2009

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Giraldo, Mario A.; Bosch, David; Madden, Marguerite; Usery, Lynn; and Finn, Michael, "Ground and surface temperature variability for remote sensing of soil moisture in a heterogeneous landscape" (2009). *USGS Staff -- Published Research*. 542.
https://digitalcommons.unl.edu/usgsstaffpub/542

Journal of Hydrology 368 (2009) 214–223

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Ground and surface temperature variability for remote sensing of soil moisture in a heterogeneous landscape

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ARTICLE INFO

Article history:
Received 14 July 2008
Received in revised form 24 January 2009
Accepted 4 February 2009

This manuscript was handled by P. Baveye, Editor-in-Chief, with the assistance of Magdeline Laba, Associate Editor

Keywords:
Ground temperature
Infrared temperature
Landuse
Soil moisture
Landscape heterogeneity
Remote sensing

SUMMARY

At the Little River Watershed (LRW) heterogeneous landscape near Tifton Georgia US an in situ network of stations operated by the US Department of Agriculture–Agriculture Research Service-Southeast Watershed Research Lab (USDA–ARS-SEWRL) was established in 2003 for the long term study of climatic and soil biophysical processes. To develop an accurate interpolation of the in situ readings that can be used to produce distributed representations of soil moisture (SM) and energy balances at the landscape scale for remote sensing studies, we studied (1) the temporal and spatial variations of ground temperature (GT) and infra red temperature (IRT) within 30 by 30 m plots around selected network stations; (2) the relationship between the readings from the eight 30 by 30 m plots and the point reading of the network stations for the variables SM, GT and IRT; and (3) the spatial and temporal variation of GT and IRT within agriculture landuses: grass, orchard, peanuts, cotton and bare soil in the surrounding landscape. The results showed high correlations between the station readings and the adjacent 30 by 30 m plot average value for SM; high seasonal independent variation in the GT and IRT behavior among the eight 30 by 30 m plots; and site specific, in-field homogeneity in each 30 by 30 m plot. We found statistical differences in the GT and IRT between the different landuses as well as high correlations between GT and IRT regardless of the landuse. Greater standard deviations for IRT than for GT (in the range of 2–4) were found within the 30 by 30 m, suggesting that when a single point reading for this variable is selected for the validation of either remote sensing data or water-energy models, errors may occur. The results confirmed that in this landscape homogeneous 30 by 30 m plots can be used as landscape spatial units for soil moisture and ground temperature studies. Under this landscape conditions small plots can account for local expressions of environmental processes, decreasing the errors and uncertainties in remote sensing estimates caused by landscape heterogeneity.

Published by Elsevier B.V.

Introduction

Ground and infrared temperatures (GT and IRT) are critical parameters needed to indirectly estimate energy fluxes from remotely sensed data (Li et al., 1999; Norman et al., 1995; Price 1983) and soil moisture (SM) for the hydrological cycle from the soil and the vegetated layers of the landscape (Carlson et al., 1990; Schmugge et al., 2002a,b). Using thermal infrared remote sensing data to estimate energy fluxes at the soil–atmosphere interface offers several advantages over ground data collection, including the production of comprehensive data for large areas, the reduction of costly logistical and labor intense ground surveys and decreased errors associated with large, individual, non-simultaneous point data readings (Bastiaanssen et al., 1998). The importance of point data for remote sensing studies has been demonstrated by research in which ground readings are used in the validation of spectral reflectance measurements from the National Aeronautic and Space Administration Earth Observing System (NASA-EOS) Landsat satellites for water content of agriculture fields (Jackson et al., 2004); in validating surface temperatures extracted from Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper plus (ETM+) (Li et al., 2004); and in modeling energy fluxes from aircraft data over agriculture fields (Kustas et al., 2004).

