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Measurement of Soil Matric Potential using a Simple Soil Moisture Meter

Mari TAKEUCHI* and Yoshitaka KUROSE

Western Region Agricultural Research Center, National Agriculture and Food Research Organization, Zentsuji, Japan

Abstract

In this study, we aimed to determine a method for measuring soil matric potential using a simple soil moisture meter (SSMM) with a contact material, such as silt loam. Silt loam as a contact material ensured water continuity between the sensor of the SSMM and the soil, enabling it to function correctly. The SSMM indicator was consistent with measurements from a conventional soil water potential sensor; thus, the soil matric potential could be estimated across multiple fields with different soil types, with an RMSE accuracy of 61-203 kPa. These results demonstrate the potential of the SSMM to estimate soil matric potential below –50 kPa (above pF 2.7) and highlight its utility as a practical field-measuring instrument.

Discipline: Agricultural Environment
Additional key words: air infiltration, citrus, silt loam, water continuity

Introduction

Citrus, soybean, and other crops are often cultivated in dry fields in Japan; citrus, in particular, requires drought stress to boost its sugar content. This is typically achieved by growing citrus in well-drained, sandy soil, with irrigation and mulching sheets to control soil moisture. Soil moisture measurement is crucial to managing crop production. Particularly, soil matric potential (SMP) can be used as an indicator of plants' response to water stress.

A tensiometer is the most commonly used device for measuring SMP in the field, but it cannot be used in dry soils because the air trapped in the porous ceramic cup forms microscopic bubbles that expand and eventually enter the pipe (Bittelli 2010, Whalley et al. 2013). The air-entry value of a typical porous ceramic cup is approximately –50 kPa (Kurose 2010), making the tensiometer ineffective for use in citrus dry fields. Therefore, a new measuring device suitable for dry soil is needed. The device should be user-friendly under field conditions and not require electrical power or specialized skills. Additionally, it should be relatively inexpensive and readily available, as soil moisture varies significantly within a field and must be measured at multiple points.

Kurose (2010) developed a simple soil moisture meter (SSMM) that can be used to estimate soil dryness levels (not SMP) in dry soil. The SSMM is commercially available and has been validated as a measuring device for citrus water stress (Kurose et al. 2016). It has also been used as an irrigation indicator for beans (Sugimoto et al. 2023), but it is unknown whether the meter can be used to measure SMP beyond the range of a tensiometer. Some reports indicated that SSMM could not be used in citrus orchard soils containing a high proportion of coarse sand and gravel. This measurement error may be due to the gap between the porous cup and coarse-textured soils with large particles, such as sand and gravel, which disrupted water continuity.

In this paper, we present a method for measuring soil matric potential using an SSMM, even in sandy soils. We modified the SSMM by incorporating permeable material and compared its performance with that of an SMP sensor. Therefore, the objective of this study was to evaluate the capacity of the modified SSMM to overcome the key limitation of tensiometers in field applications.

*Corresponding author: takeuchi.mari933@naro.go.jp
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Materials and methods

1. Materials and design of SSMM

An SSMM consists of a porous cup, pipe joint, graduated PVC pipe, and silicone stopper, as shown in Figure 1. The SSMM is inserted into the ground to a depth where the pipe joint remains above the surface. Afterward, the PVC pipe is filled with water and sealed with a silicone stopper before measurements begin. A porous cup of SSMM is the same as the cup used in tensiometers and allows air to pass when the pressure falls below approximately –50 kPa. The porous cup is manufactured by Nikkato Corp. (Osaka, Japan). As the soil dries under –50 kPa (pF 2.7), the water level in the PVC pipe decreases in response to the SMP. The graduated PVC pipe has a scale starting from 0.5 cm from the top. The user can check this water level reduction by examining the scale of the graduated PVC pipe, which indicates soil dryness. The design and principles of the SSMM are detailed in Kurose (2010). The commercially available model, designed for long-term field observations (one week or more), has a graduated PVC pipe with an inner diameter of 25 mm. In our pot experiment, the SSMM was fabricated using a PVC tube with an inner diameter of 13 mm to detect small changes.

