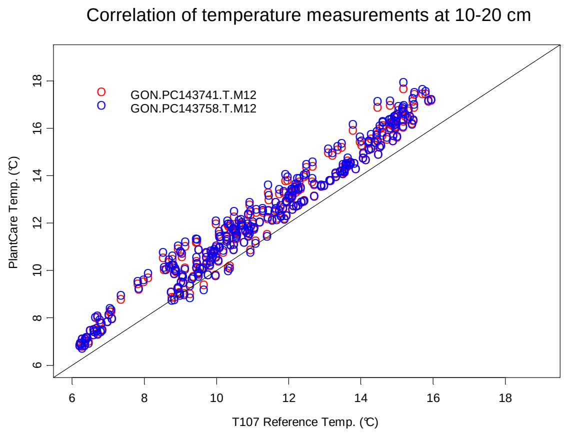


Figure 3.3. PlantCare versus Reference T107 temperature. Black line is 1:1 line.

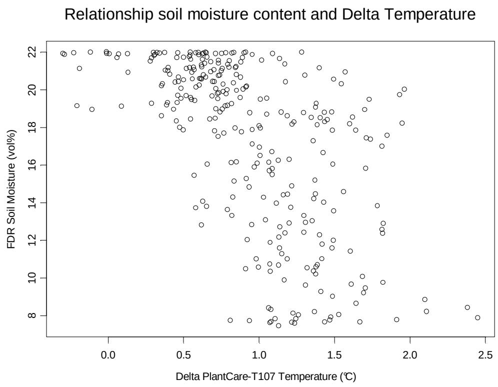


Figure 3.4. Temperature differences between sensor types is related to differences in soil moisture.

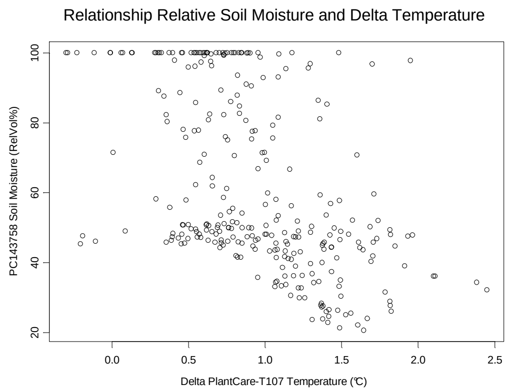


Figure 3.5. Temperature differences between sensor types is related to differences in relative soil moisture.

A similar pattern is observed for the 20-40 cm layer (Fig. 3.6). Here two PlantCare Mini-Loggers measured soil temperature from March to September in parallel. One sensor (PC143731) had a white tip suited for “natural soil (NS)”, whereas the other (PC155087) had a green tip for “Artificial substrates (AS)”. Since the green tip was not adequate (see further), the latter sensor was uninstalled and the green tip was replaced by a white one and reinstalled on November 18th at location B of the plot. Note that the reference Temperature probes (T107) are installed at Location A only (at each depth).

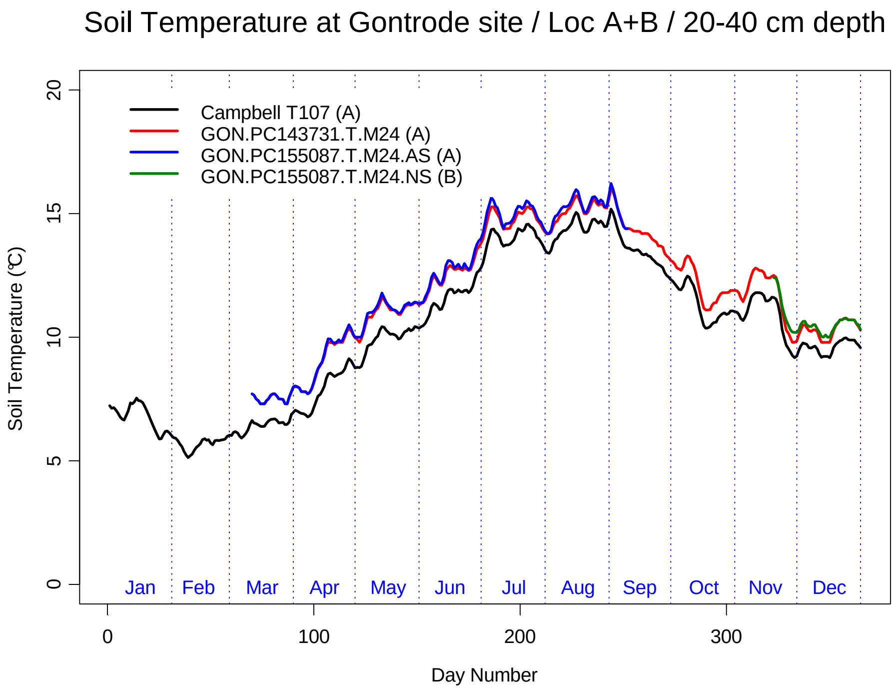


Figure 3.6. Pattern of daily averaged soil temperature of the 20-40 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

Figure 3.6. shows again that the PlantCare Temperature measurements are higher than the T107 readings. For the PC143731 sensor this positive bias is 0.87 °C and for the PC155087 sensor this is 1.03 °C (Table 3.2).

The type of tip (Artificial or Natural soil calibration) had little effect on the temperature recordings. During 183 days of measurements, there was only an average absolute difference of 0.1 °C between the PlantCare sensors and their readings were very well correlated. So the tip-type does not seem to affect temperature measurements.

Replacing the tip and installing sensor PC155087 at the B location, about 10 m away from location A where the T107 sensor is situated, but at the same depth, only slightly affects the pattern. Though only 43 days of measurements (during the wet period) may be compared until now, the correlation is high (R=0.99) but the index of agreement lowered from 0.97 to 0.69 (Table 3.2). Future recordings will reveal the differences.

Table 3.2. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	Trueness Error (%)	Precision Error (%)	Index of agreement (d)
T107	**PC143731.T.M24.NS**	**296**	**0.871**	**0.161**	**0.885**	**0.998**	**96**	**4**	**0.97**
T107	**PC155087.T.M24.AS**	**183**	**1.028**	**0.168**	**1.042**	**0.998**	**97**	**3**	**0.97**
T107	**PC155087.T.M24.NS**	**43**	**0.849**	**0.067**	**0.852**	**0.993**	**99**	**1**	**0.69**
PC143731.T.M24.NS	**PC155087.T.M24.AS**	**183**	**0.103**	**0.091**	**0.137**	**1**	**56**	**43**	**1**

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott (1981).

Figure 3.7 reveals a specific pattern of Delta Temperature over time, different from the one observed for the 10-20 cm layer (Figure 3.2). Here Delta Temperature decreases prior to day 100, then suddenly increases till about day 115 to decrease again till day 200. Note that the range of delta Temperature is much smaller in the 20-40 cm layer than in the 10-20 cm layer, which is related to the attenuation of soil temperature amplitudes with depth. This can also be observed by comparing Figure 3.8 with 3.3, sharing the same scale.

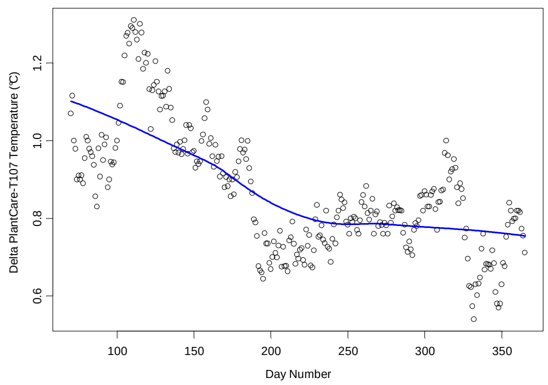


Figure 3.7. Temperature difference between PlantCare sensors and T107 over time in 20-40 cm layer – Lowess curve in blue.

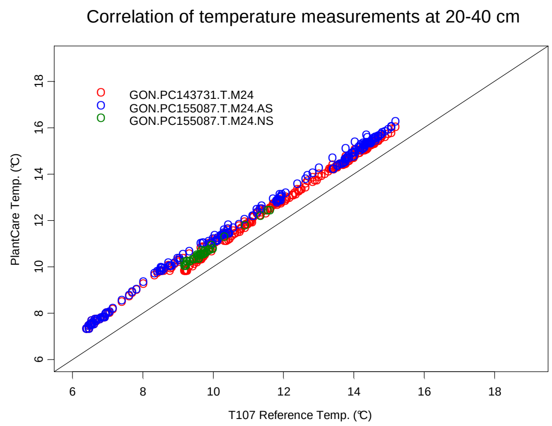


Figure 3.8. PlantCare versus Reference T107 temperature in 20-40 cm layer. Black line is 1:1 line.

The pattern between Delta Temperature and moisture content observed for the 10-20 cm layer, is not found for the 20-40 cm layer (Figures 3.9 and 3.10). Still small Delta values are found when soils are wet, but also when they are dry, and high Delta values are mainly found under wet conditions, so apparently other factors play a role here as well.

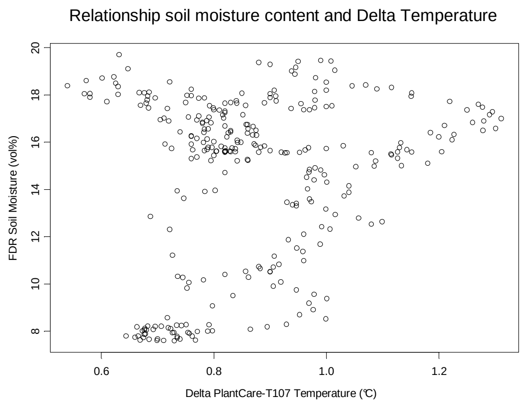


Figure 3.9. Temperature differences between sensor types is related to differences in soil moisture.

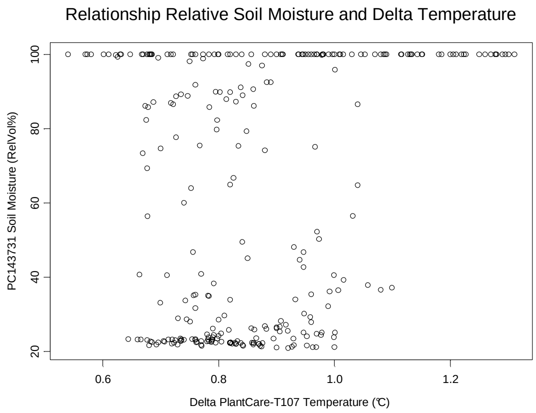


Figure 3.10. Temperature differences between sensor types is related to differences in relative soil moisture.

3.1.2. Ravels

At the Site in Ravels, initially two PlantCare sensors were installed in March 2015 at the same depth in the 20-40 cm layer, one calibrated for natural soils (NS) and one for artificial substrates (AS). During two weeks in August both PlantCare sensors were erroneously switched off, explaining the data gap.

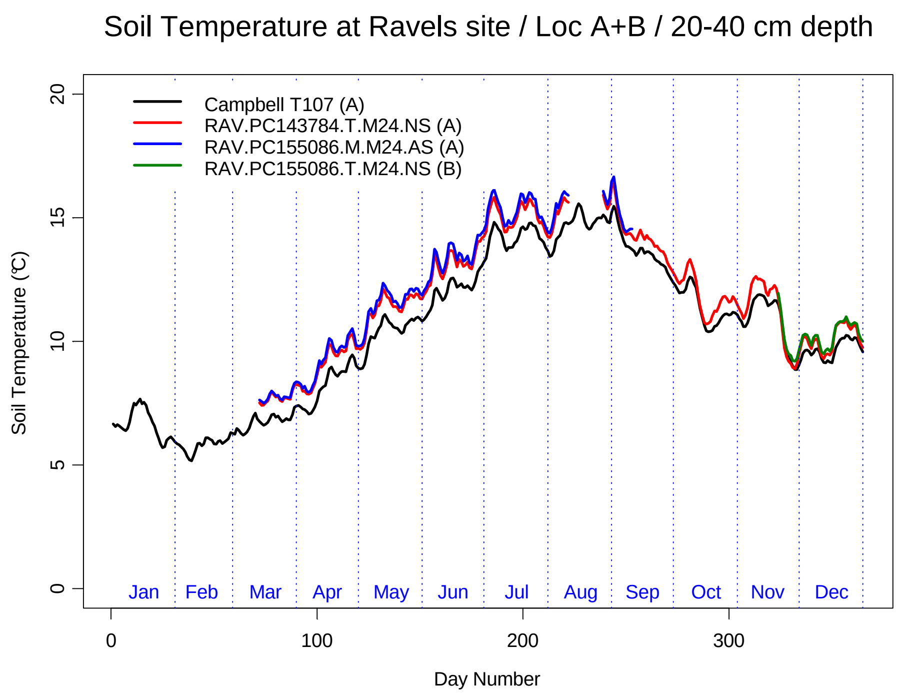


Figure 3.11. Pattern of daily averaged soil temperature of the 20-40 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

The PlantCare Temperature measurements are also on this site systematically higher than the T107 readings (Figure 3.11). Moreover, the sensor PC155086 with Artificial-substrate-tip showed a 0.2 °C higher response than the sensor PC143784 with Natural-Soil-tip (Table 3.3).

On this sandy soil, the positive bias of PlantCare sensors compared to the T107 reference ranged from 0.7 to 1.1 °C, with the larger one for the sensor with AS-Tip (as in Gontrode). Their variation is very well correlated.

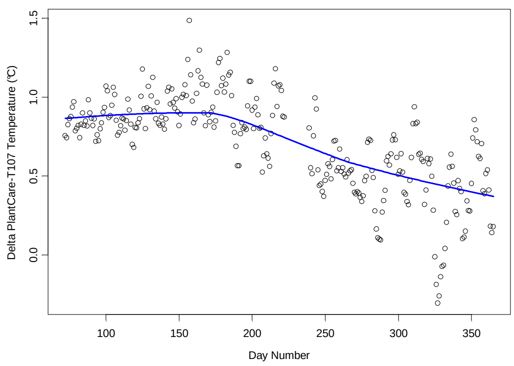
Similarly as for the Gontrode site, the index of agreement (and correlation) lowered when moving the PC155086 sensor to location B, suggesting a slightly different variation pattern due the local soil conditions, though the ups and downs are still similar (Figure 3.11).

Table 3.3. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	Trueness Error (%)	Precision Error (%)	Index of agreement (d)
T107	**PC143784.T.M24.NS**	**278**	**0.706**	**0.300**	**0.767**	**0.992**	**84**	**16**	**0.97**
T107	**PC155086.T.M24.AS**	**166**	**1.081**	**0.216**	**1.102**	**0.997**	**96**	**4**	**0.96**
T107	**PC155086.T.M24.NS**	**42**	**0.492**	**0.214**	**0.535**	**0.936**	**84**	**16**	**0.82**
PC143784.T.M24.NS	**PC155086.T.M24.AS**	**166**	**0.199**	**0.075**	**0.045**	**1**	**87**	**13**	**1**

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott (1981).

Figure 3.12 reveals a similar pattern of Delta Temperature over time as found for the 10-20 cm layer in Gontrode, decreasing from about day 200 onwards. Figure 3.13 illustrates the highest deviance from the 1:1 line by the artificial-soil-tip (blue circles), whereas the natural-soil-tip is closer to the Reference temperature, especially in the 9-12 °C range.



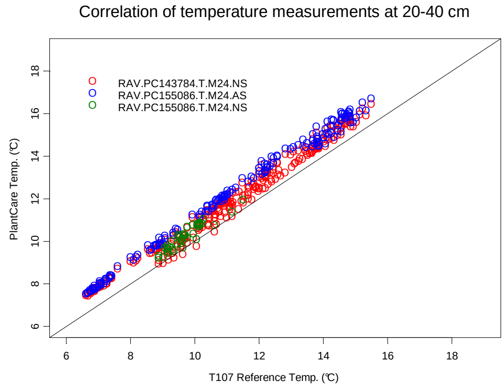
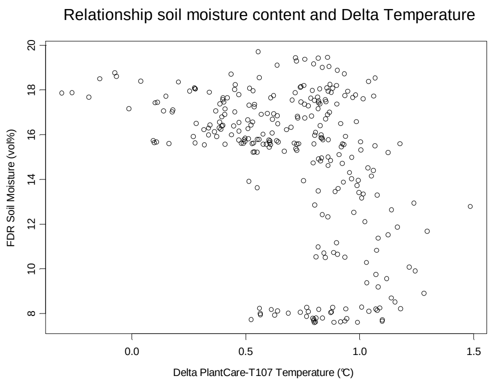


Figure 3.12. Temperature difference between PlantCare sensors and T107 over time in 20-40 cm layer – Lowess curve in blue.

Figure 3.13. PlantCare versus Reference T107 temperature in 20-40 cm layer. Black line is 1:1 line.

Figures 3.14 and 3.15 seem to support the hypothesis of the relationship between Delta Temperature (between sensor types) and moisture content. When soils are wet, the difference between PlantCare and T107 temperature readings is smaller then when the soils are dry. However delta-values > 0.5 °C can be found at various moisture levels.



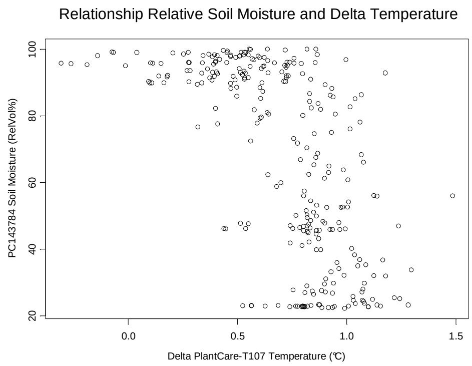


Figure 3.14. Temperature differences between sensor types is related to differences in soil moisture.

Figure 3.15. Temperature differences between sensor types is related to differences in relative soil moisture.

3.1.3. Brasschaat

At the Brasschaat site, the temperature pattern recorded by the three sensors is shown in Figure 3.16. Similarly as for the other sites, one PlantCare sensor (here PC155083) was reinstalled with a natural-soil-tip after being monitored with an artificial-substrate-tip. Again, the PlantCare Temperature readings where higher than the reference T107 readings, but now the AS tip readings were lower than the NS tip readings. But even when the AS tip was replaced by a NS tip, the temperature recordings were lower, suggesting that it is rather dependent on the individual sensor than on its tip. (Figure 3.16).

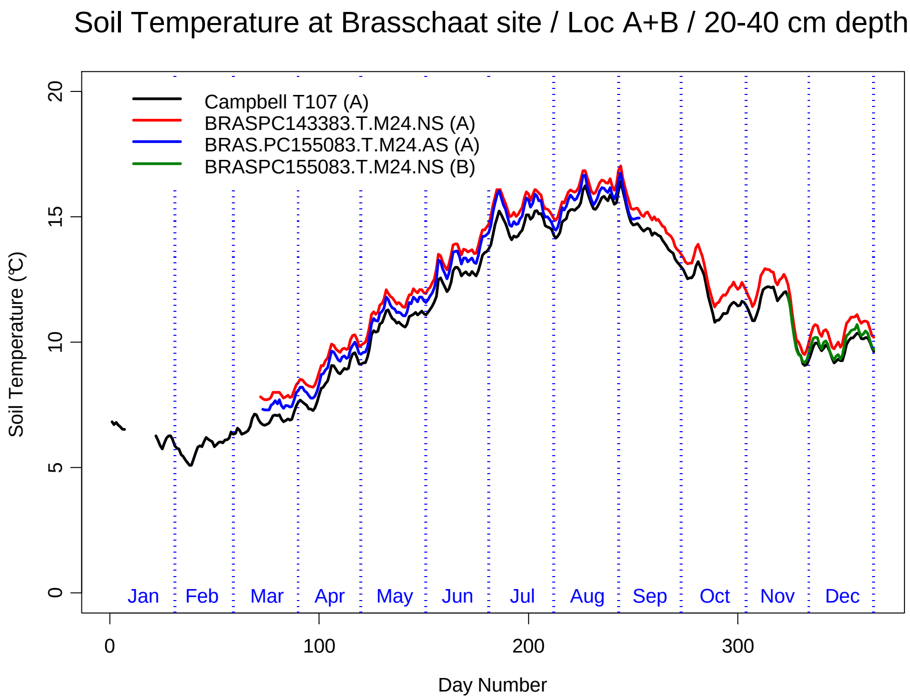


Figure 3.16. Pattern of daily averaged soil temperature of the 20-40 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

Table 3.4 indicates indeed a smaller deviance of about ~0.5°C for the AS-tip compared to ~0.75°C for the NS-tip, both relative to the T107 reference, or a negative bias when compared to each other for their common period.

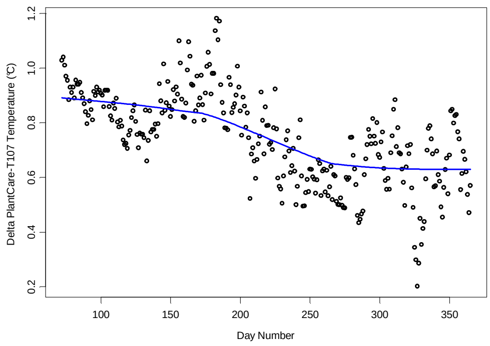
Correlation and index of agreement however remains very high (near 1). When sensor PC155083 is moved to location B, the index of agreements drops slightly indicating that the pattern of T107 is still closely followed.

Table 3.4. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	True ness Error (%)	Precision Error (%)	Index of agreement (d)
T107	PC143383.T.M24.NS	294	0.746	0.168	0.764	0.998	95	6	0.98
T107	PC155083.T.M24.AS	181	0.487	0.146	0.509	0.999	91	9	0.99
T107	PC155083.T.M24.NS	42	0.147	0.138	0.200	0.971	53	47	0.97
PC143383.T.M24.NS	PC155083.T.M24.AS	181	-0.337	0.064	0.343	1	96	3	1

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott, 1981)

Figure 3.17 shows a similar pattern of Delta Temperature over time as found for the 20-40 cm layer in Ravels, decreasing from about day 200 onwards. In contrast to the findings on the other sites, Figure 3.18 illustrates the highest deviance from the 1:1 line by the natural-soil-tip (red circles), whereas the artificial-substrate-tip is closer to the Reference temperature. When the tip of the same sensor PC188083 is replaced by a NS tip, the readings (green circles) are very close to the reference temperature, as can also be seen in Figure 3.16.



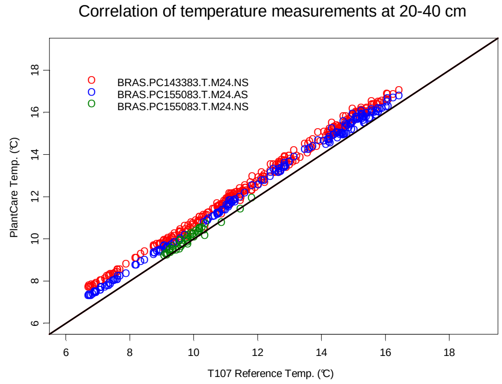
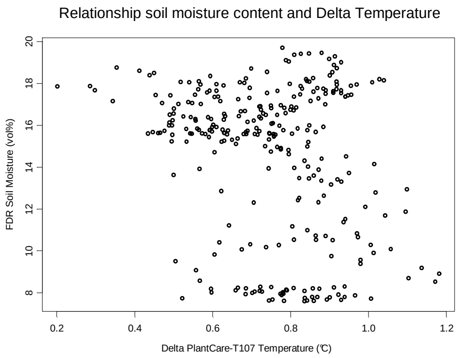


Figure 3.17. Temperature difference between PlantCare sensors and T107 over time in 20-40 cm layer – Lowess curve in blue.

Figure 3.18. PlantCare versus Reference T107 temperature in 20-40 cm layer. Black line is 1:1 line.

Figures 3.19 does not provide a clear image unlike figure 3.20 that shows that when the soil is saturated, delta temperature is rather small whereas in dessicating soils delta-temperature is larger than 0.5. Eventually, this may also indicate that one of the sensor types performs less accurate in non saturated soils than the other.



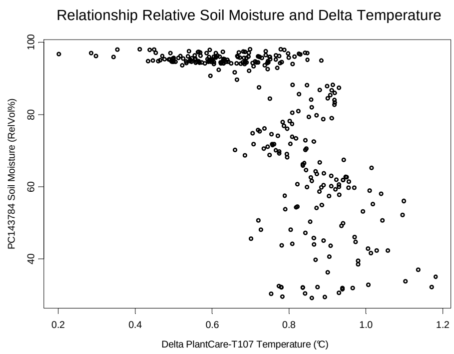


Figure 3.19. Temperature differences between sensor types is related to differences in soil moisture.

Figure 3.20. Temperature differences between sensor types is related to differences in relative soil moisture.

3.1.4. Wijnendale

The daily averaged soil temperature readings of the Wijnendale site are plotted in Figure 3.21. Note that here sensor PC143794 equiped with a NS-tip has a positive bias relative to the Campbell T107 measurements whereas sensor PC155085 with an AS –tip has a negative bias. When the latter sensor is reinstalled with a NS-tip, the negative bias remained and increased (from -0.24 to -0.80 °C), even under wet soil conditions. From September onwards, the PC143794 sensor closely follows the T107 pattern, though ups and downs seem stronger.