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0022-1694/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2009.02.010

At the Little River Watershed (LRW) in South Georgia (USA) a network of in situ instruments has been established to produce continuous point readings of hydrological and ecological variables such as soil temperature, precipitation, and soil water content with the purpose of serving for ground validation of remote sensing data and the long term study of environmental cycles (Bosch et al., 2007a). In the 2003 version of the United States Department of Agriculture-National Aeronautics and Space Administration (USDA-NASA) soil moisture experiment 2003 (SMEX03) the potential of this network to validate ecological variables estimated from different airborne and satellite remote sensing platforms was demonstrated, opening the possibility for a regionalized assessment of soil moisture conditions for which the reliability of the network will be critical (Choi et al., 2008; USDA, 2003 http://hydrolab.arsusda.gov/smex03/SMEX03v5.pdf). Linking point data to a particular landscape to monitor biophysical processes such as soil moisture (Crow et al., 2005; Li et al., 2004; Mohanty and Skaggs, 2001), evapotranspiration (Kustas et al., 2003), and surface energy fluxes (Vicente-serrano et al., 2004) requires understanding environmental conditions and underling factors that regulate such processes. Despite the fact that continuous readings are recorded from the network sites at the LRW, no research has investigated the relationship between the station point data for the variables ground temperature and soil moisture (SM) with readings from the surrounding landscape and representative landuse-land covers (LULC). Understanding this relationship is of paramount importance for the validation of remote sensing data and to produce regional representations of environmental processes at the landscape scale.

Landscape patches (fragments) are areas of landscape organization in which environmental processes have a homogeneous behavior (Nagendra et al., 2004). Identifying such a areas of spatial organization serves as a step towards a regional representation of the environmental process under study (Chmiel, 2006; Hay et al., 2002). At the LRW local variation in the point reading and its relationship with landscape fragments has not been quantified yet. Observations at the LRW suggest a complex landscape where environmental variables may change over small spatial areas (Giraldo, 2007). In fact, the LRW is a diversified landscape with a mix of landuses, low elevation hills and a variety of soil types where remote sensing data at a fine spatial resolution such as NASA-EOS Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+), are suggested to better capture the spatial complexity of the heterogeneous landscape and therefore the underlying ecological processes (Cashion et al., 2005).

In this research we hypothesize that at the LRW plots of 30 by 30 m, matching the pixel size of a satellite image such as Landsat (TM) image, are landscape units where ground (GT) and infrared temperatures (IRT) present homogeneous behavior. Also that the point readings collected by the in situ network operated by the USDA–ARS-SEWRL represent soil moisture conditions of the surrounding landscape and LULC; finally we hypothesize that GT and IRT present homogeneous behavior that can be associated with LULC. The objectives of this research are to evaluate: (1) the spatial and temporal variability of GT and IRT within landscape fragments equivalent to a pixel size of a Landsat TM image, (2) the relationship between point readings of SM, GT and IRT from a sample of the network stations and readings collected from 30 by 30 m plots; and (3) the spatial and temporal variation of GT and IRT within agriculture landuses: grass, orchard, peanuts, cotton and bare soil. The final goal is to assess if temperature readings from the network stations represent local homogeneous areas and LULC of the adjacent landscape and, therefore, if temperature data from the stations can be used as input for remote sensing applications of soil moisture (Merlin et al., 2006) and in modeling energy fluxes at the scale of landscape patches/fragments (Kustas et al., 2004).

Methods

Study area

The Little River Watershed LRW in the South Atlantic coastal plain of the United States, near Tifton, Georgia is composed of a diversity of land covers including forest, cropland, pasture, residential areas and wetlands extending over 334 km^2 within 31° 22 and 31° 49 north latitude, and within 83° 21′ and 83° 45′ west longitude. Animal production is combined with agricultural activities yielding year-round production of vegetables and row crops (Bosch et al., 2004; Cashion et al., 2005). The in situ network operated by the US Department of Agriculture–Agriculture Research Service-South East Watershed Research Lab (USDA–ARS-SEWRL) at the LRW is composed of 27 stations equipped with Stevens–Vitel Hydra-probes (Stevens Water Monitoring Systems Inc.) recording soil moisture information and ground temperature at three soil depths (5, 20 and 30 cm) every 30 min. The Hydra-probe stations are typically installed along agriculture field boundaries, fence rows, and in some cases pasture areas and surrounded by native grass vegetation. A full description of the Hydra-probe network can be found in the documents of the USDA Soil Moisture Experiment 2003 (http://hydrolab.arsusda.gov/smex03/SMEX03v5.pdf) and in the work of Bosch et al. (2007a, b). Hydra-probes measure the dielectric constant for the soil and convert it to volumetric soil moisture based upon a factory provided calibration equation. Details about the soil moisture instruments at the stations and the relationships between dielectric constant and volumetric soil moisture can be found in Gaskin and Miller (1996) and also in Campbell (1990).