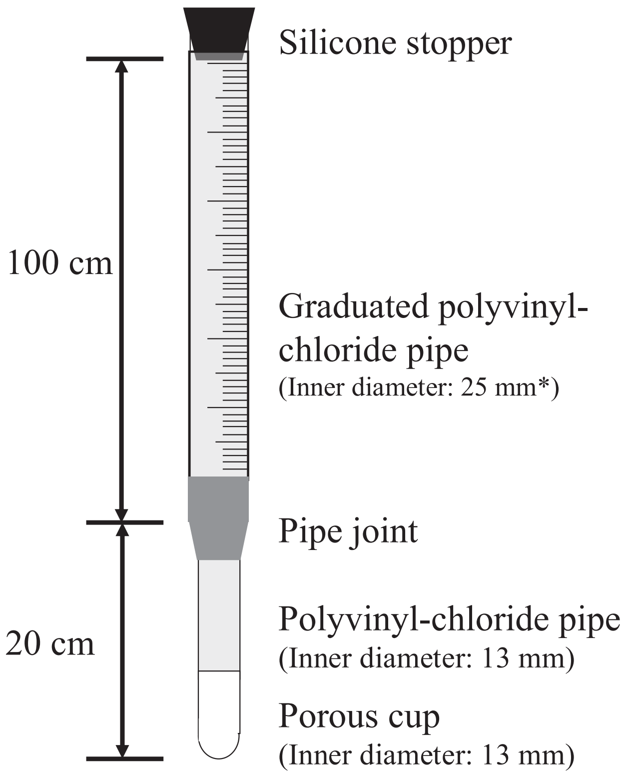

Fig. 1. Schematic diagram of SSMM

* The commercially available model has a 25-mm pipe, and the custom model in the pot experiment has a 13 mm pipe.

A fine-particle permeable material was introduced to maintain water continuity between the sandy soil and the SSMM porous cup. A commercially available silt loam (Arakidatsuchi) was used as the permeable contact material. The particle size distribution of Arakidatsuchi, according to the USDA (United States Department of Agriculture) system, was 7% clay, 60% silt, and 33% sand (Soil Science Division Staff 2017). A preliminary test was conducted to determine the extent of water diffusion in the silt loam. A porous cup was placed in the silt loam for 24 hours, and the maximum extent of water diffusion, as indicated by soil color changes, was within 3.5 cm of the cup center. Based on this result, it was determined that installing silt foam within 3.5 cm of the porous cup allowed water to seep from the porous cup into the surrounding soil. Therefore, in our experiment, the SSMM was installed so that the porous cup was centered within a silt loam layer with a diameter of 6 cm and a height of approximately 10 cm, with the silt loam extending 3 cm-5 cm above and below the cup center. The silt loam layer was prepared by inserting a round steel pipe (inner diameter: 6 cm) into the soil to a depth of 23 cm. The pipe was then removed, and the soil drawn out to create a hole. The bottom 10 cm of the hole was filled with silt loam, and the SSMM was pressed into the silt loam before backfilling with the original soil.

2. Experiments

(1) Application of silt loam as the contact material for measuring SSMM in sand

A pot experiment was conducted to test the utility of silt loam as a contact material. A two-year-old Miyagawa-wase satsuma mandarin (*Citrus unshiu* Marc.) tree was transplanted into a Wagner pot (1/2,000 a, 300 mm high) filled with sand (90% coarse sand, 8% fine sand classified according to the USDA system) on 15 March 2021 and placed in a greenhouse. Two SSMMs (inner diameter of the PVC pipe: 13 mm) were installed diagonally across the tree, and a soil water potential sensor (TEROS21; METER, WA, USA) was installed orthogonally to the SSMMs to a depth of 20 cm in the pot. The SSMMs were installed with two treatments: (i) a porous cup covered with silt loam and (ii) a porous cup without silt loam. In the first treatment, silt loam was packed around the porous cup with a diameter of 6 cm to a depth of 10 cm. The water levels of the SSMMs were visually checked and recorded daily at 7:00 and 16:00, starting from 19 July to 31 July 2021. The SSMMs were refilled with water every day after the water level was checked. The SMP measured using the TEROS21 was recorded hourly using a data logger (CR200X; Campbell

