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SMEX02: Field scale variability, time stability and similarity of soil moisture

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Abstract

Evaluation of air- or space-borne remote sensors measuring soil moisture requires strategic ground-based sampling. As part of the Soil Moisture Experiment 2002 (SMEX02), daily surface soil moisture sampling at 90–140 locations were conducted in four fields in Walnut Creek watershed, Iowa. Various combinations of soils, vegetation, and topography characterize the fields. Depending on the field's characteristics and soil moisture content, 3–32 independent measurements were necessary to capture the field mean volumetric soil moisture with a ± 2% bias and 95% confidence interval. Validation of the retrieved soil moisture products from the aircraft microwave instruments using the average of 14 samples per field is more appropriate for dry (< 10% volumetric soil moisture) or wet (>25% volumetric soil moisture) range than for intermediate soil moisture range. Time stability analysis showed that an appropriately selected single sampling point could provide similar accuracy across a range of soil moisture conditions. Analyses based on landscape position (depression, hilltop, steep slope, and mild slope) showed that locations with mild slopes consistently exhibit time stable features. Hilltop and steep slope locations consistently underestimated mean field soil moisture. Soils parameters could not be used to identify time stable features as sampling locations with relatively high sand content consistently underestimated the field mean while those locations with relatively high clay content consistently overestimated the field mean. However, the slope position characterization of time stable features was enhanced using soils properties. The mild slope locations having the best time-stable features are those with moderate to moderately high clay content as compare to the field average (28–30% clay).
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1. Introduction

Surface soil moisture structure and evolution affect surface and subsurface runoff, land surface and atmosphere feedback, and groundwater recharge. Routine availability of derived soil moisture products from existing and pending earth observing satellites will significantly enhance the characterization of the near surface soil moisture state. The soil moisture product validation, algorithm calibration, and application present numerous practical challenges. Both aircraft and satellite products are validated using footprint scale mean values determined from in-situ measurements. This validation approach is challenging as the in-situ sampling is conducted at scales that are orders of magnitude smaller than the sensor footprints and the limited sample size introduces errors in the validation. Sampling errors result from the inherent variability in space that soil moisture exhibits as a function of climatic, topographic, vegetative, and soil properties. The assessment and quantification of in-situ measurement uncertainty is necessary to characterize the microwave instrument measurement capability and retrieval algorithm's robustness and to provide guidelines developing ground sampling protocols for validation experiments. The small-scale variability of soil moisture also limits the practical application of satellite-derived products. Retrieved satellite scale soil moisture is too coarse to provide an understanding of hydrology at field or hill slope scales. The ability to down-scale satellite products requires explicit understanding of soil, topographic, and vegetation effects on soil moisture dynamics.

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Vachaud et al. (1985) postulated that fields maintain spatial patterns of soil moisture through time. If patterns are maintained, then it is possible to minimize the number of observations without significant loss of information. Grayson and Western (1998) found that single points could be used to represent mean soil water dynamics in small watersheds. Kamgar et al. (1993) also found that landscape position may be used to characterize soil moisture variability. At a regional scale, Cosh et al.'s (2004) results support the validity of time stability in the SMEX02. However, Kachanoski and de Jong (1988) indicate that these soil moisture patterns differ based on spatial scale. Results from previous studies such as Chen et al. (1997) during FIFE [First ISLSCP (International Satellite Land Surface Climatology Project) field experiment] and Mohanty and Skaggs (2001) during Southern Great Plains Hydrology 1997 (SGP97) experiments suggest that further studies are required to understand soil moisture dynamics as related to soil, vegetation, and topographic features.

Soil heterogeneity affects soil moisture content through variations in soil texture, soil water holding capacity, soil color, soil water retention, and pixel- and pore-scale hydraulic properties. Hawley et al. (1983) found that surface texture significantly influences soil moisture, while Brutsaert and Chen (1995) identified a two-stage soil drydown process where the transition between stages depends on soil properties. Soil heterogeneity also influences small-scale variability through vadose zone water dynamics with stronger effects on loamy soils than sand (Kim & Stricker, 1996; Kim et al., 1996). For SGP97 fields in Oklahoma, Mohanty and Skaggs (2001) found that fields with sandy loam soils had better time stability than those containing silt loam soils.

Land cover characteristics including canopy cover, root characteristics, and litter depth influence runoff, interception and evapotranspiration processes, and in turn, the soil moisture dynamics. Root water extraction, based on rooting depth and distribution, redistributes soil water in three dimensions. A plant's surface albedo controls the net energy available to the plant. Leaf distribution and leaf area index (LAI) control the partitioning of available energy between the soil surface and the vegetation due to solar radiation extinction. Hawley et al. (1983) suggested that vegetative cover reduces soil water variability resulting from topographic features. Based on data collected in three watersheds in Russia, Vinnikov et al. (1996) also found that vegetation differences influenced the spatial structure of soil moisture. Moreover for a field with relatively uniform soil properties and flat topography, Mohanty et al. (2000a) found that tillage and crop growth cycles controlled the evolution of soil moisture spatial structure during SGP97.

Besides soil and vegetation, topography plays a dominant role for small catchments and hillslopes (Mohanty et al., 2000a,b; Western & Blöschl, 1999; Western et al., 1998, 1999) as it provides lateral pathways that contribute to the nonstationarity of soil moisture fields. At the field scale, Hawley et al. (1983) identified topography as the most significant feature in soil moisture spatial structure and during FIFE, Charpentier and Groffman (1992) found that field variability increased with increasing topographic heterogeneity. At the watershed scale, Western et al. (1999) found soil moisture spatial structure was related to wetness indices based on topography and upslope drainage area. For the SGP97 fields, Mohanty and Skaggs (2001) found that flat topography had the poorest time stability indicating temporal variations are not discernable across space at field scales.

In this study, we use high-resolution ground sampling to investigate the time stability features of surface soil moisture and associated physical properties for four adjacent fields of the airborne polarimetric scanning radiometer (PSR) instrument during the Soil Moisture Experiment 2002 (SMEX02) in Iowa. The primary goal was to characterize the validation errors caused by in situ measurements, provide guidelines for future field campaigns seeking to validate remote sensing measurements, and identify the role of characteristic soil, vegetation, and topographic features on the measured field scale variability. As adjacent fields are studied, climate influences are assumed to be homogeneous across the fields as the precipitation correlation length scale is larger than the study area comprising the four fields. The soil moisture content (mean and variation) of time stable locations for the prediction of soil moisture at the field scale is investigated. A secondary goal was to investigate the extent of spatial organization of soil moisture while identifying time stable locations within the four fields. Analyses identify relationships among sampling location stability and physical (soil, topography, and vegetation) parameters.