A sample of eight Hydra-probe stations were used for this study forming a transect that crosses the east portion of the LRW from north to south. The stations are surrounded by a variety of land covers in a typical rural landscape with grazing, orchard, pine plantations, and row crop areas near the cities of Arabi, Chula, and Tifton (Fig. 1). Soils at the eight sites are primarily loamy sands with four sites consisting of the Tifton (TfB) soil type (Table 1), characterized by deep, well drained, moderately slowly permeable soils that formed in loamy marine sediments. Tifton soils are on nearly level to gently sloping uplands and have slopes that range from 0% to 8%. In contrast to the Tifton soils, the soil at site 50 is a Sunsweet (StD2), well drained, moderately slowly permeable soil on uplands and slopes from 2% to 25%; while the soil at site 63 is a Fuquay, FsB, characteristic of the upper coastal plain, deep to very deep well drained soil, typically under row crop agriculture (USDA, 2004).

Field data

The sample of eight Hydra-probe stations used for this study was selected with the criterion of accessibility, landscape diversity, short travel times, and short distances from the main road. These criteria permitted ground measurements to be collected at the moment of maximum insolation of the day in the time interval between 10:00 am and 4:00 pm. In addition to the point data from the LRW network, two different data sets were collected during eight field campaigns through the year 2005 and January 2006. The first data set consisted of 10 to 20 readings from a 30 by 30 m plot defined around the area where a Hydra-probe station was located. The second data set was created with readings from five 30 m transects for the landuses: grass, orchard, bare land, peanuts and cotton located near the stations: 50, 32, 66 and 40, respectively. For the transects, 8–10 readings were collected from each landuse at 3 m intervals in an area distant from the parcel borders. Sampling was conducted throughout the year with the purpose of testing seasonal effects within and among locations. The sampling dates were: March 11, March 28, April 12, May 24,

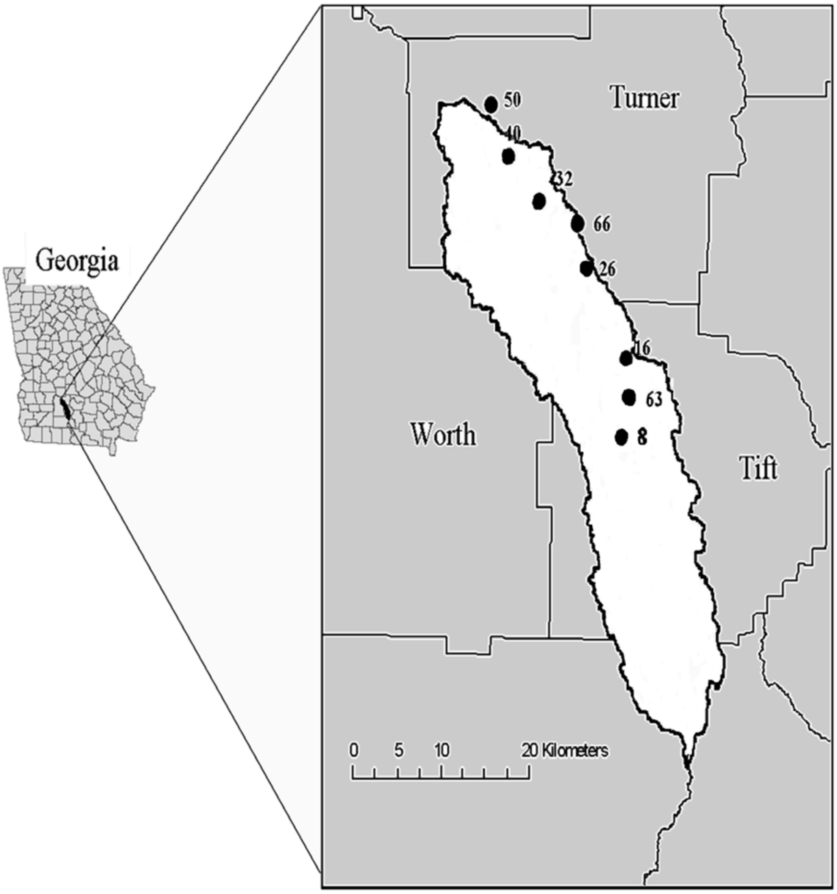

Fig. 1. Location of the study area and sampling locations within the LRW.