Sci., UT, USA). The pot was irrigated daily (0.8 L /day) from transplanting day to 19 July using a dripper hose (UniRam RC; Netafim, Tel-Aviv, Israel). The irrigation was halted from 19 July to 24 July.

(2) Field measurement of the SSMM and water potential sensor with contact material

In this study, a field experiment was conducted at the Ikano citrus field of the National Agriculture and Food Research Organization in Zentsuji, Japan (lat 34° 12′ 47″ N. long 133° 47′ 11″ E. elevation 65 m). The soil at the study site consists of gravelly loamy sand (3% clay, 8% silt, 55% sand, 34% gravel classified according to the USDA system).

Even if the filled silt loam maintains water continuity between the target soil and the porous cup, the method of measuring SMP via the filling of silt loam is not valid unless the SMP of the filled silt loam and the target soil are equal. To confirm the effect of silt loam on SMP measurement, two soil water potential meters (TEROS21) and two SSMMs (inner diameter of the PVC pipes: 25 mm) were installed diagonally across the citrus tree at a depth of 20 cm in the soil, approximately 50 cm from the edge of the base of the tree, as shown in Figure 2. As in the pot experiment, these sensors were arranged with two treatments: one was installed with silt loam in an area of 6 cm diameter and 10 cm in height, whereas the other was installed directly in the field without silt loam. The direct installation followed the procedure recommended by METER (METER 2023): the target soil was moistened and firmly compacted to cover the entire sensor disk.

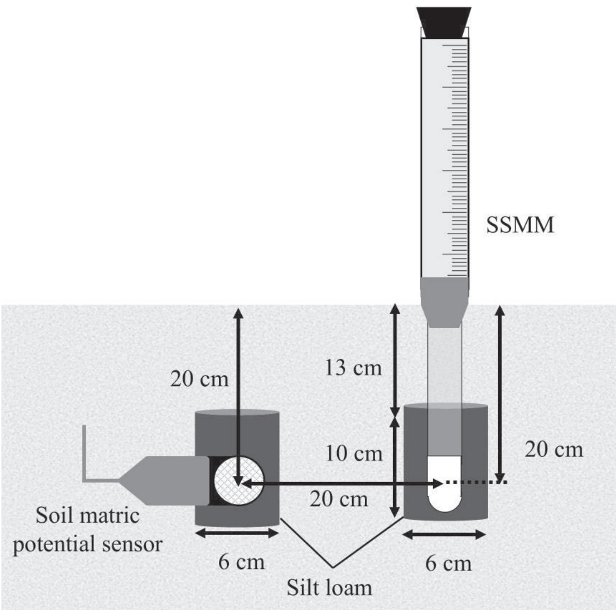

Fig. 2. Explanation of the sensor with silt loam installation in the field experiment

This sensor setup was installed 50 cm away from the base of a tree, with an identical setup without silt loam installed on the opposite side of the tree.

To confirm variation within the same field, the SSMM with silt loam and the TEROS21 without silt loam were installed at three different locations. The locations were approximately 10 m apart. The reason for comparing the SSMM with contact material and the TEROS21 without contact material is explained in the Results and Discussion section.

The water levels in the SSMM were recorded at 7:00 every week. The daily water level reduction was calculated by dividing the total weekly reduction by the number of days elapsed. The SMP was recorded hourly using a data logger (CR200X; Campbell Sci., UT, USA). The measurement period was from 15 July 2021 to 4 October 2021.