2. Study region

SMEX02 was a large-scale soil moisture experiment conducted in cooperation with the National Aeronautic and Space Administration (NASA), the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS), and other federal agencies and universities. SMEX02 was conducted in the Walnut Creek watershed and surrounding areas of Ames, IA. A detailed description of the SMEX02 experiment including the mission objective, experiment plan, and regional description can be found at http://hydrolab.arsusda.gov/smex02.

The Walnut Creek watershed, south of Ames, was the focus of watershed-scale sampling during SMEX02. In this 100 km^2 watershed, hydrologic and climatic variables are intensely monitored by the USDA National Soil Tilth Laboratory (NSTL). The regional climate is classified as humid with an average annual precipitation of 835 mm. Derived from Wisconsin age glacial till soil in the Des Moines lobe, the topography of the region has relatively low relief with poor surface drainage. Digital elevation maps (DEM) from the U.S. Geological Survey (USGS) at 25 m resolution were used to describe topography.

Considerable variability in soil texture is observed in the region ranging from fine sandy loam to clay with the majority classified as silt loam with relatively low permeability. Soil texture data, percentage sand and percentage clay used to represent soil conditions were obtained from the Iowa Soil Properties and Interpretations Database (Iowa State University, 1996). Corn and soybean crops dominate the land cover of Iowa, covering approximately 50% and 40%, respectively.

We selected four fields (WC11, WC12, WC13, and WC14) whose scale matches the ESTAR/2D-STAR airborne remote sensing products that are typically processed to an 800-m resolution (Fig. 1). The geographical location and field attributes for each field are given in Table 1. WC11 is a trapezoid shaped, predominantly corn field with a small patch of soybean planted in a depression located near the western edge of the field; WC12 is a corn field with a strong drainage feature flowing from southwest to northeast; WC13 is a soybean field with rolling topography; WC14 is a broadcast soybean field with rolling topography. WC11–14 (~ 2 × 2 km area) are oriented from north to south on the western edge of the Walnut Creek watershed and experienced similar rainfall and climate patterns. Soil moisture differences between the fields can be expected to be a combination of these characteristics.

To study within-field scale variability and spatial structure, we developed a sampling design using series of transects oriented east–west and north–south located to sample across soil types and topography (shown in Fig. 1).
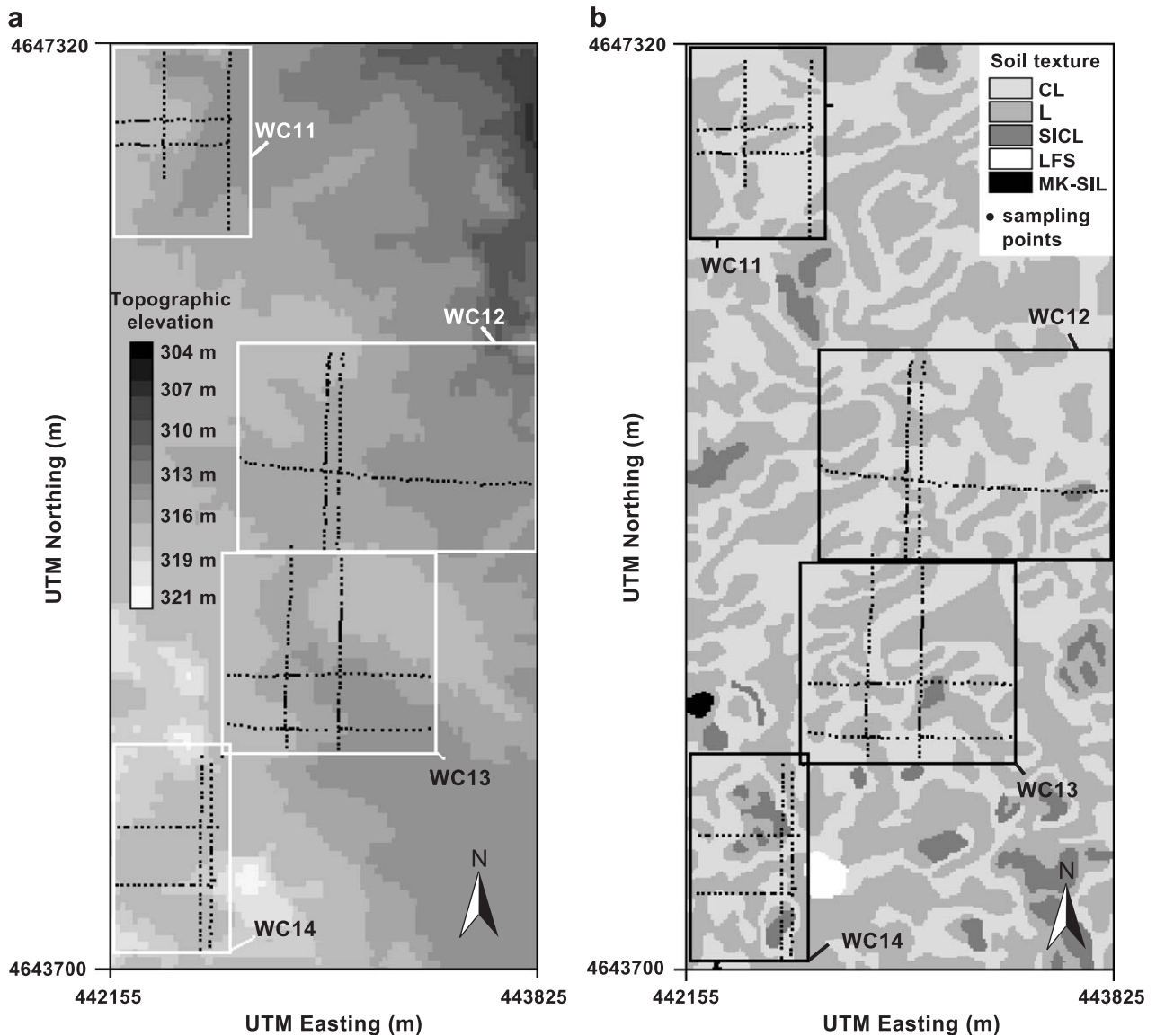

Fig. 1. Transect sampling locations in the sampled fields, WC11, WC12, WC13, and WC14, in the Little River watershed are overlain on maps of (a) topography and (b) soil texture including clay (CL), loam (L), silty clay (SICL), loamy fine sand (LFS), and mucky silt loam (MK-SIL).

