EFFECT OF WATER CONTENT ON SOIL STABILITY AND FIELD TRAFFICABILITY IN TWENTE REGION, THE NETHERLANDS

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February, 2016

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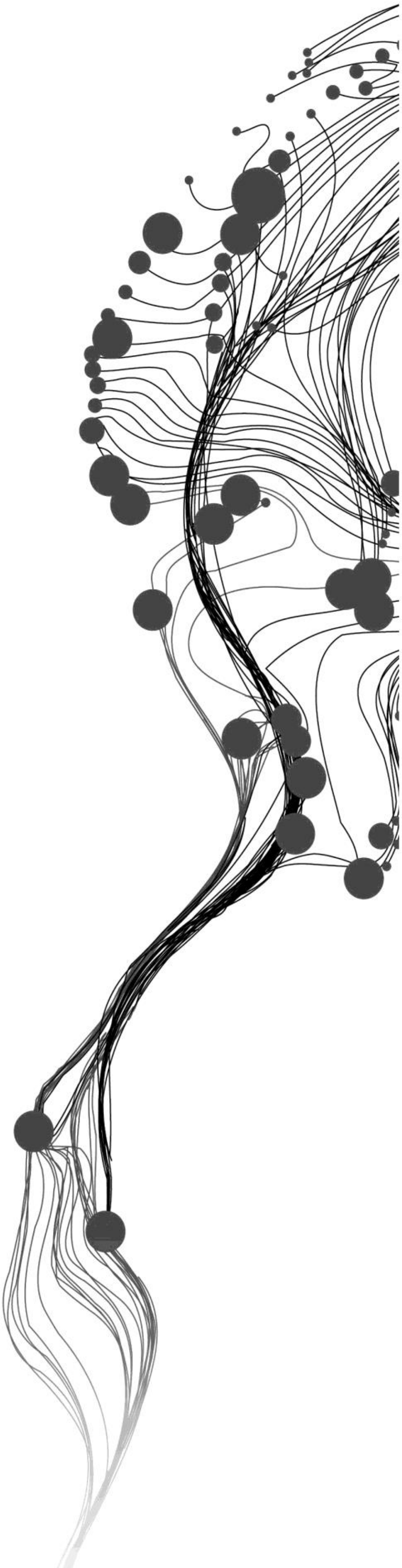

EFFECT OF WATER CONTENT ON SOIL STABILITY AND FIELD TRAFFICABILITY IN TWENTE REGION, THE NETHERLANDS

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Specialization: Water Resource and Environmental Management

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ABSTRACT

Soil compaction is a physical form of soil degradation mostly caused by intensive farming and heavy loading machinery. The study was conducted in eastern part of Netherlands, namely the Twente region with the main objective to quantify the effect of soil moisture on the penetration resistance and field trafficability. Field measurements of penetration resistance/cone index by using cone penetrometer and soil moisture determined using a combination of gravimetric and impedance probe sampling techniques. Five measurements for both cone index and theta probe with one gravimetric reading were taken at one location and, at least, three locations within a specific field about 20-30 m apart. A power relationship between penetration resistance and soil moisture was developed considering the impact of soil texture, land-cover, organic matter and agricultural practice. In every relationship the penetration resistance increase as soil moisture decreases. Land-cover and agricultural practice have a significant impact on the penetration resistance and soil moisture relationship. The result shows that land-cover is identified as important factor defining the relationship between soil moisture and penetration resistance and used as spatial field trafficability assessment parameter.

The relationship developed based on field data collection was compared with two already developed models that used by Flores et al.(2014) $CI = \exp(a + b\ln\theta)$ and Costantini,(1996) $PR = a\theta^{b}\rho^{c}$; the measured result shows better fit with Flores et al.(2014). A time series in-situ soil moisture data was collected from logger station and applied the developed relationship on it which used to predict time series penetration resistance. Based on the result obtained June, July and August are relatively favourable field traficability period compared to other time. Field trafficability for a most agricultural vehicle is possible when soil moisture is less than 0.20 $m^3 m^{-3}$ and 0.30 $m^3 m^{-3}$ for crop field and grass field respectively. For the spatial variability of field trafficability assessment, the relationship developed based on agricultural fields (crop and grass fields) was applied on the extracted SMAP L2 data. Due to coarse resolution of SMAP product there is no result difference over study area; therefore as a demonstration, the developed procedure was applied for entire The Netherlands boundary, which can be also applicable for fine spatial resolution satellite products like Synthetic Aperture Radar (SAR).

Keywords: Penetration resistance, soil moisture, field trafficability

.

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1. INTRODUCTION

1.1. Background

Soil productivity is determined by the ability to provide water and nutrient for agricultural plants. Any form of soil degradation can reduce the soil fertility and decrease soil productivity. Soil compactness is one form of soil degradation that affects crop growth by decreasing resource availability (Nawaz et al., 2013). Understanding soil process and developing a good management practice is critical for sustainably growing plants(Daniel et al., 2015). Soil management practices are closely related with ecosystem services. However, traditional high-intensive agricultural activities which use heavy machineries for tillage, planting and harvesting are often associated with soil structural degradation, increased compaction and reduced soil productivity (Hattori et al., 2013).

Soil compaction caused by repeated field traffic operation that affects bulk density, penetration resistance and soil moisture content (Barik et al., 2014). Penetration resistance is a mechanical resistance exerted by soil matrix restricts the development of crop roots which limits crop growth. At any compaction level, the penetration resistance decreases with increasing soil moisture (Lipiec & Hatano, 1998). Vaz et al. (2001) demonstrated that a decreases in soil moisture increase penetration resistance exponentially. Penetration resistance also depends on soil texture. For the same soil moisture and relative bulk density, the penetration resistance increases with an increase of fine particles percentage (Bennie & Burger, 1988). Different approaches have been developed in agriculture and related disciplines to measure soil compaction. Herrick & Jones (2002) developed a new dynamic cone penetrometer with a sliding hammer for measuring soil penetration resistance, whereas Hassan et al.(2007) estimated the effect of soil compaction by analysing bulk density.

Field trafficability can be defined as the ability of soil to support vehicles traffic and provide traction without causing permanent damage to the soil structure beyond limits that would negatively affect proper crop root growth (Paul & Vries, 1979). It is a significant factor in carrying out farm field operations, when poor trafficability can cause delays in planting, cultivating, harvesting and transporting of field crops especially after rainfall events (Kornecki & Fouss, 2001). The threshold value for trafficability is define as the soil moisture status, expressed in moisture content, at which tillage is possible with positive effects on soil structure. Droogers et al.(1996) conducted a research on three fields of the same soil texture with different management practice and concluded that soil moisture 0.37 $cm^3\ cm^{-3}$ is threshold value on grassland for field trafficability. If the soil is drier than the threshold value tillage activities can be performed without deterioration of the soil structure. It is possible to use the relationship between soil moisture and strength to predict suitability of the soil for field operations by defining critical soil water suction limits for trafficability and workability(Earl, 1996).

Beside its effect on field trafficability, soil moisture content is a significant factor for plant growth which gives information about irrigation schedule (Jiexia, 2010). The crop growth is extremely coupled to soil moisture, developing consistent growth curves requires a detailed understanding of soil moisture at the field-scale (Phillips et al., 2014). In-situ soil measurement methods give information only for point level but by nature soil moisture is temporally and spatially variable which can be obtained from remote sensing (satellite) data that helps to estimate spatial field trafficability over an area. Different satellite products are available for soil moisture estimation. For example, high-resolution satellites like Sentinel-1 and Advanced Synthetic Aperture Radar (ASAR), coarse spatial resolution satellites like Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), Advanced Scatterometer (ASCAT), Soil Moisture and Ocean salinity (SMOS) and Soil Moisture Active Passive (SMAP).Satellite data with coarse spatial resolution (30-50 km resolution and 2-3 day revisit time) are more suitable for large-scale soil moisture monitoring than the fine spatial resolution (less than 150 m and greater than 35 days revisit time)(Dente et al., 2011).

Knowing the changes in soil compaction with changes in moisture content helps to schedule farm trafficking and cultivation procedures at the suitable soil moisture content (Ohu et al., 1989).According to Kumar et al.(2015), if a database of field trafficability map is available for a particular region, then the policy makers, planners and farmers can use this information to avoid soil compaction during agricultural activities. The study was conducted in Twente region; The Netherlands. In the study area, a network of 20 soil moisture monitoring stations is operational since 2009 and five representative stations were selected for the purpose of penetration resistance and soil moisture field data collection.

This research focuses on developing the relationship between soil moisture and penetration resistance from field measurements. Penetration resistance/cone index was measured by using cone penetrometer and soil moisture measured with a combination of Theta probe and gravimetric sample methods. The relationship was developed by considering soil texture, land cover, agricultural practice and organic matter. To analyse the favourable field trafficability period, applying the developed relationship on logger stations in-situ time series soil moisture data and predict time series penetration resistance for each selected stations. Finally, the coarse resolution SMAP product which measures global soil moisture at the land surface was used simply to demonstrate the developed procedure for estimating spatial field trafficability. The relationship developed based on the land cover (grass field and crop field) was applied on the extracted SAMP data and produced spatial field trafficability map for entire The Netherlands boundaries.

1.2. Problem definition

Soil compaction is the important concern in crop production around the world. In many of the developing countries where traditional agricultural practice is common, traction by animal and to some extent by people results in compaction. It is also a big problem due to the use of heavy machinery on agricultural fields in developed countries. The degree of compaction problem mainly depends on soil moisture and soil texture classes. Lack of proper information on trafficability hampers skilful management on the timing of agricultural activities that minimizes soil compaction caused by anthropogenic activities under unfavourable trafficability conditions.

In the study area, Twente region, where machineries are heavily used on agricultural field's compaction is inevitable. Therefore, farmers need information on the trafficability of their land to avoid permanent damage to the soil structure. Such information is also important for regional water managers to control the water level that contributes to soil water availability and optimizes their water management.

1.3. Objectives

The main objective of this thesis is the quantification of the effect of soil moisture on the penetration resistance and trafficability for various soil types in the Twente region.

The specific objectives of the research are:

- To develop relationships between the soil moisture and penetration resistance for specific soil texture in the Twente regions
- To analyse favourable field trafficability period using time series of in-situ soil moisture measurements.
- To design a procedure for mapping penetration resistance based on soil moisture observation from SMAP data and its translation into spatially distributed field trafficability maps.

1.4. Research Questions

The research questions formulated to answer the objective of study are:

- How does soil moisture affect the penetration resistance in different soil types in the Twente region?
- Which time period is favourable for field trafficability for any agricultural activities in Twente region?
- What is an effective procedure for mapping penetration resistance and translate into field trafficability?

1.5. Research and Thesis structure

The research structure is designed as indicating the flow chart of Figure 1. First soil moisture and penetration resistance field data was collected by investigating the impact of soil texture, land cover, agricultural practice and organic matter content. Based on these results the relationships between soil moisture and penetration resistance was developed and a parameter for a model was calibrated. Those relationships were used in combination with in-situ time series logger station soil moisture data to predict the time series penetration resistance for favourable field trafficability conditions. The same relationships were also used in combination with satellite-based soil moisture product to estimate the spatial field trafficability across an area. In this case, SMAP L2 product was used, which is the coarse spatial resolution data just for the demonstration propose as in the future when high spatial resolution soil moisture data product available from SAR that can also be applicable.

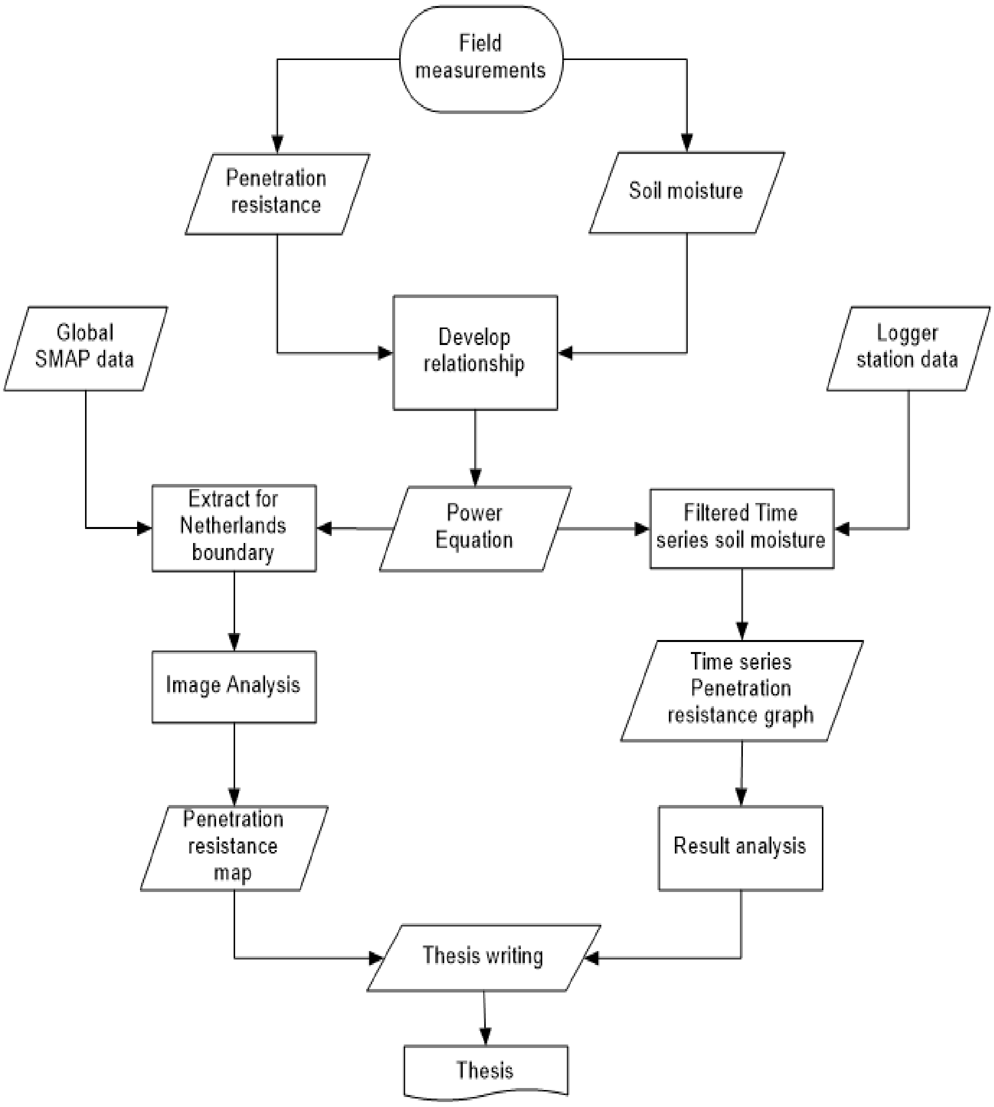


Figure 1: Flow chart indicates research structure starting from field data collection to the end of the thesis.