(3) Field application of the SSMM for estimating soil matric potential

To compare measurements obtained from a SSMM and a TEROS21, the SMP measured with TEROS21 in the field experiment was averaged over the corresponding measurement period and compared with the SSMM water-level reductions. Based on the relationship between the SSMM and TEROS21 measurements, a conversion formula was derived to estimate SMP from daily water-level reductions. The intercept was set to –50 kPa, which is the commonly referred air infiltration value of the porous cup (Kurose 2010). The formula was not applied when the water level remained unchanged.

To validate the applicability of this conversion formula across different years, the value was applied to the SSMM water level reductions measured in the same field in the following year (2022). Furthermore, to verify whether the conversion formula could be applied to fields with different soil conditions, the same sensor setups (SSMM and TEROS21) were installed in two different fields. The field where the formula was created was designated as Field A, and the other fields were designated as Fields B and C. The soil types of Field B (5% clay, 52% silt, and 43% sand) and Field C (4% clay, 44% silt, and 52% sand) were silt loam (classified according to the USDA system). The measurement method was the same as in Field A in 2021, and the measurement period was from 30 June 2022 to 30 September 2022.

Results and discussion

1. Application of silt loam as the contact material for SSMM measurement in sand

In the pot experiment, the water level of the SSMM (inner diameter of the PVC pipe: 13 mm) with silt loam responded to irrigation management. After irrigation was stopped on 19 July, the water level decreased at a rate of 90 cm per day, but it did not decrease further when irrigation resumed between July 24 and 28 (Fig. 3). In contrast, the SSMM without silt loam did not detect any noticeable changes in water level during the experiment. This result suggests that the lack of water continuity between the sand and the porous cup inhibited water release. In contrast, while using soil such as silt loam, which contains a high proportion of fine particles (clay and silt smaller than sand), as contact material, water continuity between sand and porous cup was preserved, allowing the water level of the SSMM to drop.

The SMP measured using the TEROS21 closely corresponded to the water-level reduction measured with the SSMM with silt loam (Fig. 3). This suggests that the SSMM with silt loam more accurately reflects actual soil moisture conditions than the SSMM without silt loam. This indicates that silt loam can serve effectively as contact material to maintain water continuity between the sand and a porous cup.

2. Field measurement of the SSMM and water potential sensor with contact material

The water level reductions of the SSMM with and without silt loam followed the same pattern as that observed in the pot experiment: the SSMM with silt loam showed water level changes, whereas the SSMM without silt loam showed almost no change (Fig. 4). At SMP below –100 kPa, TEROS21 measurements were consistent with those of the SSMM with and without silt loam (Fig. 5). The precipitation on 8 August caused the soil to become wet after it had dried out during the non-rain

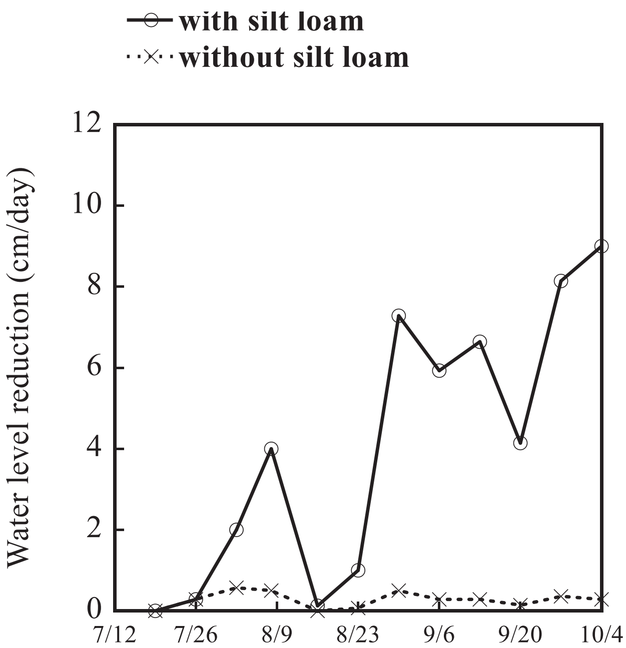

Fig. 4. Daily variations in the water level reduction of the SSMM with and without clay loam in the field experiment