Table 1
Geographic locations and field attributes for WC11, WC12, WC13 and WC14 fields

Field	UTM coordinates of the NE corner of the field	No. Sampling Pts.	Soil texture		Crop type	Average NDVI		Topography	Drainage features
			Mean % Sand	Mean % Clay		6/28	7/8		
WC11	442,616, 4,647,323	91	24.5	28.6	Corn (Soybeans)	2.41	3.72	Hilltop and slope	No
WC12	443,842, 4,646,096	132	26.1	27.7	Corn	2.54	3.67	Drainage features	Yes
WC13	443,524, 4,645,315	140	26.3	28.6	Soybeans (Rows)	0.65	1.70	Rolling	No
WC14	442,592, 4,644,527	94	24.1	29.5	Soybeans (Broadcast)	2.23	3.22	Rolling	No

Samples were collected at 25 m intervals for valleys and hilltops and with 12.5 m intervals for the length of hill slopes. At least 90 samples were collected per field. Two east–west and two north–south transects were sampled in WC11, WC13 and WC14. In WC12, a single longer east–west and two north–south transects were sampled. The soil heterogeneity, topography, and other site-specific features guided design decisions to capture the within-field variability.

Sampling points were identified using a Global Positioning System (GPS) and flagged. Soil moisture was sampled from 0 to 6 cm using an impedance probe (theta probe soil moisture sensor, type ML2 and HH2 recording device, Delta-T Devices, Cambridge, England). The theta probe uses a simplified voltage standing wave method to determine the relative impedance of the sensor (which consists of four sharpened, 6-cm-long stainless steel rods), or effectively 0–6 cm dielectric constant. The measured impedances were calibrated using gravimetric soil moisture samples. A single calibration curve was determined to be appropriate for all soil types (RMSE = 0.009% VSM). The four probes used for our measurements showed no significant differences based on in-situ tests. The depth of measurement by theta probe is comparable to that observed by L-band microwave remote sensing (ESTAR and 2D-STAR) measurements (Jackson et al., 1993). In situ samples were collected for 13 days while suspending sampling on hazardous weather days, between June 26th and July 10th, 2002. Four two-person teams conducted daily sampling for approximately 3–4 h each afternoon.

3. Methods

Vachaud et al. (1985) introduced the time stability concept to characterize the time-invariant association between spatial location and statistical parametric values of soil properties. Time-invariant probability density functions are assigned to individual locations using temporal analysis of the differences between individual and spatial average. Grayson and Western (1998) and Mohanty and Skaggs (2001), respectively, identified time-stable characteristics of soil moisture on a hill slope and within fields with varying soil, slope and vegetation at ground-sampling sites.

Time-stable point assessment uses $\theta_{i,j,t}$, the volumetric soil moisture content (VSM) at location i in field j and time t, to calculate the field mean as

$$\bar{\theta}_{j,t} = \frac{1}{n_{j,t}} \sum_{i=1}^{n_{j,t}} \theta_{i,j,t} \tag{1}$$

where $t = 1, 2, \ldots, n_t$ (number of dates), $j = 1, 2, \ldots, n_c$ (number of fields), $i = 1, 2, \ldots, n_{j,t}$ (number of sampling points within field j at time t). The mean relative difference and variance of the relative difference for each sampling point are calculated by

$$\bar{\delta}_{i,j} = \frac{1}{n_t} \sum_{t=1}^{n_t} \frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}} \tag{2}$$

$$\sigma(\delta)_{i,j}^2 = \frac{1}{n_t - 1} \sum_{t=1}^{n_t} \left(\frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}} - \bar{\delta}_{i,j} \right)^2 \tag{3}$$

The mean relative difference at a sampling point quantifies the location's bias and, in doing so, identifies whether that location is wetter or drier than the field on average. The variance characterizes the precision of that measurement. The ability to both effectively eliminate systematic bias and accurately capture the field mean at each sampling time is important. Thus, the root mean square error (RMSE) of the relative differences, which includes bias and accuracies metrics, is computed from the mean and variance as

$$\mathrm{RMSE}_{i,j} = \left(\bar{\delta}_{i,j}^2 + \sigma(\delta)_{i,j}^2 \right)^{1/2}, \tag{4}$$

provides a single metric to identify the best sampling locations. Using rank-ordered $\mathrm{RMSE}_{i,j}$ for each field, the point with the highest time-stability is identified as the one with the lowest RMSE. Throughout the remainder of this analysis the term "RMSE" describes the RMSE of the relative differences. This scaling has the advantage of allowing evaluation for the entire range of observed soil moisture values at a field and comparisons among fields. An acceptable RMSE threshold can be used to identify locations within a field that consistently replicate the mean soil moisture within an allowable degree of error. In addition, RMSE can differentiate the relative value of sampling at extremely wet and dry locations based on their variability.

Time stability analysis identifies appropriate sampling points from a suite of existing points. However, a priori selection of appropriate sampling locations requires the ability to identify those locations using available physical parameters. Statistically significant differences among group (based on soil, topography, or drainage class) mean values are identified by conducting an analysis of variance (ANOVA) using a one-way classification (Snedecor & Cochran, 1989). In this study, the term ANOVA refers to a one-way ANOVA that is used to compute the pooled error variance and to provide an F test of the null hypothesis that the population means are equal. The ANOVA is used to identify if significant differences in time stability of soil moisture exist among physical parameters (e.g., soil texture and topography).