This leads to the following thesis structure with seven chapters:

The first chapter introduces the background information of the research topics, problem definition, the objective and the research question of the study. The second chapter refers to the study area which explains the description of the study area and monitoring network station and site selection criteria. The third chapter deals with theory that emphasis on in-situ determination of field trafficability and predicting field trafficability from soil moisture and soil bulk density. Forth Chapter describes field and laboratory measurements that include field measurements of penetration resistance, soil moisture (theta probe and gravimetric sample) and laboratory estimation of organic matter and gravimetric soil moisture. It also describes the sampling strategy of field activities.

The fifth chapter presents the result of relationship developed between soil moisture and penetration resistance on the bases of soil texture, land use impact, organic matter impact, agricultural management activities and also present field measurements in comparison to previously developed model. The analysis and discussion on in-situ time series soil moisture help to identify favourable field trafficability period and spatial field trafficability extracted from the SMAP L2 product is in chapter six. The last chapter seven contain conclusion and recommendation of the thesis.

For agricultural machinery field trafficability, soil moisture and topography are the main limiting factors, but this research focus only on the effect of soil moisture on trafficability assuming that the effect of topography is ignored because the study area almost flat.

2. STUDY AREA

2.1. Description of study area and monitoring network

The study area is located in the east part of the Overijssel province in The Netherlands, covering the regions called Twente, and Salland region. Twenty (20) soil moisture and soil temperature stations have been installed across an area of approximately 50 km by 40 km ($52^0$05'– $52^0$27'N, $6^0$05' -$7^0$00'E). Since 2009 the loggers in each station, which consist of one Em50ECH$_2$O and EC-TM ECH$_2$O probes start measuring both soil moisture and soil temperature. The data loggers take measurements in every minute and are programmed to store an average value every 15 min. This measured result downloaded twice in a year.

The area is quit flat with an elevation ranging from -3m to 50m above sea level (a.s.l).The most dominant land cover is meadows used for grazing by cattle, which is harvested and fertilized several times in a year. The precipitation is spread evenly across the year with an average of about 760 mm year^{-1} and the monthly average air temperature ranges from 3^0C in January to approximately 17^0C in July. There are four main soil types in the area: Sandy soils, Loamy, man-made sandy thick earth soil and peat soils http://www.itc.nl/library/papers_2011/scie/dente_twe.pdf.The small box on the left side corner of Figure 2 represents The Netherland boundary and the larger map stands for the soil map of Twente region (study area) with red point represents soil moisture station.

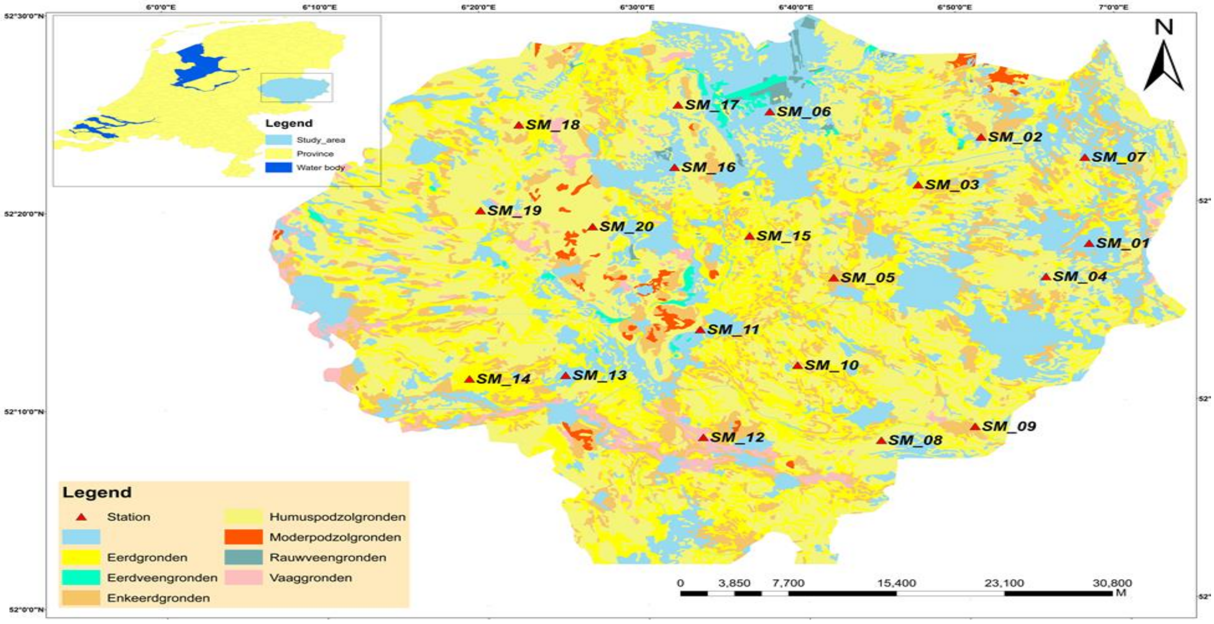


Figure 2: Study area (part of Twente region) with soil map taken from ITC data supplied during core module exercise and the point represent the location of the stations.

2.2. Site selection

To develop the relationship between penetration resistance and soil moisture for field trafficability assessment field data collection took place. Five representative stations considering soil texture (SM_08, SM_09, SM_05, SM_07, SM_03 and SM_04) were selected. The soil textural class of the network station according to Dente et al. (2011) is presented in Table 1. For each station, 2-3 fields were taken to capture spatial variability and variation in land cover. In addition to that, SM_03 and SM_09 were selected because it falls within a single SMAP pixel. In total two corn fields, five grass fields and four harvested wheat/barley fields were sampled for a period from 11th Sept. up to 3rd of Nov. The Google Earth map in Figure 3 shows the location of each soil moisture station with a current land cover of selected station. Current land cover and agricultural activities taken place during data collection on the selected field presented in Table 2.

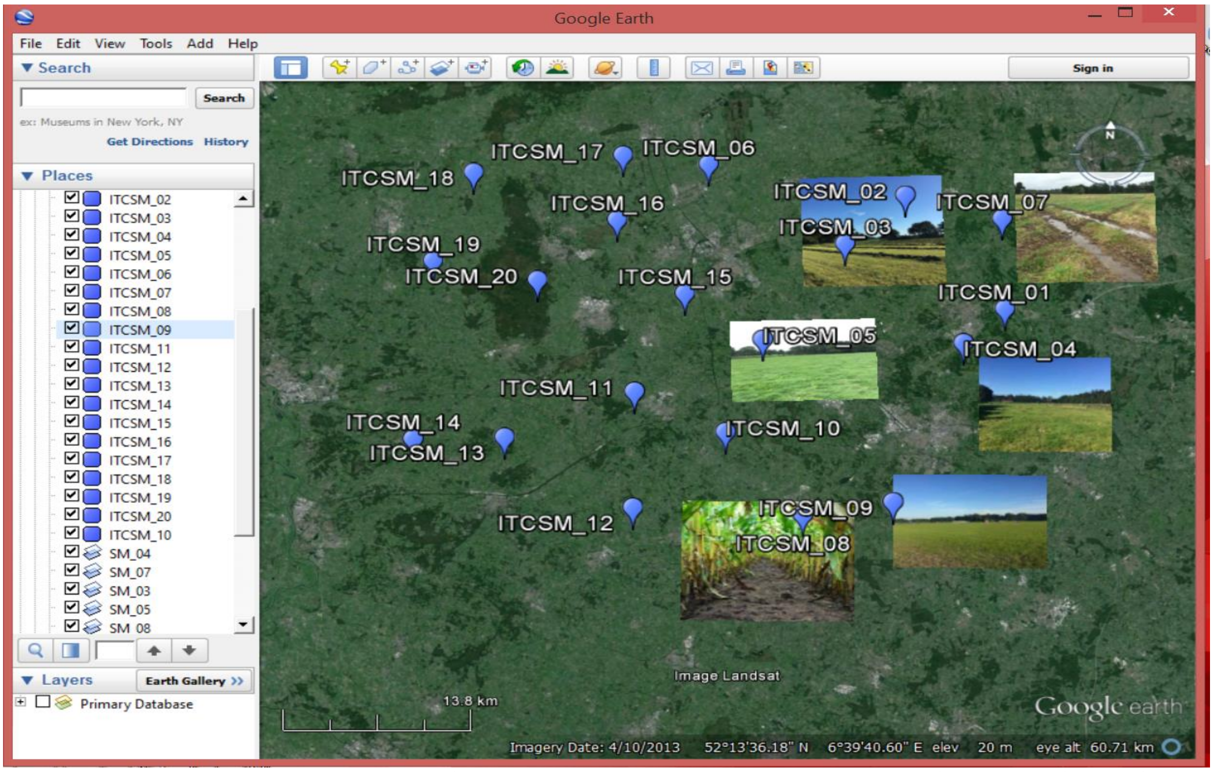


Figure 3: Google earth map shows selected stations with photographs illustrating the land cover conditions during the field work period.

Table 1: Soil type of the fields where the monitoring soil moisture station are installed, adopted from Dente et al. (2011)

S/N	Name of station	Soil Type
1	SM-08,SM-10,SM-13,SM-15,SM-17,SM-19 &SM-20	Fine sand
2	SM-03,SM-14 & SM-18	Loamy fine sand
3	SM-02,SM-05,SM-09 & SM-11	Man-made sandy thick earth soil
4	SM-01,SM-07 & SM-12	Sandy clay loam
5	SM-06 & SM-16	Sandy
6	SM-04	Loam

Table 2: Current land cover and agricultural activities in the field that took place during field work in 2015.

Station	Land cover	Agricultural activities
SM_03	Grassland	Grass cut week 28 Sept – 2 October
SM_04	Grassland	Grass cut week 28 Sept – 2 October (field 2)
SM_07	Corn & harvested barely	Barely harvested before 11 Sept
SM_08	Corn & grassland	Corn harvested week 3 Oct & grass cut before 11 Sept
SM_09	Harvested barely	Barely harvested before 11 Sept

3. THEORY

3.1. In-situ determination of trafficability

Penetration resistance (PR) is mainly influenced by the cohesion and friction of particular soil particles, soil moisture, soil type and bulk density(Costantini, 1996; Vaz et al., 2001). The US Army Corps of Engineers has developed standard in-situ measurement techniques for estimation of the penetration resistance using a cone penetrometer. The cone penetrometer measures the frictional resistance of the soil as it is inserted vertically into the soil column by applying a constant force. The soil penetration resistance measured by a cone penetrometer is also named soil cone index (CI)(Kumar et al., 2012), which is reported in units of force per unit area ,e.g. pounds per square inch (psi), where by one psi is equal to 6895 Pascal (Frankenstein et al., 2015). For trafficability assessment the soil CI is directly related to the vehicle cone index (VCI),which is defined as a minimum CI value for coarse-grained soil required for a particular vehicle to achieve a given number of passes ,usually one pass(VCI_1) or 50 pass (VCI_{50})(Flores et al., 2014). A comparison of the VCI and the soil CI will result in a prediction of whether the vehicle is mobile or not in a particular soil (Sally, 1993). The VCI is applicable to all types of ground-based vehicles, which is also allows direct comparison between various vehicles regardless of the type of traction elements employed (Priddy & Willoughby, 2006). Table 3 presents the range of VCI values for different vehicle type's representative for one and fifty passes. Flores et al. (2014) investigated trafficability condition for specific military vehicle (Light Armored Vehicle) which it's $VCI_1 = 32$ and $VCI_{50} = 72$ psi; and for the purpose of their study they referred to $CI < VCI_1$ as "no go" condition, $VCI_1 < CI < VCI_{50}$ as "slow go" condition and $CI > VCI_{50}$ as "go" condition. The relationship between penetration resistance and soil moisture based on soil texture have showed different response curve. For example Dexter et al.(2007) conducted a research in Poland, the measurement was carried out on crop field just before and after harvest at different soil depths(10,20,30 and 40 cm) and developed power relationship Figure 4a whereas Kumar et al.(2012) inspect a research on no-tilled and conventional tilled fields in Canada and developed linear relationship Figure 4b. The purpose of their study was not to predict the CI with soil properties but to examine the trends of CI variations with in individual soil properties under selected tillage systems.

Penetration resistance versus soil moisture relationships for conventionally tilled soils was observed to differ with respect to the nature of cropping and trafficking activities. A relationship between penetration resistance and soil moisture could be only applicable for specific time periods with respect to cultivation practice , so that use of a singular relationship to determine the effect of water content on penetration resistance reading for tiled soils for different growing season condition could cause a problem(Lapen et al.(2004).