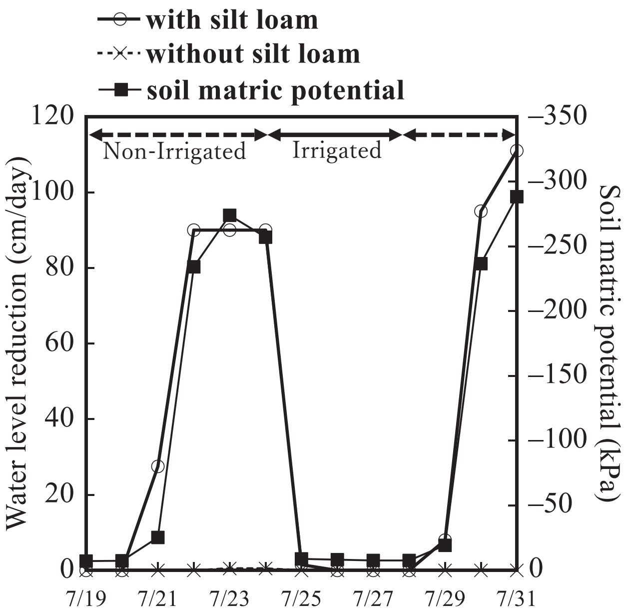

Fig. 3. Daily variations in the water level reduction of the SSMM with and without clay loam and soil matric potential in the pot experiment

The irrigation period is indicated with arrows. The inner diameter of the PVC pipe used in the SSMM is 13 mm.

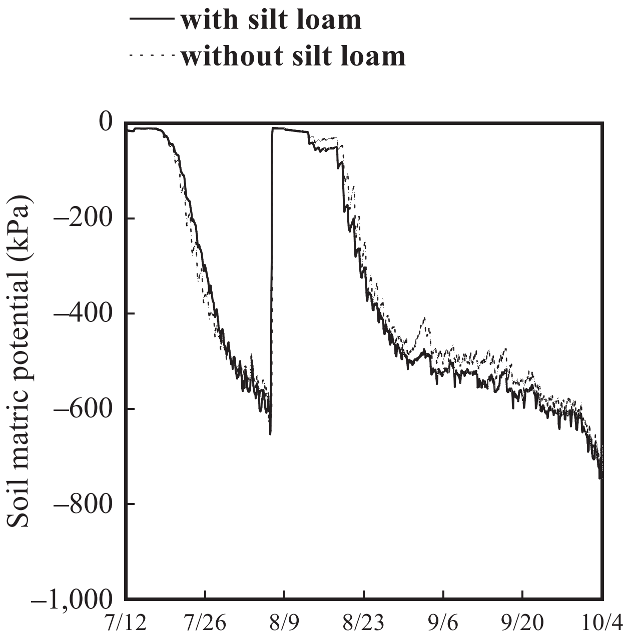

Fig. 5. Hourly variations in the soil matric potential using TEROS21 with and without clay loam in the field experiment

period. This process could be captured by both TEROS21 with and without silt loam. At most, the difference between with and without silt loam was approximately 60 kPa. Considering the measurement accuracy of TERSO21 (± 10%, METER 2023), this difference was determined to be within the margin of error. These findings suggest that silt loam can ensure water continuity between the porous cup of the SSMM and the target soil in fields with sandy or gravelly soils, where maintaining water continuity is difficult. Furthermore, the SMP of the target soil could be estimated from the water-level reduction observed in the SSMM with silt loam.