4. Results

4.1. Statistical properties of footprint scale soil moisture

Time series of soil moisture (Fig. 2) shows that the individual SMEX02 fields differ both with respect to soil moisture mean and variability. The strongly drained field with higher sand content and corn cover (WC12) is the driest field and also exhibits the lowest variability. During the initial drying sequence at the beginning of SMEX02, corn cover with a lower sand content (WC11) and row cropped soybeans (WC13) were slightly wetter and had much greater variability than the broadcast soybeans with a lower sand content (WC14). This variability decreased throughout the drydown phase. After rainfall, a slight increase in variability was observed for WC12 and WC14, but no change was evident for WC11 and WC13. Fields with no strong drainage patterns (WC11, WC13, and WC14) showed nearly identical average soil moisture values after the July 5th rainfall event. However, the corn field (WC11) dried slower than the soybean fields (WC13 and WC14). This difference likely reflects the corn's higher leaf area index of 4.33 m^2/m^2 for WC11 as compared to 2.01 and 2.96 m^2/m^2 for WC13 and WC14, respectively (Anderson et al., 2004) and the corn's stronger light extinction properties that serve to shade the soil surface and to preferentially partition atmospheric water losses to transpiration over soil evaporation. Thus, soil profile water losses due to evapotranspiration are likely to be more
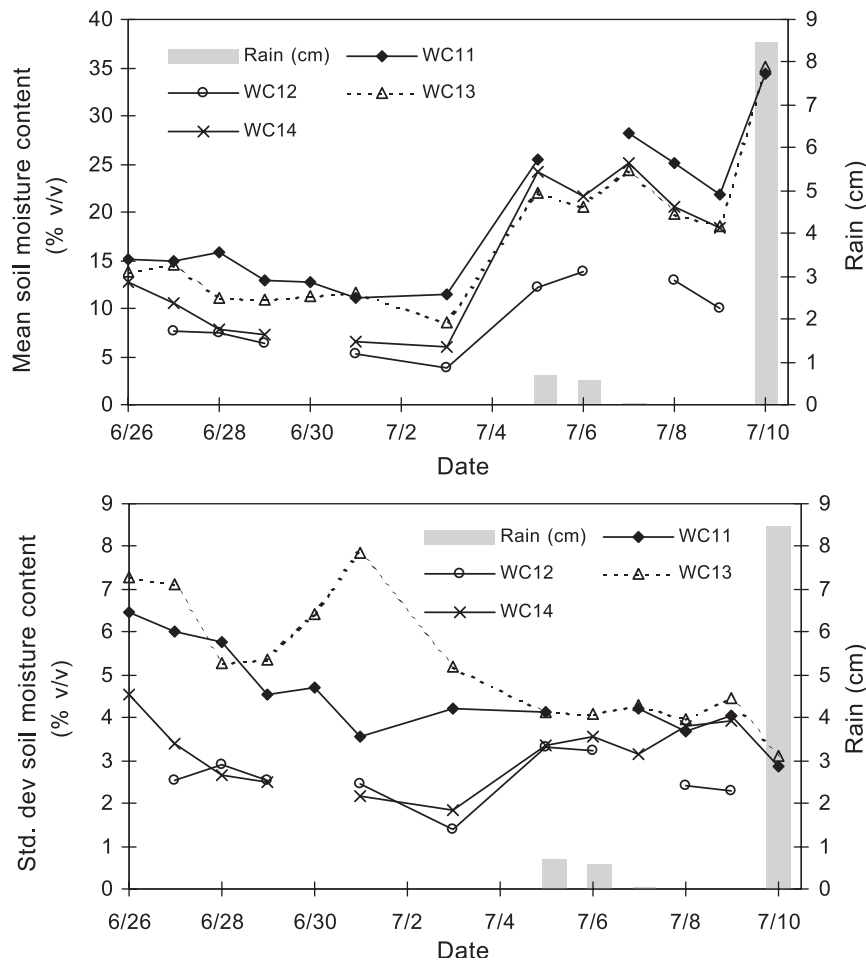

Fig. 2. Mean and standard deviation of volumetric soil moisture content by field during the SMEX02 experiment.

uniformly distributed with depth in the corn fields than the soybean fields.

A relationship between soil moisture variability and field mean becomes evident when standard deviation is scaled by the field mean. The coefficient of variation $(CV = \sigma(\theta)/\theta)$ versus mean soil moisture is well characterized by an exponential fit $CV = A \exp[B\theta]$. Table 2 lists the regression results and the empirical parameters A and B for the four fields. The parameters A and B indicate the relative variability (proportional effect) and the dependence of variability on mean moisture conditions (nonlinearity), respectively. WC13 has the greatest relative variability under dry conditions and a relatively rapid decrease in variability with increasing wet (higher moisture) conditions. In contrast, WC14 has lower variability for dry conditions and a limited decrease with increasing wet conditions.

Having established these parameters, the relationship between mean soil moisture content, confidence interval, and the number of required samples can be quantified. For a significance level α, i.e. with $(1 - \alpha)100\%$ confidence, the error will not exceed a specified volumetric soil moisture content e when the sample size $n = (z_{\alpha/2}\,\sigma/e)^2$ where z is the standard normal variable with exceedence probability $\alpha/2$. Fig. 3a shows the relationship between required sample size and average field soil moisture content within an error of $\pm 2\%$ volumetric soil moisture at a 95% confidence level. Results show that as few as 3 and as many as 32 samples may be required to adequately capture the mean of various fields. Relatively few samples are required for wet and dry conditions as compared to intermediate soil moisture values. The greatest number of samples required to capture the field mean differs by field and occurs when the field mean moisture content is between 12% and 20% VSM. For these conditions, at most eight independent samples are required for WC12 while up to 32 samples are required for WC13.