November 30, and December 1 of 2005; and January 13 and January 14 of 2006. The variables soil moisture, ground and surface temperature were measured simultaneously at each one of the locations for each one of the data sets mentioned. Physical differences between ground and surface temperature and its applications to remote sensing can be found in detail in the works of Carlson et al. (1990); Chen et al. (2005); Goward et al. (1985); Kustas et al. (2004); Norman et al. (1995) and Schmugge et al. (2002a,b) among others.

Ground temperature (GT) at 10 cm depth was measured using a digital thermometer (TPD32 Omega Engineering, Inc.) while surface temperature (IRT) was recorded from approximately 1 m above the surface using an infrared thermometer (OS643 Omega Engineering, Inc.). Soil moisture (SM) was recorded using a Theta capacitance probe ML2X Theta probe (Dynamax, Inc.) that measures dielectric constant similarly to the Hydra-probe devices of the LRW in situ network. The Theta probe consists of a probe and a data logger that storage the measurements taken with the probe sensors. Specific details about operation and calibration of the Theta probe can be found in the Theta probe user manual at ftp://ftp.dynamax.com/Manuals/ML2x_Manual.pdf. In the same study area of our research the work of Bosch et al. (2006) showed that Theta probe readings present a relatively good agreement with gravimetric analysis of soil moisture, but that micro topography and the variation within small samples may increase errors within the gravimetric reading. In this case Theta probe readings averaged 6.6% lower than gravimetric readings. In our research, soil moisture readings were collected with the same equipment on all dates and operated by the same personnel to minimize the effects of human errors and systematic errors.

Precipitation

Precipitation data were collected using the LRW rain gage network (Bosch et al., 2007b), from gages located at each plot. Rainfall in the LRW is evenly distributed throughout the year, with frequent short-duration high-intensity thunderstorms in the summer. Ground and surface temperature are strongly correlated with soil moisture content since the latent heat and sensible heat components of the energy balance at the surface level are affected by soil water contents (Goward et al., 1985). An analysis of precipitation was performed to understand whether or not the sites were wet or dry when the samples were collected. The field work included dry conditions on May 24, November 30 and January 13, wet conditions on March 28, January 1st and January 14 and two intermediate conditions on the sampling days of April 11 and March 11.

Statistical analysis

Descriptive statistics such the mean and the standard deviation were generated for the variables GT and IRT at each site and for each one of the reading dates. We used one way analysis of variance (ANOVA) to compare variation among and within plot and landuse, as well as the variation among plots and landuses for the variables GT and IRT. In this analysis, an F value is generated and a statistical significance for the difference between and within groups established at the probability level of 0.05, 0.01 or less. ANOVA analysis produces strong results when the dataset presents similar variance and has a normal distribution. The assumptions of normal distribution and homogeneous variance for the ANOVA

Table 1
Location, soil information and annual precipitation for the study sites. Coordinates are in UTM, WGS84.

Site	Y Coordinate[a]	X Coordinate	Elevation (m)	Land cover	Soil name[b]	Soil symbol	USCS soil class 1st layer	USCS soil class 2nd layer	Total 2005 Precipitation PT 2005 (cm)
8				Grass	Ocilla	Oc	loamy sand	sandy clay	150.2
16	3494245.16	256307.44	123	Grass	Tifton	TfB	loamy sand	Sandy loam	150.2
26	3502328.72	252215.12	115	Row crop	Alapaha	Ah	loamy sand	Sandy clay	147.7
32	3507196.64	249514.28	123	Grass	Tifton	TfB	loamy sand	Sandy loam	140.5
40	3511504.48	246611.08	134	Row crop	Tifton	TfB	loamy sand	Sandy loam	141.0
50	3516116.84	244911.43	113	Grass	Sunsweet	StD2	Sandy loam	Clay	151.3
63	3490204.59	258057.01	110	Grass	Fuquay	FsB	oamy sand	Sandy clay	132.4
66	3504345.43	256398.32	116	Bare soil	Tifton	TfB	loamy sand	Sandy loam	138.0

[a] Coordinates are in UTM, WGS84.