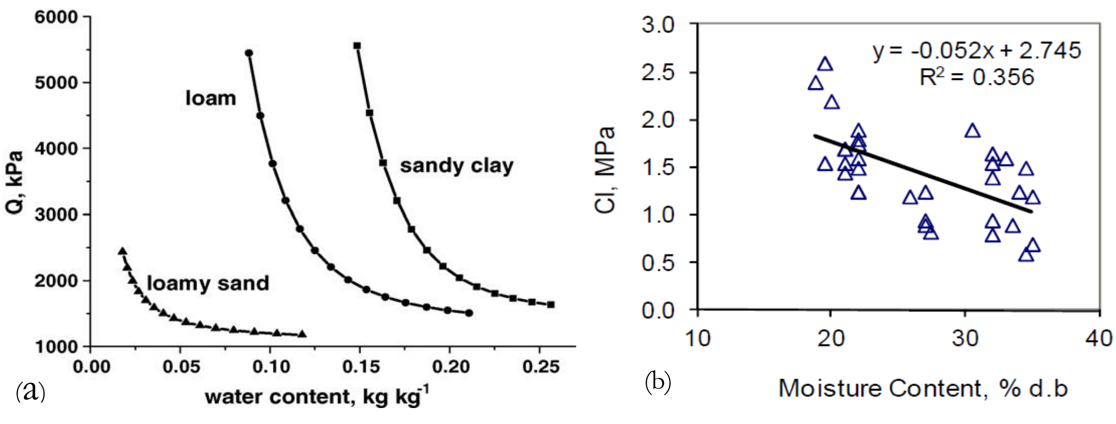
Due to variation in measuring instruments and purpose of studies, different unit was used for presenting penetration resistance in different papers. For the clarity of the unit difference in Figure 3 (a&b) and CI (psi) presented in this thesis, Table 4 shows the relation (conversion) value of those units.

Table 3: Range of vehicles cone index (VCI_1 & VCI_{50}) for different vehicles (low contact pressure to Rear-wheel drive) adopted from Department of US Army (1994).

Category	Range		Type of Vehicles
	VCI_1	VCI_{50}	
1	12 or less	29 or less	Lightweight vehicles with low contact pressures (less than 2.0psi)
2	12-21	30-49	Engineer and high-speed tractors with comparatively Wide tracks and low contact pressure
3	21-26	50-59	Tractors with average contact pressures.
4	26-30	60-69	Tractors with high contact pressures and all-wheel-drive trucks and trailed vehicles with low contact pressure
5	31-35	70-79	Most all-wheel-drive trucks, a great number trailed vehicles.
6	35-44	80-89	A great number of all-wheel drive and rear-wheel drive trucks and trailed vehicles intended primarily for highway use
7	45 or greater	100 or greater	Rear-wheel drives vehicles and other that generally are not expected to off roads

Table 4: The unit conversion between psi,kpa and Mpa that commonly used for presenting penetration resistance.

Units	psi	kpa	Mpa
1psi(pound square per inch)	1	6.9	6.9×10^{-3}
1kpa(kilo Pascal)	0.14	1	10^{-3}
1Mpa(mega Pascal)	145	10^3	1



(a) (b)

Figure 4: Relationship between penetration resistance & soil moisture for different soil texture adopted from Dexter et al.(2007) (a) and Kumar et al.(2012) (b).

3.2. Predicting field trafficability

In addition to direct measurement of penetration resistance for trafficability assessment different methods were carried out to estimate penetration resistance from some soil parameters (bulk density, soil moisture or suction head and soil texture). A typical equation (equation 1) used by Costantini,(1996) for prediction of penetrometer resistance based on soil moisture and bulk density, the study was carried out on cultivated fields and on different improved pastures fields which were previously grazed and obtained the relationship coefficients as presented in Table 6.

$$PR = a\theta^{b}\rho^{c} \qquad (1)$$

where, PR is penetration resistance in kpa, ρ is bulk density (kgcm-3), θ is soil moisture (m3m-3) and a,b& c are adjustable parameters. Flores et al.(2014) used model (open loop and other methods) for soil moisture simulation and measured in-situ cone index by hand held cone penetrometer for field trafficability assessment, then developed relationships between soil moisture and CI (equation2) on different soil texture classes.

$$CI = \exp(a + b\ln\theta) \qquad (2)$$

where θ expressed in volume percentage and a & b are regression coefficient that depends on soil texture which presented in Table 5. In general studies, e.g. Kumar et al.(2012) showed that penetration resistance decreases as soil moisture increase and increase as bulk density increase, but have found different relationships. For instance, Busscher et al.(1997) established an inverse linear relationship between soil moisture and CI, whereas John et al.(1988) established an exponential relationship between soil moisture and CI and also reported on the direct relationship between bulk density and CI. Earl(1996) measured CI by cone penetrometer and soil water suction directly by tensiometers at 5 and 15 cm depths on grass field and crop fields for different soil types; he concluded that based on relationship between soil water suction and CI it is possible to predict the suitability of soil for field operations by defining critical soil water suction limits for trafficability.

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Table 5: Coefficients of cone index-soil moisture relationship for different soil texture: $CI = \exp(a + b \ln \theta)$ adopted from Flores et al.(2014).

Soil textural class	a	b
Silty sand	12.524	-2.955
Clayey sand	15.506	-3.53
Clay	11.936	-2.471
Silt	14.236	-3.137
Clay of high plasticity	13.686	-2.705
Silt of high plasticity	23.641	-5.191
Organic silt, organic clay	17.399	-3.584
Organic clay, organic silt	12.189	-1.924

Table 6: Results of the nonlinear regression estimation of coefficients for the relationship between penetration resistance, soil moisture and bulk density : $PR = a\theta^{b}\rho^{c}$ adopted from Costantini,(1996).

Soil type and depth(cm)	Coefficients		
	a	b	c
Red kandasol			
10	2.49	-0.36	1.28
20	3.03	-0.66	2.86
10&20	2.95	-0.54	2.74
Red dermosol			
10	17.4	-0.78	1.09
20	12.8	-0.75	2.01
10&20	15.3	-0.77	1.52

4. FIELD AND LABORATORY MEASUREMENTS

4.1. Penetration resistance

For the assessment of field trafficability, in-situ penetration resistance and soil moisture estimation was performed on fields in the proximity of selected stations. The penetrometer is an instrument used to measure soil penetration resistance. Different penetrometers were introduced by different authors for assessment of penetration resistance. In this research, the cone penetrometer developed by British Military Engineering was used. The instrument consists of a light allay aluminium body Figure 5 with a curved Perspex window in its upper face and two folding handles for operating the instrument that provides CI reading varying from(0-300 psi) for estimating the trafficability conditions.

Figure 5: Picture shows cone penetrometer and field penetration resistance/cone index measurement.

4.2. Soil moisture

Soil moisture is one of the major important parameters that governing field trafficability. Different techniques have been developed for estimating soil moisture. For this research, a gravimetric method was employed in combination with a portable impedance probe known as the Theta-probe by Delta-T Devices Ltd.(1999).The gravimetrically determined soil moisture served as the purpose for calibration of the Theta-probe measurements.

4.2.1. Gravimetric

Gravimetric soil moisture determination is more accurate and commonly used for calibrating other soil moisture estimation methods, but this method is more time consuming and tedious (Zazueta & Xin, 1994). Figure 6 shows field core sampling for gravimetric measurement. The core sample rings volume of 100 cm^3 were weighed using the digital weighing machine and their initial weights were recorded and labelled Soil samples were collected from the upper soil surface depth of 0-10 cm. The samples were brought to the laboratory and put in the oven for 24 hrs at 105°C. Once the oven drying was complete the samples were weighed again and their weights were .the soil moisture was calculated as expressed by equation 3. Figure 7 shows the matchups and 1:1 graph of theta probe and gravimetric. The relationship is linear and has a good fit at moderate soil moisture content but as soil moisture greater than 0.4 $m^3\,m^{-3}$ the theta probe became saturated and reads constant value.

$$\theta_g = \frac{M_w - M_d}{M_d - M_c} \quad \text{or} \quad \theta_v = \frac{V_w}{V_s} = \frac{\theta_g * \rho_s}{\rho_w} \tag{3}$$

Where, M_w, M_d and M_c weight before dry, weight after dry and weight of ring in gram, θ_g and θ_v moisture content in gram and volumetric ratio, V_s and V_w volume of soil and volume of water, ρ_s and ρ_w are density of soil and density of water respectively.

Figure 6: How Core soil sampled during field data collection, for gravimetric soil moisture estimation.

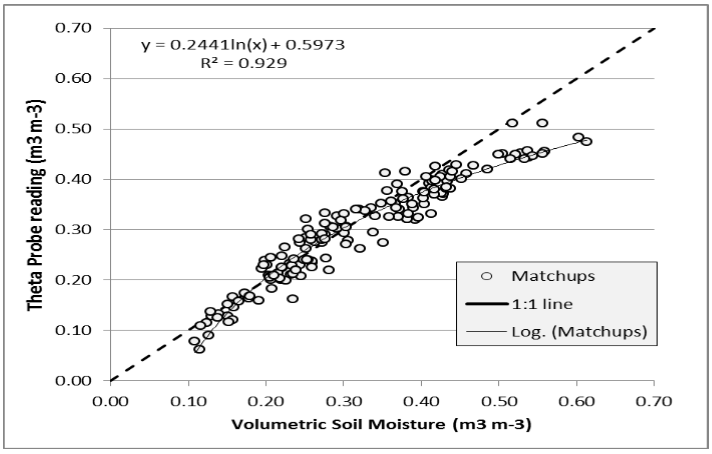


Figure 7: Graph of matchups and 1:1 between Theta probe and gravimetric soil moisture estimation methods.

4.2.2. Theta Probe

Theta probe (TP) is a device used to measure volumetric soil moisture content. It applies 100 MHz sinusoidal signal through a transmission line to a sensing array whose impedance depends on the dielectric constant of soil matrix (Miller & Gaskin, 1996). The changes in the transmission line impedance are dependent almost solely on the soil's apparent dielectric constant. Because the dielectric of water (~80) is very much higher than soil (typically 3 to 5) and air (1), the dielectric constant of soil is determined primarily by its water content. Thus, 0.0 $m^3.m^{-3}$ corresponds to a completely dry soil, and pure water gives a reading of 1.0 $m^3.m^{-3}$ (Delta-T Devices Ltd.,1999).Since the theta probe reading depends on dielectric constant, calibration with gravimetric is needed to get reliable soil moisture result. In-situ soil moisture measurements using Theta probe field measurements was done as shown in Figure 8.

Figure 8: Photo shows Theta probe soil moisture reading during field data collection at SM_09.

4.3. Organic matter estimation

Organic matter (OM) content is one of the soil properties that have an impact on the penetration resistance for trafficability assessment. Estimation of organic matter was done by the Loss on Ignition methods (Robertson, 2011). This method does not require the use of any chemicals rather a muffle furnace. It calculates organic matter by comparing the weight of soil before and after ignition.

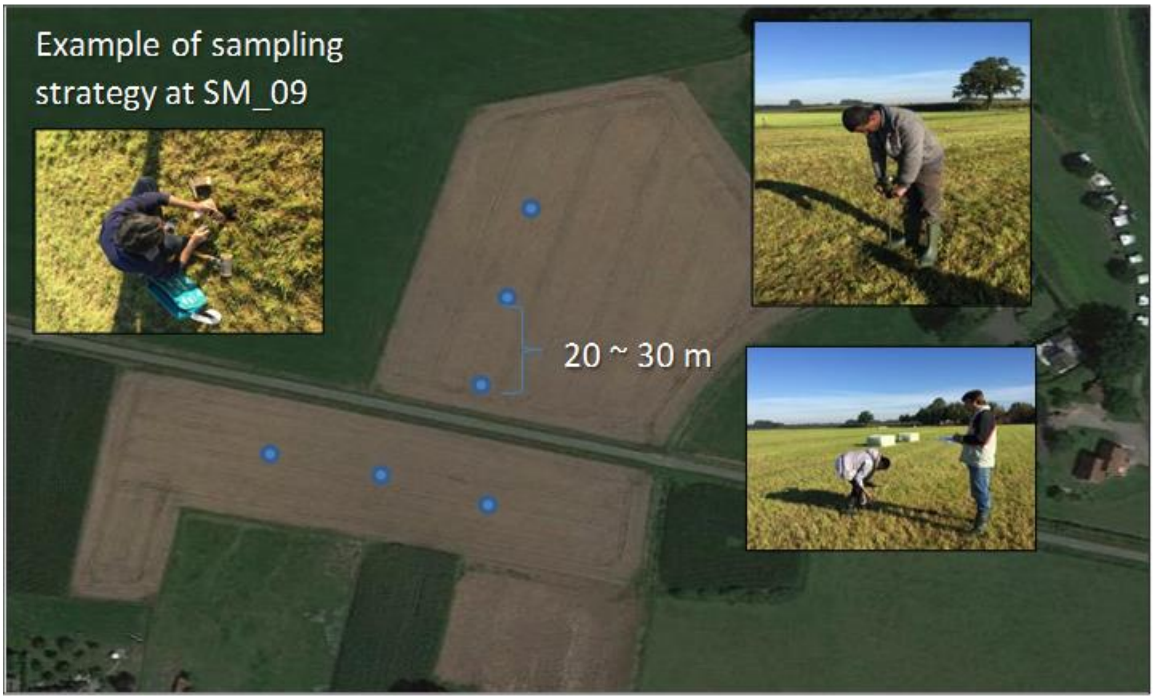
$$OM\% = \frac{\text{weigh before ignition}(g) - \text{weigh after ignition}(g)}{\text{weigh before ignition}(g)} x100 \qquad (4)$$

Soil samples taken for gravimetric soil moisture estimation was directly used for organic matter estimation also. Once the sample was oven dried for 24 hrs. at 105^0C and all moisture removed, the sampled soil was sieved with 2 mm sieve. The crucible was weighed and labelled carefully. Weigh 5 gm of each oven dried sample using a scale of precision to 0.001 gm. and put into the crucible. Then put the sample in the furnace at 375^0C for 16hr. The next day after 16 hrs switch off the furnace and wait till it cooled to 150^0C.