3. Field application of the SSMM for estimating soil matric potential

The water level reduction of the SSMM with silt loam was compared to the SMP measured using TEROS21 without silt loam because there was no significant difference between the SMP measured using TEROS21 with or without silt loam. Correlation analysis revealed a significant negative correlation between the two variables (water level reduction of the SSMM with silt loam and SMP measured using TEROS21 without silt loam), with a correlation coefficient of –0.871 (Fig. 6). Therefore, water level reduction may be used to estimate SMP. The conversion formula based on this relationship is as follows:

$$y = -74.0x - 50$$

where y is the SMP and x is the water level reduction of the SSMM. Its coefficient of determination was estimated to be 0.759 (Fig. 6).

Although the converted values tended to underestimate the SMP during the dry period in early August (Fig. 7A), data from a single year seem sufficient to generate a conversion formula that can be applied to subsequent years to approximate SMP measurements in the field in the following year (Field A). The root mean square error (RMSE) calculated between the measured value and the converted value in Field A was 203 kPa. Compared to the findings in Field A, the RMSE in Field B was 172 kPa, and the converted values tended to overestimate the potential (Fig. 7B). In Field C, the soil did not tend to be dry, and the RMSE was 61 kPa because the SMP remained at –300 kPa or higher (Fig. 7C).

These results indicate that an SSMM can effectively estimate the approximate variation of SMP using the conversion formula, even in fields with different soil types, because the water level reduction of the SSMM depends on the SMP. The measurement accuracy of TEROS21 used in this study was ± 10% (METER 2023), and a similar level of accuracy would probably be needed to develop a usable sensor for research experiments. Therefore, the developed SSMM is not a research-level measuring instrument. However, it can be considered valid for capturing the general trend of soil matric potential in agricultural fields, particularly when specialized equipment such as power supplies or data loggers are not available.

Conclusion

In this study, we demonstrated that water continuity could be maintained even in dry sand by installing an SSMM with silt loam around a porous cup. We also showed that the SMP of the filled silt loam closely matched that of the surrounding soil. In addition, we proposed a formula to calculate SMP from the daily water-level reduction in the SSMM. These results indicated that an SSMM with contact material can monitor SMP beyond the measurement range of tensiometers. Furthermore, regardless of soil type, the measured values were consistent with those obtained from conventional water potential sensors. Taken together, these findings highlight the potential of the SSMM as a simple tool for measuring SMP below –50 kPa.

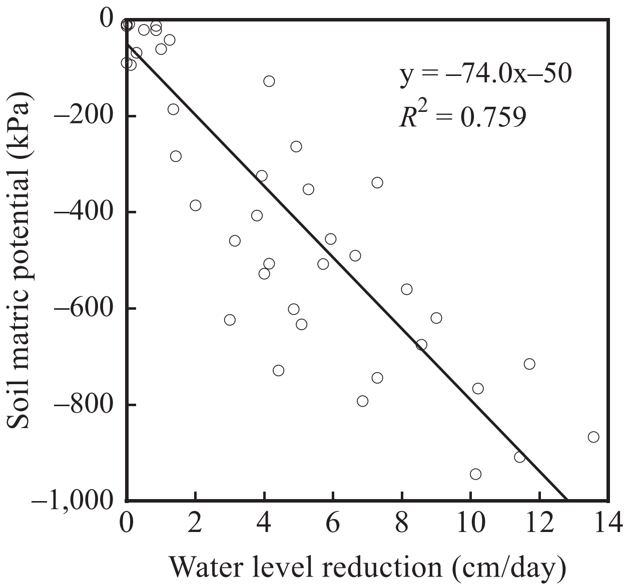

Fig. 6. Relationship between the SSMM water level reduction and the soil matric potential
This figure includes data from three locations in the same field.