[b] A full description of the soil map units can be found at USDA-National Resource Conservation Service (USDA-NRCS) Soil Survey Geographic Database (SSURGO) http://www.soils.usda.gov/survey/geography/ssurgo/.

were test for each data sampling date. We verified the homogeneity of the variances using the Levenee test and the normality of the dataset using the Skewness and Kurtosis test. The individual results for Kurtosis and Skewness test showed that the data sets are normally distributed since values were close to 0 for both variables In all the ANOVAs where statistical significance was found, a Tukey/Tamhane *post-hoc* test was performed to detect the groups for which the difference was significance. When homogeneous variance within the groups was detected, a *post-hoc* Tukey test was applied and Tukey groups of similar behavior were formed. In the scenarios in which the variance was not homogeneous the Tamhane *post-hoc* test was used.

Pearson's correlation coefficient was also used to evaluate the level of association between the variables GT, IRT and SM. The Pearson's correlation coefficient is defined by Cangelosi et al. (1976) as an abstract measure of the degree of the relationship between two variables. This coefficient corresponds to the square root of the coefficient of determination that considers the proportion of variation in one population-variable that is explained by the variance of the other population-variable. Highly correlated patterns have values close to 1, uncorrelated patterns have values close to 0 and inversely correlated patterns have values close to −1.

Results

Precipitation

The annual precipitation for 2005 at the eight study sites ranged from 151.3 to 132.4 cm, with an average of 143.9 cm (Table 1). A detailed description of the 12-day period precipitation previous to the temperature sampling is provided in Giraldo (2007). This analysis showed that during rainfall events all the sites sampled in this study received simultaneous precipitation with no significant statistical differences in the amount of rainfall among sites previous to each one of the sampling collections. Thus, soil moisture and surface temperature behaviors are expected to be the result of local environmental conditions operating at the site location.

Descriptive statistics for IRT and GT field readings

Descriptive statistics

Descriptive statistics for the variables GT and IRT collected from the 30 by 30 m plots are presented using two levels of aggregation: (1) at the watershed level and (2) the site level. At the watershed level, there are no apparent differences in the average values of GT and IRT by date when the plots data is analyzed together (Table 2). The average temperature for the series of eight readings showed close values between both variables with a maximum average difference of 6.7 °C during the summer reading (May 24) and a minimum average difference of −0.2 °C for the late fall readings (November 30–December 1). However, GT consistently showed the lowest average standard deviation for the eight readings with a range of values between 1.1 and 2.2 °C, while the IRT range was between 2 and 4.4 °C (Table 2), indicating a level of stability in the ground temperature and a more unstable behavior in the IRT readings. The largest average standard deviation for IRT was observed in the late fall reading (November 30–December 1) while for the GT the maximum average standard deviation was found in the mid spring (May 24).

When aggregating the values at the site level across all sample dates, differences were found between the GT and IRT in particular plots. For instance, plots at station 26 and 63 showed average values of GT greater than IRT, while, sites 32 and 66 have an opposite behavior (Table 2). Overall, GT showed smaller average standard deviation variability than IRT for the eight sampled plots, varying in the range of 0–1 °C while for IRT the variation was in the range of 1–2 °C. In this way, GT showed less variation in a given location or in a particular sampling time than IRT. This analysis suggests site specific differences in the values for both variables that are independent of water supply in the form of precipitation. Each variable should be analyzed in the context of other environmental factors acting at the local scale.

Temporal variation of GT and IRT

The temporal analysis of average GT and average IRT (Table 2) at the plot level through the 8 dates showed the highest range of GT among plots on May 24, 2005 with a range of values between 25 and 32 °C, while the lowest range was in the April 12 readings with only 1 °C of difference. For IRT the highest range was found on November 30, 2005 with 12 °C of difference while 5.5 °C was found as the lowest range on January 13, 2006. Highest ranges of temperatures correspond to the plot collections conducted during dry periods while low ranges were associated with dates in which readings were collected a few days after a rain event. When compared with GT, IRT showed higher ranges of values for a single set of readings.

The average standard deviation for GT for the eight plots showed overall values under 1.4 °C through the eight reading dates with the lowest values observed on March 28, 2005, April 12, 2005 and January 13, 2006. This indicates a high level of in-field homogeneity for the variables with some clear exceptions for some sites for a given date such as site 8 and site 63 indicating also the influence of site specific effects. In addition to those dates January 14, 2006 also presented low average standard deviations for IRT (Table 2). Although the general trend showed an upper threshold of 2 °C standard deviation, the readings on May 24, November 30 and December 1, 2005 were generally above this limit in almost all the sites.

Table 2
Descriptive statistics for GT and IRT by site and date of field data collection.