Then remove the sample and put in the desiccator for 30 min. Finally, remove samples from the desiccator and weigh those samples. To check the reliability of this method, the same sample was kept in 675^{0}C for the next 16 hrs and found 0.1% increment which shows non-significance difference from the first results. Therefore, the selected procedure is reliable for estimation of organic matter content.

4.4. Field sampling strategy

The measurements were taken from the upper surface of 0-10 cm depth. For each selected field three representative points approximately 20-30 m apart were chosen. At each point, five penetration resistances measurements with corresponding Theta probe measurements were collected. The collected data analysed by taking the average value of each point and create a relationship with corresponding soil moisture content. Similar to penetration resistance, the five theta probe reading were collected for each point and calibrated by a gravimetric method which its sample was also collected corresponding to every third theta probe reading. The overall sampling strategy during field work is shown in Figure 9.



● 5 Theta probe + 1 matching gravimetric & 5 Penetration resistance

Figure 9: The sampling strategy of the field work with screen shoot of Google earth map of the SM_09 station.

5. RESULTS

5.1. Soil moisture Vs Penetration resistance

Texture, mineralogy, chemical properties and organic matter are the important components of soil type that affects the penetration resistance (Costantini, 1996). In this study, a relationship between penetration resistance and soil moisture was developed by considering the impact of soil texture, land-cover, organic matter content and agricultural practice.

Soil texture impact on the penetration resistance vs soil moisture for all selected stations on the specific field are illustrated by scatter plots presented in Figure 10 (a-f). The relationship between penetration resistance and soil moisture for each field was displayed differently. It is difficult to compare results from fields with different soil texture; because the relationship developed for the same soil texture in different land cover shows significant variation. For instance, from Figure 10 SM_08_corn and SM_08_grass the CI ranges from 40-70 psi and 80-105 psi for soil moisture between 0.10 & 0.25 $m^3 m^{-3}$and 0.17&0.36 $m^3 m^{-3}$ respectively. Similarly, for SM_4 field1 and SM_04 field2, CI ranges from 56-124 psi and 61-95 psi for soil moisture between 0.31&0.52 $m^3 m^{-3}$and 0.23&0.45 $m^3 m^{-3}$ respectively, which shows other factors have a larger impact on the penetration resistance than soil texture. This variation was mainly caused by the effect of land cover and agricultural activities practiced in the particular fields. Therefore to understand the effect of soil texture on the relationship of penetration resistance and soil moisture, the other factors (land cover, management practice, and Bulk density) should be relatively uniform. Dexter et al. (2007) found a clear effect of soil texture on the penetration resistance and soil moisture relationship Figure 4a within the same condition of other factors. The relationship between penetration resistance and soil moisture fit more in power than in linear equation which was also found by Vaz et al. (2001). All test fields exhibited a decrease in penetration resistance when soil moisture increased except for one barley field (SM_07) Figure 10 f. A similar result was also reported by different studies (Dexter et al., 2007; John et al., 1988; Kumar et al., 2012).

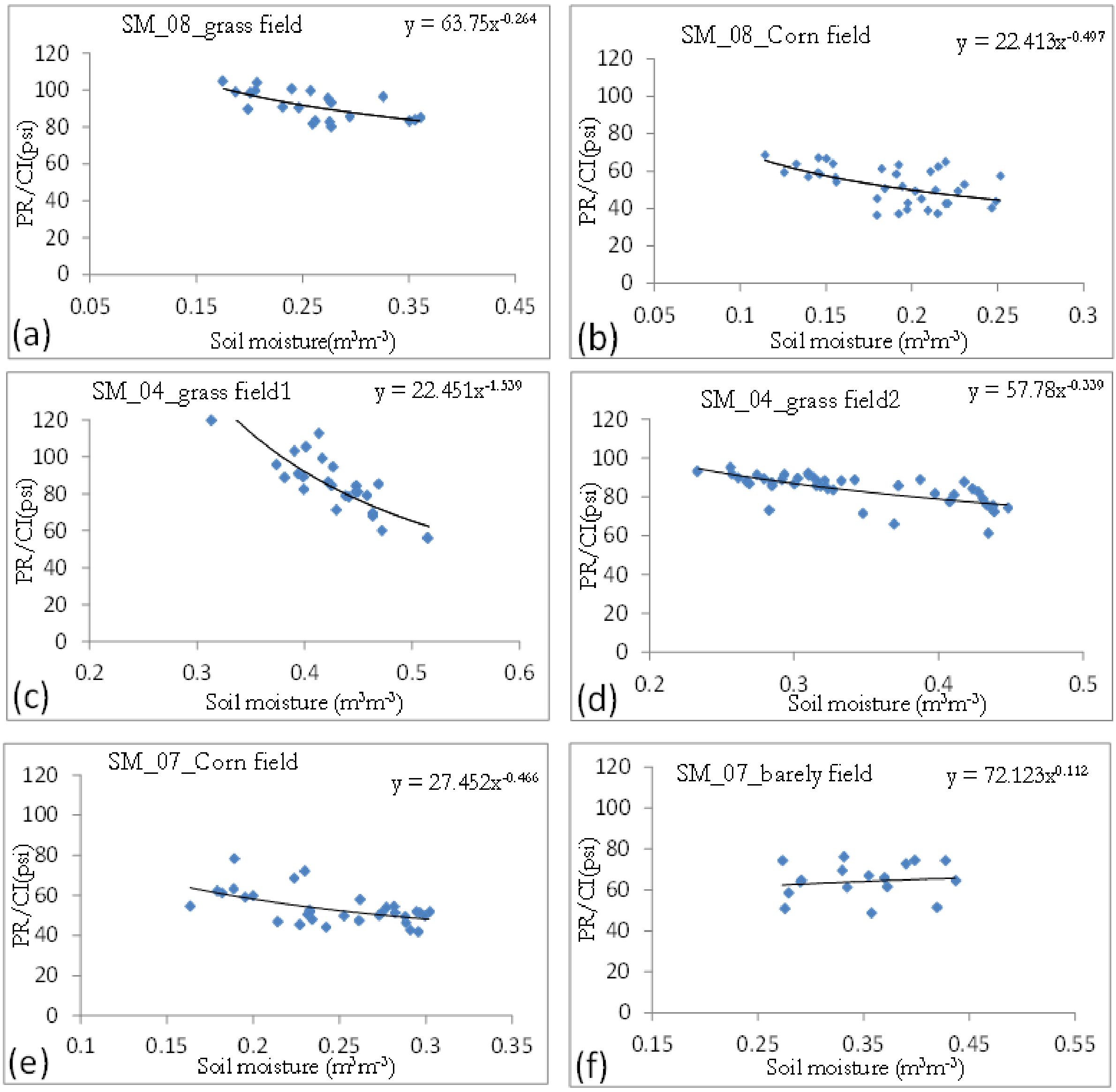


Figure 10: Scatter plot of penetration resistance vs soil moisture for six fields showing soil texture impact.

5.1.1. Land use impact

Figure 11 shows the relationship between penetration resistance and soil moisture for different land covers. The main land covers are grass field and crop fields (corn field & barely field). The other land uses (forest and residential area) are not the interest of this study, so trafficability assessment for the study area was mainly depends on agricultural fields. The CI value for corn field and barely field have the same order of magnitude which ranges from 40-80 psi with soil moisture between 0.12 and 0.34 $m^3 m^{-3}$, whereas for grass field CI value ranges from 50-112 psi with soil moisture between 0.21 and 0.52 $m^{3}m^{-3}$. Land cover affects the relationship between penetration resistance and soil moisture because of significant dynamics of soil moisture due to the:

- Hydrological aspect: In grass-field it is expected that low drainage and low evaporation compared to corn field which received almost the same amount of rain fall.
- Mechanical aspect: Soil structure disturbance in a ploughed corn field that makes loose the soil and highly decreases the penetration resistance of the upper surface.

From the result, it possible to deduce that land cover is the most important governing factor for spatial field trafficability assessment.

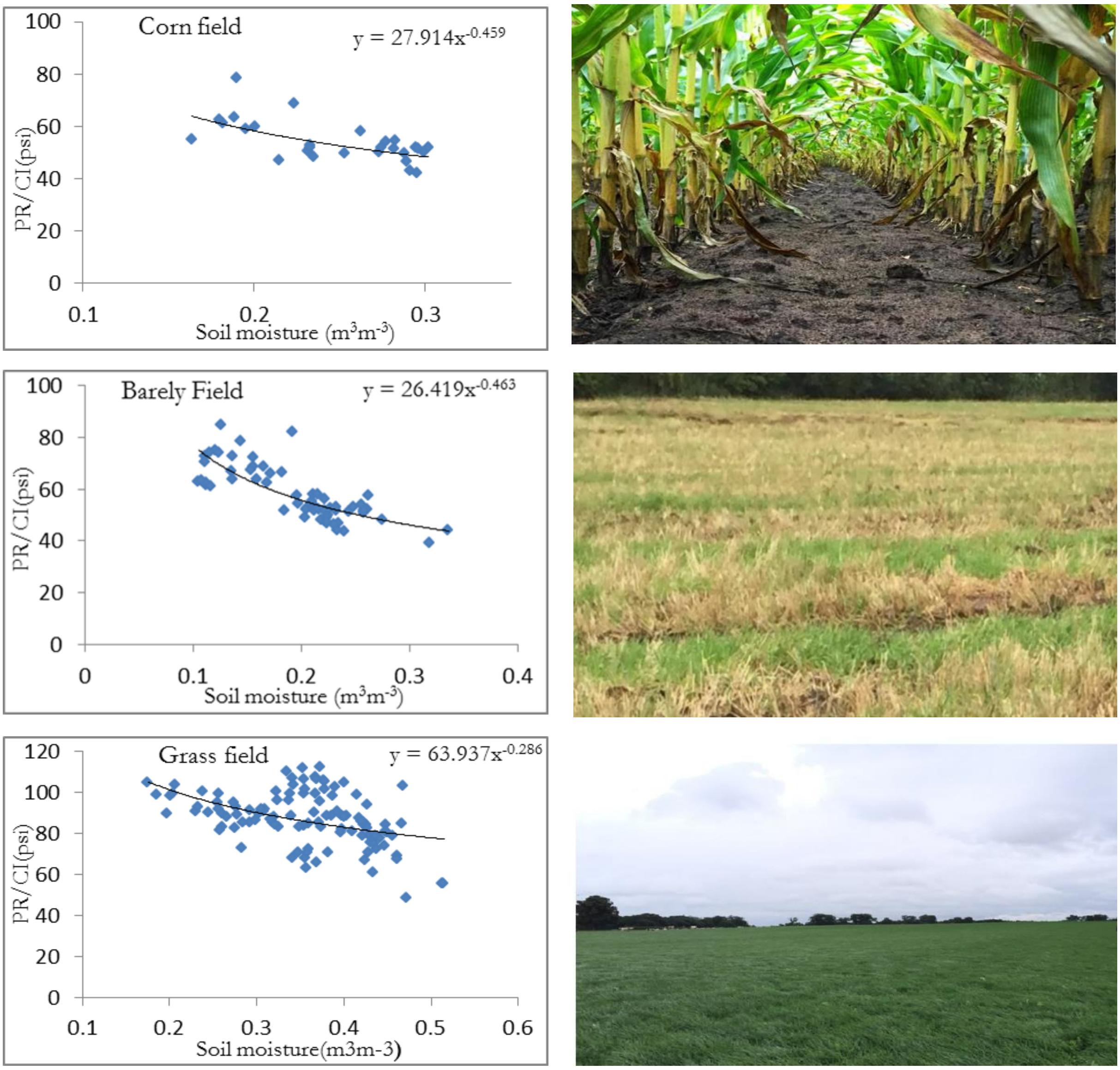


Figure 11: Relation between penetration resistance and soil moisture grouped by a land cover with its corresponding photo.

5.1.2. Organic matter impact

The percentage of estimated organic matter for each fields are presented in Table 7. In SM_04 the highest organic matter content recorded (9.5%). From Figure 10c on SM_04 field1 maximum CI value and also higher soil moisture were recorded. The result of two grass fields Figure 12a (SM-03&SM_04) shows that penetration resistance increases as organic matter increase which contradicts with results of previous studies by Celik et al.(2010); Stock & Downes(2008) who stated a strong increase in penetration resistance at low organic matter content. This contradicting result was obtained mainly in SM_04 field1 because of continued free grazing on the fields which contributed to high CI values by creating soil compaction as observed during field data collection Figure 13 (a &b) and animal dung mixed with the soil which contributed to high organic matter content.; whereas in the SM_03 movement of machinery for grass cut which creates high soil compaction that contributes for the increment of CI value. On the other hand, comparison was made between two crop fields (SM_07 and SM_09) that have almost the same organic matter content (3.4 & 3.5% respectively) and the result shows a relatively there is no significant penetration resistance difference for specific soil moisture content regardless of the other factor Figure 12b. Generally, on grass field, higher organic matter and also maximum CI measurement was observed, which indicate that land cover has more impact on the relationship developed in a different aspect. Like soil texture, the impact of organic matter can be identified only if other factors of the two comparable sample fields would have to be uniform.

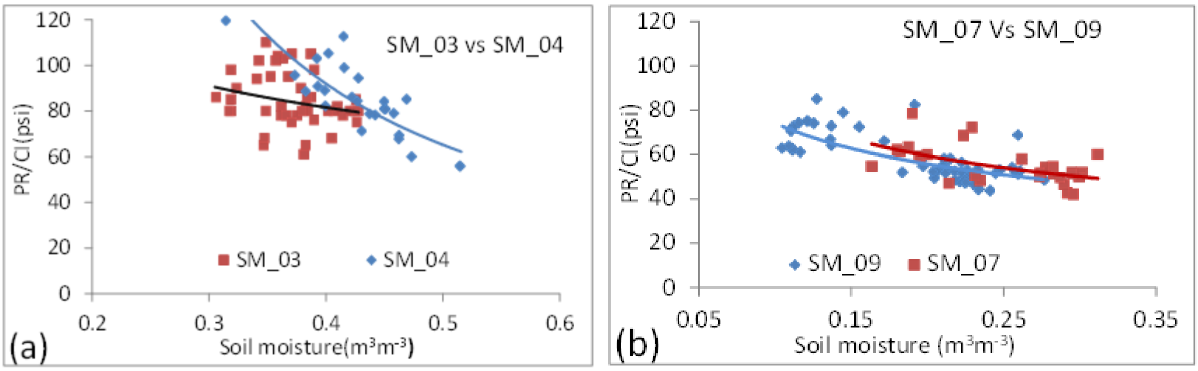


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Figure 12: Scatter plot shows organic matter impact for SM_03 Vs SM_04 (a) and SM_07 vs SM_09 (b).