The ground sampling protocol used to calibrate and validate soil moisture products from aircraft microwave brightness observations during the SGP97, SGP99, and SMEX02 campaigns typically consisted of 14 soil moisture samples per 800 × 800 m field. Using the Table 2 relationships of coefficient of variation versus mean soil moisture, Fig. 3b shows the 95% confidence interval based on the average field soil moisture content when collecting 14 samples per field. Given this sample size, our results suggest that validation of the microwave brightness algorithm is most robust for drier (< 10% VSM) or wetter soil conditions (>25% VSM) than for moderate soil moisture values. Under
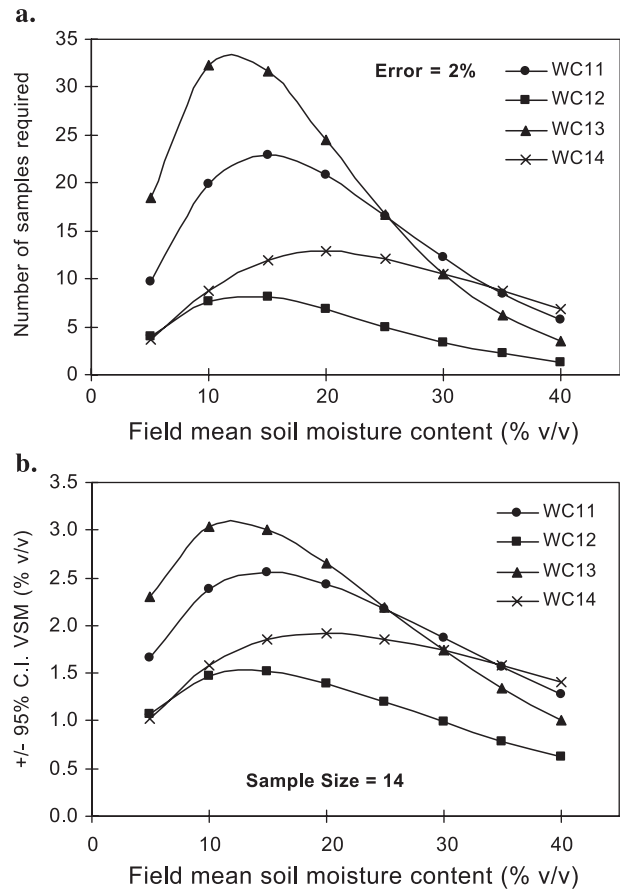

Fig. 3. The modeled relationship between sample size, 95% confidence interval and field mean soil moisture for (a) the number of independent soil moisture samples required to capture the field mean soil moisture content with a 95% confidence interval width of $\pm 2\%$ VSM and (b) one side of the 95% confidence interval as a function of soil moisture content for the 14 sample per field protocol.

moderate moisture conditions, there is considerable uncertainty as to the true mean field soil moisture for those fields with highly variable soil moisture. Thus, the true field mean is better defined for some fields than for others. For example, if the true field mean were 10% VSM, 14 samples from field WC13 would result in $\pm 2.4\%$ VSM, while the same sampling protocol in the neighboring field, WC12, would result in $\pm 1.5\%$ VSM. With respect to sensor validation, a priori knowledge of field-scale variability could be used to select the fields. Posterior knowledge might be used to eliminate highly variable fields from analyses or to incorporate the potential error of the sample mean into validation studies.

In summary, among the four fields, the strongly drained field with higher sand content and row-cropped corn land cover (WC12) requires the fewest independent samples to characterize the field mean behavior for the SMEX02 observation period. The soybean organized in rows (WC13) with rolling topography and higher sand content requires the most number of independent samples. The high biomass, broadcast soybeans with lower sand content

Table 2
Regression relationship between the coefficient of variation (CV) and the mean soil moisture content $(\bar{\theta})$ where $CV = A \exp[B\bar{\theta}]$

Field	A	B	R^2
WC11	0.890	− 0.067	0.91
WC12	0.597	− 0.075	0.75
WC13	1.327	− 0.082	0.92
WC14	0.500	− 0.050	0.89

(WC14) produced relatively low sampling requirements and row-cropped corn with lower sand content (WC11) produced intermediate sampling requirements. Based on these results we infer that, vegetation, cropping practice, soil, and topography jointly control the soil moisture distribution within the Walnut Creek watershed. The decreased variability in field WC13 (rows of soybeans) as compared to WC14 (broadcast soybeans) suggests that the row structure enhances wet and dry distinctions within a soil moisture field. Management practices are an additional factor that may be important for characterizing the within-field variability.

4.2. Time stability of soil moisture and associated physical properties

If a region exhibits time stable characteristics, selection of stable sampling points offers an efficient alternative to random sampling of many points. Fig. 4 shows the time stability characteristics $\delta_{i,j}$ ranked from smallest to largest for each field. Locations having negative $\delta_{i,j}$ values consistently underestimate the field average while locations having positive values consistently overestimate the field average. WC11 and WC14 fields exhibited the greatest time stability with WC14 having the lowest variability. Both WC12 and WC13 exhibit higher variability at sampling locations relative to field mean. Based on Fig. 4, there is a high likelihood of identifying a single time stable sampling location as approximately 13–18% of the locations (12–22 per field) have values that on average capture the field mean

with ± 5% VSM while 27–37% of the locations (32–38 per field) have values that on average capture the field mean with ± 10% VSM. The error bars in Fig. 4 illustrate that the drier points tend to have lower variability and RMSE values than the wetter points. This suggests that improved consistency will result from the selection of slightly drier sampling points. This finding is consistent with Mohanty and Skaggs (2001) for a silty loam soil with gently rolling topography and mixed grassland cover (LW13) in the southern great plains under semi-humid hydroclimatic condition during the SGP97 field experiment.

Among the four fields, the broadcast soybeans with a lower sand content (WC14) produced the best time-stable soil moisture pattern as indicated by the relatively low variability and magnitude of the mean relative difference for all sampling locations. The corn land cover with a lower sand content (WC11) also produced a good time-stable soil moisture pattern. The fields with higher sand content, the corn field with well-defined drainage features (WC12) and the row soybean field with rolling topography (WC13), had considerably higher variability of the mean relative difference for all sampling locations. These results suggest that fields with higher soil water retention because of lower sand content may produce more time stable soil moisture patterns. In addition, strong drainage features result in non-stationarity of soil moisture fields due to horizontal distribution of soil water.