Sites	3/11/2005		3/28/2005		4/12/2005		5/24/2005		11/30/2005		12/1/2005		1/13/20065		1/14/20065		Average Mean	Average STDV
	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV		
GT																		
8	12.72	1.13	16.98	0.69	20.56	0.54	29.27	0.99	14.89	1.07	14.41	1.58	N/v	N/v	11.08	0.57	17.13	0.94
16	15.83	2.06	17.61	0.97	18.66	1.41	30.90	1.64	16.77	1.21	15.92	1.17	16.65	0.68	12.87	0.74	18.15	1.23
26	14.84	1.14	16.15	0.25	19.06	0.66	32.29	1.13	16.54	1.44	15.73	0.95	17.29	0.44	11.99	0.96	17.99	0.87
32	14.32	0.82	16.04	0.63	18.89	0.50	28.21	1.54	16.49	1.02	14.93	1.06	16.83	0.79	11.34	0.77	17.13	0.89
40	15.42	1.25	14.83	0.57	19.44	0.71	28.67	1.39	15.26	1.01	13.41	1.16	15.68	0.79	8.98	1.19	16.46	1.01
50	15.63	1.31	15.78	0.87	19.44	0.28	25.11	1.14	13.17	1.06	12.64	0.77	14.76	0.65	9.61	0.46	15.77	0.82
63	17.28	1.09	17.14	1.68	19.41	0.53	30.83	0.61	17.06	0.71	17.20	0.60	17.38	0.32	13.17	0.78	18.68	0.79
66	14.44	1.36	16.03	0.45	19.91	0.58	29.62	1.18	17.35	1.24	15.99	1.03	16.66	0.63	11.78	0.43	17.72	0.86
Average	15.06	1.27	16.32	0.76	19.42	0.65	29.36	1.20	15.94	1.09	15.03	1.04	16.47	0.61	11.35	0.74	–	–
IRT																		
8	12.04	2.10	12.72	1.63	23.94	1.96	35.61	2.23	10.79	1.54	15.48	3.39	N/v	N/v	8.31	1.77	16.98	2.09
16	16.81	1.35	16.88	2.55	12.78	0.53	36.80	2.68	15.81	4.09	18.81	2.91	17.72	0.66	10.28	1.30	18.23	2.01
26	15.63	1.45	12.74	0.95	16.62	1.50	36.98	1.14	15.98	2.60	14.06	2.27	17.12	0.64	9.96	1.05	17.39	1.45
32	17.41	1.55	13.19	1.18	16.04	0.93	39.47	2.28	23.17	2.44	18.97	2.96	20.94	1.18	10.97	1.14	20.02	1.71
40	19.86	2.39	11.11	0.91	17.28	0.99	34.67	2.46	16.11	3.54	13.44	3.03	16.13	1.13	5.21	1.22	16.73	1.96
50	21.18	1.93	9.64	0.71	17.32	1.68	30.79	1.16	12.10	2.14	10.74	2.01	15.49	0.38	6.47	1.69	15.47	1.46
63	15.00	0.48	13.59	1.41	15.33	0.41	34.09	1.96	13.71	0.84	16.47	1.79	16.17	0.52	11.41	0.91	16.97	1.04
66	17.04	2.04	14.02	1.40	17.78	0.89	42.69	3.04	17.50	2.36	14.71	3.07	18.25	1.23	10.33	1.69	19.04	1.97
Average	16.87	1.66	12.99	1.34	17.14	1.11	36.39	2.12	15.65	2.44	15.34	2.68	17.40	0.82	9.12	1.35	–	–

Table 3
Analysis of variance of GT for thein eight field data collections at the small plots.

		Ground temperature				
		Sum of squares	df	Mean Square	*F*	Sig.
03-11-2005	Between groups	359.490	7	51.356	9.319	.000
	Within groups	325.137	59	5.511		
	Total	684.627	66			
03-28-2005	Between groups	221.358	7	31.623	12.775	.000
	Within groups	215.363	87	2.475		
	Total	436.721	94			
04-12-2005	Between groups	137.764	7	19.681	13.148	.000
	Within groups	181.119	121	1.497		
	Total	318.884	128			
05-24-2005	Between groups	1446.426	7	206.632	43.431	.000
	Within groups	528.110	111	4.758		
	Total	1974.536	118			
11-30-2005	Between groups	811.072	7	115.867	28.910	.000
	Within groups	545.066	136	4.008		
	Total	1356.139	143			
12-01-2005	Between groups	911.935	7	130.276	35.623	.000
	Within groups	497.365	136	3.657		
	Total	1409.300	143			
01-13-2006	Between groups	298.177	6	49.696	37.948	.000
	Within groups	141.434	108	1.310		
	Total	439.612	114			
01-14-2006	Between groups	733.731	7	104.819	52.888	.000
	Within groups	235.846	119	1.982		
	Total	969.578	126			