Table 3.5 provides statistical evaluation values. Relative to the reference temperature T107, both PlantCare sensors have a relative small bias of ~0.25 °C when located nearby, but a larger bias when moved to location B (~0.80 °C). Again, index of agreement is smaller when the distance of the sensors is 10 m apart indicating another temperature profile but there is still some spatial correlation. Over all, correlation remains high among temperature sensors..

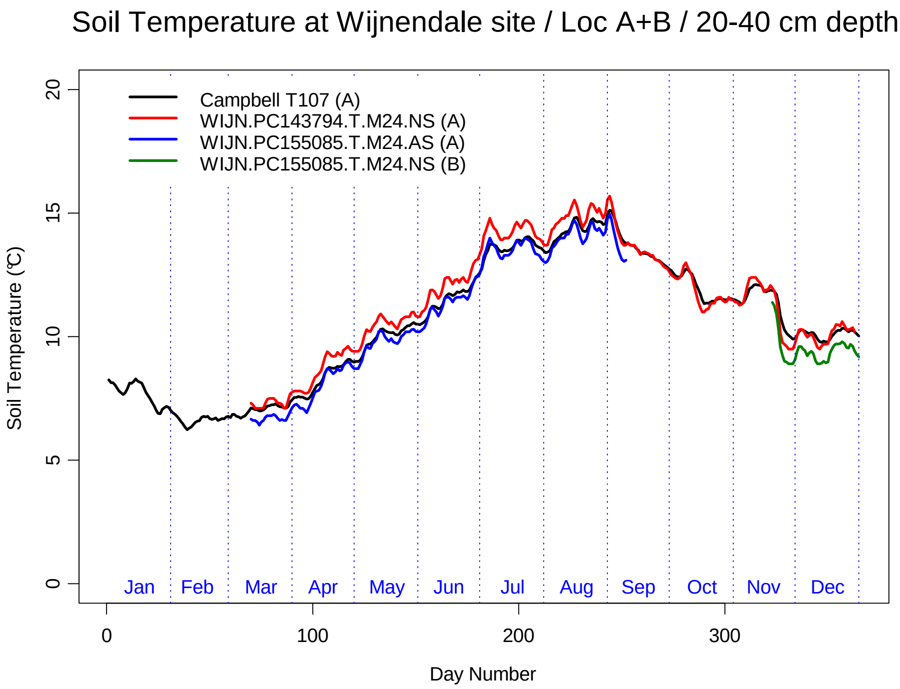


Figure 3.21 Pattern of daily averaged soil temperature of the 20-40 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

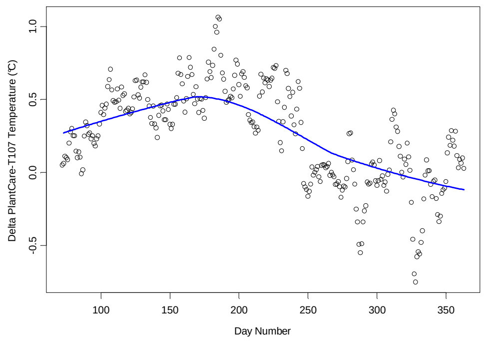
Note that for the two sensors placed next to each-other, here they have the largest systematic difference (0.7 °C) of all observed sites, while they are perfectly harmonized in recording temperature variation. This indicates that individual (calibration) differences or properties may exist among PlantCare sensors.

Table 3.5. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	Trueness Error (%)	Precision Error (%)	Index of agreement (d)
T107	**PC143794.T.M24.NS**	**294**	**0.263**	**0.331**	**0.422**	**0.99**	**38**	**61**	**0.99**
T107	**PC155085.T.M24.AS**	**183**	**-0.238**	**0.188**	**0.303**	**0.99**	**61**	**38**	**1.00**
T107	**PC155085.T.M24.NS**	**43**	**-0.799**	**0.227**	**0.83**	**0.92**	**92**	**7**	**0.62**
PC143794.T. M24.NS	**PC155085.T.M24.AS**	**183**	**-0.69**	**0.068**	**0.694**	**1.00**	**99**	**1**	**0.98**

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott (1981).

Figure 3.22 again shows a similar pattern of Delta Temperature over time as found before, starting to decrease arround day 200. Figure 3.23 illustrates the positive and negative bias around the 1:1 line for all readings.



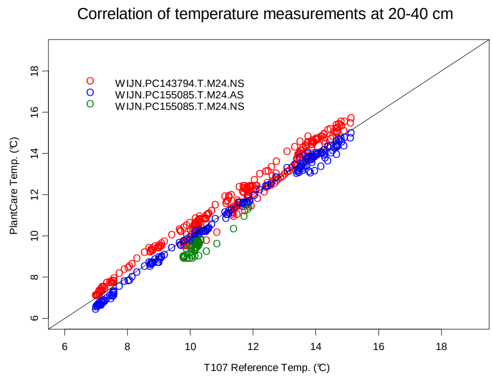
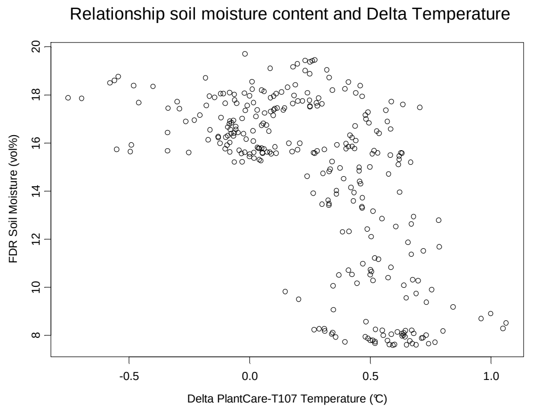


Figure 3.22. Temperature difference between PlantCare sensors and T107 over time in 20-40 cm layer – Lowess curve in blue.

Figure 3.23. PlantCare versus Reference T107 temperature in 20-40 cm layer. Black line is 1:1 line.

Figures 3.24 shows for PC143794 with NS tip, which has on average a positive bias relative to T107 readings (Red in Fig 3.23), has a zero or even negative bias when soils are wet, and a positive bias under drier conditions. However, a different picture is provided when analyzing the relative soil moisture readings of that same sensor. Here, zero and negative delta Temp values are observed between roughly 40 and 60 Vol% relative moisture, whereas positive bias when relative soil moisture is greater than 60 Vol%. It indicates already that FDR and PlantCare moisture measurements provide different information.



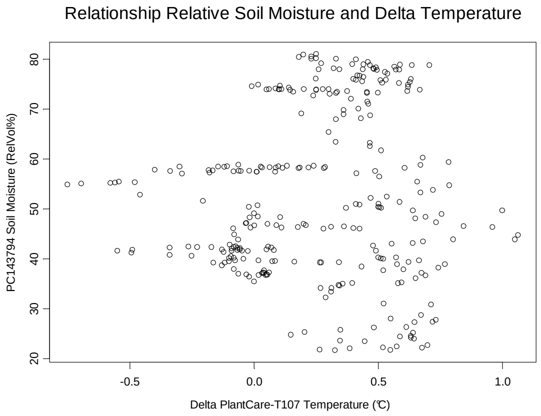


Figure 3.24. Temperature differences between sensor types is related to differences in soil moisture.

Figure 3.25. Temperature differences between sensor types is related to differences in relative soil moisture.

3.1.5. Zoniën

Soil temperature recordings for Zoniën during 2015 are given in Figure 3.26. From April to September two PlantCare sensors, each with a different tip, ran in parallel and generated similar outputs (index of agreement = 1). Average difference between the PlantCare sensors was only 0.07 °C. Hence, the type of tip had no effect on the temperature measurements. There was a positive bias (0.42-0.65 °C) relative to the T107 measurements, but this bias became smaller from september onwards. The sensor moved to location B registered temperature values with a very small bias, but slightly different pattern evidenced by a lower index of agreement (Table 3.6).

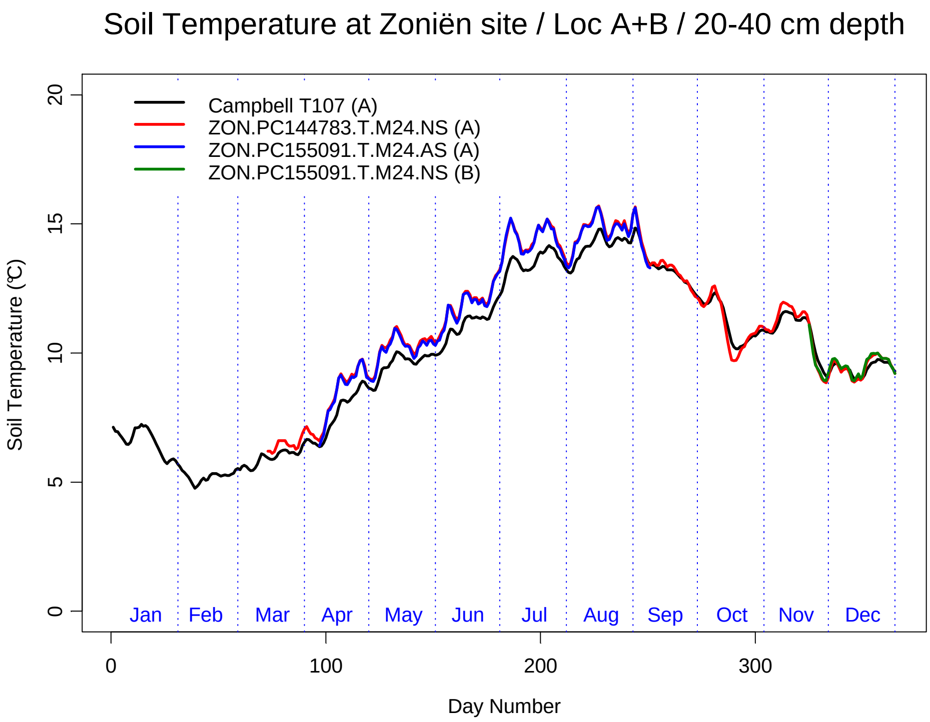


Figure 3.26. Pattern of daily averaged soil temperature of the 20-40 cm depth layer measured using a Campbell 107 probe and two PlantCare Mini-Loggers.

Table 3.6. Predictive quality of PlantCare Temperature measurements compared to reference sensor.

Ref.	PlantCare	n	MPE bias	SDPE noise	RMSPE accuracy	R	Trueness Error (%)	Precision Error (%)	Index of agreement (d)
T107	**PC144783.T.M24.NS**	**293**	**0.419**	**0.415**	**0.59**	**0.99**	**50**	**50**	**0.99**
T107	**PC155091.T.M24.AS**	**155**	**0.652**	**0.313**	**0.723**	**0.99**	**81**	**19**	**0.98**
T107	**PC155091.T.M24.NS**	**41**	**0.032**	**0.226**	**0.225**	**0.87**	**2**	**98**	**0.93**
PC144783.T. M24.NS	**PC155091.T.M24.AS**	**155**	**-0.073**	**0.52**	**0.089**	**1**	**66**	**34**	**1**

MPE = Mean Prediction Error, SDPE = Standard deviation of the Prediction Error, RMSPE = Root Mean Square Prediction Error, R = correlation coefficient, d = Index of Agreement (Willmott (1981).

Consistently, Figure 3.27 shows the decreasing pattern of Delta Temperature between sensor types from July till the end of the year with near zero bias in december. Figure 3.28 illustrates the positive bias, and partly the readings on the 1:1 line in the 9-15°C range. According to the FDR readings, zero and negative bias are related to moisture contents > 15 Vol% (Figure 3.29) and partially high Rel Vol% readings of the PlantCare sensor. Inconsistently, there is also a peak at 40 Rel Vol% with zero and negative bias which is hard to explain at this moment.

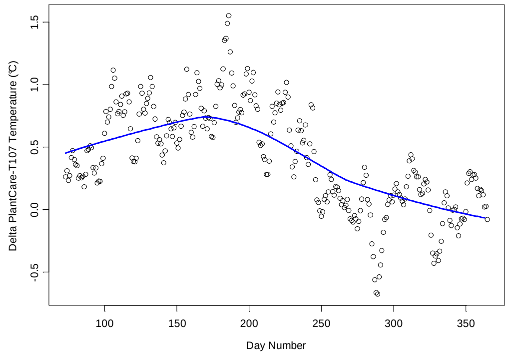


Figure 3.27. Temperature difference between PlantCare sensors and T107 over time in 20-40 cm layer – Lowess curve in blue.

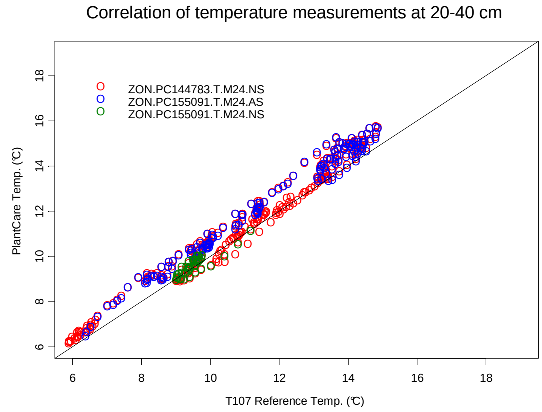


Figure 3.28. PlantCare versus Reference T107 temperature in 20-40 cm layer. Black line is 1:1 line.

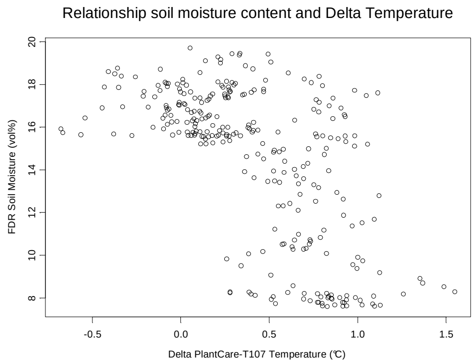


Figure 3.29. Temperature differences between sensor types is related to differences in soil moisture.

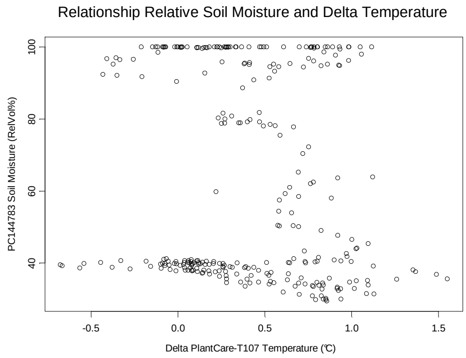


Figure 3.30. Temperature differences between sensor types is related to differences in relative soil moisture.

3.2 Soil moisture measurements

Relative soil moisture contents measured with the PlantCare sensors are compared with soil water content measured with Campbell FDR sensors operational on the sites since 2010 and also related to gravimetrical moisture content from monthly field measurements.

3.2.1. Gontrode

From the 5 observation sites, only at the Gontrode site soil moisture was monitored in two fixed depth layers: M12 (10-20 cm) and M24 (20-40 cm). At the other sites the monitoring was focused on the M24 layer only.

Soil moisture in M12 layer

The evolution of soil water content over the year 2015 as measured with several devices is given in Figure 3.31. The blue line represents the moisture measurements recorded by the Campbell FDR Soil Water Reflectometer ranging from 23.2 to 37.9 Vol%. The black dots are monthly reference field measurements of soil moisture (gravimetric analysis) started in March, reaching a maximum of 39 Vol% in May and a minimum of 17.9 Vol% in August. Unexpectedly, moisture content was quite high (35 Vol%) in September, but at an expected level in October, November and December. A spline was fitted to indicate the trend. Two PlantCare sensors (PC143741 & PC143758) both with a felt for Natural Soil, measured during 295 days the relative moisture volume (scale on right Y-axis), ranging from 20.6 -100 RelVol% (Table 3.7). The recordings (moisture and temperature) from the first 15 days were considered not reliable and are greyed in the graph. Since, in theory, no more water (in absolute Vol%) than the ϴs level can be stored in the soil layer, 100 RelVol% of the PlantCare was set equal to this field moisture level. Note that in second half of November and most days in December 100 RelVol% was

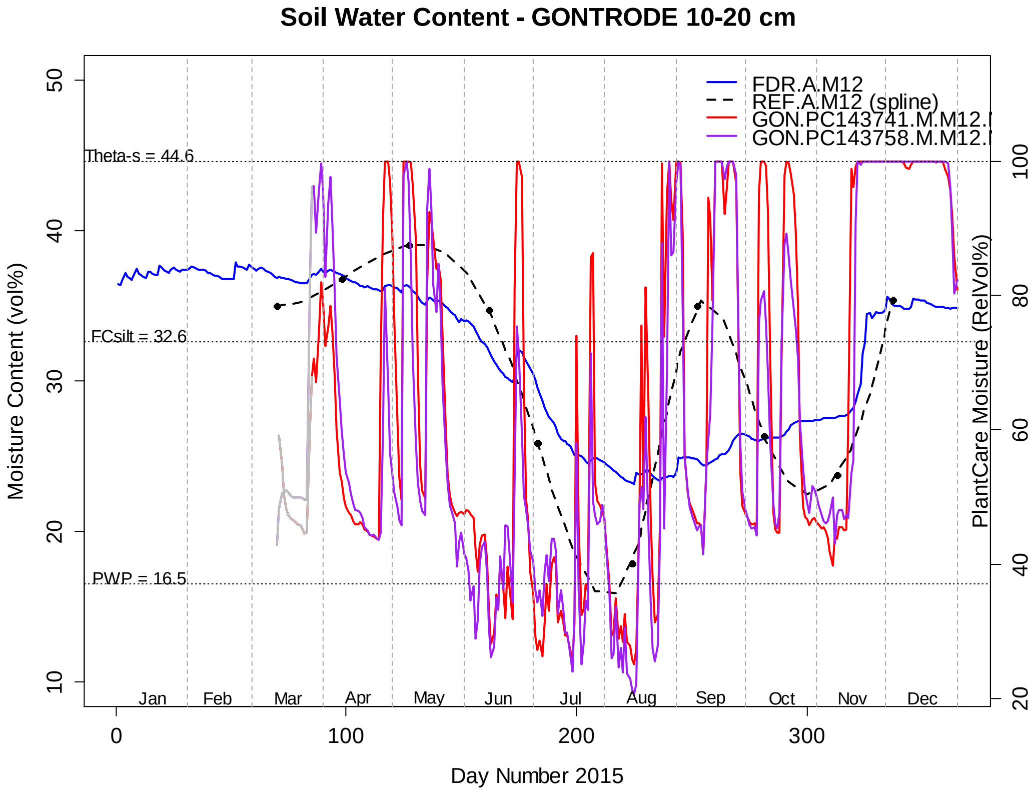


Figure 3.31 Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for Natural soil (NS). Soil water retention characteristics Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

reached while FDR and reference measurements registered around 35 Vol%, substantially less than ϴs, but higher than FC.

PlantCare data suggest that the driest period is mid August (about 20 RelVol%) when the reference measurements equaled 17.9 Vol% (Table 3.7), close to the permanent wilting point of 16.5 %. At that moment FDR response was also at its minimum (23.2 Vol%) but this level is in absolute terms higher than the reference measurements, suggesting that FDR does not adequately record the low moisture levels or its calibration is not adequate enough in the dry range.

Table 3.7. Summary statistics of moisture measurements in Gontrode Location A 10-20 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (Gravimetric)	Vol%	10	17.90	26.02	34.84	30.98	35.30	39.00
FDR measurement	Vol%	365	23.15	26.30	34.48	31.79	36.68	37.87
GON.PC143741.M.M12	RelVol%	295	25.08	44.90	50.38	64.46	96.12	100
GON.PC143758.M.M12	RelVol%	296	20.62	44.43	50.29	61.59	87.66	100

Taking the scale differences into account, it is still obvious that fluctuations of relative soil moisture readings by PlantCare sensors are much more pronounced than the FDR response, which is clearly observed when the PlantCare readings are linearly rescaled (Figure 3.32). Though the two PlantCare sensors have the same characteristics (felts) and react similarly to moisture changes (same pattern), amplitudes differ slightly, which might partly be explained by soil variability, even at locations 20 cm apart, but maybe also by different contact of the felts with the soil matrix.

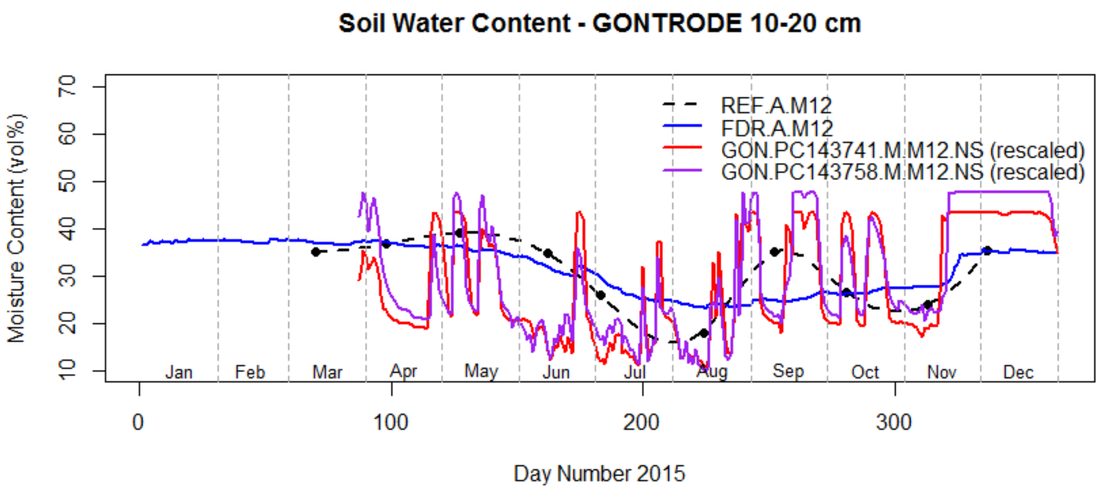


Figure 3.32 Evolution of soil water content during 2015 (same as Figure 3.21) but with rescaled PlantCare readings according to a zero-intercept linear model. Scaling factor 0.43211 for PC143741 and 0.47660 for PC143758.

Figure 3.33 combines information on the distributions and relationships of all data-series. The distribution of the reference measurements (histogram) indicates that for this analysis we currently have more observations in the wet range (> 30 Vol%) than in the dry range (< 20 Vol%). Therefore we will continue monthly sampling in 2016. Over the whole year 2015, more FDR readings were observed in the wet than in the dryer range with few observations around 30 Vol%. For the PC143741 sensor most readings are in the classes 40-60 RelVol% and 80-100 RelVol% and for PC143758 in the classes 40-50 and 90-100 RelVol%. Most observed soil temperatures at that soil depth are between 10-12 °C. As already explained above, soil temperature readings of both PlantCare sensors are perfectly correlated, while moisture output is less correlated (Rho = 0.94). The correlation is particularly less above 60 RelVol% (Figure 3.33) with PC143758 biased towards a lower response than PC143741. Spearman correlation of the PC sensors with the FDR sensor is relatively low (0.31-0.35). The locally weighted regression line suggests almost no correlation between these sensor types below 30 Vol% but a positive correlation above that level. With the limited set of reference observations, relationship with PC response is rather unclear, but correlation values are of the same order of magnitude than the FDR response (around 0.7). Interestingly is the negative correlation of FDR with temperature, showing some hysteresis effect in the scatterplot. It is logical that high moisture contents were mainly observed during wintertime when soil temperatures are low. The Rho is clearly more negative than between PC moisture and temperature. Below 60 RelVol%, moisture-temperature correlation is relatively well, whereas above 60 RelVol%, the scatterplot indicates various trajectories in the response of both sensors. Note that the erroneous data in the PC installation phase was discarded prior to the calculation of this correlation matrix, so this cannot explain part of this scatter. The data suggests that the PlantCare moisture response (> 60 RelVol%) might vary with soil temperature.

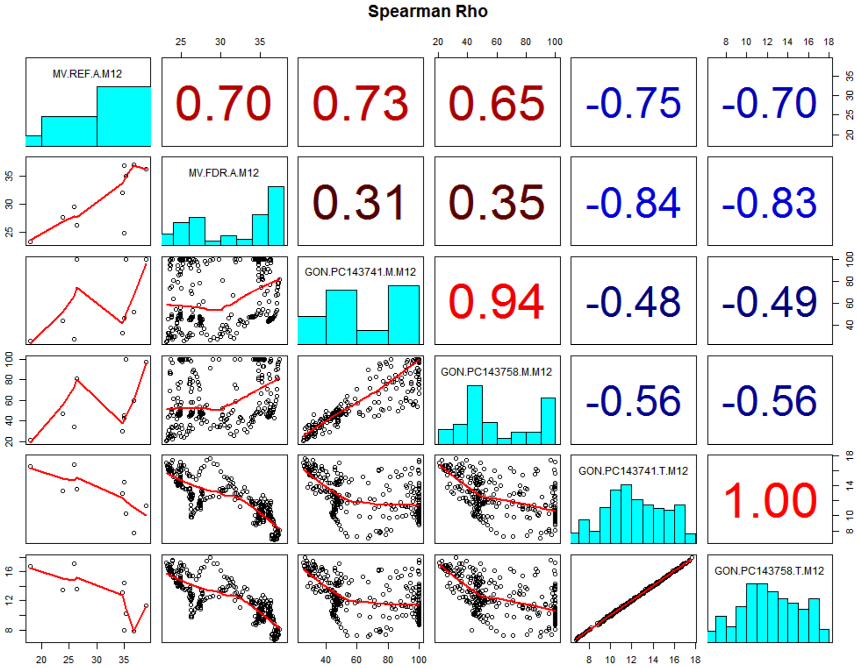


Figure 3.33 Matrix Spearman-correlation scatterplot with LOWESS regression line (in red) for Reference moisture measurements (MV.REF.A.M12), FDR readings (MV.FDR.A.M12), and PlantCare moisture and temperature readings (PC143741 and PC143758). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

The peaks recorded with PlantCare sensors may be explained by rain events on the plot (Figure 3.34). The massive peak in June (on 22.06.2015) may be explained by 20.4 mm of rainfall, but this effect faded away next days when rain was small or absent. Note that this event can also be clearly observed in the FDR readings, but with much less amplitude (Fig 3.32). End of July, several days of rain induced new peaks, particularly by the 7.1 and 18.1 mm events. A period of several rainy days as in September invoked a wider PlantCare peak and a delayed peak in the FDR readings. Lots of rain second half of November with an extreme event of 18.9 mm/day pushed the PlantCare readings to 100 RelVol% and they remained at that level for more than a month. It shows that PlantCare data is well reflecting the impact of rain events and that the sensors are much more responsive to these events than the FDR sensor. Note that these observations were performed at limited depth (10-20 cm) and that fast and intense reaction to rain events is expected to decline with depth.