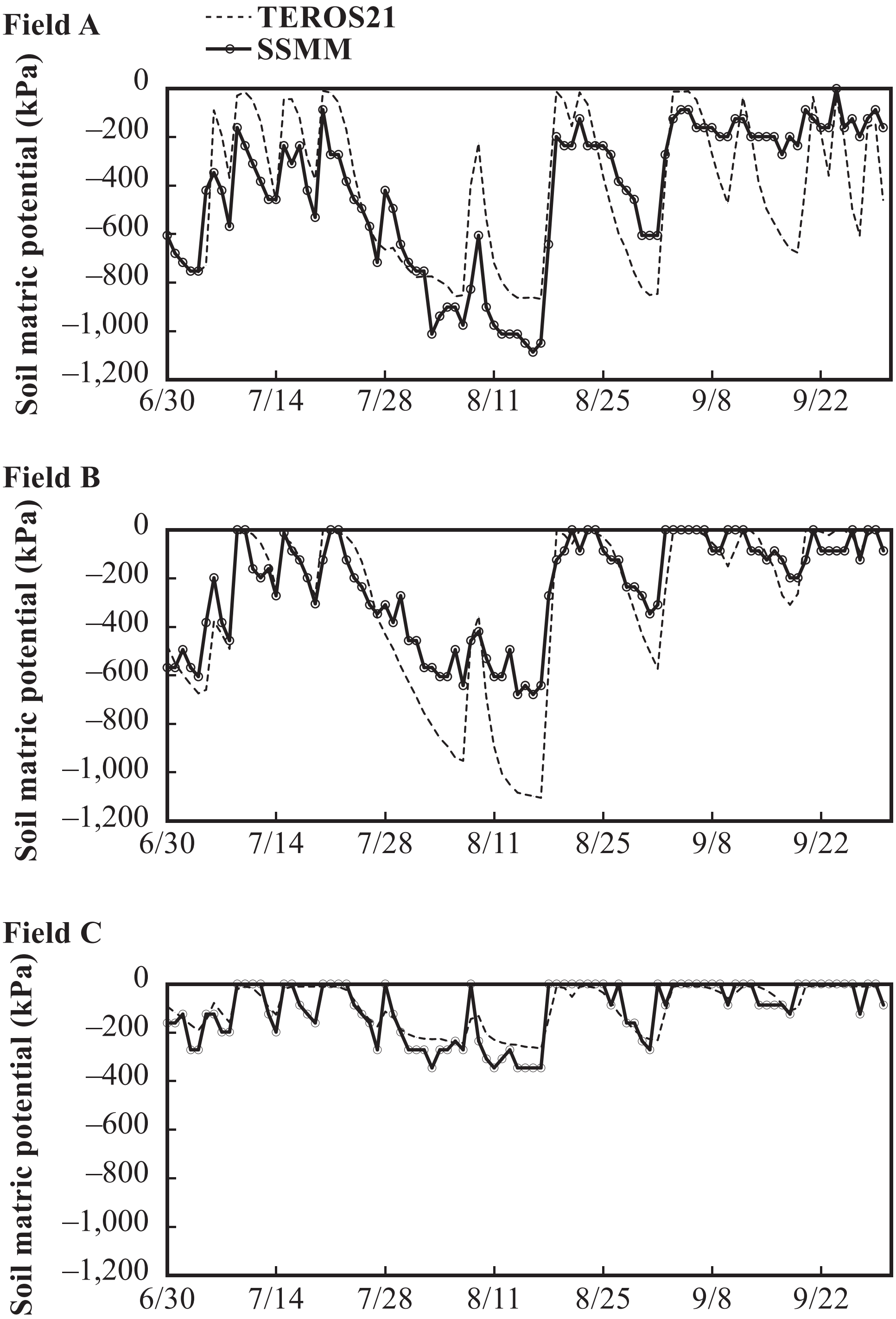

Fig. 7. Comparison between the SSMM and the soil matric potential sensor in Fields A, B, and C

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