Analysis of variance ANOVA

To evaluate statistical differences among the plots for the variables GT and IRT a one way ANOVA was conducted for each sampling date. The results showed statistical difference for both variables at the probability level of 0.01 in all the field data collections (Tables 3 and 5). The difference between sites is represented in the ANOVA by the mean square value *between groups*, while the variation within each site is represented by the mean square value in the *within group* category.

ANOVA analysis of GTThe maximum and minimum limits of the range of observations correspond, respectively, to the readings on May 24, 2005 with the highest average GT and the lowest on April 12, 2005. Since both limits of the range were found on two different times in the spring season and since the remaining values within the range do not appear to be linked to a particular time of the year, it is reasonable to affirm that there is no seasonal effect on GT variations among sites.

The analysis of the mean square values in the *within groups* category of the ANOVA showed relatively small values in all eight

Table 4
Tukey groups of significance difference between sites for GT at the 0.01 probability level. Numbers indicate number of times both small fields were found grouped together.

Sites	Land cover	8	16	26	32	40	50	63	66	Total
8	Grass		1	1	5	3	0	1	5	16
16	Grass	1		5	4	1	0	4	3	18
26	Row crop	1	5		6	2	2	3	5	24
32	Grass	5	4	6		3	3	3	4	28
40	Row crop	3	1	2	3		5	2	3	19
50	Grass	0	0	2	3	5		2	1	13
63	Grass	1	4	3	3	2	2		4	19
66	Bare soil	5	3	5	4	3	1	4		25
Total		16	18	24	28	19	13	19	25	

data collections. The range of values for this analysis was between 1.3 and 5.5, with the lowest on January 13 and the highest on March 11, 2005. These low values indicate relatively small local variation of GT within a plot around a Hydra-probe reading station through the year. Considering the statistical difference within the plots for GT showed by the ANOVA, Tukey *post-hoc* analysis was used to identify groups of sites that have similar behavior on a given reading date. In this analysis sites sharing the same Tukey group have no statistical difference in their means for a given variable.

In Table 4, the number of times that a pair of plots is grouped together in the Tukey analysis is indicated by the number within the matrix. Since eight are the total number of readings performed, this is the highest possible number in which two sites can be grouped together. The most dissimilar small plots present the lowest grouping number (0) while the most similar plots will show the highest grouping number, in this case 6. The total number of Tukey groups that a site has is an indicator of its similarity (high total number) or dissimilarity (low total number) with other sites and, therefore, a measure of the spatial heterogeneity of the sampled area.

The Tukey analysis showed the plot around site 50 as the most dissimilar for the variable GT since it was grouped with other groups only 13 times. In this case only site 40 showed similarity with site 50 by being grouped together a total of 5 times (62.5%). On the other hand, site 32 presented the greatest similarities with other plots for this variable with a total of 28 groups, followed by site 26 with 24 groups. These two sites showed the most similar behavior since they were grouped together in 6 (75%) occasions, while sites 8 and 50, and 16 and 50 showed the most dissimilar behavior since they did not share a similar group for any of the 8 readings of this experiment.

ANOVA analysis for IRT

The analysis of variance for the variable IRT (Table 5) showed the readings on November 30 with the maximum difference between sites since high values of mean square between groups were found. The minimum difference between sites was found on March 28 corresponding to the lowest values for the mean square between groups. The results of the analysis showed that high and low values of mean square between groups are not necessarily associated with a particular season, suggesting the lack of seasonal effects on the behavior of the sites. This observation also applies to the mean square difference observed within groups in which readings collected from two continuous dates present the maximum and minimum values for the set of observations. On the other hand, for IRT the range of differences within the groups is greater than those observed for the GT analysis, confirming that at the 30 by 30 m plot level IRT present a less homogeneous behavior with a high in-field variation. Comparing the IRT ANOVA results with those from GT discussed above the reading dates for which lowest and highest values were found are different for both variables suggesting a different set of ecological variables influencing the specific response of them.