Table 7: Organic matter content of selected fields in the study area

No	SM_Station	Field	OM%
1	SM_03	grass	6.1
2	SM_04	grass	9.5
3	SM_07	corn	3.4
4	SM_08	corn	3.7
		grass	4.4
5	SM_09	barely	3.5

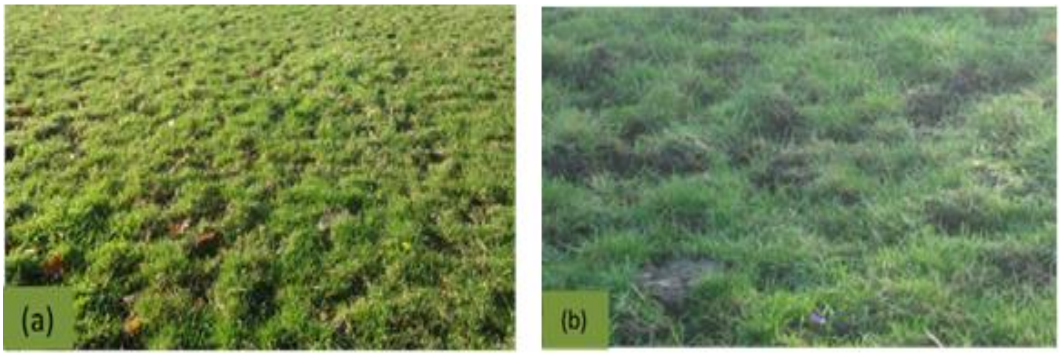

Figure 13: Photo taken from SM_04 shows highly compacted field by animal feet (a) and soil mixed with animal dung which contribute to high organic matter (b)

5.1.3. Agricultural management activities

In addition to land cover different management activities have an impact on the relationship of penetration resistance with soil moisture; for instance, SM_04_field1 and SM_04_field2 have the same land cover but different management practice. In field1 continuous free grazing by cattle was allowed whereas in field2 machineries were used to cut the grass in which the two graphs Figure 10 (c & d) show a different response curve.

Agricultural practices that cause soil compaction have an influence on penetration resistance which also directly affects bulk density levels(Gracia et al., 2012). Such activities that took place in the field during data collection period caused variability not only between two fields but also between two consecutive field observation dates within the specific field. The value of CI significantly increased after grass cut when compared to before grass cut, similar results were reported by Landsberg et al.(2003), where penetration resistance measurement before and after crop harvest was studied. As example, on SM_03 Figure 14 the CI value ranges from 60-75 psi and 80-115 psi before and after grass cut respectively for nearly the same soil moisture condition.

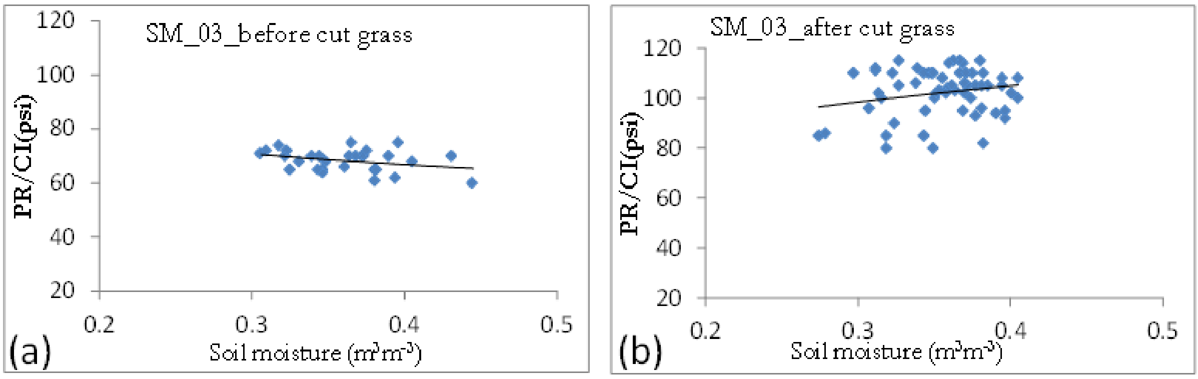

Figure 14: Penetration resistance variability due to agricultural activities within the same soil moisture range, before grass cut (a) and after grass cut (b).

From the sampled fields, there was no management interference during the sampling period on SM_09 and SM_07 (corn field only), whereas SM_04 field1 experienced a relatively uniform interference on all sampling days. The graph of those fields shows a consistent relationship of the penetration resistance with the soil moisture compared to the other fields. This does not mean that it shows a normal-condition relationship of penetration resistance with soil moisture, because still there is the effect of previous management activities on penetration resistance causing an increase (compaction) or decrease (plough) the CI value. Figure 15 shows the practical problem observed due to agricultural activities during data collection period. In a grass field CI highly increased after cut grass whereas in the case of crop field CI measurement was not even possible after a ploughed land as the upper surface (0-10 cm) became very loose. From the above it can be deduced that agricultural management activities have a significant impact on the relationship between penetration resistance and soil moisture for trafficability assessment.

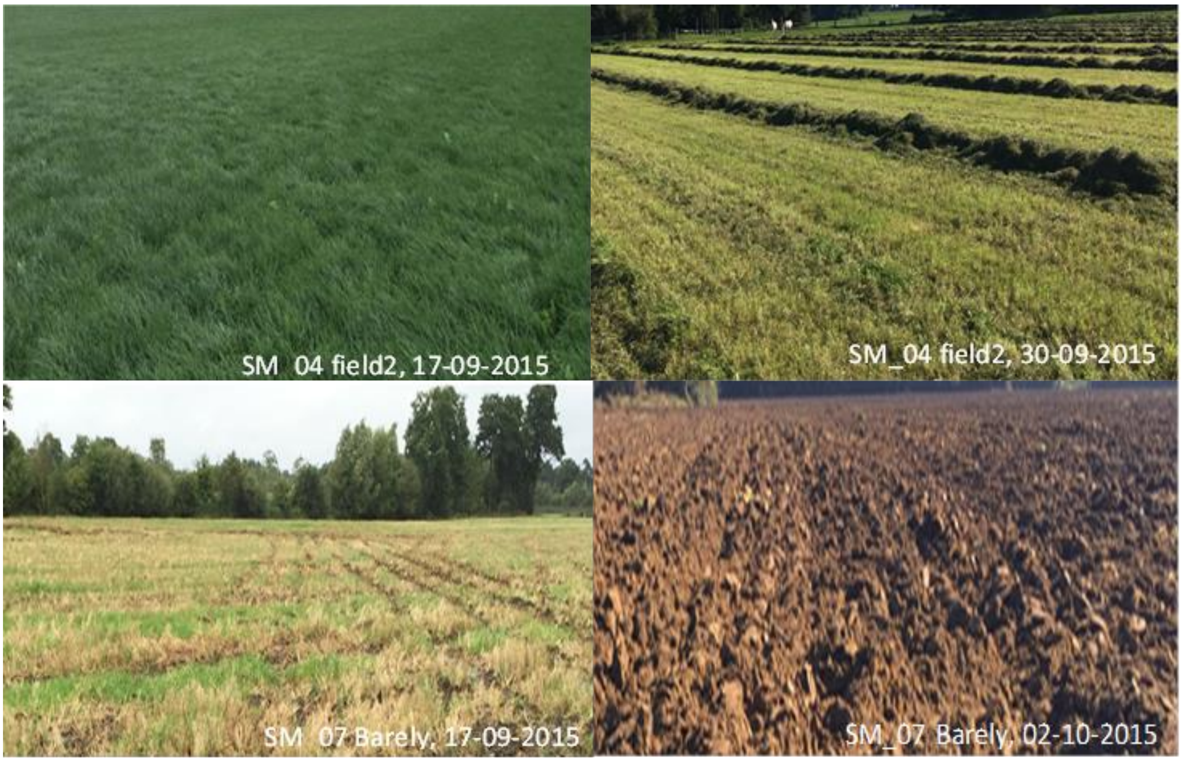

Figure 15: Picture taken during field data collection shows that variation in the field conditions due to agricultural activities.

5.2. Comparing field measurements with model estimates

Comparing the relationship developed based on field measurement with the previous model helps to see the similarity of this research with the model and if there is a difference between them, what are the main causes for the variation. The comparison was done based on the objective function; root mean square error (RMSE), mean absolute error (MAE) and correlation (R^2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(CI_{ms} - CI_{sim})^2} \tag{5}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(CI_{ms} - CI_{sim})\right| \tag{6}$$

where CI_{ms} is field measured cone-index, CI_{sim} simulated cone-index by the model equation and *n* is a total number of samples. The field measured penetration resistances was plotted with the model simulated result as presented in Figure 16. The models developed by Flores et al. (2014) describe the CI relations as indicated in equation 2 ($CI = \exp(a + b\ln\theta)$). From the statistics of objective function Table 8 relatively lower RMSE CI value 7.76 psi, 8.20 psi and higher R^2 of 0.67, 0.72 was acquired for SM_09 and SM_04 respectively. Based on those statistics value and graphical representation on Figure 16, the relation developed in SM_09 and SM_04 relatively have a good fit with this model, whereas SM_03 and SM_07 have a marginal fit. It was found that all the fields proved to have a better fit with this model as compared to other model developed by Costantini, (1996)(refer annex 1) which simulated based on relation presented in equation 1 ($PR = a\theta^b\rho^c$). But in the case of SM_08 Figure 16 (e & f) shows almost the same response for both models. The value of coefficient obtained for simulation of CI according to model is presented in Table 9. Those obtained coefficient based on field measured data have a significant difference with the one developed by models (Table 5 & Table 6), this variation may come due to different reasons but the main factor of variation is agricultural activities that practiced on the sampled fields during and before field data collection.

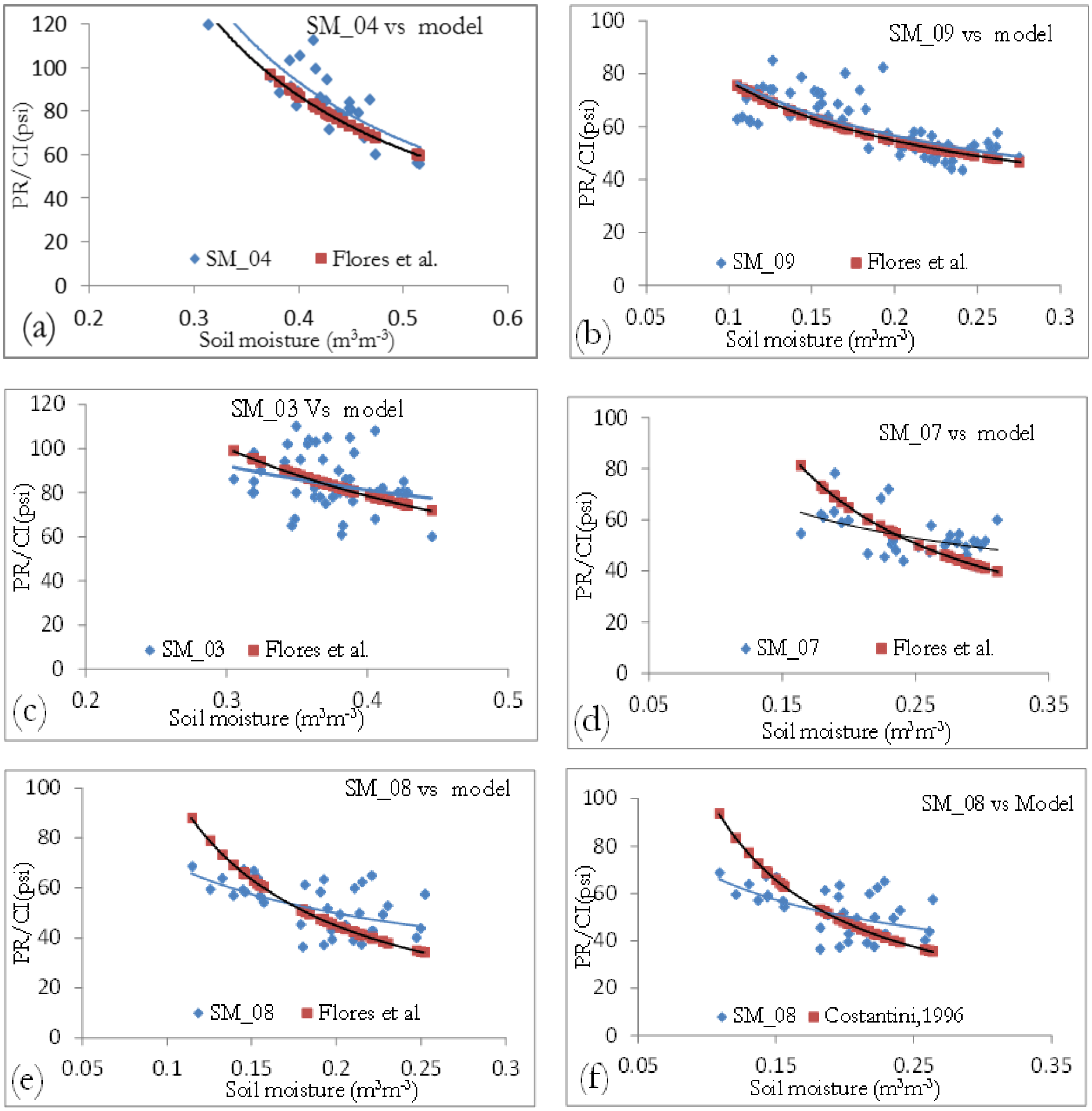

Figure 16: Comparing field measurements data with other previously developed model (Flores et al., 2014(a-e) and Costantini, 1996(f)), the line represents power relation for field- measured data (blue) and for model estimated (black).