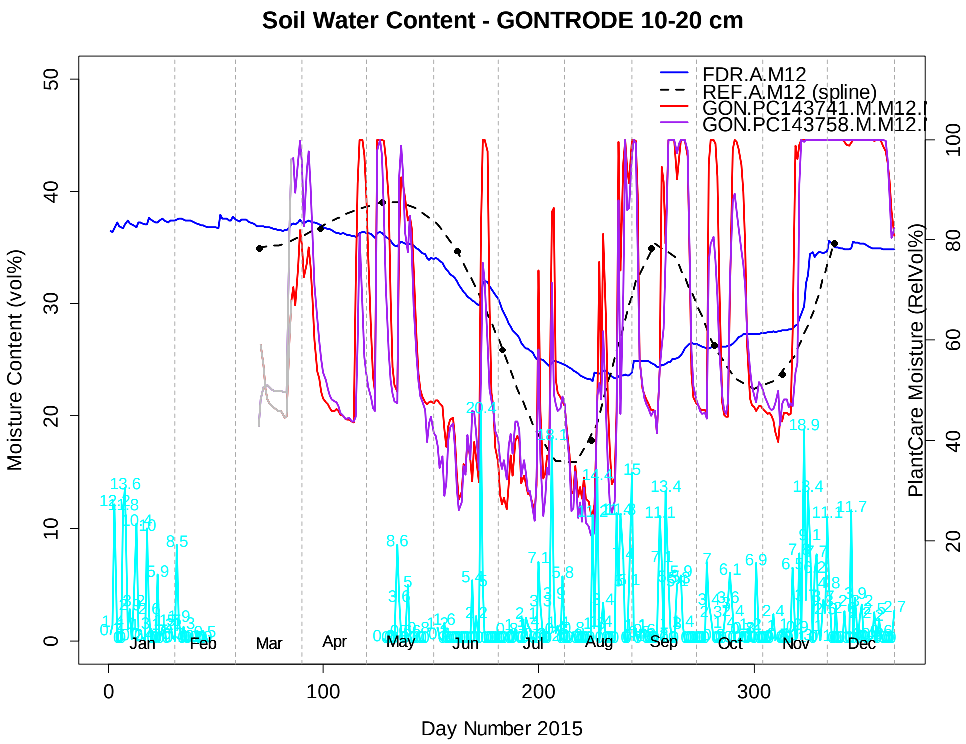


Figure 3.34. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings (Figure 3.31).

Soil moisture in M24 layer

In the 20-40 cm layer two PlantCare sensors were installed, one sensor (PC143731) with a felt calibrated for natural soil (NS) and another (PC155087) with a felt calibrated for artificial substrate (AS). The felt of the latter was replaced at the end of the year and relocated (location B) on the site and measured 42 days during 2015.

Summary statistics of the data are given in Table 3.8. Compared to Table 3.7 of the 10-20 cm data, one may observe that slightly lower moisture levels were recorded for the 20-40 cm layer. Since this layer holds less organic matter, this is plausible. Note that the PlantCare sensor with the Artificial-soil-felt never reached the 100 RelVol%, but also when the felt was replaced (and the sensor was recalibrated) the maximum value was 84.3 RelVol% even when the soil was saturated (Figure 3.35).

Table 3.8. Summary statistics of the moisture measurements in Gontrode Location A 20-40 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (Gravimetric)	Vol%	10	14.50	19.60	24.30	27.45	35.83	42.17
FDR measurement	Vol%	365	18.79	19.15	33.65	29.93	39.66	46.44
GON.PC143731.M.M24.NS	RelVol%	280	20.88	23.42	58.25	61.20	100	100
GON.PC155087.M.M24.AS	RelVol%	167	18.65	28.71	36.42	38.99	47.77	75.21
GON.PC155087.M.M24.NS	RelVol%	43	59.67	81.31	82.21	81.78	83.00	84.29

The 20-40 cm layer was saturated the first 120 days of the year 2015 with absolute reference water contents around 40 Vol%. This is higher than the maximum saturated water content (ϴs = 37.3 and 34.8 Vol%) empirically derived from the soil water retention curves in Annex I. From May to end of June the moisture content decreased systematically, showing a good correlation between FDR and field reference measurements. The decrease of PC143731 with NS-felt is even faster, whereas PC155087 with AS-felt decreased more slowly. In July, August and September moisture peak responses of both sensors are visible, but not in October though peaks were observed in the 10-20 cm layer (Figure 3.34). However, the rise mid November to 100 RelVol% is similar to the 10-20 cm layer. The same rise is noticed by the PC155087 sensor with NS-felt (green line), but 80 RelVol% is reached instead of 100 RelVol%. However, this sensor was newly installed at location B, where ϴs seems to be higher compared to location B (47 vs. 37.3 Vol%, data in Annex). Since 37.3/47 is also 80% it shows that there is some empirical evidence to relate 100 RelVol% response tot ϴs values derived from soil water retention curves, when comparison among different soils is needed.

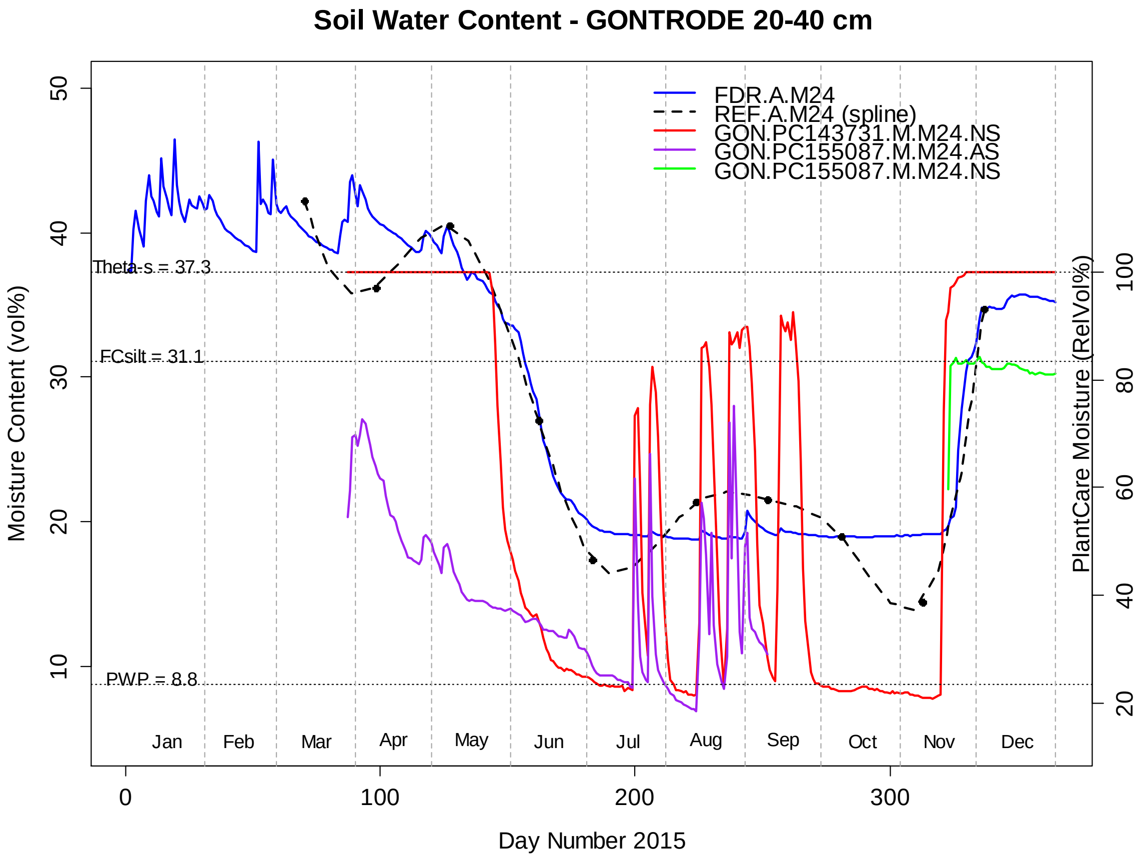


Figure 3.35. Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for Natural soil (NS) and artificial substrate (AS). Soil water retention characteristics Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

Note that the FDR measurements are closely following the reference measurements and that the bottom values (14.5 and 18.8 Vol% respectively) are also minima in the PlantCare response (20.9 and 18.7 RelVol%). However, while based on gravimetrical and FDR data one would conclude that PWP is not reached, the bottomline of the PlantCare readings suggest that PWP is reached in July and October. When as in Figure 3.35, 100%RelVol% is set equal to ϴs, then 20.9 RelVol% would equal 7.8 Vol% which is rather close to the lab reported PWP of 8.8 Vol%.

The response range of PC155087 equiped with the AS-felt is much more narrow than the other sensor equipped with a NS-felt. However, similar peaks (high-lows) were observed with both felts.   When the PlantCare response is rescaled using the reference moisture measurements and the AS-signal is amplified (Figure 3.36), we can see that peaks are still visible (compared to FDR measurements) when 100 RelVol% is already reached by the sensor with NS-felt. Also, the drying-out trajectory of the soil seems much slower according to a sensor with AS than with NS felt. Furthermore discrimination of multiple peaks in August and September seems better with AS than with NS felts (Figure 3.36). On the other hand, the bottomline suggests PWP is not observed with the AS-combination.

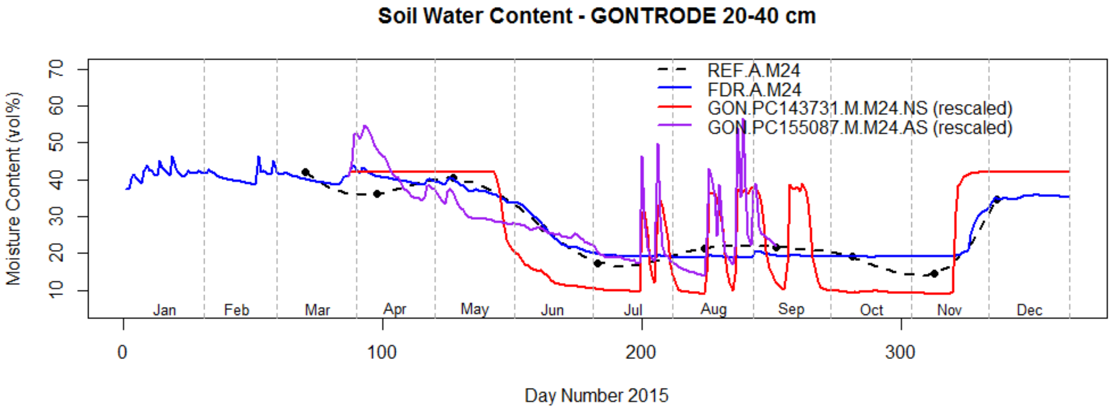


Figure 3.36 Evolution of soil water content during 2015 with rescaled PlantCare readings according to a zero-intercept linear model with Ref. measurements as response. Scaling factor 0.42084 for PC143731 and 0.75171 for PC155087.

Figure 3.37 depicts the correlation among the time-series of the 20-40 cm layer. A better correlation is found between the Ref. moisture level and FDR and PlantCare readings than in the 10-20 cm layer. The PC sensor with NS correlates better that the one with AS, showing a negative linear response for reference moisture > 35 Vol%.

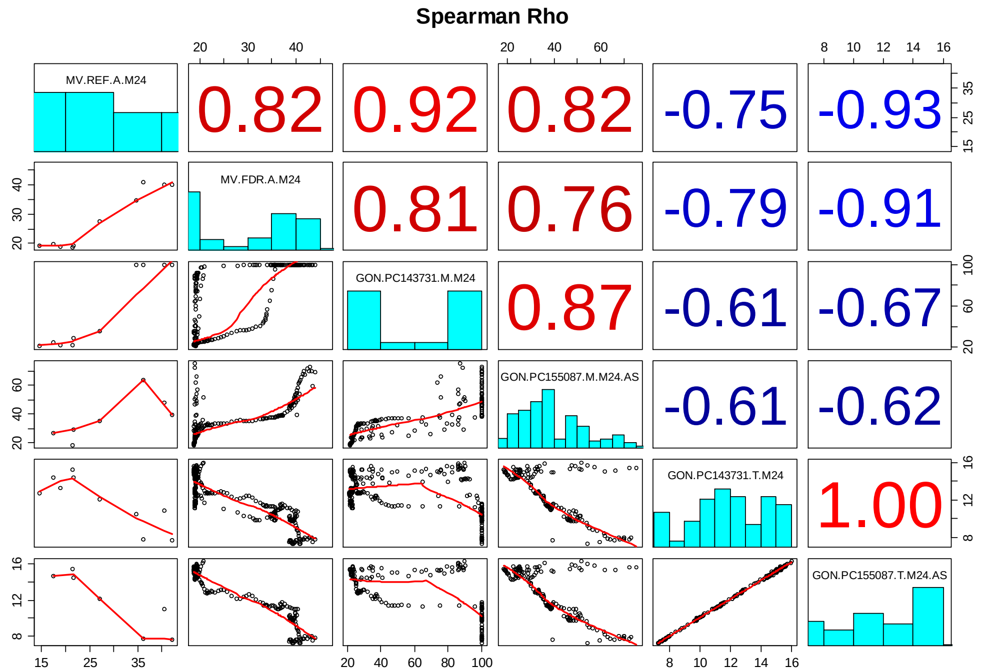


Figure 3.37. Matrix Spearman-correlation scatterplot for Reference moisture measurements (MV.REF.A.M24), FDR readings (MV.FDR.A.M24), and PlantCare moisture and temperature readings (PC143731 and PC155087). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

Sensitivity in FDR response in the low moisture range (< 20 Vol%) seems low, but this is also the case for PlantCare sensors. FDR and PlantCare responses have a kind of sigmoid relationship with many scatterpoints at the extremes. Especially the PC response between 20-100 RelVol% when soils are at FDR measured moisture levels below 20 Vol%

When the rain events are superimposed on the series plot (Figure 3.38). The massive peak in June (on 22.06.2015) clearly observed in the 10-20 cm layer is surprisingly not 'seen' by PC143731, and only slightly by PC155087 with AS felt. In contrast, the major rain events in July, August, September and November are recorded as peaks in the PlantCare response. Also in the lab-experiment was observed that some sudden changes in moisture content are missed by the PlantCare sensors, probably because of air entrapped in the felt. Once slightly moistioned, apparently the response reactivates.

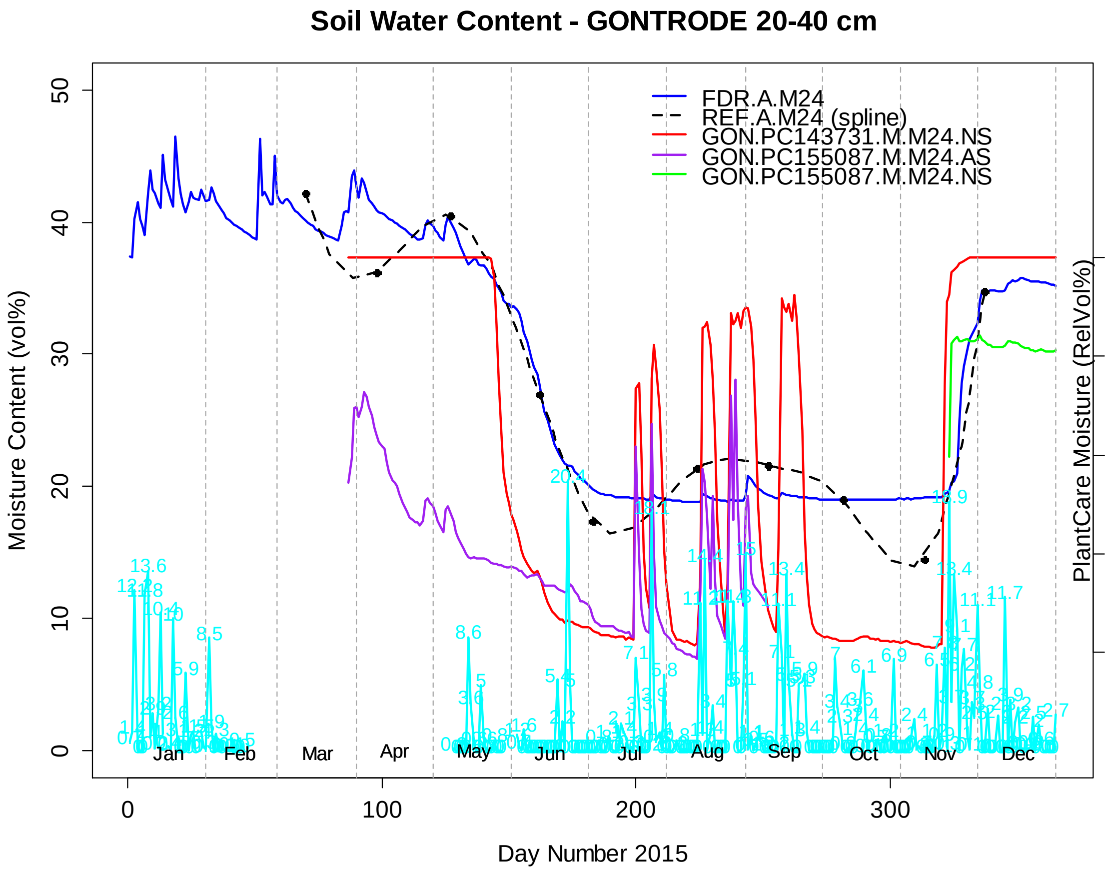


Figure 3.38. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings

Similarly as observed in the 10-20 cm layer, the soil gets saturated in the 20-40 cm layer from mid-November onwards, observed by all moisture measurements. This is clearly linked with the end of forest transpiration through shedding of the leaves.

3.2.2. Ravels

At this coniferous site, two PlantCare sensors were installed in the 20-40 cm layer, one sensor (PC143784) with a felt calibrated for natural soil (NS) and another (PC155086) with a felt calibrated for artificial substrate (AS). The felt of the latter was replaced at the end of the year and relocated (from location A to B) within the site and measured 42 days during 2015 (Table 3.9).

Summary statistics of the data are given in Table 3.9. One may observe that slightly lower moisture levels were recorded for the 20-40 cm layer in Ravels than in Gontrode (Table 3.8) which is logical since it concerns sandy soils with lower water holding capacity. Note that the PlantCare sensor with the artificial-soil-felt maximally reached 42.5 RelVol%, whereas when the felt was replaced the maximum value attained 100 RelVol% upon saturation (Figure 3.39).

Table 3.9. Summary statistics of the moisture measurements in Ravels Location A for the 20-40 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (gravimetric)	Vol%	10	9.40	13.69	16.65	16.92	18.71	26.90
FDR measurement	Vol%	365	11.29	13.73	19.20	17.80	20.70	25.05
RAV. PC143784.M.M24.NS	RelVol%	87	22.21	42.38	77.10	67.04	93.96	100
RAV. PC155086.M.M24.AS	RelVol%	166	22.92	30.24	33.19	33.66	38.91	42.5
RAV. PC155086.M.M24.NS	RelVol%	42	91.79	97.26	98.35	98.04	100	100

The FDR signal shows a decreasing moisture content from January to July, with a prominent rain event peak beginning of April. In July and August there is a baseline around 11 Vol%, though gravimetrically measured values indicate lower moisture contents (~9.4 Vol%) still higher than the wilting point (~ 7 Vol%). This illustrates again that FDR might overestimate moisture content in the dry range. Beginning of September FDR-based moisture values raise till the April level and show several peaks (end of September and beginning of December).

The baseline of PlantCare readings follow this trend but also show distinct peaks, those from the PC143784 equipped with NS-felt clearly as the most pronounced compared to the sensor with AS-felt. The first peak in April coincides with the FDR peak and a minor peak by the AS-sensor. The peak end of July is manifest for the PlantCare sensors but unnoticeable in the FDR response. Missing PlantCare data occurred two weeks in August (due to unintentional switching off of the device). When moisture levels raise beginning of September, PC143784 response immediately increases to high levels. When the AS-felt for sensor PC155086 is replaced by a NS-felt (and relocated to B) a similar pattern with the other PC sensor is observed.

When the PlantCare responses are rescaled to the actual moisture contents, the signal from the NS-sensor is most informative. The peaks end of July coincide nicely, but this is not the case for the AS-peak around 20th of July or the NS-peak beginning of June. Since the NS peaks seem to be better covered and explained by rainfall events (Figure 3.41) than the AS-peaks, the NS signal seems more reliable.

Correlation between Reference moisture and FDR is not so well (Figure 3.42) while correlation between Reference moisture and both PlantCare sensor readings is higher. When making abstraction from the responses to rainfall events, there is a good correlation (rho=0.85) between FDR and NS-readings, and this correlation is higher than between FDR and AS-readings.

Correlation between PlantCare temperature responses is perfect, as is observed on all sites. For PC155086, negative correlations are found for many datapoints between moisture and temperature readings, but a number of readings occurring between 14 and 16°C apparently escape from a good linear relationship. This is clearly different from the pattern observed for PC143784 with an NS felt, where apparently other factors do play a role.

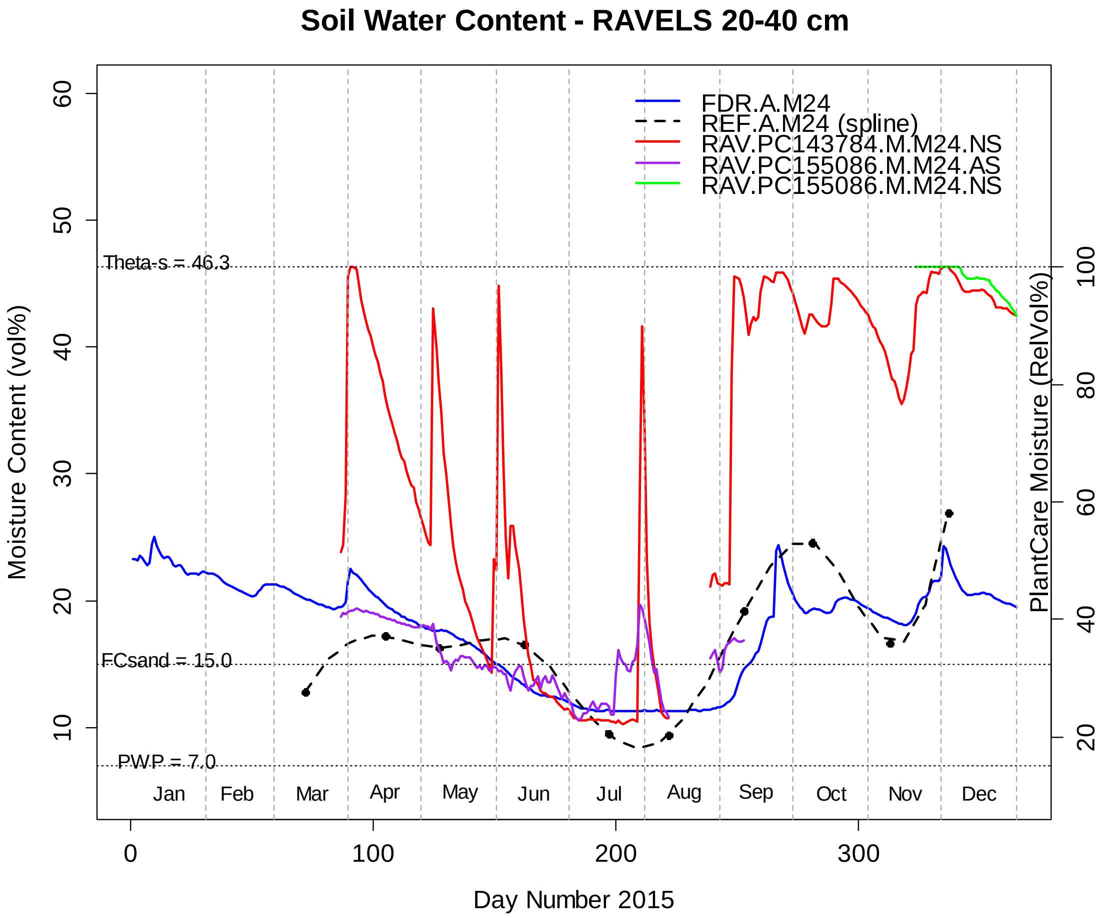


Figure 3.39. Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for Natural soil (NS) and artificial soil (AS). Soil water retention characteristics: Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

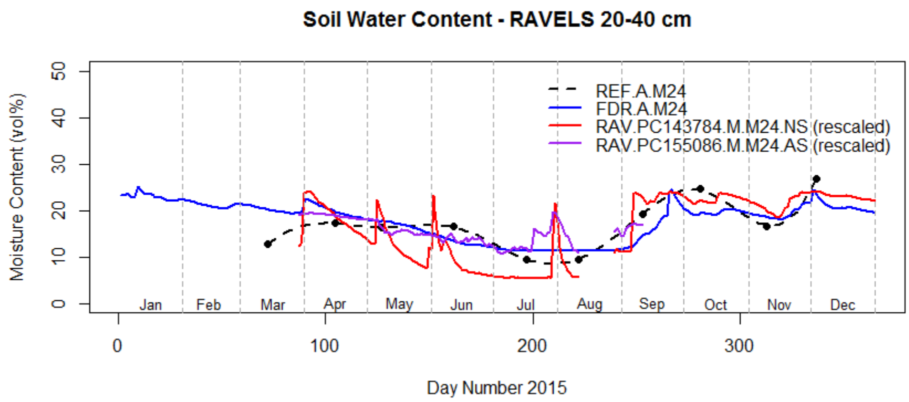


Figure 3.40. Evolution of soil water content during 2015 (same as Figure 3.39) but with rescaled PlantCare reading s according to zero-intercept linear model with Reference measurements as response. Scaling factor 0.24082 for PC143784 and 0.46552 for PC155086.