The results indicate that for any one field, a number of satisfactory sampling points are available. To characterize
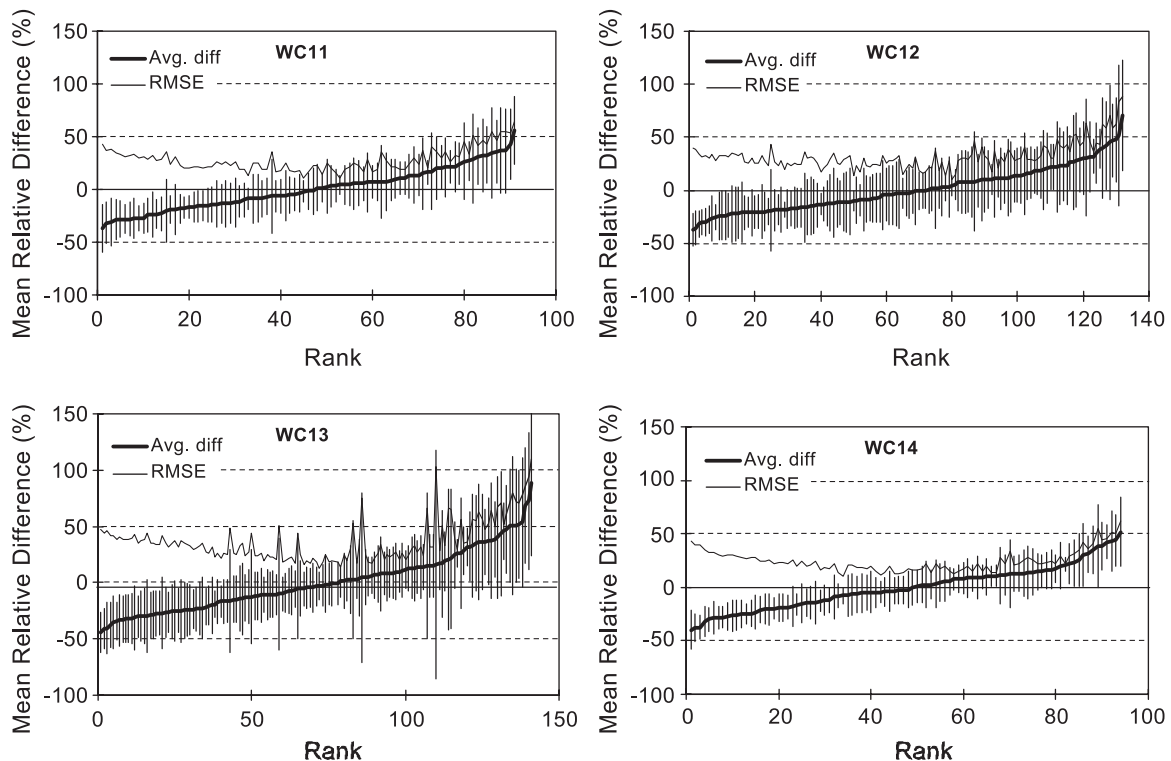

Fig. 4. Rank ordered mean relative difference with one standard deviation error bars and root mean square error for each sampling location by field.
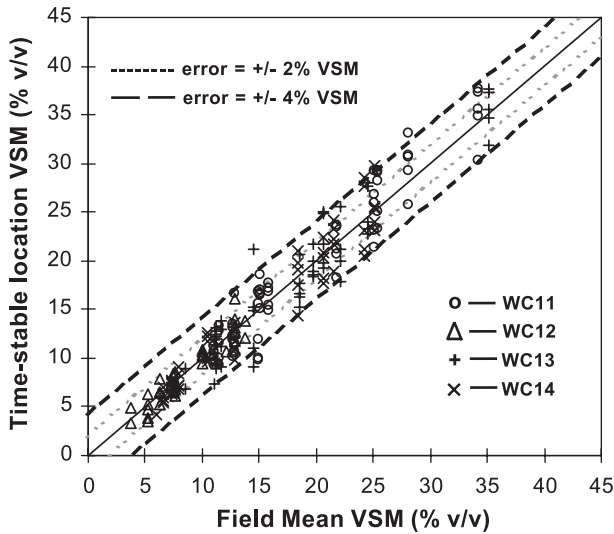
Fig. 5. Comparison of field mean soil moisture versus sampling location using the five highest time stable locations per field.

studies including one or more of these factors have been used to understand soil moisture variability (e.g., Famiglietti et al., 1998; Hills & Reynolds, 1969; Mohr & Famiglietti, 2000; Romano & Palladino, 2002).

Here, ANOVA statistical tests were used to identify relationships between sampling locations' physical properties and their mean relative difference. The four physical properties examined and the bases used to categorize these properties are: (1) the percentage clay (PC) categorized using ranges of values from the soils database, (2) the percentage sand (PS) categorized using ranges of values from the soils database, (3) the soil texture using clay, loam, and silty clay types, and (4) the topography using hill slope position (hilltop, depression, steep slope, and mild slope). DEM derived information regarding hill slope position is used to provide information about the variation of topography. Landscape positions are categorized based on the degree of slope for each cell location as hilltop (0–0.9%), depression (0–0.9%), mild slope (0.9–1.7%), or steep slope (greater than 1.7%).

For all fields, ANOVA tests of the mean relative differences indicate that sampling site time stable properties can be differentiated based on soil properties and hill slope positions (Table 3). In addition, ANOVA tests of the standard deviation of the mean relative differences demonstrate that the observed variability of time stability can be differentiated based on soil properties for individual sampling sites at all fields and based on hill slope position for the strongly drained field with higher sand content and corn land cover (WC12) and the broadcast soybean field with lower sand content (WC14). Although the three soil properties are correlated, percentage clay and percentage sand were better able to discern time stability features than soil texture, a composite index of sand, silt, and clay fractions.

Fig. 6 shows the mean relative difference categorized by soil features. Sampling sites having the highest sand content tend to generate the least time stability phenomena for all fields. This is in contrast to observations based on the overall texture of the field in the previous section. This result indicates that the texture at the individual sampling location relative to the field-average value is more critical for interpretation. Locations with a greater amount of loam

the value of field mean prediction using such satisfactory points, five locations having $\delta_{i,j}$ values closest to zero were used individually to predict the field average soil moisture content at each field. Fig. 5 shows that the time stable locations provide accurate predictions of the field mean with low variability and a small bias. These results indicate that the temporally stable locations can predict the field means well.