Table 8: The statistics value of the objective function for both models which obtained during comparison with field measured data.

	Flores et al,2014			Costantini, 1996		
Station	RMSE	MAE	R2	RMSE	MAE	R2
SM-03	12.40	12.50	0.28	17.83	14.20	0.28
SM_04	8.20	9.41	0.72	14.92	11.00	0.66
SM-07	9.83	8.95	0.55	11.50	9.70	0.51
SM_08	12.85	9.40	0.52	11.83	9.50	0.56
SM_09	7.76	5.54	0.67	14.60	10.96	0.69

Table 9: Value of coefficients obtained the relationship between penetration resistances, soil moisture and bulk density for estimation of CI using already developed model.

	Flores et al,2014		Costantini, 1996			
Stations	a	b	a	b	c	ρ
SM-03	7.50	-0.85	14	-1.70	1.20	1.14
SM_04	9.20	-1.50	16	-1.80	2.50	1.01
SM-07	7.50	-1.20	11	-0.80	1.20	1.41
SM_08	7.40	-1.11	14	-0.60	1.10	1.36
SM_09	5.50	-0.55	10	-0.80	1.50	1.27

6. DISCUSSION

6.1. Applying the developed relationship on in-situ time series data

Identifying the best field trafficability period is one of the important mechanisms that help to minimize the impact of soil compaction on the loss of agricultural production. After developing the relationship between penetration resistance and soil moisture from field collected data, the developed parameterization for Twente region in was applied on time series soil moisture data to predict time series penetration resistance of the selected stations. The equation presented in Table 10 (y and x represent CI and soil moisture respectively) developed on different land cover, SM_03 and SM_04 grass field, SM_07 and SM_08 corn filed and SM_09 barely filed. A five-year time-series soil moisture data was analysed Figure 17 shows 2011 as a sample and Figure 18 represents the derived time series penetration resistance of the analysed five years (2010-2014).

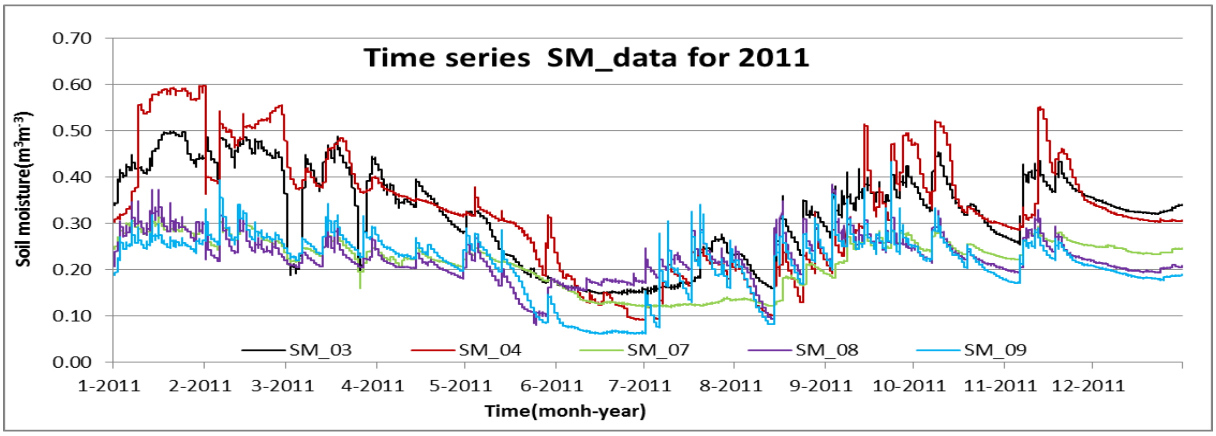

Figure 17: Time series soil moisture recorded at selected stations for 2011

The result clearly displayed that soil moisture varies from season to season and also from field to field (temporal and spatial variability). The temporal soil moisture variability from season to season mainly depends on the weather condition, at rainy season the soil moisture also increased whereas in dry period and sunny time at which evapotranspiration high and relatively soil moisture lowers. Difference in land cover is the main factor for soil moisture spatial variability both between and within the stations. SM_03 and SM_04 record maximum soil moisture readings, whereas the other stations represent crop fields with relatively similar soil moisture variability. Fields of high soil moisture content generally display a lower cone index, however such relationship might not necessarily hold among different land cover types as different relationships were developed and applied for each field. For example, highest soil moisture value was observed on SM_03 and SM_04 and as the same time maximum cone index of 130 psi was obtained Figure 18.

Based on soil moisture measurements from selected stations and predicted time series penetration resistance of the five consecutive years (2010-2014), it is possible to see the impact of seasonality on field trafficability. Even though variability of cone index resulting from variability in soil moisture exists between the same seasons of different years, the months of June, July and August generally prove to be the preferable period for field trafficability. However, this season does not necessarily represent the appropriate period for all agricultural activities. For instance, during field data collection it was observed that the period between the mid of September and end of October was the critical time for farmers to cut and store animal forage (grass & corn). From the readings of the logger stations and observed field data, soil moisture increment was not only triggered by rain fall but also from ground water table rise as it was clearly observed in station SM_04 and SM_07, a phenomenon to possibly occur at any other station. At those critical seasons of agricultural activities, regional water managers should control maximum uprising of the water table.

Table 10: The equation shows the relationship developed between cone-index and soil moisture for selected station of the representative field.

Stations	Developed relationship equation
SM-03	$y=54.31*x^{-0.44}$
SM_04	$y=57.78*x^{-0.34}$
SM-07	$y=29.90*x^{-0.41}$
SM_08	$y=22.41*x^{-0.49}$
SM_09	$y=26.44*x^{-0.473}$

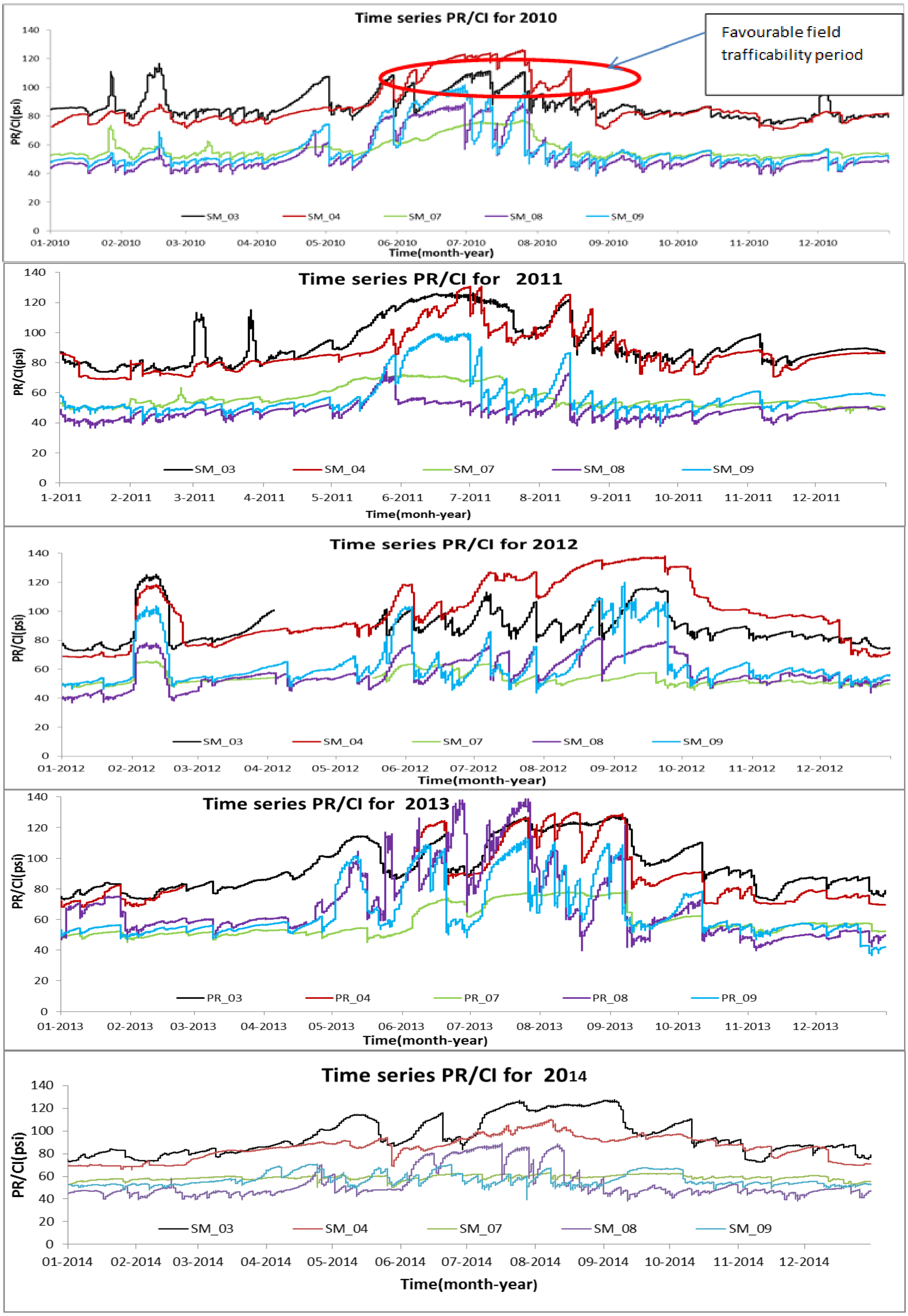

Figure 18: Predicted time series penetration resistance for 2010 to 2014 for the selected station, calculated based on a developed equation in Table 10.

6.2. Estimating trafficability

Trafficability is a significant factor in carrying out farm field operations, a poor trafficability can cause delays in cultivating, planting, harvesting and transporting of field crops(Kornecki & Fouss, 2001).

The relationship developed between penetration resistance with soil moisture presented in Figure 10 and Figure 11 considering the impact of soil texture and land cover respectively. All of the data collected on field was re-classified into two main parts based on land cover, namely grass field and crop field. The relationship between penetration resistance and soil moisture was varied more based on land cover than other parameters hence, spatial field trafficability for the study area can be predicted based on those two land cover classes. From Figure 15 comparison of the developed model with field measured results of SM_04 and SM_09 shows better fit with Flores et al.(2014). In SM_04, the interference of agricultural activities (animal grazing) was consistent during field observation period throughout the field, whereas in SM_09 there was no agricultural interference during such period. Therefore, to minimize the impact of agricultural activities on the relationship between CI and soil moisture, the relationship coefficients in Table 9 (a, b) obtained for SM_04 and SM_09 was used to predict model CI value ($CI = exp (9.2+ -1.5 ln (\theta))$ for grass field and ($CI = exp (5.5+ -0.55 ln (\theta))$ for crop field respectively and the predicted CI value using those relation was presented in Annex1 as table format. Comparing the predicted CI result for field measured soil moisture with the range of VCI in Table 3, if the soil CI is greater than the VCI_{50} , trafficability is possible without causing any problem for a particular vehicle type within that given soil moisture content. According to Flores et al. (2014), $CI < VCI_1$, $VCI_1 < CI < VCI_{50}$ and $CI > VCI_{50}$ were considered as no go, slow go and go respectively.

On a grass field, CI ranges from 27-134 psi Figure 19 (blue) for soil moisture between 0.18 and 0.52 m^{3}m^{-3} which indicate movement of most agricultural vehicles on the field is possible without causing damage to the soil. This statement holds true regardless of the impact of different agricultural activities especially compaction occurring due to grass cut and continuous free grazing increase CI value beyond the normal condition. Applying the better-fit equation of those fields for other fields helps to minimize the extreme bias difference but still there are conditions for the source of errors.

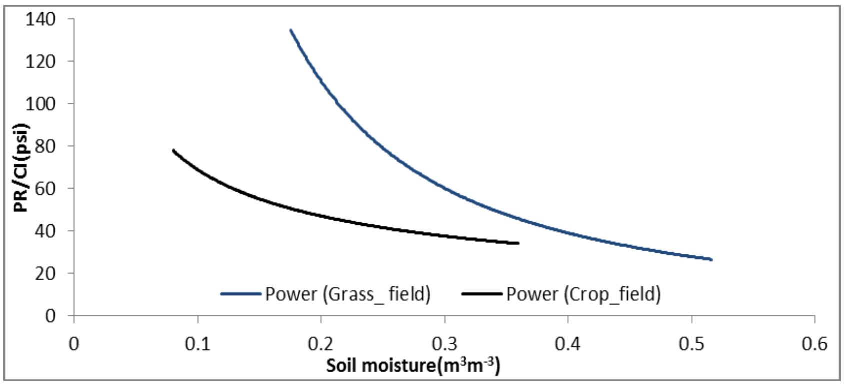

Figure 19: Penetration resistance vs soil moisture developed after applying coefficients obtained for SM_04 and SM_09 on a grass field (blue) and crop field (black) respectively.

In the case of crop fields Figure 19 (black) CI ranges from 34-75 psi for soil moisture between 0.10 and 0.36 m ^{3}m^{-3} in which the movement of some agricultural vehicles on the field causes a problem. The agricultural practice (ploughing) on the crop field affect the CI in two aspects, compaction which increases the CI and loose the upper surface that decreases CI. Those problems highly affect the relationship between CI and soil moisture Figure 10 (SM_07 barely field) resulting in CI increase as soil moisture increase, which contradicts with the reality. The agricultural activities both by machinery and animal practiced under wet soil conditions can cause soil degradation that results in a decrease in productivity which supports findings of Hattori et al., (2013).In Figure 20 the photo taken on different field observation date from SM_07 and SM_04 station shows the degrees of damage caused by agricultural vehicles and free grazing during field observation. The CI of this specific field shows movement for most vehicles is possible within high soil moisture which causes such problem. Developing relationship between CI and soil moisture for predicting trafficability without considering the agricultural activities implemented in the field leads to wrong interpretation. In order to get an accurate prediction of trafficability, fields without any agricultural activities or very less activities required.