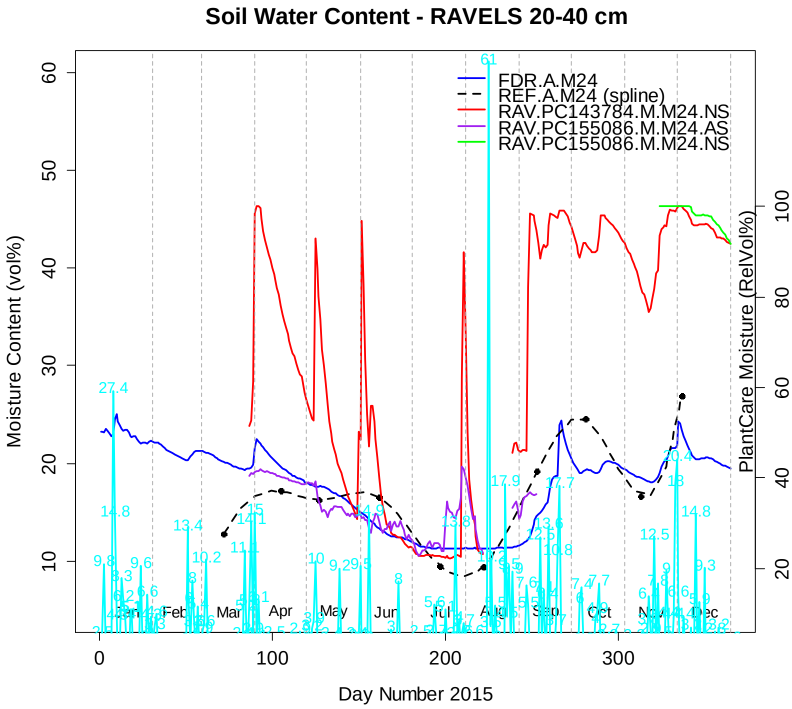


Figure 3.41. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings

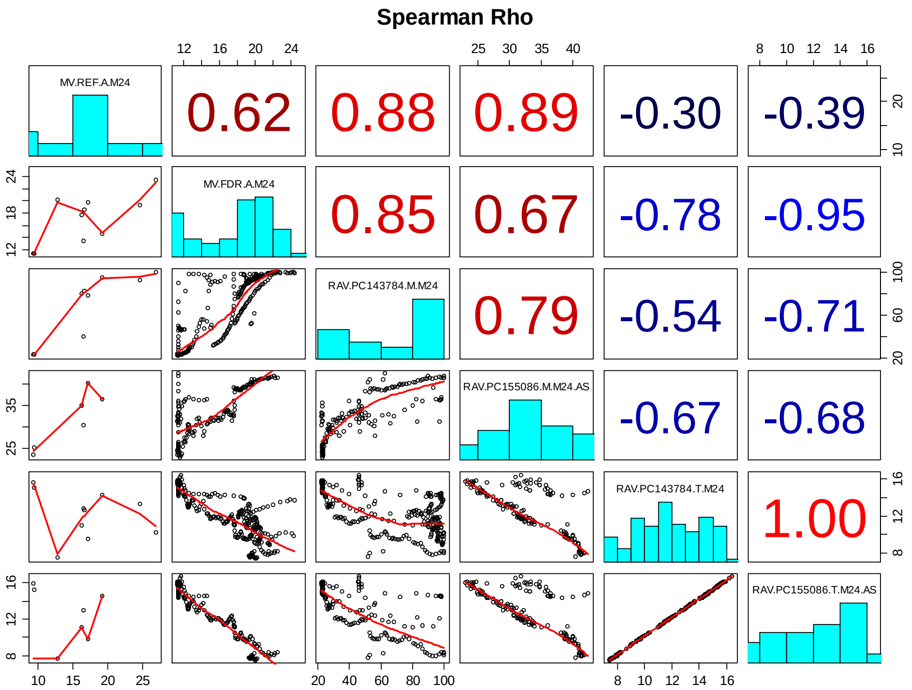


Figure 3.42. Matrix Spearman-correlation scatterplot for Reference moisture measurements (MV.REF.A.M24), FDR readings (MV.FDR.A.M24), and PlantCare moisture and temperature readings (PC143784 and PC155086). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

3.2.3. Brasschaat

In the 20-40 cm layer of the Brasschaat site, two PlantCare Mini-Loggers were installed as on the other sites, one sensor (PC143383) with a felt calibrated for natural soil (NS) and another (PC155083) with a felt calibrated for artificial substrate (AS). The felt of the latter was replaced at the end of the year and relocated (to location B) and measured 42 days during 2015.

Summary statistics of the data are given in Table 3.10. Note that the reinstalled PC155083 sensor with NS felt reported a continuous 100 RelVol% response at the end of the year, when the soil was wet (Figure 3.43). Upon desiccation in Spring 2016, this response is expected to decrease in parallel with FDR readings.

Table 3.10. Summary statistics of the moisture measurements in Gontrode Location A 20-40 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (Gravimetric)	Vol%	10	6.30	11.45	14.55	14.40	17.60	19.66
FDR measurement	Vol%	351	7.59	13.43	16.24	15.29	18.06	21.04
BRAS.PC143383.M.M24.NS	RelVol%	279	29.12	65.48	93.29	78.80	95.29	98.00
BRAS.PC155083.M.M24.AS	RelVol%	167	30.58	35.12	36.08	37.25	38.17	63.54
BRAS.PC155083.M.M24.NS	RelVol%	42	100	100	100	100	100	100

The 20-40 cm layer was near field capacity till end of March 2015 with absolute water contents around 20 Vol%. This is only half of the saturated water content (*Θs*) as derived from the SWR-curves (Annex I), indicating that rainwater is easily drained from the sandy topsoil. From beginning of April to the end of June the moisture content decreases monotonically, showing a good correlation between FDR, field reference measurements and PC143383.NS readings. Conversely, the decrease in (relative) water content is almost not visible in the AS-sensor readings (see also Figure 3.44) in contrast to the rewetting trajectory where the increasing trend is noticeable.

From July onwards, the PC143383 response is very sensitive to rain events (Figure 3.45), inducing peaks from 40 RelVol% immediately to 100 RelVol%. Once several consecutive rain events occur, the PlantCare sensor remains constantly at a high level (here 95-100 RelVol%). It is strange that less intensive rain events (e.g. 7.5 - 9 mm/day) during a drying out trajectory do not cause clear peaks in the PlantCare response while intensive rain events (> 20 mm/day) seem to induce a strong response, at least in this sandy soil with high hydraulic conductivity.

Figure 3.46 depicts the Spearman correlation among the time-series of the 20-40 cm layer. There is a good correlation (rho=0.95) between FDR and reference moisture measurements. FDR response correlates with the baseline points of the PlantCare-NS-readings (see points on diagonal), but not with the peaks (more dense in the wet range). The moisture readings of both sensors are correlated but the range of AS-readings is narrow compared to the NS-readings, indicating differences in sensitivity. In contrast, the temperature readings are perfectly correlated. Negative correlation is observed between temperature and both FDR and PlantCare-NS readings, while no correlation is found between temperature and PlantCare-AS readings.

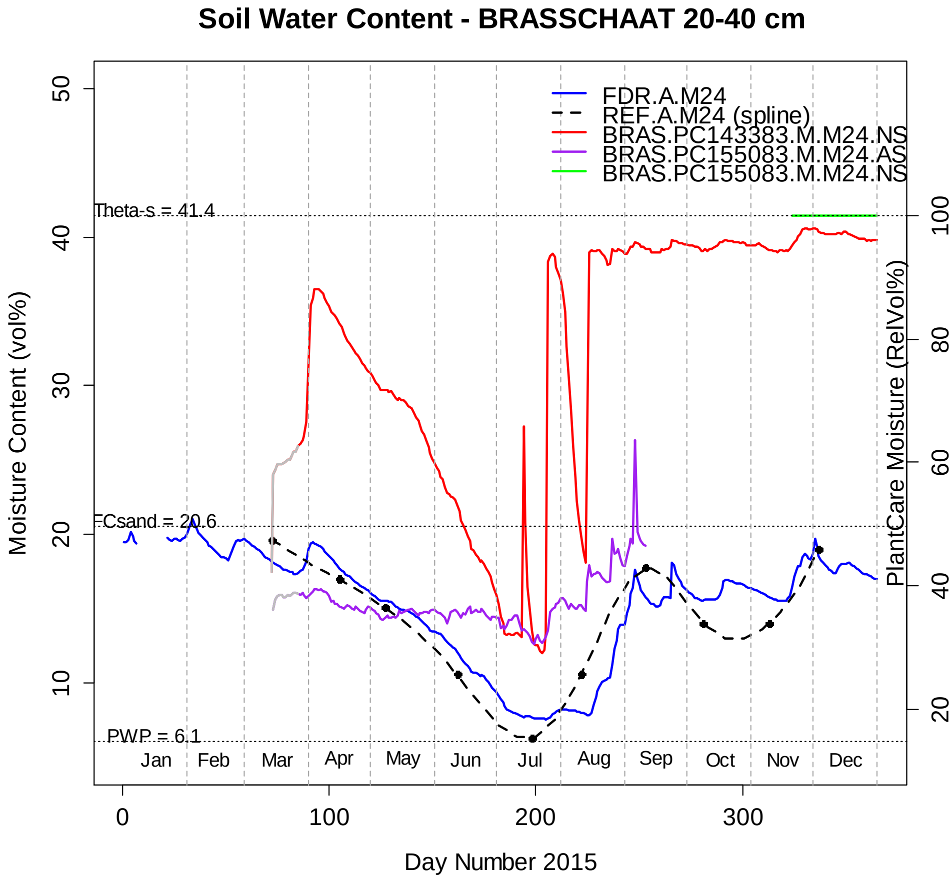


Figure 3.43. Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for Natural soil (NS) and artificial substrate (AS). Soil water retention characteristics Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

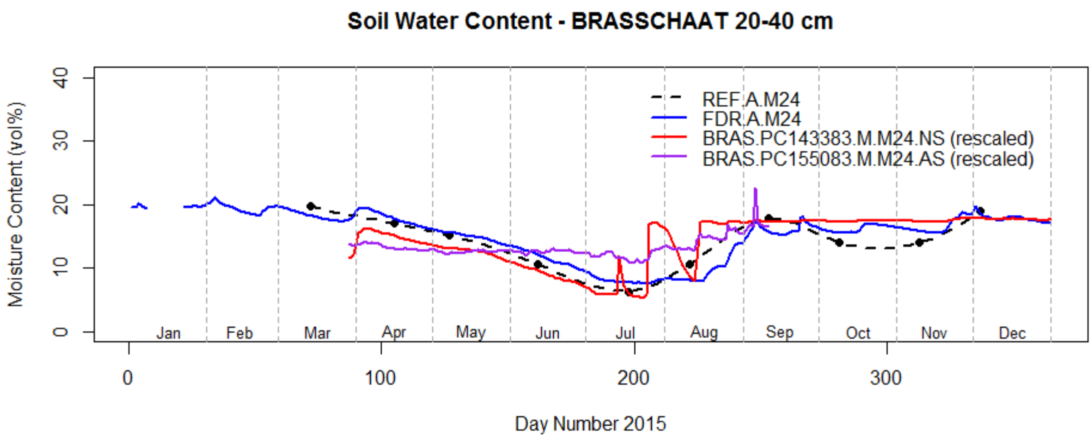


Figure 3.44. Evolution of soil water content during 2015 (same as Figure 3.35) but with rescaled PlantCare readings according to zero-intercept linear model with Reference measurements as response. Scaling factor 0.42084 for PC143731 and 0.75171 for PC155087.

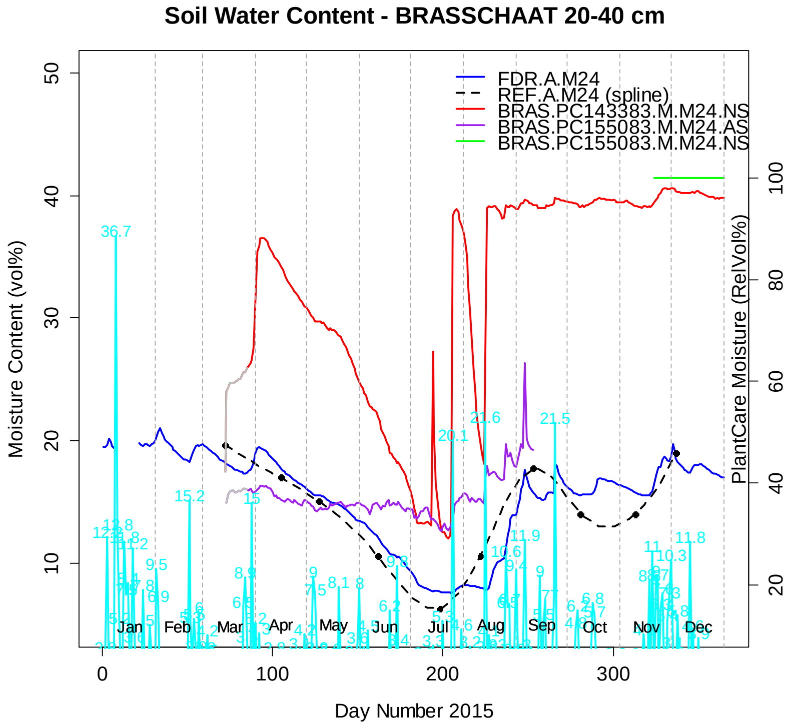


Figure 3.45. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings

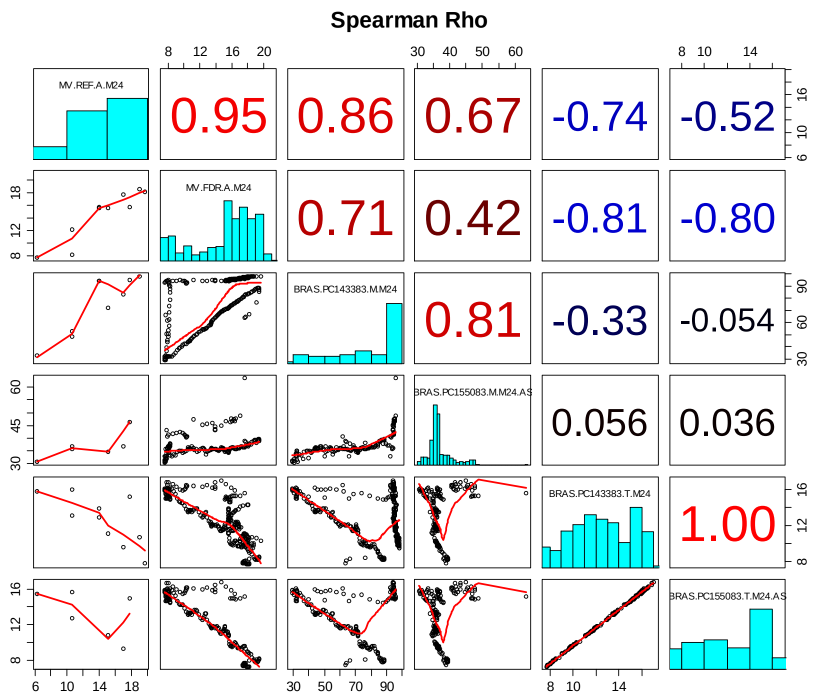


Figure 3.46. Matrix Spearman-correlation scatterplot for Reference moisture measurements (MV.REF.A.M24), FDR readings (MV.FDR.A.M24), and PlantCare moisture and temperature readings (PC143383and PC155083). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

3.2.4. Wijnendale

In the 20-40 cm layer also two PlantCare Mini-Loggers were installed in Wijnendale, sensor (PC143794) with a felt calibrated for natural soil (NS) and PC155085 with a felt calibrated for artificial substrate (AS). The latter felt was replaced and relocated the same way as for the other sites. Summary statistics of the data are given in Table 3.11. Reference moisture and FDR moisture content have similar statistics. With respect to the PlantCare readings, note that 100 RelVol% was never reached on this site, in contrast to most other sites. Only PC155085, when its AS-felt was replaced to an NS-felt, recorded a high response (Table 3.11 and Figure 3.47).

The Loamy sand soil high in organic matter of the Wijnendale site has about twice the field capacity (~40.8 Vol%) as observed for the other sandy soils (Brasschaat = 20.6 vol % and Ravels = 15.0 Vol%). Since this FC is close to Θs and 100% relative moisture content of the PC sensors is set equal to Θs, response curves of reference moisture, FDR and NS-readings are showing parallel patterns. On this site relative soil moisture is about twice that of absolute soil moisture (Figure 3.47).

From March to August a monotonical decrease is observed in the soil water content of the 20-40 cm layer, from ~40 Vol% (Field Capacity) to ~20 Vol%, which remains above wilting point (~12 Vol%). Nice in parallel, the PC143794 sensor with NS felt decreases from 80 RelVol% to about 20 RelVol%, whereas the sensor with AS-felt, remains at about 40 RelVol% during the drying out trajectory. Mid of August a peak is observed for each PlantCare sensor, which is clearly linked with a rainfall event of 12.2 mm (Figure 3.50). In one day, an enormous rainfall event of 46.5 mm increased relative soil water content with 20 RelVol%, and the absolute soil water content as observed by the FDR sensors with 10 Vol% which is consistent with the proportional scale.

Table 3.11. Summary statistics of the moisture measurements in Wijnendale Location A 20-40 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (Gravimetric)	Vol%	10	18.20	24.82	27.95	29.11	32.80	40.14
FDR measurement	Vol%	365	19.06	24.72	28.09	30.22	36.99	42.12
WIJN.PC143794.M.M24.NS	RelVol%	277	21.67	39.50	48.29	51.42	60.25	81.04
WIJN.PC155085.M.M24.AS	RelVol%	66	27.71	40.08	40.67	39.90	41.11	46.79
WIJN.PC155085.M.M24.NS	RelVol%	43	92.88	96.08	96.71	96.63	97.00	98.83

It is important to note that these rain events are observed by both sensors. Consistently, if the soil is in its dry range, rainfall events are more clearly observed than when the soil is moist or wet. For instance, beginning of July, a rainfall event of 10.3 mm is visible in the PC143794.NS readings, but not in the PC155085.AS readings whereas beginning of May, PC155085.AS recorded a peak (11.7 mm according to Figure 3.50) but only slightly visible in the PC143794.NS and FDR readings. All moisture measurements indicate that soil water reserve in the 20-40 cm layer is not replenished at the end of the year, as it was in February/March according to the FDR time series.

When the PlantCare data is rescaled to Vol% (about ½ = factor ~0.52 for NS readings) as in Figure 3.48, we can see that the PlantCare NS readings provide similar information as FDR and reference moisture measurements in contrast to the AS readings. Note that the range of NS readings is wider: higher relative moisture values in the wet range and lower relative moisture contents in the dry range compared to FDR and when rescaled also compared to reference measurements. This illustrates the high sensitivity of the PlantCare moisture measurements when the NS felt is used in contrast to the PC sensor with artificial-soil-felt.

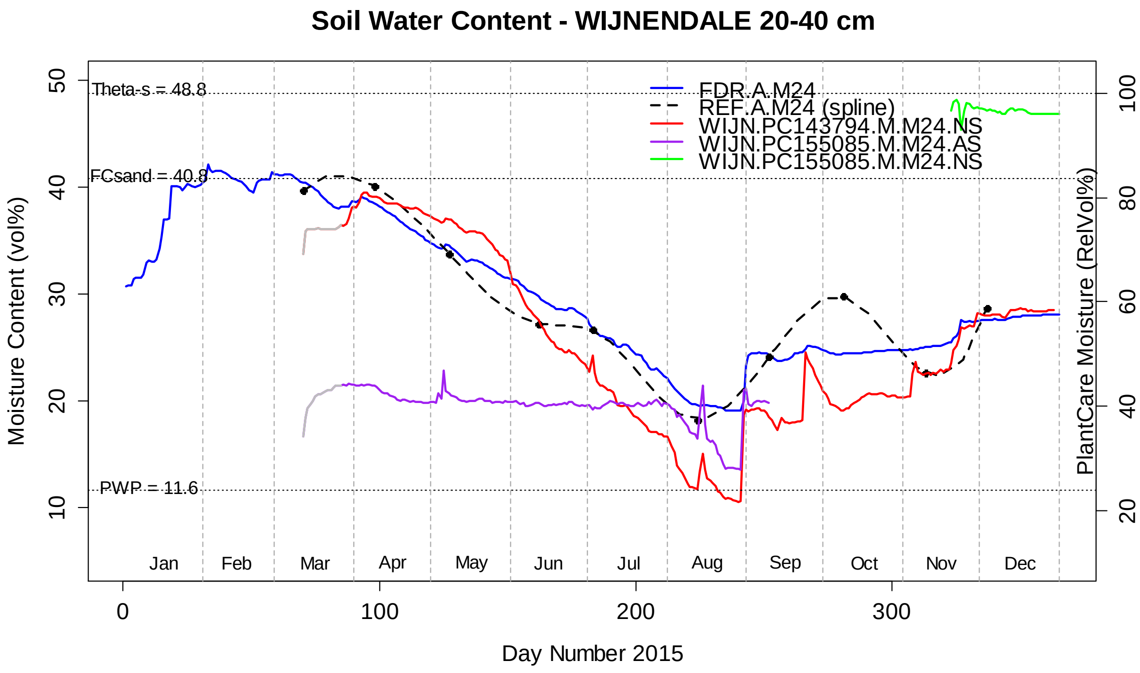


Figure 3.47. Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for natural soil (NS) and artificial soil (AS). Soil water retention characteristics Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

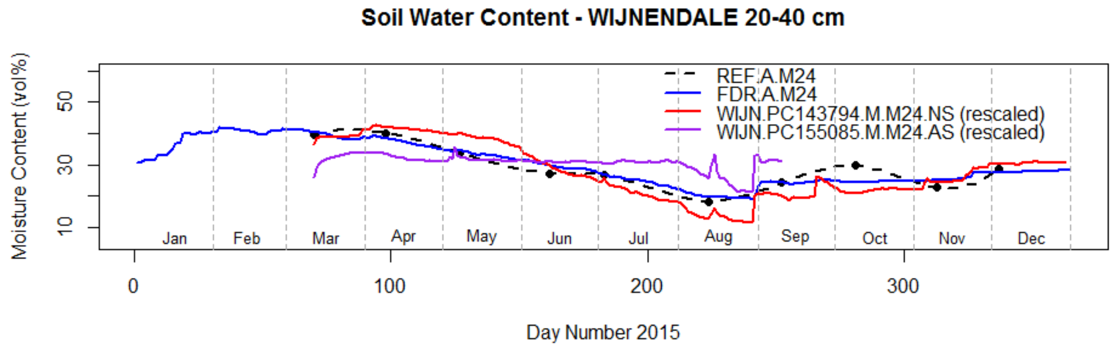


Figure 3.48. Evolution of soil water content during 2015 (same as Figure 3.35) but with rescaled PlantCare readings according to a zero-intercept linear model with Reference measurements as response. Scaling factor 0.52559 for PC143794 and 0.76293 for PC155085.

For this site and soil layer, correlations between all data-series are rather high (Figure 3.49). As already explained before, PlantCare NS readings are well correlated with FDR and reference moisture measurements. PlantCare AS readings show a limited range, they correlate well with PlantCare NS readings within the 20-40 RelVol% range, but not at all in the 40-80 RelVol% range (Figure 3.49). Likewise, PlantCare AS readings show a very weak correlation from 20-40 RelVol% but a strong negative correlation between 40-45 RelVol% (related to the peaks) in contrast to the NS readings. Correlation between temperature and FDR and NS readings is similar. Hence, for this layer soil moisture content could be roughly estimated just by using soil temperature as predictor.