4.3. Sub-field scale soil moisture variability and associated physical properties

The common physical properties of temporally stable points at the 800 m resolution were investigated to identify forcing factors that cause specific time-invariant stability features. Mohanty and Skaggs (2001) suggest that at a particular point in time soil moisture content is influenced by: (1) the precipitation, (2) the texture of the soil, which determines the water-holding capacity, (3) the slope of land surface, which affects runoff and infiltration, and (4) the vegetation and land cover, which influences evapotranspiration and deep percolation. Many other data analysis

Table 3
F-values for tests of difference in mean values by sampling property

Sampling location property	WC11		WC12		WC13		WC14	
	$\bar{\delta}$	$\sigma(\delta)$	$\bar{\delta}$	$\sigma(\delta)$	$\bar{\delta}$	$\sigma(\delta)$	$\bar{\delta}$	$\sigma(\delta)$
Percentage clay	<0.001***	0.035*	<0.001***	0.002**	<0.001***	0.021*	<0.001***	0.004**
Percentage sand	<0.001***	<0.0001***	<0.001***	<0.001***	<0.001***	0.013*	<0.001***	0.010**
Soil texture	0.006**	0.885NS	<0.001***	0.005**	0.011*	0.023*	<0.001***	0.010**
Topography	0.002**	0.475NS	<0.001***	<0.001***	<0.001***	0.139NS	0.016*	0.023*

The test examines mean relative difference ($\bar{\delta}$) and standard deviation of relative differences ($\sigma(\delta)$).
NS indicates non-significant difference at the 0.05 probability level.
  *Indicates significance at the 0.05 probability levels.
  **Indicates significance at the 0.01 probability levels.
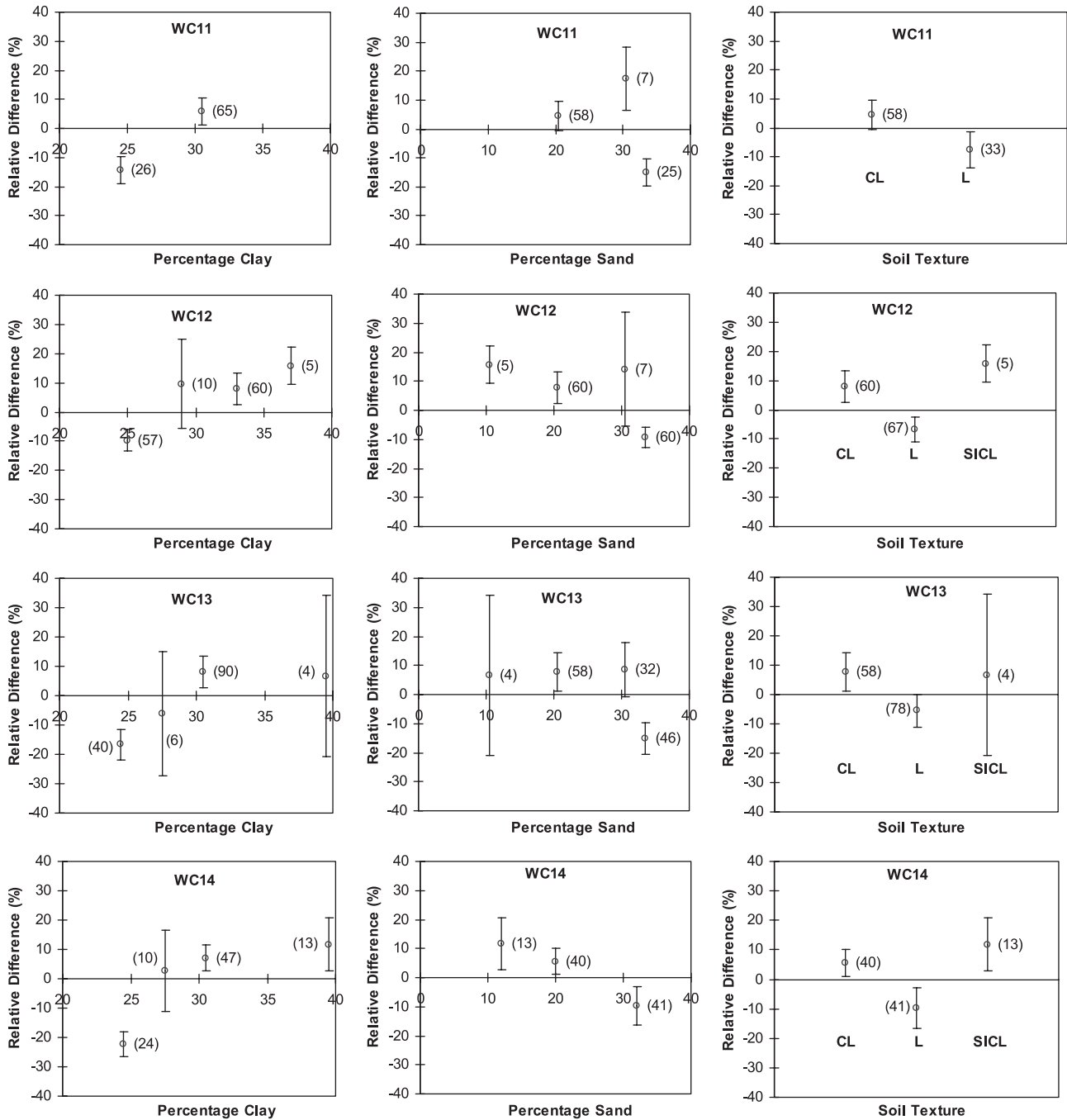 ***Indicates significance at the 0.001 probability levels.

Fig. 6. Mean relative difference and 95% confidence interval by field and soil parameter, percentage clay, percentage sand, and soil texture. Soil textures include clay (CL), loam (L), and Silty Clay (SICL). In addition, the number of locations with each soil parameter is shown.

and relatively high percent sand consistently underestimate the field mean. None of the soil textures can be used to identify sampling sites that are close to the mean relative difference (i.e., $\delta_i = 0$) as the 95% confidence intervals show a wet (dry) bias for clay (loam) soils. The transition from wet to dry bias occurs at approximately 31% sand and 28% clay and corresponds to the field average percentage of sand and clay. The best soil indicator of time stability was the 27% clay soils, closely matching the field average percentage clay, found in WC12, WC13 and WC14.