On the other hand it also possible to estimate field trafficability from soil moisture or soil suction which is also supported by Earl, (1996).Based on the predicted CI from time series soil moisture Figure 18 and also from field collected data Figure 19, field trafficability for a most agricultural vehicle is possible when soil moisture is less than 0.20 m^3 m^{-3} and 0.30 m^3 m^{-3} for crop field and grass field respectively. In a time when soil moisture is greater than those values for specific fields, farmers have to take care while entering their fields and also the regional water managers should take appropriate management measures especially during critical periods for the agricultural activities. Not only farm machinery but also animal (free grazing) can cause significant degradation of grass field Figure 20.

Figure 20: Cause of un appropriate field trafficability on crop field by vehicle and free grazing on a grass field.

6.3. Estimation of field trafficability spatially using SMAP L2 product

In-situ soil moisture measurement gives information only for specific points. Satellite products like SMAP, however, have capabilities to monitor soil moisture globally. Soil moisture result of April to December 2015) was extracted from global SMAP L2 product for the study area as plotted in Figure 21a.The relationship developed between penetration resistance and soil moisture based on field data for grass field and crop field was applied to estimate the penetration resistance. Like trafficability estimated based on field measured soil moisture data, May June and July were observed as the better field trafficability period after SMAP product analysis Figure 21b

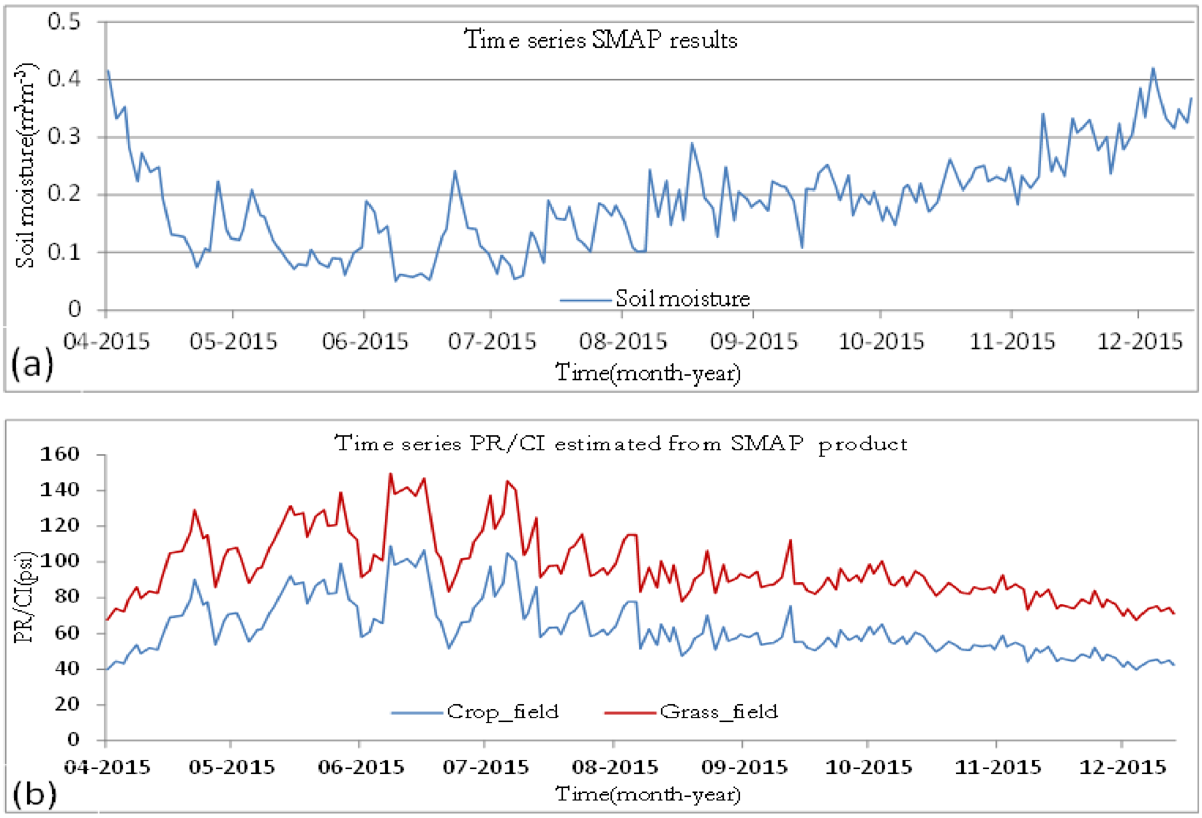

Figure 21: Soil moisture extracted from SMAP result for nine months (April to December (a) and estimated penetration resistance based on a grass field (red) & crop field (blue) (b).

SMAP L2 product has a limitation that has a coarse spatial resolution which could not show a significant variation within a small area. This coarse resolution problem can be resolved by using higher resolution soil moisture products. But for this thesis SMAP L2 product was used simply to demonstrate how the developed procedure works, which can be also applicable for any other higher resolution soil moisture products. From extracted SMAP result Figure 23a only two pixels value covers the study area, this coarse spatial resolution result do not show significant spatial variability of field trafficability over an area. Therefore to see the spatial variability based on developed relation (procedure) for grass field and crop field, it is better to consider the SMAP product for the entire The Netherlands boundary. There are few information gaps between SMAP pixels and boundary, hence to fill this gap and acquire continues soil moisture value image simple interpolation (Nearest Neighbour) was applied Figure 23b Using already developed relationship between penetration resistance and soil moisture, penetration resistance map was created for nine months on ILWIS by using an operation called “map calculation”. The overall procedure for estimating field trafficability is presented in Figure 22 in the form of flow chart.

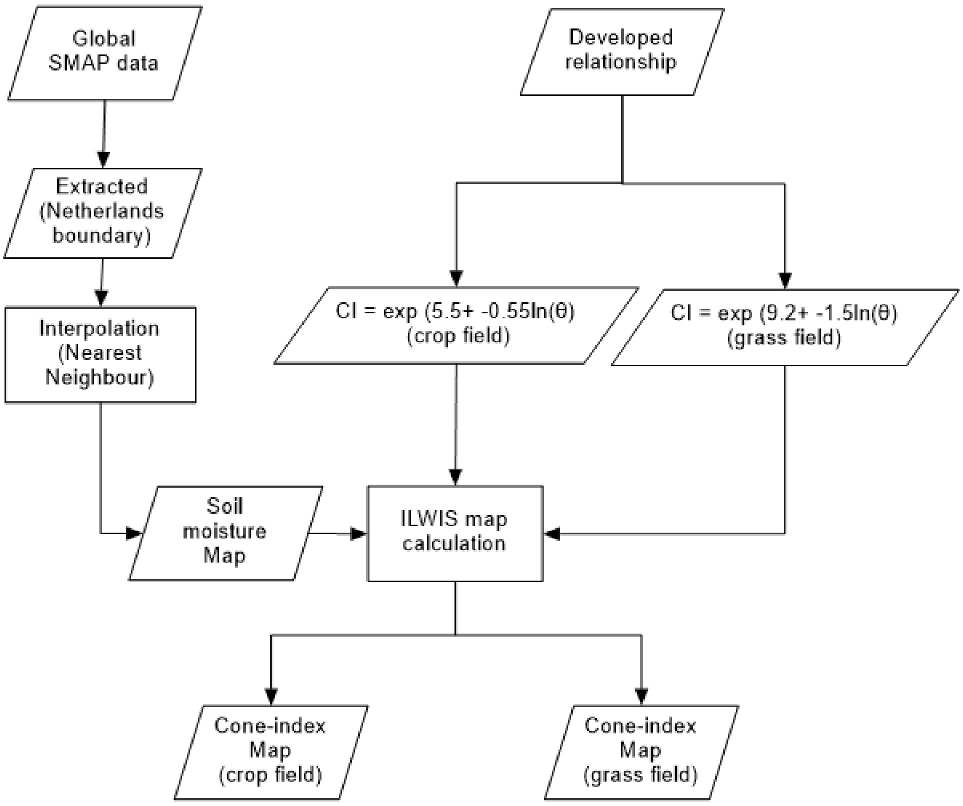

Figure 22: Flow- chart shows the conversion procedure from developed relationship to field trafficability.

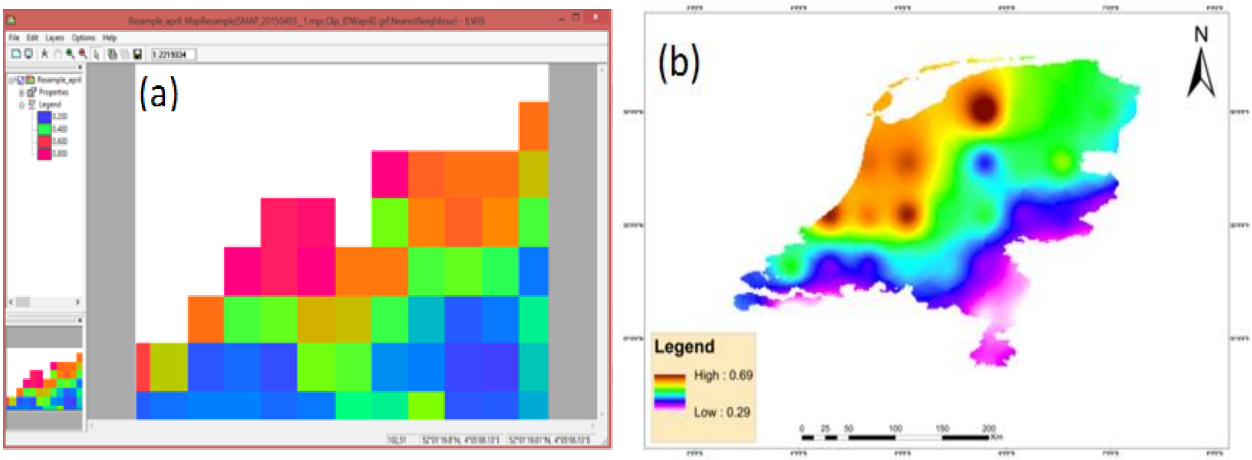

Figure 23: Extracted SMAP result (a) and interpolated continuous soil moisture for entire Netherlands (b) taken as a sample on April 13, 2015.

The estimated field trafficability conditions are easily understandable when considered for specific vehicle condition. From Table 3 vehicle cone index ranges VC_1 and VC_{50} are 26 - 30 & 60-69 respectively for tractors with high contact pressure. These VCI values were taken as a reference as it can more or less represent some of the machinery used for agricultural activities. The predicted cone index was reclassified into three classes as non-trafficable condition (CI< 30), less trafficable (30 <CI <60) and good trafficable condition without causing damage on soil structure (CI >60).

The relation developed for grass field and crop field was applied on SMAP result and produced two different trafficability maps presented on Figure 24(a-h) and annex 3. The non-trafficable condition was observed over a large area in April, November and December at both land cover,a less trafficable condition in August, September and October whereas good trafficability condition observed in May, June and July especially in grass fields.

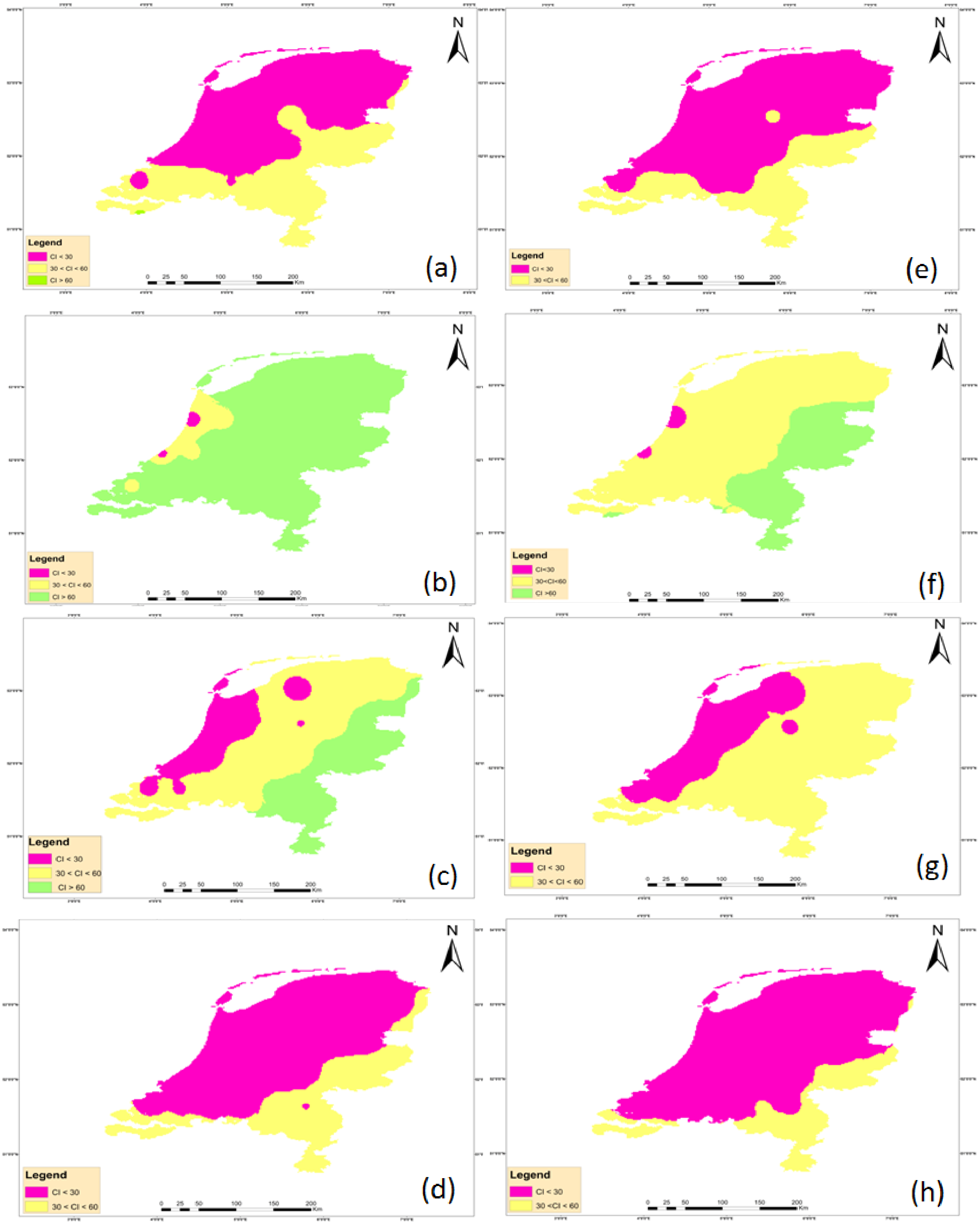

Figure 24: Cone index value predicted from SMAP result of the months April, June, September and December for grass field condition (a, b, c, &d) and crop field (e, f, g, &h) respectively.