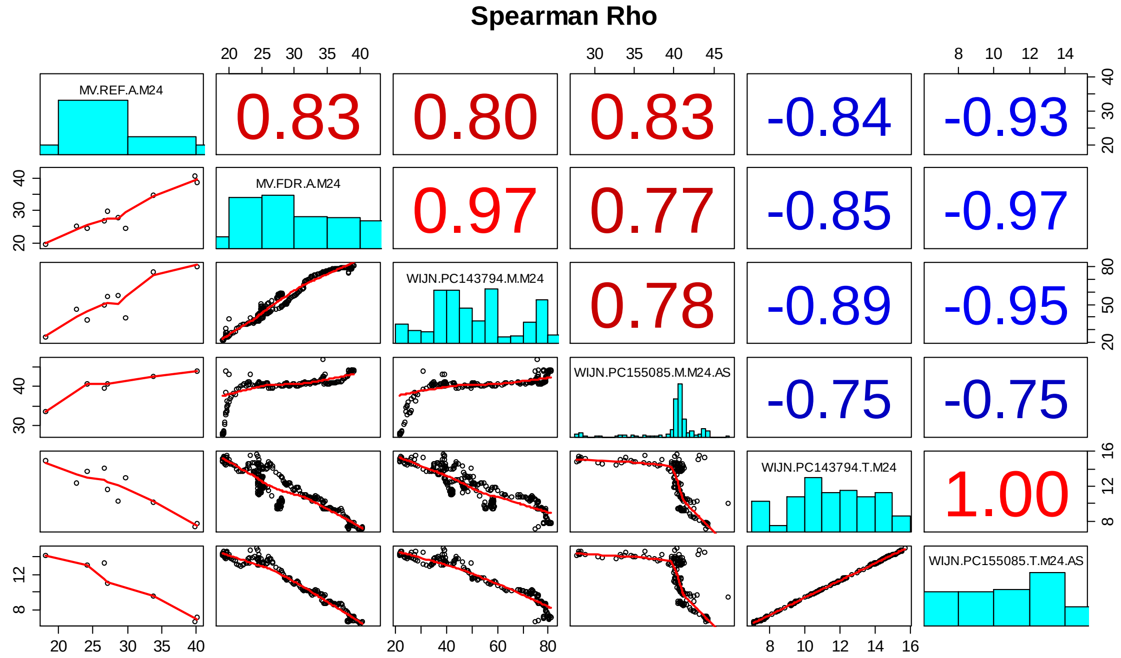


Figure 3.49. Matrix Spearman-correlation scatterplot for Reference moisture measurements (MV.REF.A.M24), FDR readings (MV.FDR.A.M24), and PlantCare moisture and temperature readings (PC143794 and PC155085). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

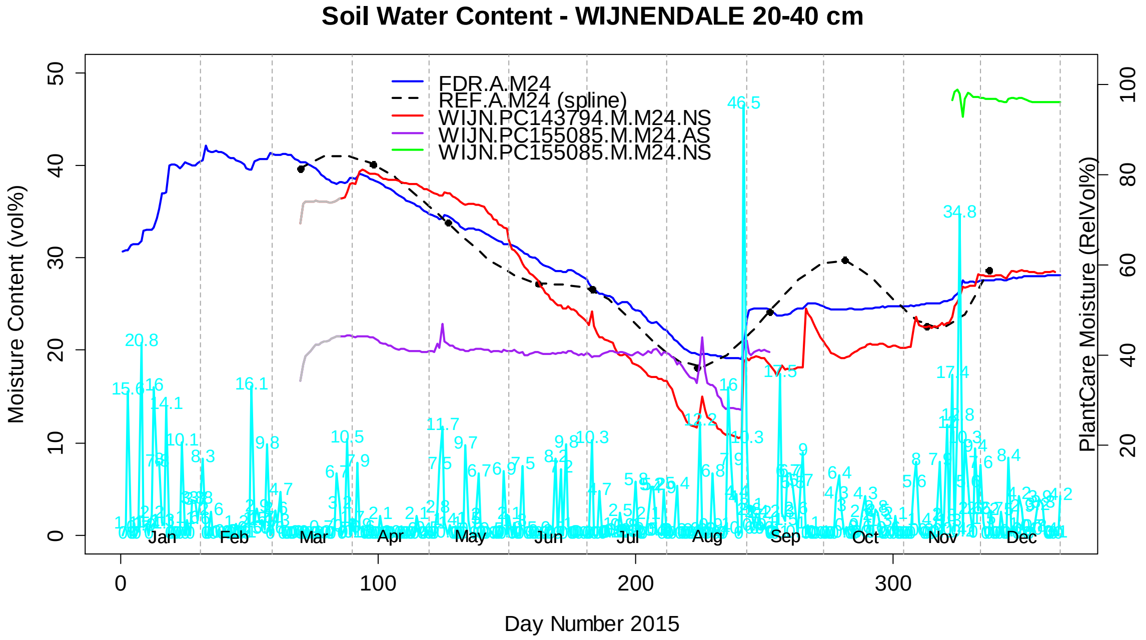


Figure 3.50. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings

The effect of rain events on FDR and PlantCare response (Figure 3.50) is already partially discussed before. Jumps in moisture content are often explained by rainfall peaks. However, some responses in PlantCare readings are disproportional to the rainfall intensity, for instance in September 2015, where no large peak is observed after the 17.5 mm rainfall event, but a large peak at the 9 mm rain event which concluded however a rainy period. This shows that (1) local precipitation amounts need to be checked and (2) more detailed analysis at a finer time scale (hourly data instead of daily aggregated data) is needed to see the response of rain events and soil moisture changes. If at the same time, sap-flux measurements of trees could be combined and analysed together with rain events and soil moisture fluctuations, this would be very interesting. In the end, this would provide information to what extent trees can benefit from rain events, how they induce soil moisture changes and consequently on the importance of recording these short-time changes in the soil using devices that are sensitive enough.

3.2.5. Zoniën

In the 20-40 cm layer of the Zoniën site, two PlantCare sensors were installed, one sensor (PC144783) with a felt calibrated for natural soil (NS) and another (PC155091) with a felt calibrated for artificial substrate (AS). The felt of the latter was replaced at the end of the year and relocated (location B) on the site and measured 41 days during 2015.

Summary statistics of the data are given in Table 3.12. Note that this is the only site where a maximum of 100 RelVol% is reached by a PlantCare sensor with AS-felt, though this was only during a one shot event, beginning of May (Figure 3.51). Most other readings are between 32 and 60 RelVol%, while between 30 and 100 RelVol% with NS-felt.

Table 3.12. Summary statistics of the moisture measurements in Gontrode Location A 20-40 cm soil layer.

	Unit	N	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Reference moisture (Gravimetric)	Vol%	11	23.40	28.50	33.10	32.28	36.17	41.43
FDR measurement	Vol%	365	24.50	27.82	33.91	32.59	37.39	38.92
ZON.PC144783.M.M24.NS	RelVol%	279	29.42	38.04	40.67	61.10	96.69	100
ZON.PC155091.M.M24.AS	RelVol%	155	32.42	37.25	39.67	41.93	43.50	100
ZON.PC155091.M.M24.NS	RelVol%	41	56.08	99.17	100	90.13	100	100

The reference water content and FDR readings indicate a decline from begin of April to mid of August. Then a small rise mid of August linked to rainfall events (see further) and a steep rise second half of November (Figure 3.51). See how the FDR and PC144783.NS readings show a similar pattern over the observation period though the PlantCare response is “amplified” compared to the FDR response. The NS peaks are mostly visible in the response of PC155091.AS as well, but the dry period in July/August of the AS apttern is not so clearly reflected as in the NS readings. Furthermore response range (apart from the 100 RelVol% peak) is narrow and holds less information than the NS readings.

On the other hand, NS-readings are for a rather long time at their maximum (100 RelVol%), i.e. in December and April 2015, but presumably also in January, February and March which would mean that in 5 out of 12 months the maximum response is recorded on these silt loam soils and no variation at all. In contrast, some moisture content fluctuation (variation) is recorded in the gravimetrical moisture analysis and FDR response during this period. However, the eco-hydrological significance of this variation in a saturated soil may be questioned. More important for the vegetation is the water availability during the growing season. Permanent wilting point (~15 Vol%) is never reached when based on gravimetrical measurements or FDR readings (minimum 23-24 Vol%). In the driest period still about 30 RelVol% of water is measured according to PlantCare observations.

Figure 3.52 plots the rescaled PlantCare readings together with the absolute moisture contents as measured by FDR and reference method. Again sensitivity of the PlantCare signal is shown showing higher response in the wet range and lower response in the dry range. A nice parallel pattern between PlantCare NS and FDR signal is visible between July en December, whereas a deviating pattern is observed in March, May and June.

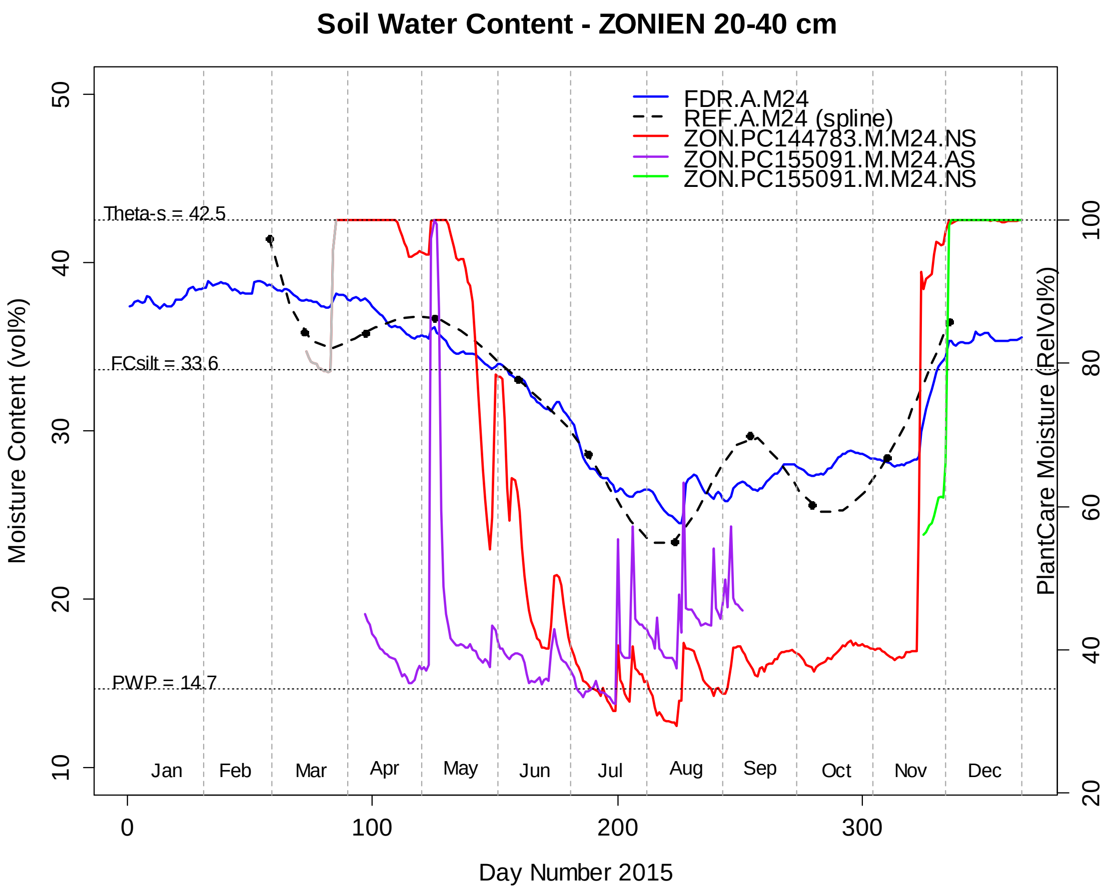


Figure 3.51. Evolution of soil water content during 2015 according to FDR measurements, monthly sampling and gravimetrical moisture determination (reference), and PlantCare readings (right Y axis) using felts calibrated for natural soil (NS) and artificial soil (AS). Soil water retention characteristics Permanent Wilting Point (PWP), Field capacity (FCsilt) and saturated water content (Theta-s; ϴs) for the given soil layer are indicated as well.

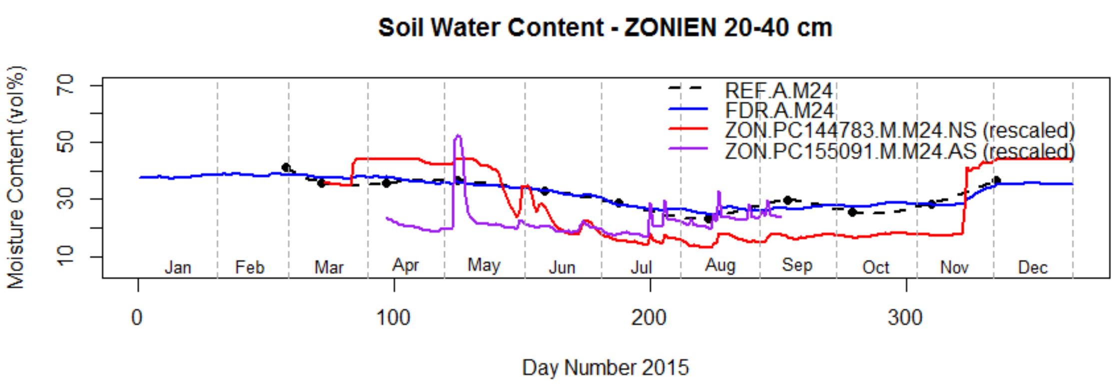


Figure 3.52. Evolution of soil water content during 2015 (same as Figure 3.35) but with rescaled PlantCare readings according to zero-intercept linear model with Reference measurements as response. Scaling factor 0.42084 for PC143731 and 0.75171 for PC155087.

Figure 3.53 confirms that FDR and PlantCare NS readings correlate well, in contrast to FDR and PlantCare.AS (rho=-0.15). Negative correlations are also found between FDR and PlantCare NS readings and temperature (as expected) but not between PlantCare AS readings and temperature indicating erroneous responses.

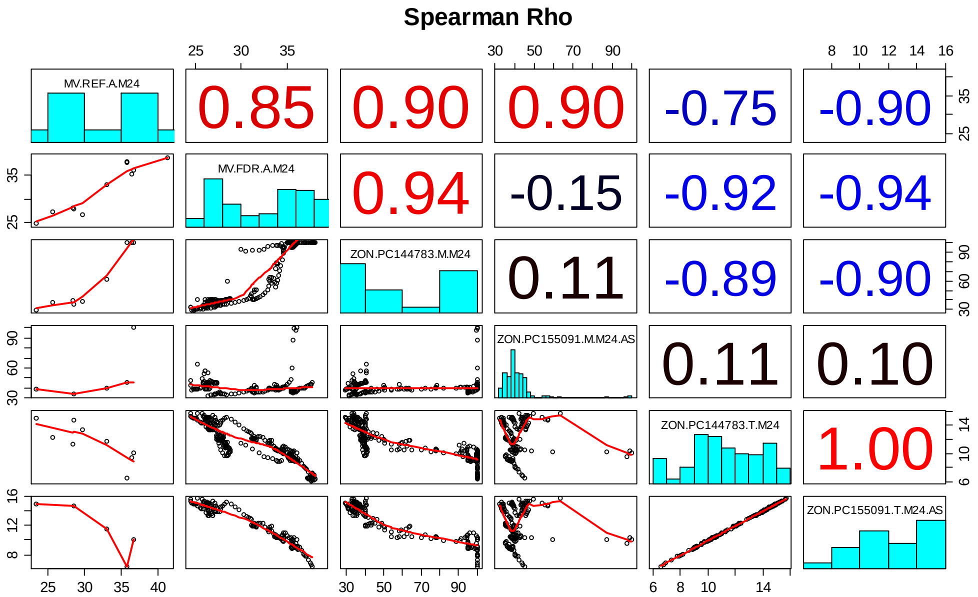


Figure 3.53. Matrix Spearman-correlation scatterplot for Reference moisture measurements (MV.REF.A.M24), FDR readings (MV.FDR.A.M24), and PlantCare moisture and temperature readings (PC143731 and PC155087). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

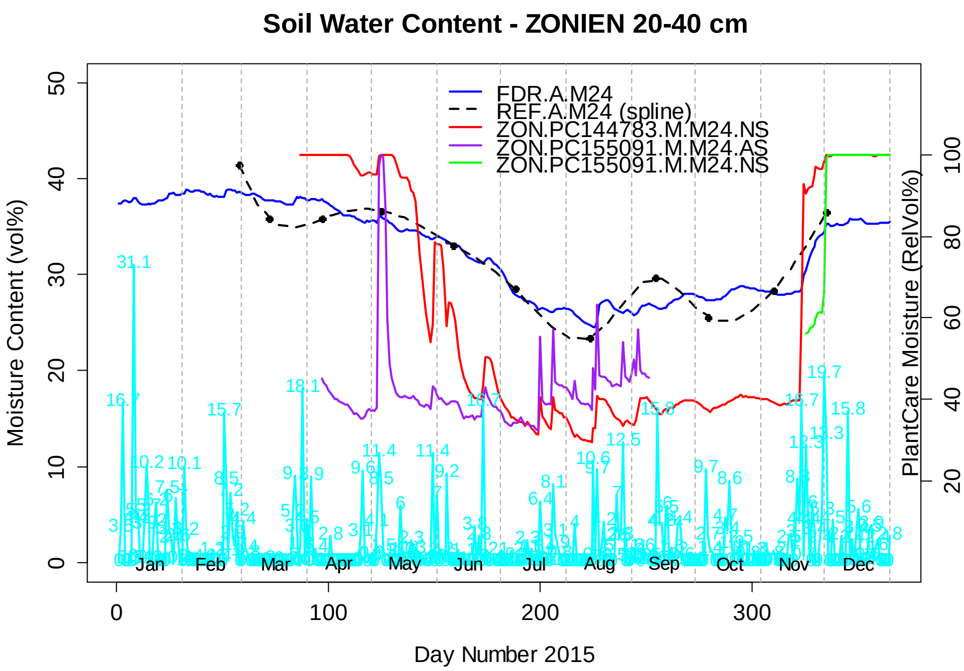


Figure 3.54. Rain events with daily precipitation sum (mm/day) added to the plot of soil moisture recordings

Finally 3.54 links local rain events with PlantCare response. Most PlantCare peaks are clearly related to rain events and hence PlantCare data provides rainfall information. Consecutive rain events like those starting in mid-November lead to a strong increase in relative moisture content, replenishing soil water reserves to the winter level. A similar response is seen with the relocated PC155091 sensor when its felt was replaced from AS to NS. When the PlantCare response is at 100% in wintertime, obviously no information is provided anymore on rainfall events, nor variation in soil water contents near saturation.

3.3 PlantCare Experimental lab-tests

3.3.1. Run 1

In this run, a rain event of 20 mm was simulated on a dry soil (1.20 ± 0.29 Vol% moisture content) by bringing 1.12 L of tap-water on an experimental area of 0.056 m². Given the volume of the tested soil, this would theoretically increase the soil moisture content from 1.2 to ~10 Vol% assuming soil moisture has time to get evenly distributed across the entire soil volume. Figure 3.55 shows that upon wetting moisture content as measured by HH2 Delta-T sensor is 34.62 ± 1.31 Vol%, while both PC sensors indicate a relative moisture content around 43 RelVol%.

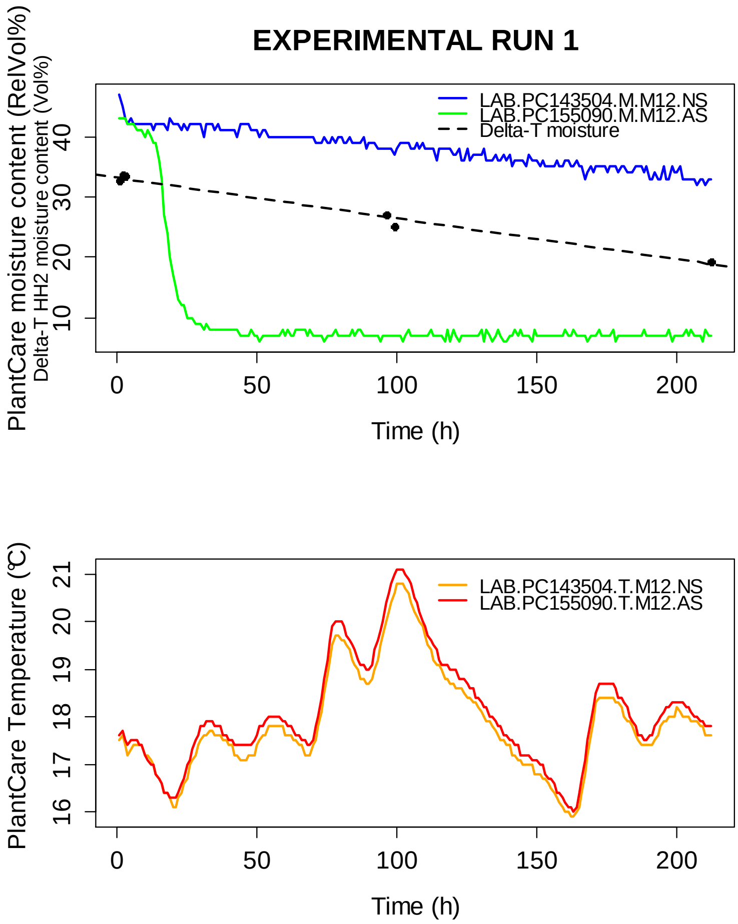


Figure 3.55. Relative soil moisture (upper panel) and soil temperature (lower panel) readings from two PlantCare sensors with different felts in the same container with a wetted soil drying out by auto-evaporation.

While PC143504 sensor readings decline readily with time, following correctly the trend of the reference Delta-T soil moisture measurements, the PC155090 sensor with green felt, calibrated for artificial soil, suddenly drops to a low relative moisture level of 6-8 RelVol%, which is clearly an unexpected response. It is possibly caused by the fact that the suction of the soil is larger than from the AS-felt. However, when looking at the temperature response of both sensors (Fig 3.55 and 3.56), correlation is very well and PC155090 does not deviate from PC143504 as for moisture. This demonstrates that moisture and temperature measurements are independent from each-other and not affected by type of felt.

The test soil dries out at an average rate of 1.63 Vol% per day whereas PC143504's relative soil moisture decreases at a rate of 1.16 RelVol% per day.

Spearman correlations of PlantCare readings are given in Figure 3.56. Temperature is perfectly correlated while relative moisture only at the start of the experiment.

Relative moisture and temperature are slightly negatively correlated, adding water initially cooled down the soil with 1.5°C but with the drying process temperature raised again. Note that the soil temperature was also influenced by the variable ambient room temperature.

The conclusion of the first test run is that for the same silt-loam soil volume, temperature response is identical but relative soil moisture is strongly deviating depending on the type of felt. The PC sensor with a green felt calibrated for artificial soil was not adequately measuring relative soil moisture compared to the reference soil moisture desiccation trend. Both the relative soil moisture and temperature outputs showed low noise and provided a stable signal.

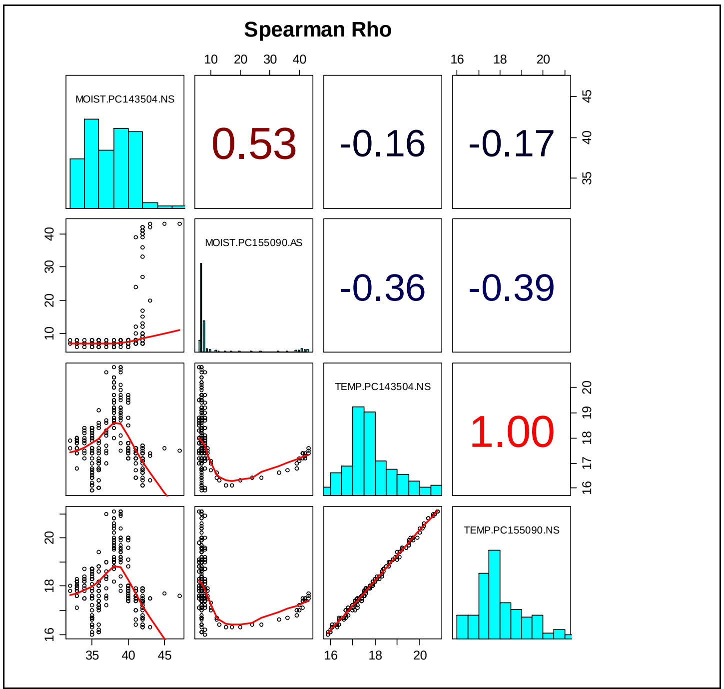


Figure 3.56. Matrix Spearman-correlation scatterplot for laboratory RUN1 of PlantCare moisture and temperature readings with felts calibrated for Natural soil (NS) and artificial soil (AS). Distribution is indicated on diagonal, Spearman rho-coefficients in the upper part and scatterplot with lowess regression in the lower part.