Fig. 7 shows the mean relative differences based on hill slope position. The pattern of time stability is consistent across sites with relative differences being underestimated for hilltops and steep slopes, overestimated for depressions and well represented by mild slopes. Depression locations overestimate field average values by 4 to 24% with WC12 and WC13 exhibiting the extreme deviations. Hilltop and steep slope locations consistently underestimate field average values by 13% and 6–10%, respectively. Mild slopes exhibit excellent time stability features for all sites.
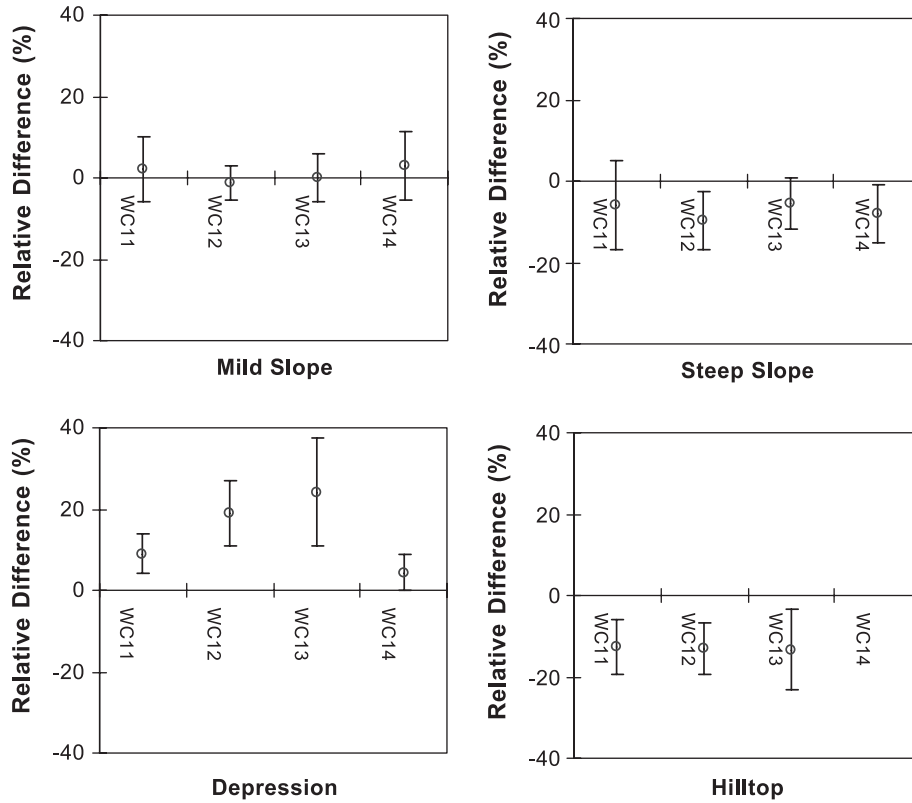
Fig. 7. Mean relative difference and 95% confidence interval by field and hill slope parameter.

Soil moisture variability and evolution is a complex function of topography, soils and vegetation. In this study, locations with mild slopes comprised 29%, 64%, 42%, and 31% of all sampled locations for fields WC11 to WC14, respectively. Fig. 8 shows the time stability characteristics of the mild slope locations subcategorized by clay content. The sites with mild slopes and percentage clay equal to or greater than the field average (28–30%) provide better time

stability than those mild slopes having low percent clay content (23%). Less variability was found for locations having higher clay content than those with average clay content. For the fields with a narrow range of high percentage clay, WC12, and WC13, locations with above average clay content on mild slopes have potential for being time stable. However, poorer time stability is evident for the field with pockets of very high percent clay (38%), WC14. These results indicate preferable locations for characterizing mean field soil moisture will have moderate slopes and intermediate to moderately high percent clay under soybean and corn land covers in the Walnut Creek watershed.
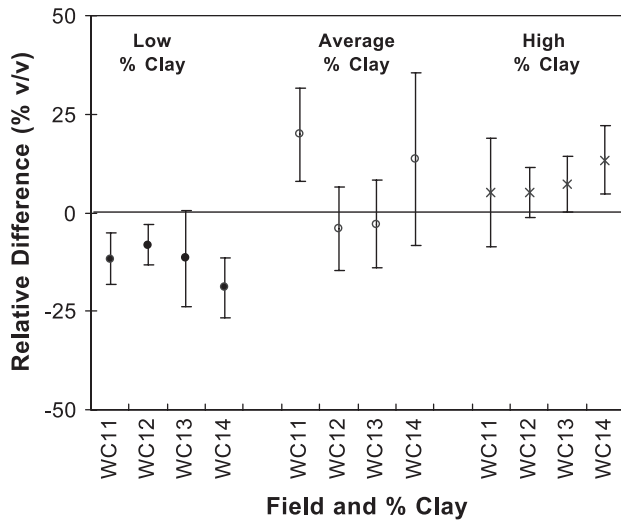
5. Conclusions

Based on our analysis of ground soil moisture data at 4 adjacent fields in the Walnut Creek watershed during SMEX02, vegetation, cropping practice, soil texture, and topography jointly control the spatio-temporal persistence/ variability in the watershed. Fields with strong drainage features (WC12) tend to be characterized by lower average moisture content and higher within field variability. Given the within-field variability differences among fields, the sample size necessary to capture the field mean varies by field as well as by soil moisture content with the largest number of samples requirement for moderate soil moisture values. The relationship between the field soil moisture

Fig. 8. Mean relative difference and 95% confidence interval by field and percentage clay for mild slope locations.

coefficient of variation and the field mean, as described by a two-parameter exponential relationship, may be used to determine the required sample size for a given field mean and confidence interval. The findings have significant implications for the analysis and validation of retrieved soil moisture products derived from air-borne microwave measurements. The field variability may be used to distinguish the error that results when validating a soil moisture product using the sample mean rather than the true field mean from errors in the remotely sensed measurement and the retrieval algorithm.

Although within-field soil moisture was highly variable, between 27% and 37% of all sampled points within the watershed exhibit good time stability characteristics and capture the field mean behavior. Both soil properties and topography may be used to distinguish time stability. We found that the percentage clay or the percentage sand predicted time stability features better than soil texture. The joint characterization of a potential sampling location's soil property and topography suggests the best time stable locations have mild slopes and moderate to moderately high clay content. The study's focus on readily available soil and topographic properties supports the future exploration of similar properties in other regions and for different space and time scales to characterize the generality and robustness of these results.

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