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7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

The objective of this study was to quantify the effect of soil moisture on penetration resistance and field trafficability. The relationship between penetration resistance and soil moisture developed based on field measurements. The field data was collected under a variety of conditions of soil texture, organic matter, land cover and agricultural practice. The result shows that the impact of soil texture and organic matter on the relationship was not clearly noticeable as other factors were found to have a more prominent effect. The impact of land cover and agricultural activities has a significant influence on the relationship between penetration resistance and soil moisture. The effect of land cover, as an example on grass field the CI increased beyond normal condition due to additional resistance from grass cover and previous agricultural practices, whereas on crop field ploughing the field create loose soil which extremely reduce CI value. Therefore, land cover is identified as a most important factor affecting field trafficability.

The field data was used to make an estimate of CI by using two models, $CI = \exp(a + b\ln\theta)$ by Flores et al.(2014) and $PR = a\theta^{b}\rho^{c}$ used by Costantini,(1996). The developed relation on the base of field data collection has a better fit with Flores et al. (2014), but there is a significant difference between coefficients estimated based on field data and model. This difference of coefficient value observed mainly due to the difference in agricultural activities practiced between sampling fields for measured data and model observed. The developed relationship was applied on logger station in-situ time series soil moisture data and predicted time series of penetration resistance which shows June, July & august are the months with favourable field trafficability season. Field trafficability on grass field has significance difference on crop field within the same soil moisture range. Based on the result, field trafficability can be applicable without causing significant damage to soil structure when soil moisture nearly less than 0.2 m^3 m^{-3} and 0.30 m^3 m^{-3} for crop field and grass field respectively. SMAP L2 product was used as a demonstration of the designed procedure to visualize spatial variability of field trafficability over entire Netherlands. If you have high spatial resolution soil moisture product this method could be useful for mapping field trafficability.

7.2. Recommendations

Compacted soil and loose surface have a great impact on developing a good relationship between soil moisture and penetration resistance for field trafficability assessment. Agricultural practices (activities) are the major cause of those problems. Based on this problem the following recommendation was formulated.

- ✓ On ploughed crop field, to evaluate the effect compaction on the relationship between penetration resistance and soil moisture the measurement will be taken from sub-surface (10-30 cm).
- ✓ To get a reliable relationship between penetration resistance and soil moisture for field trafficability, measurements should be taken on the field that is free of agricultural interference.
- ✓ Further investigation would be required related to how long the impact of agricultural practice last to come to normal condition.

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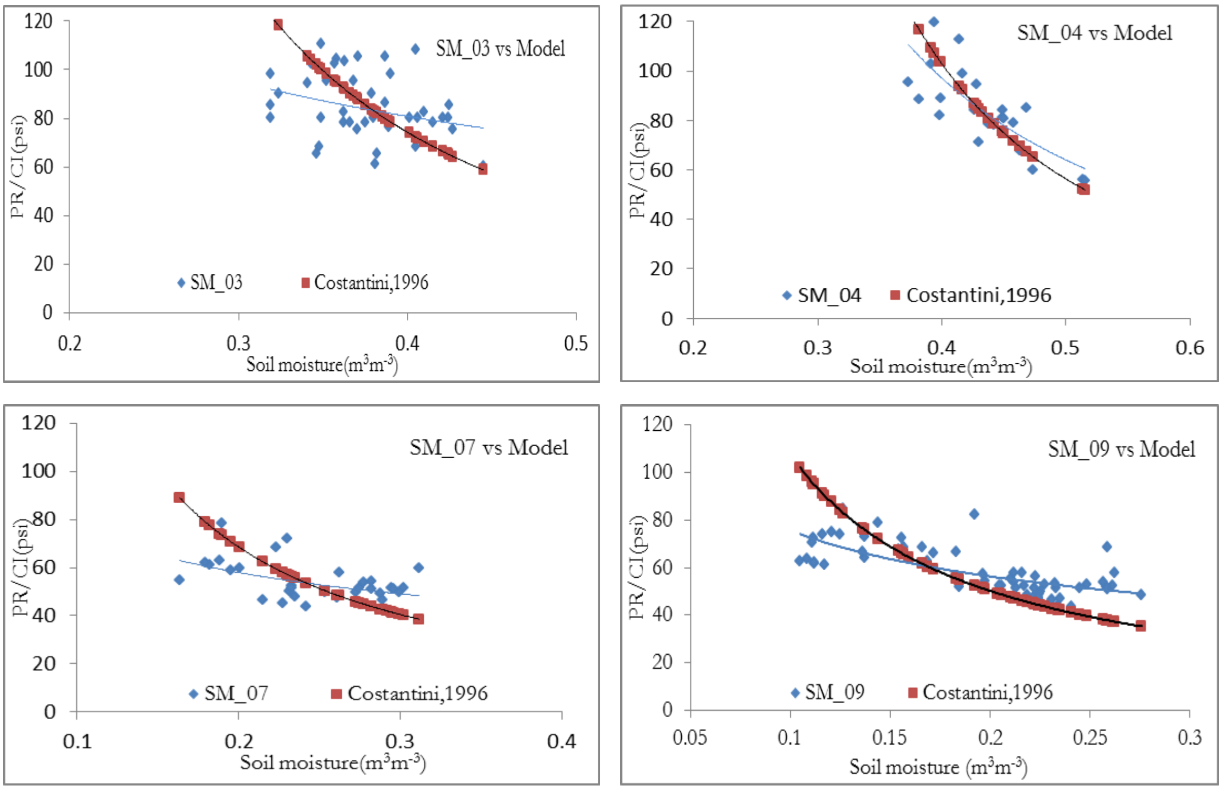
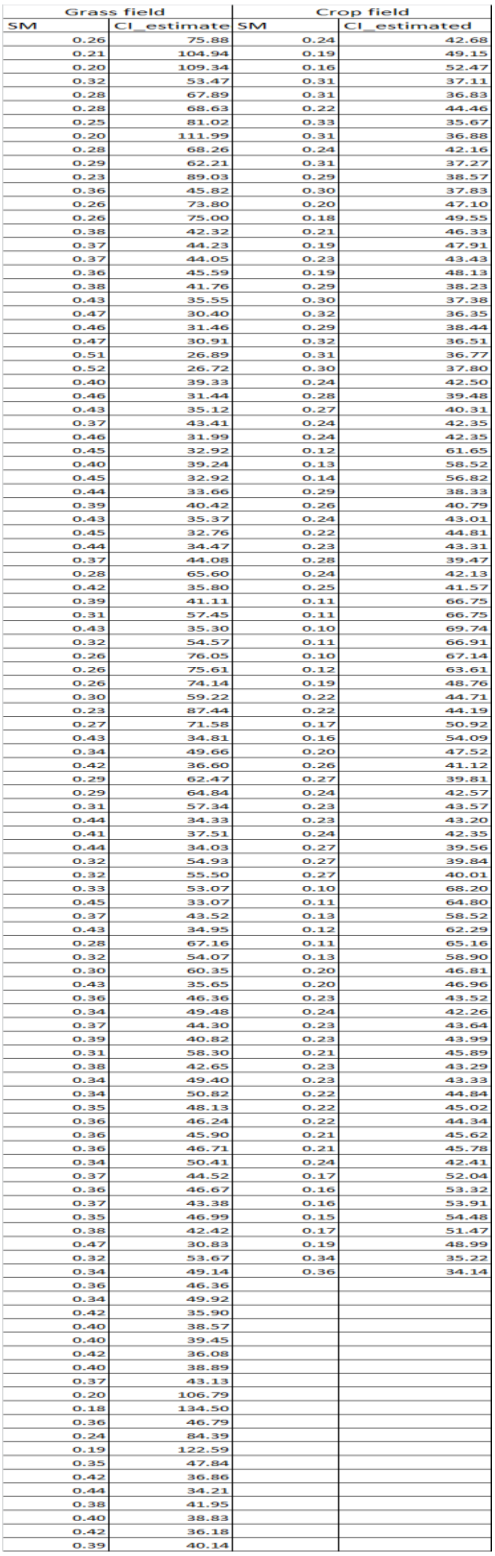
ANNEX

Annex1: Comparing the fit of field measurements data with previously developed model (Costantini,1996)



Annex2: table of estimated CI based Flores et al.(2014) model for grass field and crop field as described in section 6.2 and its graph plotted on Figure 18.



Grass field		Crop field	
SM	CI_estimate	SM	CI_estimated
0.26	75.88	0.24	42.68
0.21	104.94	0.19	49.15
0.20	109.34	0.16	52.47
0.32	53.47	0.31	37.11
0.28	67.89	0.31	36.83
0.28	68.63	0.22	44.46
0.25	81.02	0.33	35.67
0.20	111.99	0.31	36.88
0.28	68.26	0.24	42.16
0.29	62.21	0.31	37.27
0.23	89.03	0.29	38.57
0.36	45.82	0.30	37.83
0.26	73.80	0.20	47.10
0.26	75.00	0.18	49.55
0.38	42.32	0.21	46.33
0.37	44.23	0.19	47.91
0.37	44.05	0.23	43.43
0.36	45.59	0.19	48.13
0.38	41.76	0.29	38.23
0.43	35.55	0.30	37.38
0.47	30.40	0.32	36.35
0.46	31.46	0.29	38.44
0.47	30.91	0.32	36.51
0.51	26.89	0.31	36.77
0.52	26.72	0.30	37.80
0.40	39.33	0.24	42.50
0.46	31.44	0.28	39.48
0.43	35.12	0.27	40.31
0.37	43.41	0.24	42.35
0.46	31.99	0.24	42.35
0.45	32.92	0.12	61.65
0.40	39.24	0.13	58.52
0.45	32.92	0.14	56.82
0.44	33.66	0.29	38.33
0.39	40.42	0.26	40.79
0.43	35.37	0.24	43.01
0.45	32.76	0.22	44.81
0.44	34.47	0.23	43.31
0.37	44.08	0.28	39.47
0.28	65.60	0.24	42.13
0.42	35.80	0.25	41.57
0.39	41.11	0.11	66.75
0.31	57.45	0.11	66.75
0.43	35.30	0.10	69.74
0.32	54.57	0.11	66.91
0.26	76.05	0.10	67.14
0.26	75.61	0.12	63.61
0.26	74.14	0.19	48.76
0.30	59.22	0.22	44.71
0.23	87.44	0.22	44.19
0.27	71.58	0.17	50.92
0.43	34.81	0.16	54.09
0.34	49.66	0.20	47.52
0.42	36.60	0.26	41.12
0.29	62.47	0.27	39.81
0.29	64.84	0.24	42.57
0.31	57.34	0.23	43.57
0.44	34.33	0.23	43.20
0.41	37.51	0.24	42.35
0.44	34.03	0.27	39.56
0.32	54.93	0.27	39.84
0.32	55.50	0.27	40.01
0.33	53.07	0.10	68.20
0.45	33.07	0.11	64.80
0.37	43.52	0.13	58.52
0.43	34.95	0.12	62.29
0.28	67.16	0.11	65.16
0.32	54.07	0.13	58.90
0.30	60.35	0.20	46.81
0.43	35.65	0.20	46.96
0.36	46.36	0.23	43.52
0.34	49.48	0.24	42.26
0.37	44.30	0.23	43.64
0.39	40.82	0.23	43.99
0.31	58.30	0.21	45.89
0.38	42.65	0.23	43.29
0.34	49.40	0.23	43.33
0.34	50.82	0.22	44.84
0.35	48.13	0.22	45.02
0.36	46.24	0.22	44.34
0.36	45.90	0.21	45.62
0.36	46.71	0.21	45.78
0.34	50.41	0.24	42.41
0.37	44.52	0.17	52.04
0.36	46.67	0.16	53.32
0.37	43.38	0.16	53.91
0.35	46.99	0.15	54.48
0.38	42.42	0.17	51.47
0.47	30.83	0.19	48.99
0.32	53.67	0.34	35.22
0.34	49.14	0.36	34.14
0.36	46.36		
0.34	49.92		
0.42	35.90		
0.40	38.57		
0.40	39.45		
0.42	36.08		
0.40	38.89		
0.37	43.13		
0.20	106.79		
0.18	134.50		
0.36	46.79		
0.24	84.39		
0.19	122.59		
0.35	47.84		
0.42	36.86		
0.44	34.21		
0.38	41.95		
0.40	38.83		
0.42	36.18		
0.39	40.14		

Annex3: Cone index value predicted from SMAP result of the months May, July, August, October and November for grass field condition (a, b, c, d & e) and crop field (f, g, h ,i & j) respectively.