3.3.2. Run 2

In a second experiment (RUN2), 2240 ml of water was added to the test soil after completion of RUN1, which equals 40 mm of simulated rainfall. Prior to RUN2, the sensors were not excavated nor recalibrated.

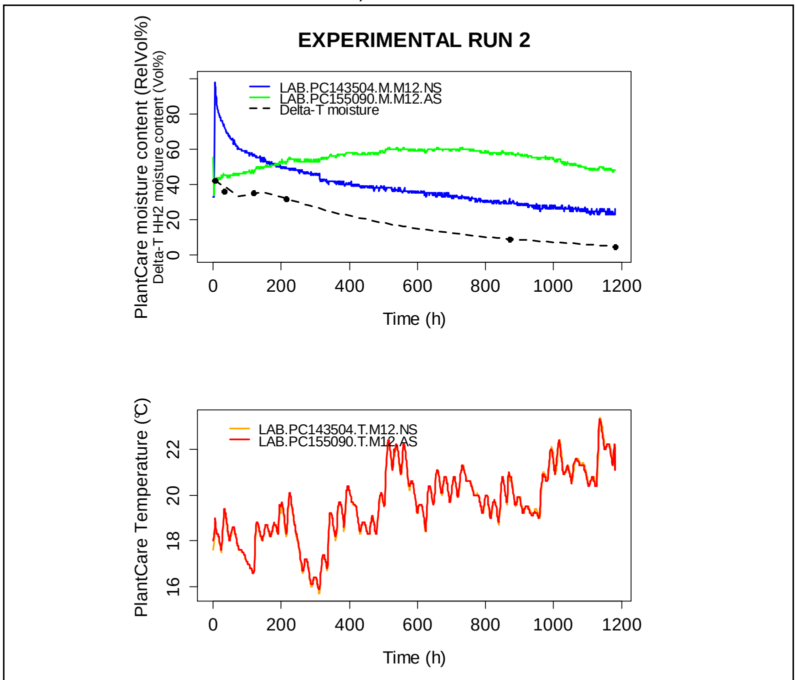


Figure 3.57. Relative soil moisture (upper panel) and soil temperature (lower panel) readings from two PlantCare sensors with different felts in the same container with a wetted soil drying out by auto-evaporation.

As shown in Figure 3.57, the sensor PC143504 with NS felt showed a logical response and a trend parallel to the soil water content measured with the HH2 device. The peak response of this sensor was within 3 hours of the simulated rain event (water added on 11:15h and peak response recorded at 14:05h) which is probably related to the time for movement of the moisture front till the depth of the sensor's felt.
The first 50 hours the excess water is redistributed over the soil volume and the moisture content decreases rapidly and then evaporation takes over.

Unexpectedly, sensor PC155090 with artificial soil felt reacts the opposite. Relative soil moisture increases untill 600 h (negative correlation between sensors) and then decreases slowly till the end of the experiment (positive correlation between sensors). Overall Spearman correlation is negative (Figure 3.58).
In contrast, soil temperature is perfectly correlated. For the NS calibrated sensor,

soil moisture and temperature are negatively correlated when relative moisture is between 20-60 RelVol% but uncorrelated between 60-100 RelVol%. Conversely, soil moisture and temperature for the PC sensor calibrated for artificial substrate is positively correlated over the whole relative moisture range.

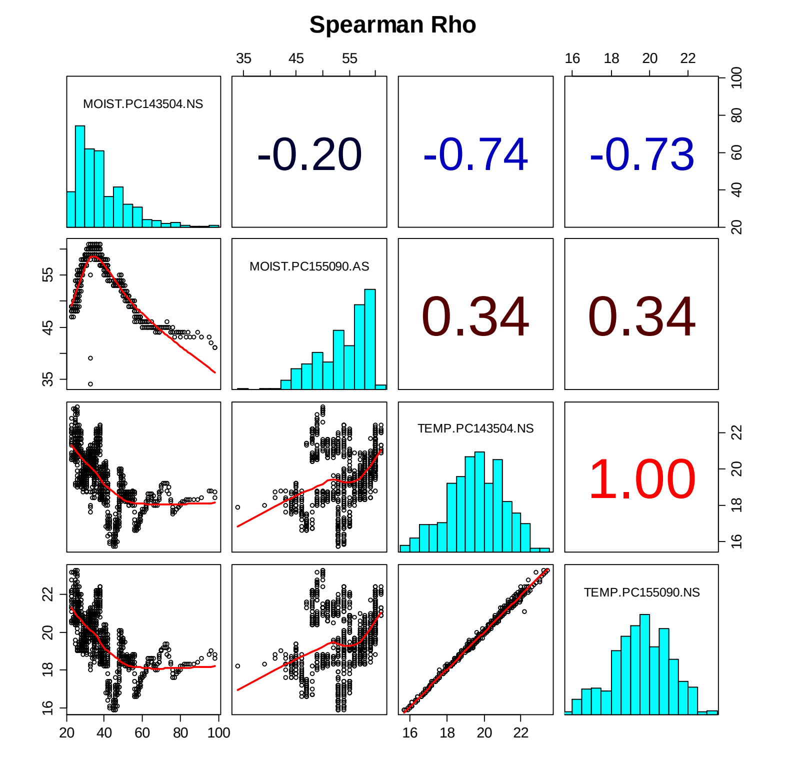


Figure 3.58. Matrix Spearman-correlation scatterplot for laboratory RUN2 of PlantCare moisture and temperature readings with felts calibrated for Natural soil (NS) and artificial soil (AS).

3.3.3. Run 3

For experimental RUN3, again a rain event of 2240 ml of water was created on time 0h directly onto the dry soil (5.0 ± 1.04 Vol%) as it was left after RUN2. Here, an immediate response was recorded for PC155090 with AS felt reaching shortly 100 RelVol% but 4 hours later the readings dropped to 56 RelVol%. Presumably water has percolated fast through a soil crack along the stick towards the tip of this sensor inducing an immediate response.

The other sensor however, calibrated for natural soil, did not react immediately on the simulated rain event and did not show a peak at all (Figure 3.59). Hence, the rain event "peak" remained unseen by PC143504 this time though the readings increased very slowly the first 250 hours and then decreased during normal evaporation.
This indicates that when the soil is very dry and "connection" is lost between the felt of the sensor and the soil, unreliable relative moisture contents may be recorded. Presumably air entered the felt and it took about 500 h till the sensor was measuring again the expected relative moisture contents in the same way as observed in RUN2.

The recordings of the PC155090 stopped because batteries were exhausted after 1562h (65 days) of operation and about 10 downloads of data (which is intensive). Since this sensor equipped with a green felt calibrated for artificial soil did not adequately recorded relative soil moisture, further lab experiments with this combination stopped.

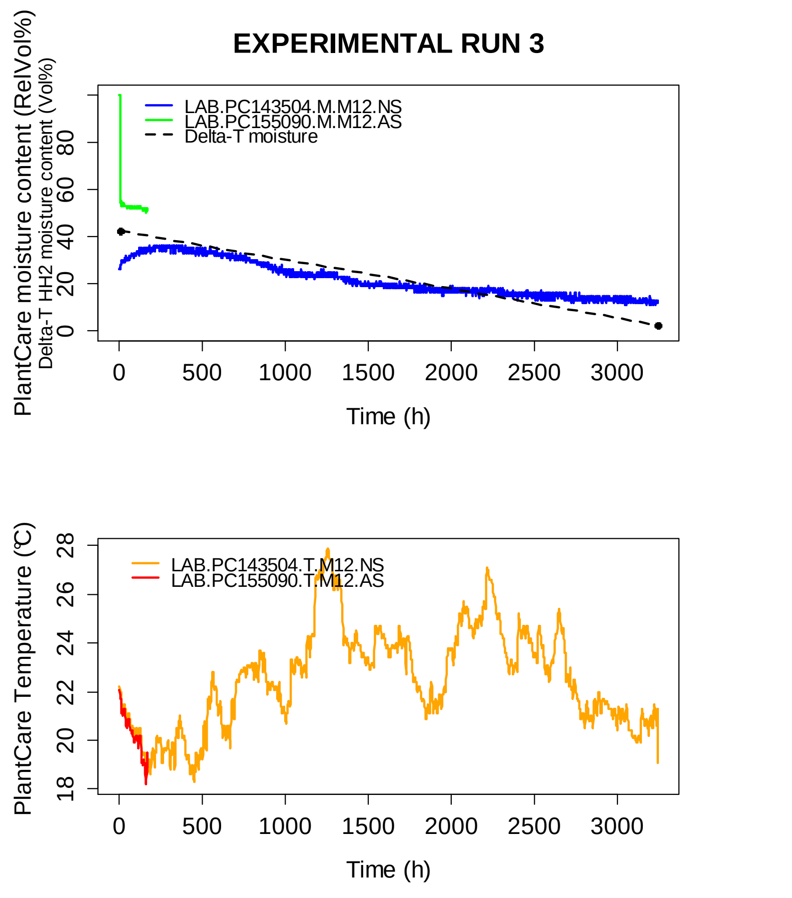


Figure 3.59. Relative soil moisture (upper panel) and soil temperature (lower panel) readings from two PlantCare sensors with different felts in the same container with a wetted soil drying out by auto-evaporation.

3.3.4. Run 4 & 5

These last tests were using the PC143504 sensor calibrated for natural soil only. In RUN4, 20 Vol% of water (i.e. 40mm, 2240 ml) was gently poured into the container holding the extremely dry silt-loam soil (2.65 ± 0.80 Vol%). After this RUN4, when soil was dry again (8.58 ± 1.11 Vol%), RUN5 was started with half the amount of simulated rain (i.e. 20mm, 1120 ml water added). Both responses are plotted in Figure 3.60. Note that the reference moisture measurements show an average difference of less than 10 Vol%. Initially when the topsoil is saturated, the moisture content is similar, then with redistribution of moisture the difference increases and then gradually decreases over time.

The relative soil moisture reponse however differs largely, which is strange because it concerns the same sensor. RUN4 is as expected. The 40 mm of water induced a peak of 96 RelVol%. However RUN5 does respond negatively to the added 20 mm and then remains at its baseline of about 20 RelVol% which is also attained by RUN4 after approximately 1000h. However when this baseline is attained, the soil moisture as measured by the Delta-T HH3 still tends to decrease. Apparently this sensor with natural soil felt was unable to record relative moisture contents lower than 19 RelVol% or about 10 Vol% (Figure 3.61) .

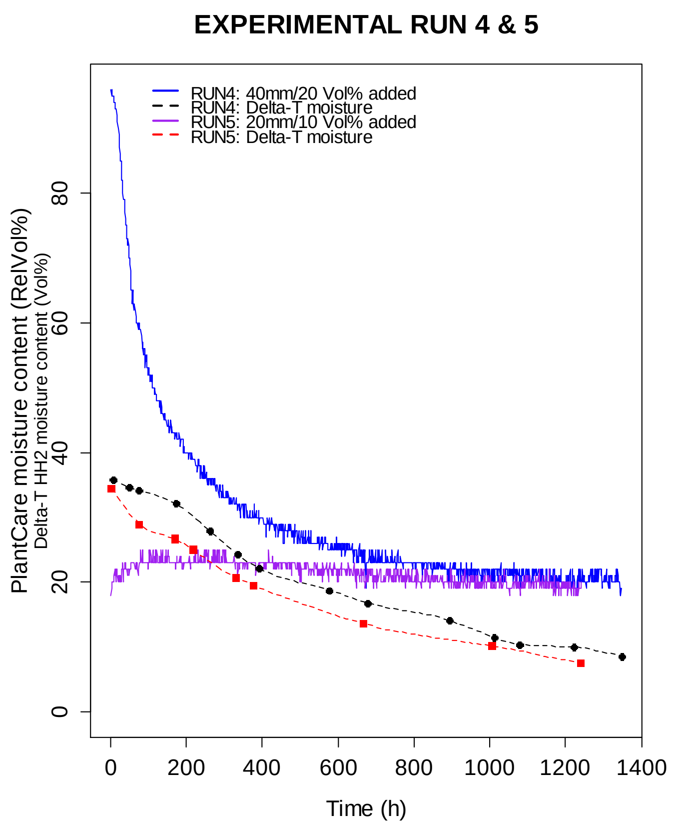
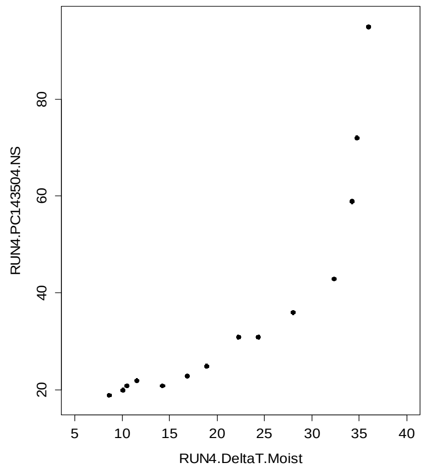


Figure 3.60. Relative soil moisture (upper panel) and soil temperature (lower panel) readings from two PlantCare sensors with different felts in the same container with a wetted soil drying out by auto-evaporation.



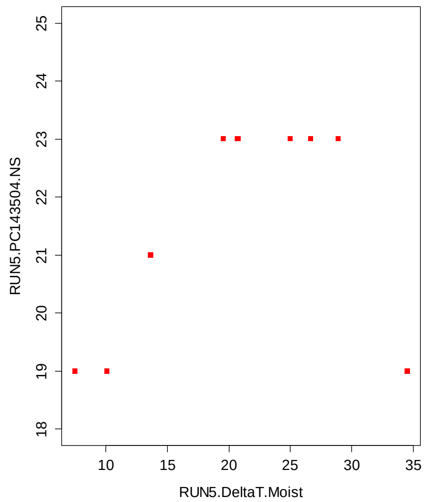


Figure 3.61. Relationship between PC143504 relative soil moisture and Delta-T HH2 moisture measurements for RUN4 (upper panel) and RUN5 (lower panel).

3.3.5. Conclusions of the laboratory runs

Folowing conclusions can be drawn from the experimental runs with the two PlantCare sensor-felt combinations:

- type of felt does not affect temperature measurements which were always well correlated showing similar patterns;
- the PlantCare sensor with green felt, calibrated for artificial soil is not performing adequately for the mineral silt-loam test soil and not in line with the Delta-T soil moisture measurements, nor with expected trend of (relative) soil moisture decrease due to evaporation;
- in general, the PlantCare sensor with white felt, calibrated for natural soil, is correlated with the reference Delta-T measurements and follows the expected trend of soil moisture decrease, however:
  - o sometimes it might happen that “connection” with the soil is lost and then the sensor does not respond to sudden soil moisture changes (e.g. simulated rain events) as was observed in RUNs 3 and 5. However, the same sensor can be reactivated when stayed in the soil (evidenced by RUN4 following RUN3); seems independent from how dry the soil gets (start of RUN4 was more dry than RUN5) which makes this behaviour rather unpredictable.

  - Relative soil moisture for the test-soil showed a baseline of 19 RelVol% when measured with the NS felt corresponding with ~10 Vol% as measured with the delta-T moisture meter; however the Delta-meter could measure lower (absolute) moisture levels unable to detect by the PlantCare sensor.
- Upon water saturation of the soil (e.g. by 40 mm rain event), a peak of near 100% may be recorded by the PC sensor with NS felt within 3 h, showing immediate response en high sensitivity especially in the absolute moisture range between 30-40 Vol%;
- When the PlantCare sensor is following a drying out trajectory, no abnormal or unexpected peaks were recorded, showing a quite stable signal; hence the peaks observed in the field should be linked with effective rain events and are most likely not attributed to possible fluctuations of the sensor;
- When recording on an hourly basis, and logging frequently (>10 times) the whole dataset, batteries may be low after approximately 1562h (~65 days). Recharging the batteries without replacing them would be convenient.

3.4 Practical experiences with PlantCare Sensors

3.4.1. General

Over all, PlantCare sensors were easily set, calibrated and installed. We measured according to hourly intervals which provides a good temporal resolution for most of our studies. Data was downloaded each month during normal field sampling events (sampling of soil solution) and took less than 5 minutes per sensor. The process of read-out is not difficult to learn and can be easily performed by most people. They should however check if the device is operating well based on the LED signals. If battery level is low (expected each 3 months), than batteries should be replaced immediately. The replacement of the batteries is quite easy and does not interrupt the data series, but technicians should always have a set of full batteries with them.

As shown later, the memory storage capacity is adequate and memory should be wiped out only after one year of hourly measurements. The connector pins are tiny and care should be taken than no soil material gets into the connector, but all connections worked properly at least during the 9 months of operation.

More specific experiences are provided regarding calibration, installation, maintenance, logging, autonomy and data processing in the next sections.

3.4.2. Calibration

Calibration of the Mini-Loggers was conducted together with Leon van Hamersveld from Eijkelkamp. Calibration end points were air dry (with felt in dry paper) and water saturated (wet end). Calibration took about 2 hours.

In contrast to installation and settings, the calibration procedure is not well described in the PlantCare Minilogger documentation (Operating Instructions). We recommend to add a small section to these instructions.

3.4.3. Installation

Installation may be critical in heavy-textured soils. We inserted a Mini-Logger in a silt loam garden soil to test its performance and autonomy to record temperature and soil moisture from 26.11.2015 to 24.04.2016 . The felt was water saturated (i.e. 100 RelVol%) upon installation. The outcome of hourly measurements are presented in Fig 3.62.

In contrast to soil temperature, which was recorded well, soil moisture remained at 100 RelVol% over this 5 month period. Hence no information on variation of (relative) soil moisture was provided, though the soil was not continuously water logged. It shows that checking the performance of the Mini-logger some days after installation is really necessary.

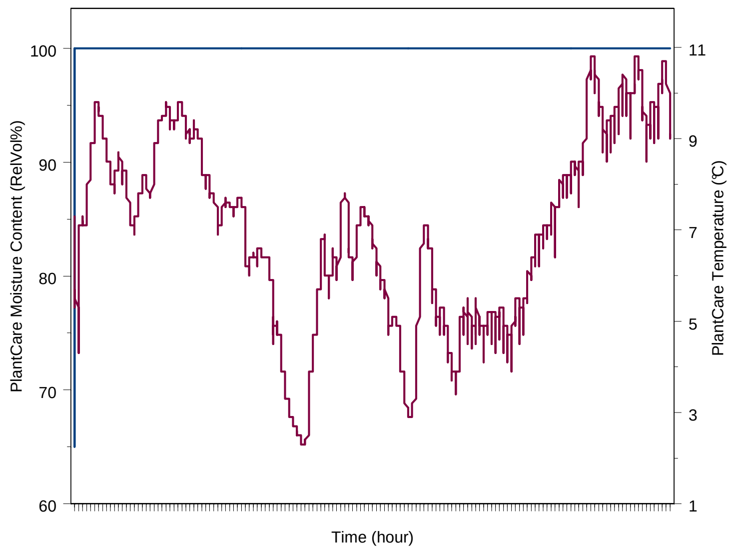


Figure 3.62. Relative soil water content (blue) and Temperature (red) of continuous garden soil test from 26.11.2015 to 24.04.2016.

Furthermore we believe it is better to install the PlantCare Mini-logger with a felt not completely saturated with water. If upon installation the felt is at about 60-80 RelVol% the moisture content will more easily equilibrate with the actual soil water content which can then be monitored the days after installation. This way we might avoid a situation where the PlantCare remains at 100 RelVol% as in the garden soil test. Checking the soil water content response regularly after installation is a prerequisite for reliable measurement of soil moisture. It is obvious that this is quite difficult when the soil is more wet than its field capacity when the readings are near 100% . Hence, installation is best during Spring when the soil contents vary according to a drying out trajectory, i.e. between April and June (for Western Europe).

3.4.4. Maintenance, logging and autonomy

During logging, all PlantCare sensors were maintenance-free. Care should be taken so that no dirt or soil material gets into the small data connector or socket, but no operating problems were encountered over the last 9 months. Upon replacement of batteries, it was clear that the weatherproof IP67 housing was indeed water-tight. Note that for all sensors we let the plastic cap on the logger as extra protection.

Logging using USB sticks was also quite reliable. No data was lost. The only event that happened once was that the field technician unintentionally switched the device off after logging, which was only noticed after the next logging session. It would therefore be convenient to be able to visually control if the device is “on”, but we understand that power consumption will be higher with an extra LED indicator.

The most critical point is the power consumption of the PlantCare devices, especially when data is logged monthly. When applying two standard Duracell “pluspower” or “Turbo” 1.5 V Alkaline AA batteries, initial voltage would be theoretically around 3000 mV. PlantCare sensors report battery status in each log file and this information is plotted in Figure 3.63.

Note the different initial status of the batteries at installation (roughly between 2600 and 2900 mV) but also the voltage when batteries were replaced (by new ones) at day 250, remarkably also below 2800mV.

The rate of power consumption (i.e. slope from day 100 to ~day 225) was similar for all sensors, and similar after battery replacement (from day 250 onwards). In absolute terms, with monthly data read-outs and hourly measurements, battery voltage decreased at an average rate of -3.08 mV day^{-1} with a min-max range of -2.54 to -3.72 mV day^{-1}. Rates did not differ among sites (differences in soil type and hydrological regime) nor by type of felt.

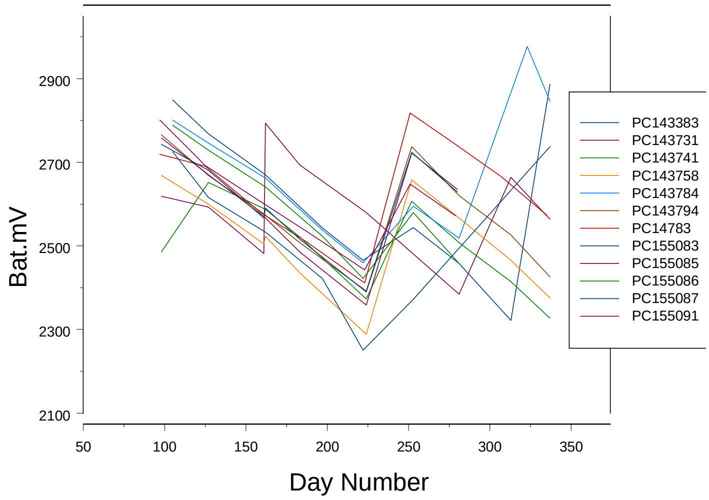


Figure 3.63. Evolution of battery voltage (mV) during operation of all PC sensors

A battery-empty alarm was generated when voltage dropped below 2400 mV (range 2251-2486 mV) which was empirically after 3.8 months (~2700 hours) of operation on our sites. When battery voltage dropped below 2300 mV, "USB power fail" error was generated and read-out could be hampered, though this was not encountered. Possibly some safety margin was applied here.

In any case, replacement of Alkaline batteries was required every 3 months to ensure continuous operation with monthly logging, which is a too short period. For remote areas, replacing batteries 4 times a year is not acceptable.

Eijkelkamp suggested to use Energizer batteries. Therefore, in future we will test with Energizer Lithium AA type ENEL 91 batteries and see how this might extend autonomy of the PlantCare sensors.

However, we recommend PlantCare Ltd. to check if Mini-Loggers could not be equipped with recharcheable batteries (Li-ion or NiMH). Ideally, recharging could then be performed using the same USB upload/download cable by means of an USB port on a laptop/field computer or using a high perfomance power bank.
Hence, recharging and data-logging could be conducted during the same sampling event keeping the Mini-Logger active and in optimal condition for a longer time. No opening of the cover (casing) is required in the field to replace the batteries so that the inner housing is kept free from moist or dirt and cannot be damaged. This would be a major hardware improvement for this device.

According to the documentation, PlantCare sensors could store in their memory up to 12000 records. Just as voltage, free memory percentage decreased linearly and at the same rate for all sensors (Fig 3.64), except for PC143784, which was switched off and then batteries were replaced. The rate of memory consumption was typically -0.264 % day^{-1} (with min-max range of -0.261to -2.266). Hence, with hourly measurement intervals 379 days of operation or slightly more than one year of data can be stored in the PlantCare memory.

So, memory storage capacity is adequate.

Hence, data storage is not critical with this device in contrast to its autonomy when powered by 2 AA Alkaline batteries.

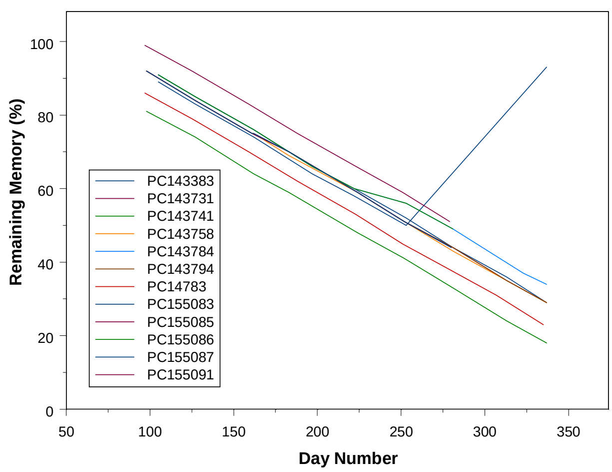


Figure 3.64. Evolution of memory consumption (free memory in %) during operation

3.4.5. Data processing

As explained in section 2.4.1, PlantCare's Mini-Logger data are stored in PVD files with a specific header and a data series with straithforward data attributes: a Date-Time stamp, moisture and temperature readings. This simple ASCII format allows easy checking of the Mini-Logger information in the field on all kinds of computer systems and facilitates data transfer.

No dedicated software is required to decode or read the data and the PlantCare users are not obliged to use the PlantCare DataViewer, even when this software is freely available. Experience learns that computer business knows fast developments in hard- en software so that application software and specific file formats get fastly outdated making data transfer and processing (especially of older (encrypted) datasets) a nightmare.

Therefore we strongly support and prefer the use of basic and simple file formats like PVD files for data elaboration.

4 Preliminary Conclusions

4.1 Temperature measurements

Based on the monitoring data of 2015, the following conclusions can be drawn:

- Except for one sensor in Wijnendale, all installed PlantCare Mini-Logger sensors measured slightly higher temperatures than the Campbell T107 reference temperature, with a maximum average bias of 1.08 °C. Hence, if an accuracy of less than 1°C is not required, PlantCare and Campbell sensors are considered equivalent for soil temperature measurements;

- There is no consistent difference in Temperature measurement between PlantCare sensors with different tips (Natural Soil vs. Artificial Substrate felts). Systematic differences in output from PlantCare sensors are presumably more related to individual characteristics of the sensor and its calibration than to the type of felt;

- The difference between PlantCare sensors and reference temperature T107 (delta Temp.) varies during the year and decreases in most instances from July till the end of the year. We found a relationship of delta Temp. with the moisture content of the soil. In wet soils delta Temp. is usually small compared to dry conditions;

- Overall differences (combination of bias and noise) among temperature sensors are small, and relative accuracy for all observations is less than 0.69 °C. In most cases, the bias (trueness error) between nearby located sensors is larger than the noise (precision error). Hence, we proclaim that temperature changes are more reliably recorded than the absolute temperature levels;

- When a sensor is moved and reinstalled 10 m further away on the same site, the index of agreement with the reference T107 measurements always decreases and, depending of the site, bias or noise determine the deviances. It shows that in forest soils different temperature patterns probably due to small scale variation of soil properties can be reliably detected using PlantCare Mini-Loggers.

4.2 Moisture measurements

The preliminary conclusions we can draw with respect to monitoring of soil moisture are:

- PlantCare Mini-Logger relative moisture readings do follow the seasonal pattern of soil moisture content over the year which is, depending of the soil type, more or less in concordance with the FDR and reference measurements;

- Mini-Loggers with natural soil felt (NS) clearly produce another signal than when equipped with an artificial soil felt (AS). The latter reacts much slower and is much less informative and reliable for the sites and soils under study. Therefore it was concluded to replace all AS felts with NS felts already in November;

- FDR response correlates well with the baseline points of the PlantCare-NS-readings, but not with the peaks which are clearly related to rain events, so PlantCare is much more responsive to the effects of rain and short time variations in moisture content than the FDR sensor. However it is yet unclear if plants (in our case trees) respond as fast to moisture changes as the Mini-Loggers do. If this would be the case, Mini-Loggers have a large potential for eco-hydrological studies;

- When comparing FDR sensors and Mini-Loggers, we should clearly bear in mind that Mini-Loggers provide point measurements while our FDR devices integrate moisture contents over 30 cm. Logically, Mini-Loggers could be more affected by preferential hydrological flows in the soil profile than FDR devices. Conversely, it is much easier to install Mini-Logger sticks without disturbing the natural soil conditions than FDR rods;

- Compared to reference gravimetrical moisture contents, FDR apparently does not adequately record the low moisture levels and might overestimate volumetric moisture content in the dry range whereas PlantCare with NS felt does not provide any more information when saturated (100 RelVol%) although reference moisture content is still varying;

- Especially in heavy textured soils (silt-loam to clay), Mini-Loggers with NS-felt remain for a long (winter) period at 100 RelVol%, providing no further information other than that the soils are water-saturated; for these soils more suitable felt types should be developed;

- When PlantCare relative moisture levels of 100% are set equal to saturated water content (Θs) derived from empirical soil water retention curves of the observed soil layer, some proportional relationships can be seen between relative soil moisture and absolute soil moisture percentage. However, little can be predicted based on PlantCare observations about the relative moisture content at permanent wilting point (or at high matric potentials);

- Lab experiments confirm the field observations that PlantCare Mini-Loggers with NS felts do not record lower relative moisture levels than 19 RelVol%, not even in completely air-dry soils. If plants (trees) are able to use water contents less than 19 RelVol% in our types of soil and under our climatic conditions, we need specific felts that could provide information at high matric potentials for studies on drought effects;

- The data suggests that the PlantCare moisture response (> 60 RelVol%) might vary with soil temperature;

- Both in the field and lab-experiment it was observed that some sudden changes in moisture content are missed by the PlantCare sensors, probably because of air entrapped in the felt when drying out. Once slightly moistened, apparently the response reactivates, but this process may affect data reliability. If this is due to local conditions (preferential flow paths in the soil profile) several PlantCare sensors need to be installed to ensure reliable data acquisition at plot level;

- It is observed that less intensive rain events (e.g. 7.5 - 9 mm/day) during a drying out trajectory do not cause clear peaks in the PlantCare response while intensive rain events (> 20 mm/day) seem to induce very strong responses, however this might be related to interception by the canopy and can only be verified when effective throughfall precipitation is related to the PlantCare readings;

- In general PlantCare data seems to provide additional information on soil moisture regimes than provided by FDR and gravimetrical measurements. It seems important to investigate how well the PlantCare data are correlated with effective plant available water and effective water use by the vegetation.

5 Further research and recommendations

We suggest to conduct following applied research using PlantCare Mini-Loggers:

- Continuation of PlantCare Mini-Logger measurements on the 5 Level II sites is envisaged to display and analyse temporal variation over a longer time span of at least 2 growing seasings. As such, specific patterns in the dry-out and wetting sequences can be further analysed and explained;

- In order to describe spatial variation a large set (e.g. >= 16 Mini-Loggers) should be installed for a specific depth within a site to check their intercorrelation and overall performance. It should be determined how many Mini-Loggers are required to adequately describe the relative soil water content of a forest site and how this is modulated by forest type and soil type. In addition one could investigate the effect on the response of distance to trees or presence of (specific) ground vegetation or shrubs;

- Variation with depth needs to be clarified by installing Mini-Loggers at similar depths as the FDR sensors. Do they follow similar patterns with depth and can they provide complementary information ?

- Topo-sequences of PlantCare sensors on slopes for instance could reveal interesting information on soil water availability of vegetational zones with varying hydrological requirements;

- Linking PlantCare sensors with groundwater table monitoring data (e.g. Divers) could reveal interesting correlations and support to mechanistic water balance models;

- One should try to link PlantCare readings with effective transpiration rates of plants in order to see how well relative soil water content is correlated with water (un)availability. Doing this for trees is a next challenge for INBO. Especially the development of felts best suited for specific soil/plant combinations (e.g. Luvisol/Beech forest) could be beneficial to adequately describe and monitor water cycling in specific forest ecosystems and derive stress indicators for both drought events as anoxic conditions during waterlogging.

- For convenient use of Mini-Loggers in remote areas we recommend PlantCare to develop Mini-Loggers with long-life rechargeable batteries, that can be recharged using conventional USB power banks and using the existing USB upload/download cable. Prior to the data logging with an USB memory stick, the Mini-Loggers could then be energized again to their full capacity ensuring reliable operation for at least 6 months when recording hourly measurements.

Acknowledgements

We would like to thank Bregt Diependaele from Eijkelkamp for informing us on PlantCare products and Leon van Hamersveld for discussing the setup of the experiment and a critical reading of the draft report.

We also thank Dr. Walter Schmidt for providing us PlantCare Mini-Loggers to test them and for his interest in our work. We are helpfully willing to test and discuss new improvements of Mini-Logger devices.

Annex 1: Soil water retention characteristics

Site Gontrode

Location A

M12

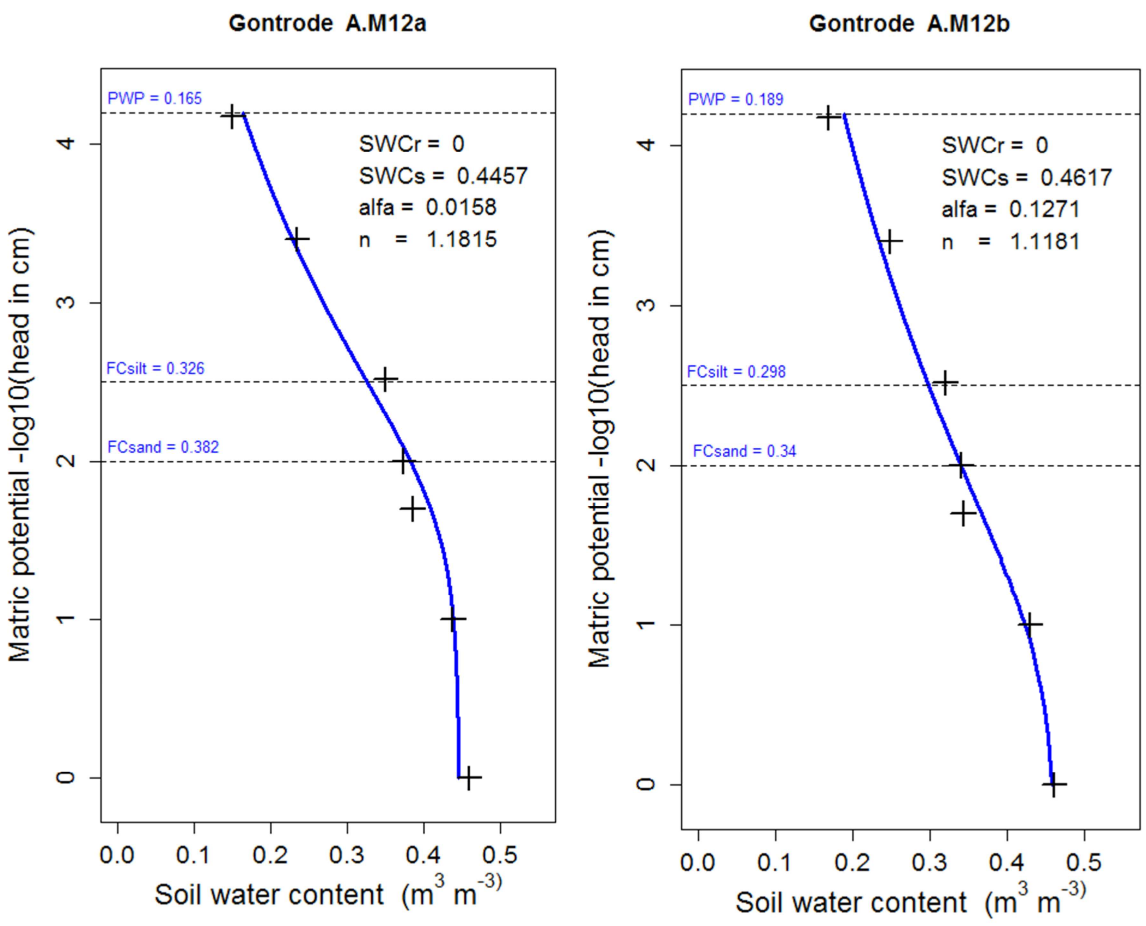


Figure A1. Soil Water Characteristic of the 10-20 cm layer in site Gontrode. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

M24

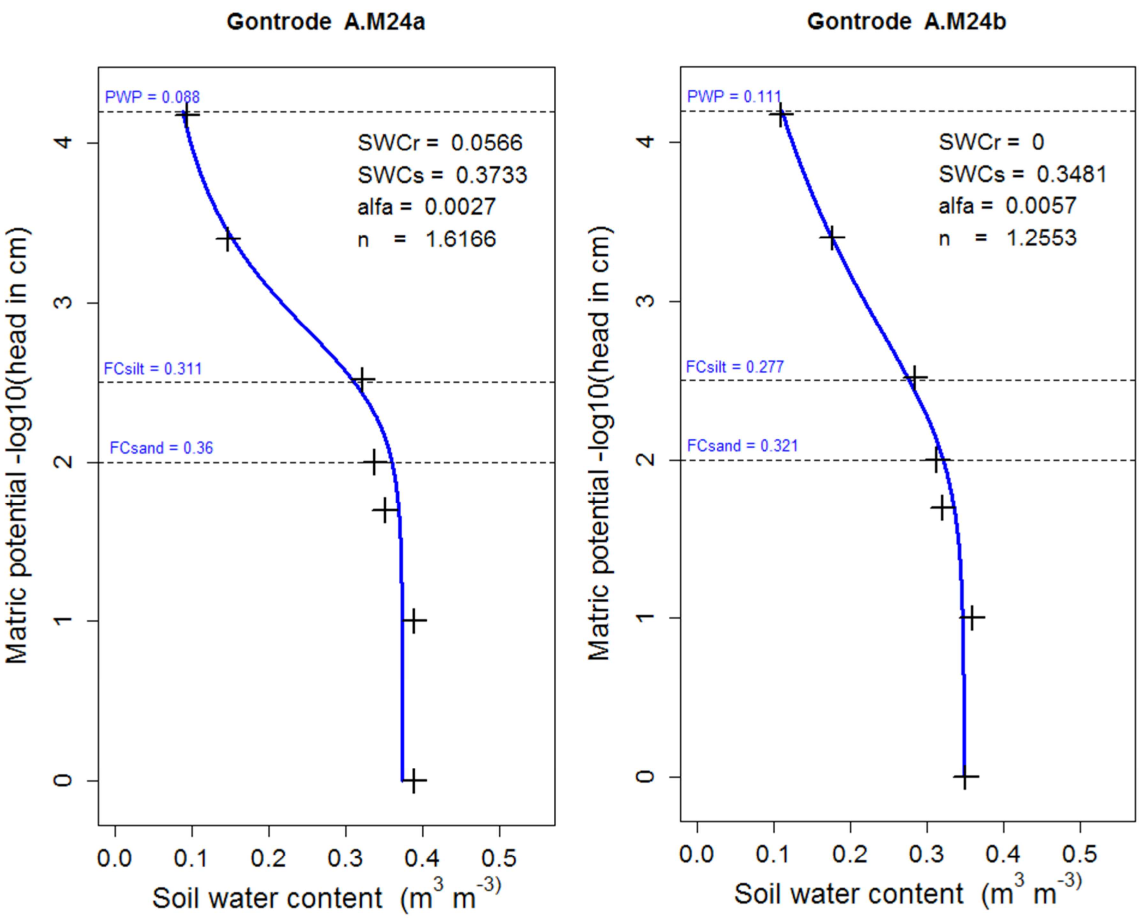


Figure A2. Soil Water Characteristic of the 20-40 cm layer in site Gontrode. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Location B

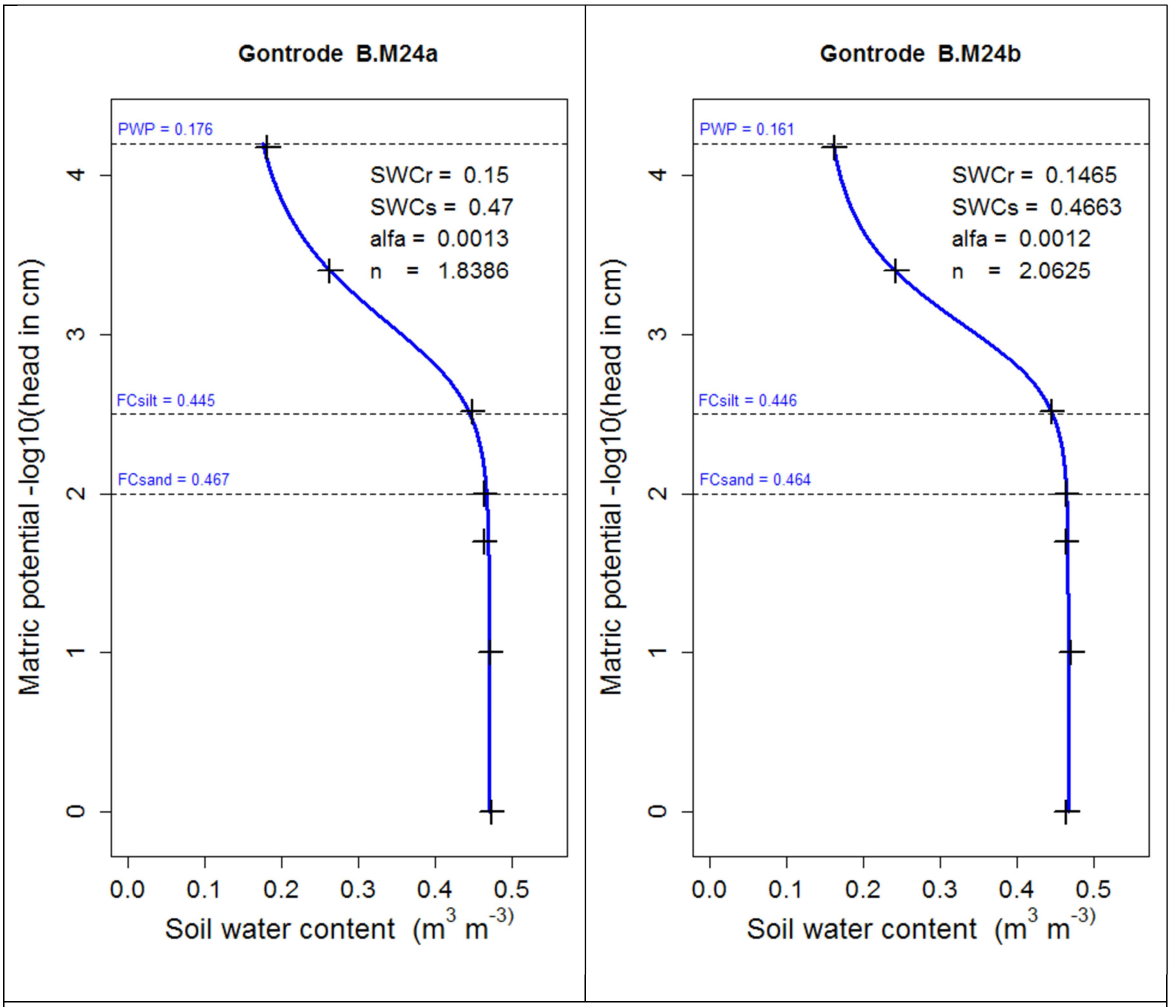


Figure A3. Soil Water Characteristic of the 20-40 cm layer in site Gontrode. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Site Ravels

Location A

M24

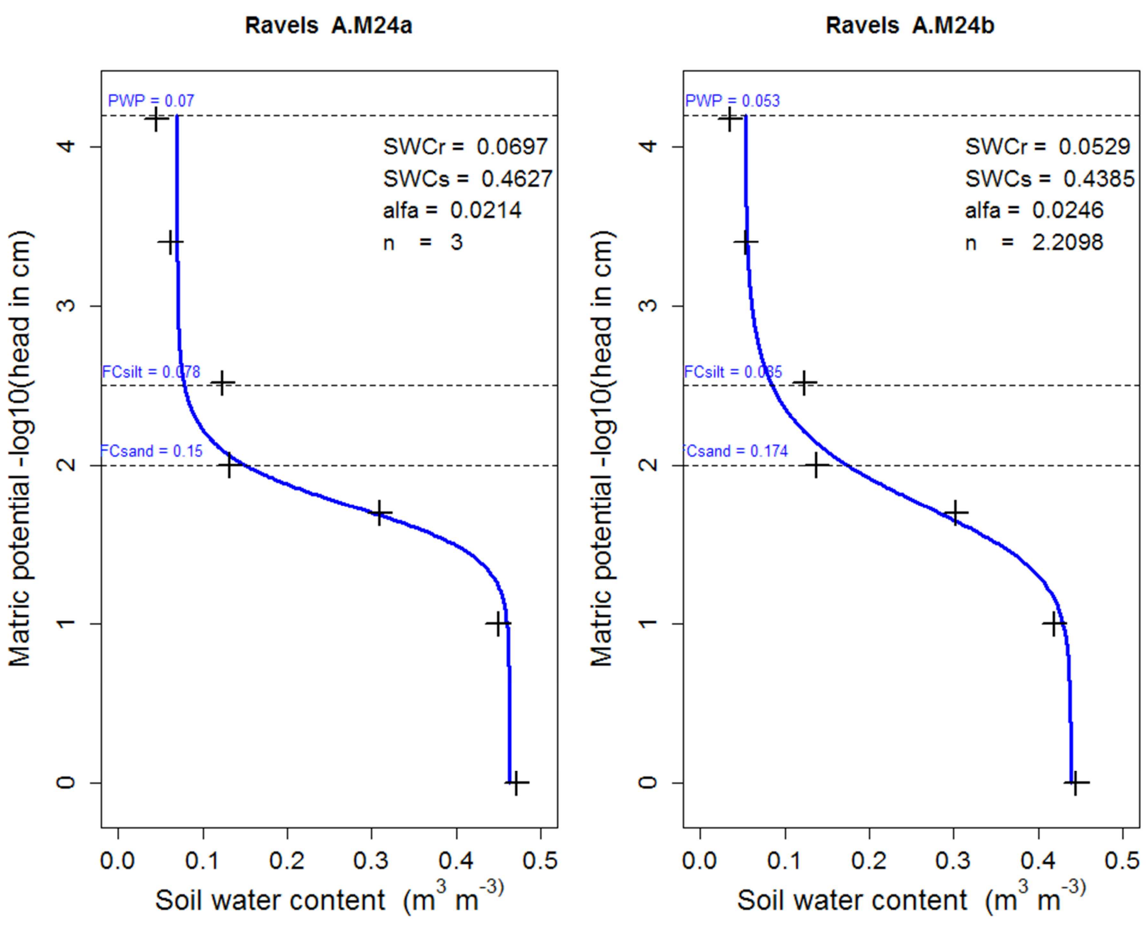
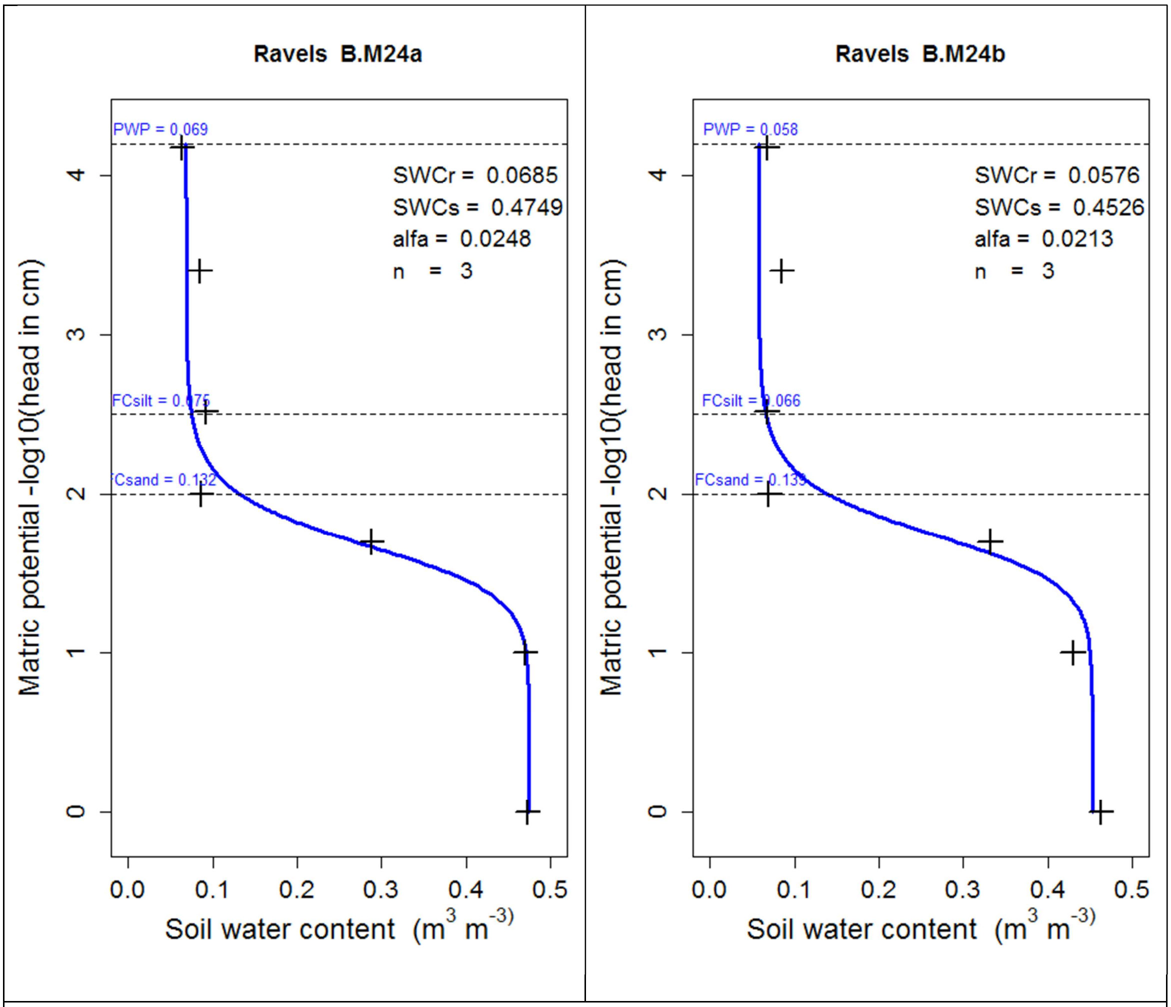


Figure A4. Soil Water Characteristic of the 20-40 cm layer in site Ravels. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Location B

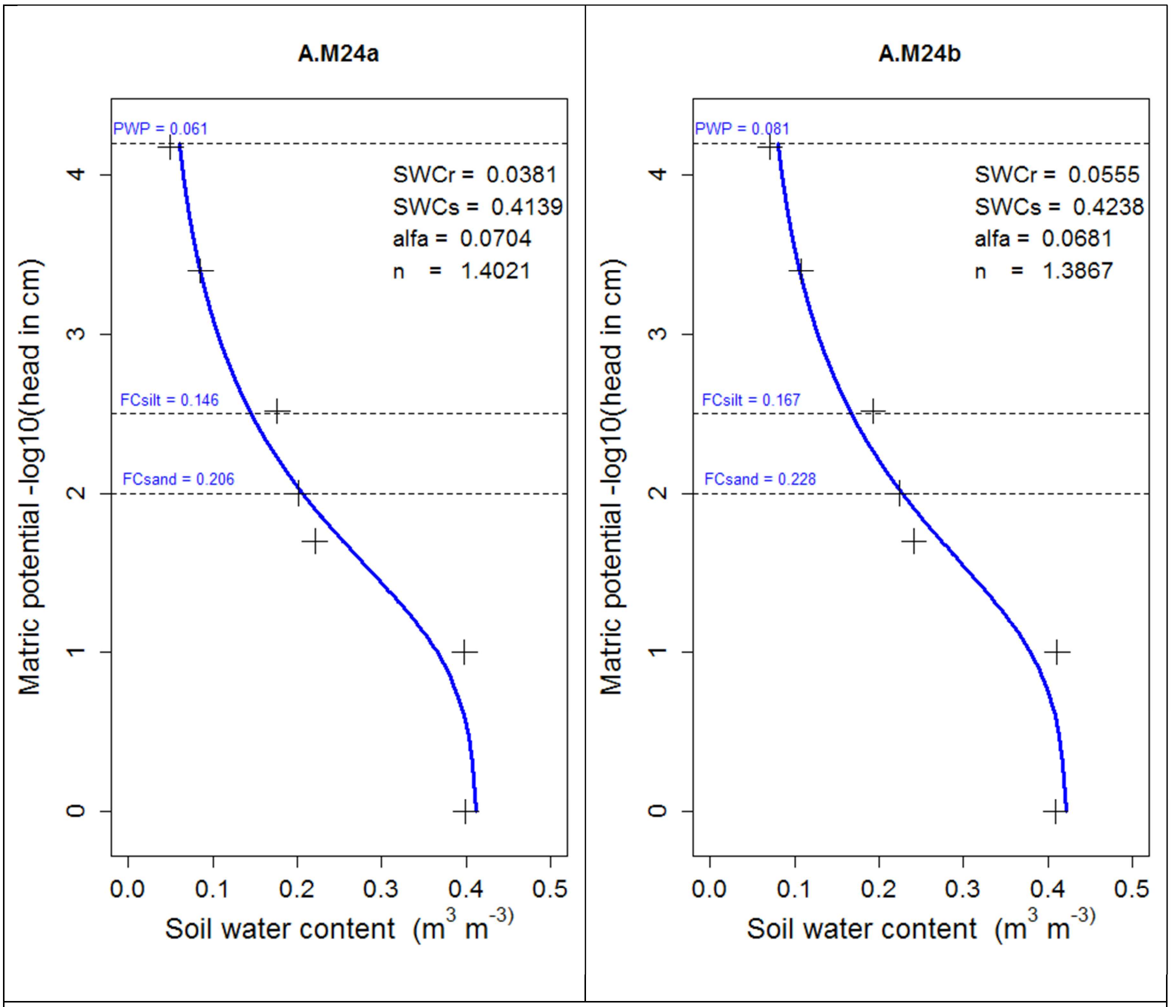


Soil Water Characteristic of the 20-40 cm layer in site Ravels. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Site Brasschaat

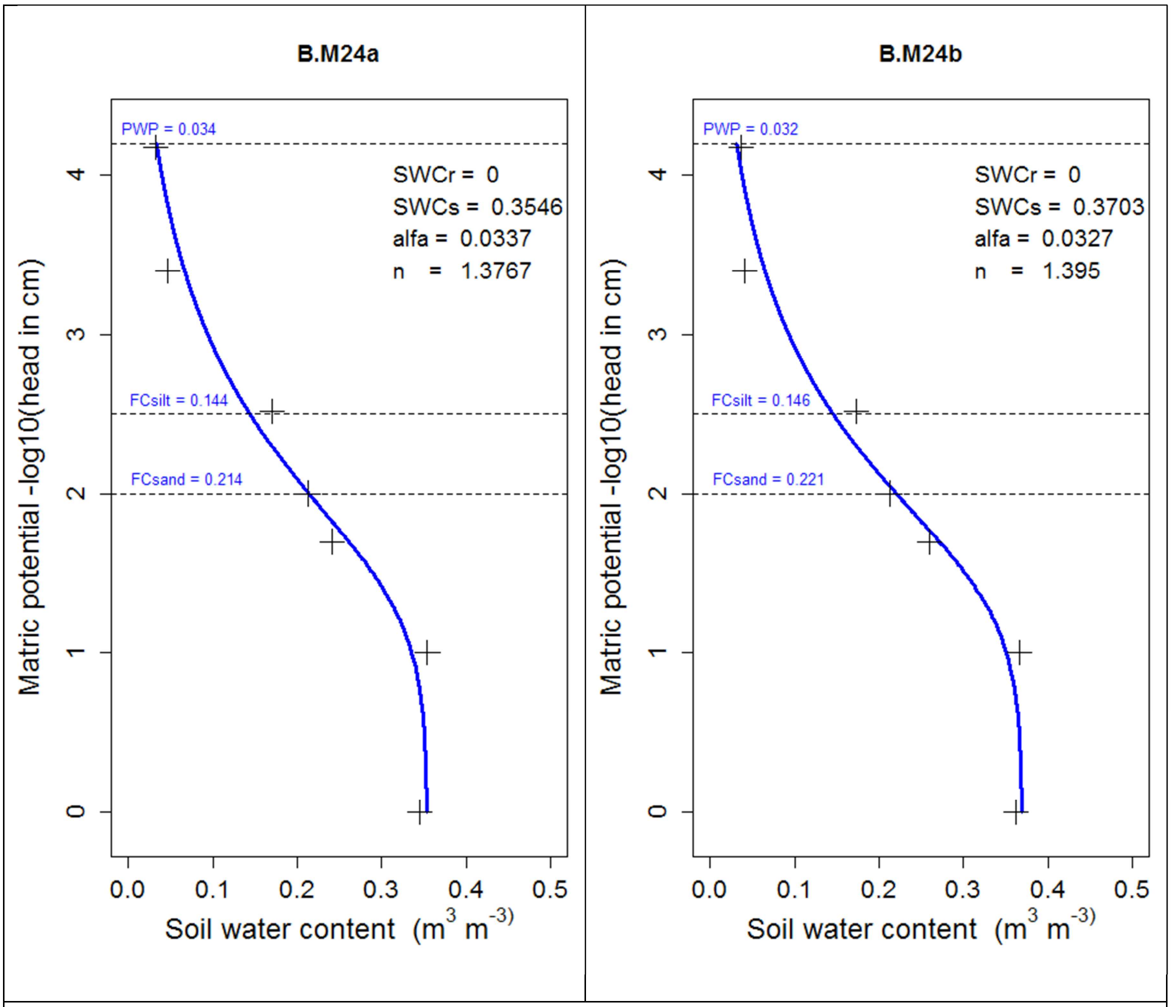
Location A

M24



Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Location B

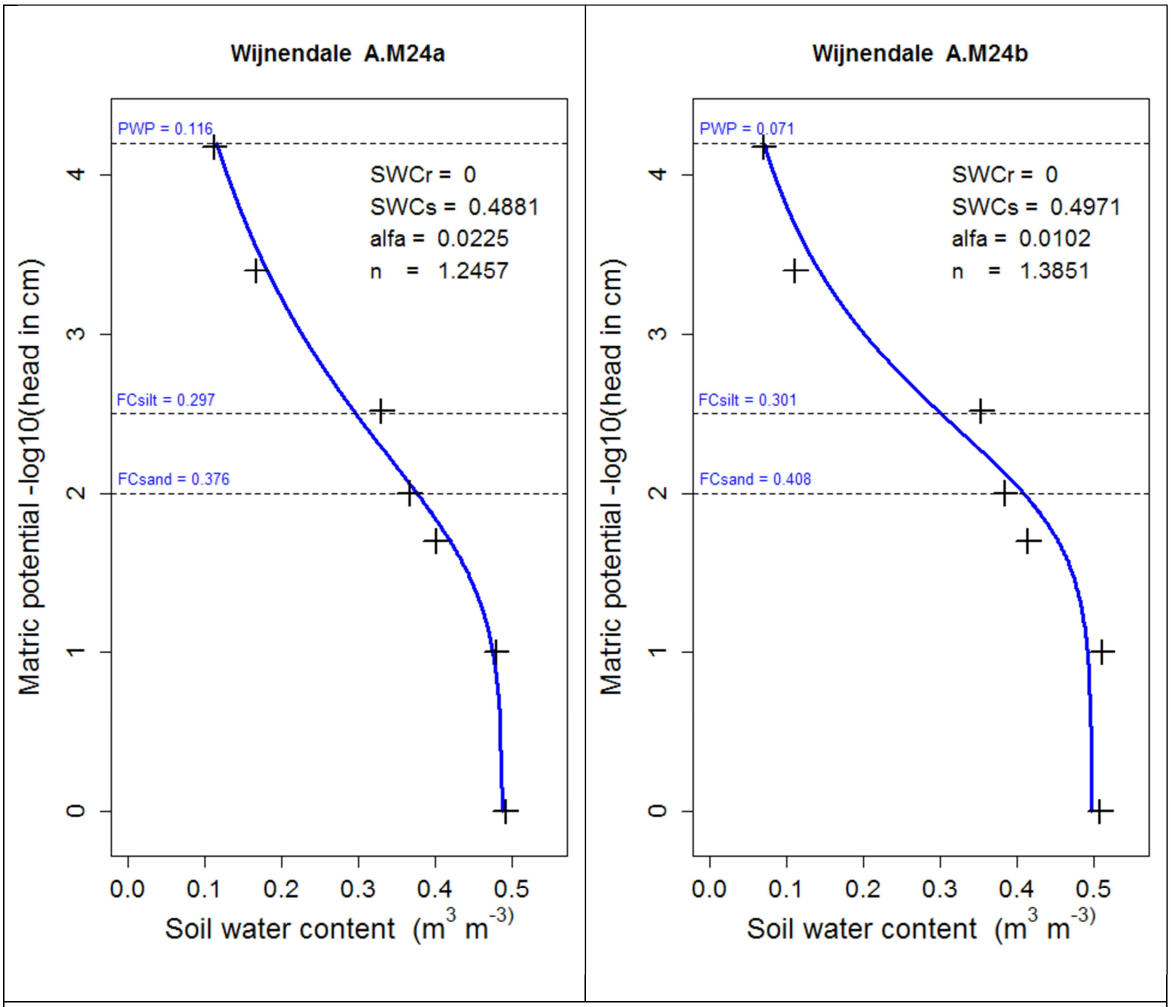


Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Site Wijnendale

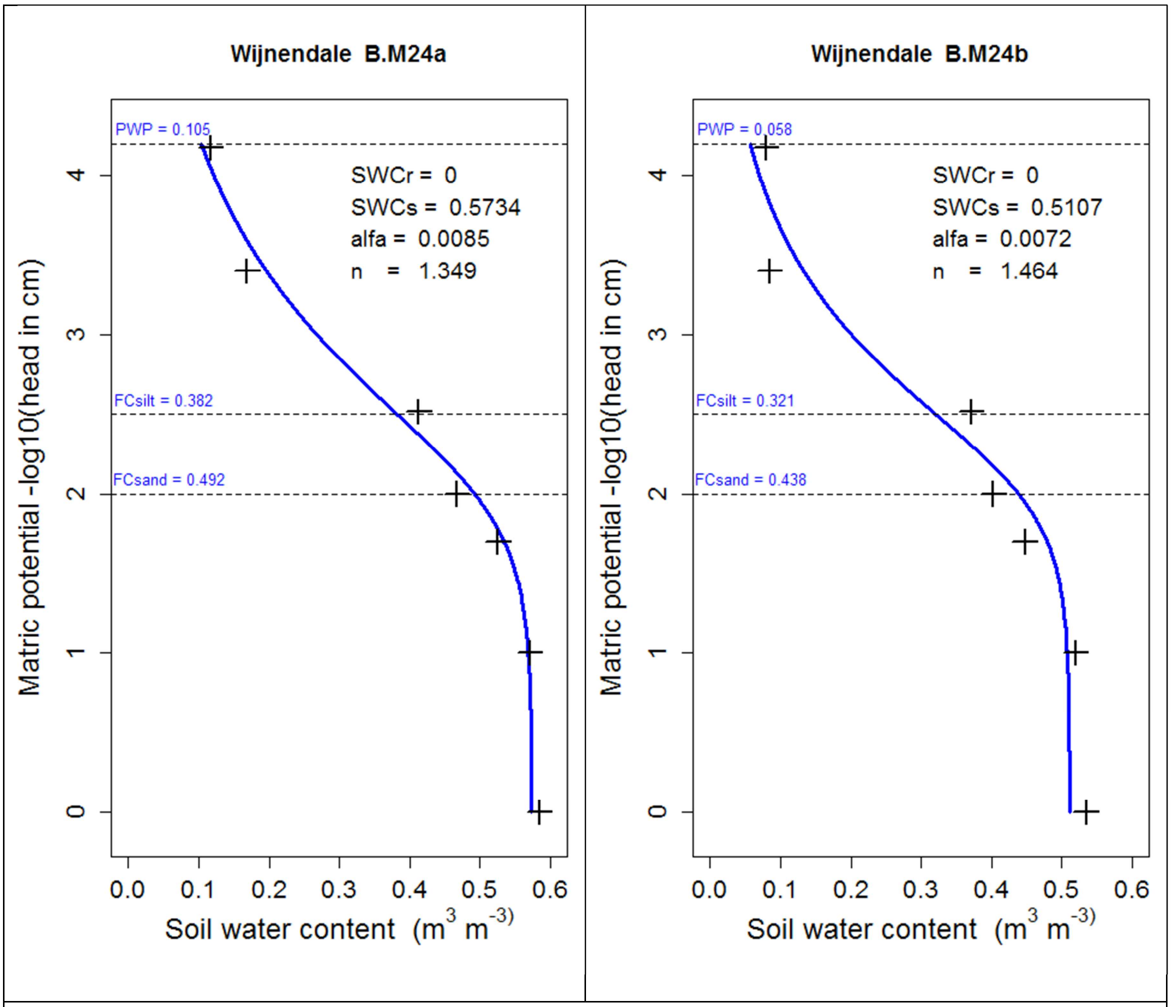
Location A

M24



Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Location B

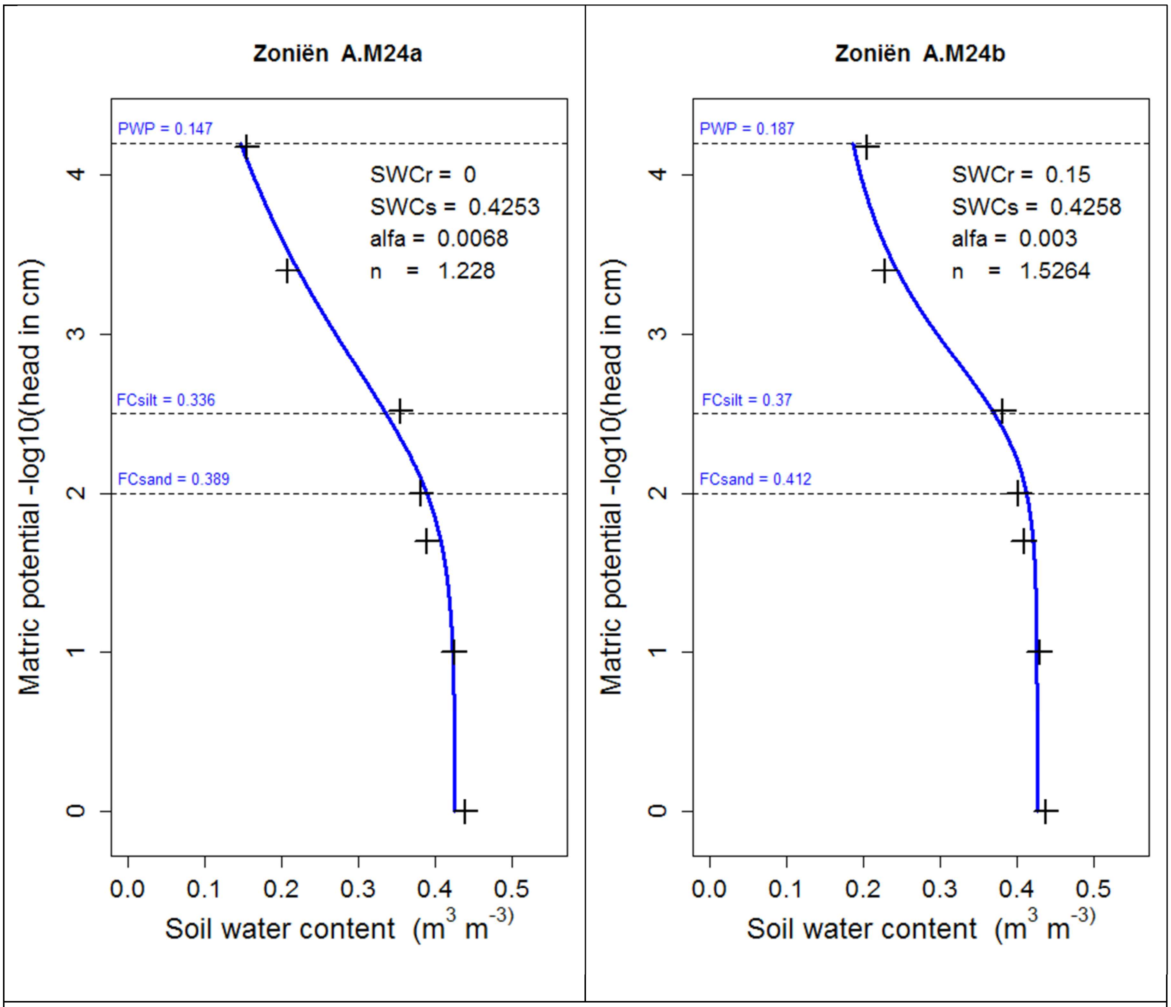


Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Site Zoniën

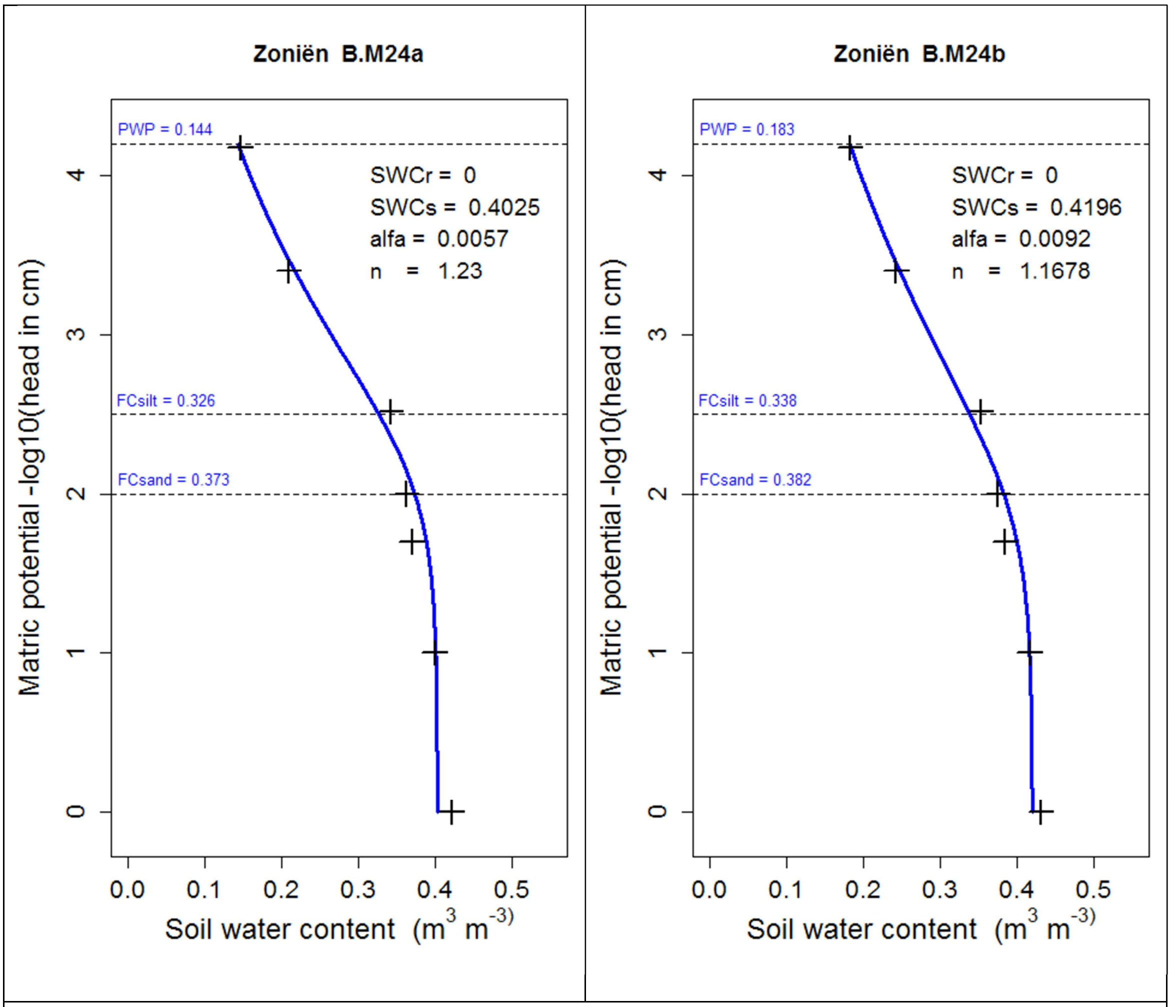
Location A

M24



Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

Location B



Soil Water Characteristic of the 20-40 cm layer in site Brasschaat. Blue line is soil water retention curve modeled by Van Genuchten equation with parameters: SWCr (residual water content), SWCs (saturated water content), alfa and n. In addition estimated values for Field Capacity for sand (at -20 kPa, pF=2) and silt (-33 kPa, pF=2.5) and Permanent Wilting Point -PWP (-1585 kPa, pF=4.2) are given for each curve.

6 References

Campbell Ltd., 2003. CS616 & CS625 Water Content Reflectometers User Guide.

Cools, N., De Vos, B., 2011. Availability and evaluation of European forest soil monitoring data in the study on the effects of air pollution on forests. iForest 4, 205-211.

Cornelis, W.M., Ronsyn, J., Van Meirvenne, M., Hartmann, R., 2001. Evaluation of Pedotransfer functions for predicting the soil moisture retention curve. Soil Sci Soc. Am. J. 65(3), 638-648.

Fleck, S., Cools, N., De Vos, B., Meesenburg, H., Kirchner, T., Fischer, R., 2016. The aggregated ICP Forests Level II soil database links soil information with long-term observations of forest condition in Europe. . Annals of Forest Science In Print.

IUSS Working group WRB, 2007. World reference base for soil resources 2006, first update., FAO, Rome, 128 pp.

Matile, L., Berger, R., Wächter, D., Krebs, R., 2013. Characterization of a New Heat Dissipation Matric Potential Sensor. Sensors 13, 1137-1145.

Mikkelsen, J.H., Cools, N., De Vos, B., Roskams, P., 2008. Soil Profile Description and Classification (WRB-2006) of the 11 Flemish Level II Intensive Monitoring Plots, Research Institute for Nature and Forest (Instituut voor Natuur- en Bosonderzoek), Brussel.

R Core Team, 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Soil Survey Staff, 2003. Keys to Soil Taxonomy, 9th Ed. 9th ed. USDA, Washington, DC.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil. Sci. Soc. Am. J. 44, 892-898.

Verstraeten, A., Neirynck, J., Genouw, G., Cools, N., Roskams, P., Hens, M., 2012. Impact of declining atmospheric deposition on forest soil solution chemistry in Flanders, Belgium. Atmospheric Environment 62, 50-63.

Willmott, C.J., 1981. On the validation of models. Phys. Geogr 2, 184-194.

Zanella, A., Jabiol, B., Ponge, J.F., Sartori, G., De Waal, R., Van Delft, B., Graefe, U., Cools, N., Katzensteiner, K., Hager, H., Englisch, M., 2011. A European morpho-functional classification of humus forms. Geoderma 164(3-4), 138-145.