Tukey groups of similar mean IRT showed site 50 also as the most dissimilar one for the IRT with 10 groups, while site 26 is

Table 5
Analysis of variance of IRT for the in eight field data collections at the small plots.

		IRT/Surface temperature				
		Sum of Squares	df	Mean Square	*F*	Sig.
03-11-2005	Between groups	1539.447	7	219.921	22.115	.000
	Within groups	586.732	59	9.945		
	Total	2126.179	66			
03-28-2005	Between groups	1249.264	7	178.466	26.030	.000
	Within groups	596.483	87	6.856		
	Total	1845.747	94			
04-12-2005	Between groups	3937.694	7	562.528	108.676	.000
	Within groups	626.321	121	5.176		
	Total	4564.016	128			
05-24-2005	Between groups	4184.867	7	597.838	37.484	.000
	Within groups	1770.364	111	15.949		
	Total	5955.231	118			
11-30-2005	Between groups	6246.775	7	892.396	43.272	.000
	Within groups	2804.712	136	20.623		
	Total	9051.486	143			
12-01-2005	Between groups	3024.892	7	432.127	18.178	.000
	Within groups	3233.047	136	23.772		
	Total	6257.939	143			
01-13-2006	Between groups	1230.531	6	205.089	78.274	.000
	Within groups	282.975	108	2.620		
	Total	1513.506	114			
01-14-2006	Between groups	1870.899	7	267.271	44.290	.000
	Within groups	718.120	119	6.035		
	Total	2589.020	126			

Table 6
Tukey groups of significance difference between sites for IRT at the 0.01 probability level

Sites	Land cover	8	16	26	32	40	50	63	66	Total
8	Grass		1	3	1	3	0	3	2	13
16	Grass	1		4	3	1	0	3	3	15
26	Row crop	3	4		5	5	2	6	6	31
32	Grass	1	3	5		2	1	4	3	19
40	Row crop	3	1	5	2		5	2	3	21
50	Grass	0	0	2	1	5		1	1	10
63	Grass	3	3	6	4	2	1		4	23
66	Bare soil	2	3	6	3	3	1	4		22
Total		13	15	31	19	21	10	23	22	

the most representative site with a total of 31 similarity groups (Table 6). Coinciding with the results observed for GT, a strong relationship between plots 50 and 40 was observed, sharing a total of 5 groups (62.5%), while a weak relationship exists between plots 8 and 50, and 16 and 50 for which no groups were shared in this study.

Overall, no seasonal effect was found in the spatial variation of GT or IRT within and among sites. The eight sampled plots presented greater homogeneity for the variable GT than for the variable IRT, although no statistical differences were found in the point data within the 30 by 30 m area for any of the two variables. The statistical differences found among sites are similar for both variables and suggest site specific effects on the variable behaviors. Some sites were identified as presenting a unique behavior for those variables while others have a more similar behavior, indicating spatial diversity in the GT and IRT behavior among the samples sites.

Plot correlation among IRT, GT and SM

Pearson's correlation coefficients were calculated for the variables GT, IRT and SM recorded from the 30 by 30 m plots and aggregated under two schemes: by reading date and by site. In the data aggregated by date, positive correlations between these variables were statistically significant at the probability level of 0.01 for all the sampling dates. Between these variables the correlation coefficient ranged between 0.28 and 0.75. The correlation with SM was statistically significant only for half of the sampling dates for both GT and IRT. For those dates, there was a negative correlation with SM and GT and IRT, with the exception of the reading on April 11, 2005 (Table 7). These observations suggest a close relationship between GT and IRT and more variation in the relationship between GT/IRT and SM.

The correlation analysis performed between variables at the site level showed high positive correlation between GT and IRT that was significant at the probability level of 0.01 (Table 8). The level of association for these variables ranged between 0.81 for site 50 and 0.98 for the site 26. A negative correlation was found for SM and GT and IRT (significant at the probability level of 0.01) for all the sites, except for site 16 in which the correlation was significant at the 0.05 probability level between IRT and SM. These results are in agreement with those reported by Carlson et al. (1990); Carlson et al. (1995); Goward et al. (1985) finding negative correlations between SM and GT and positive correlations between GT and IRT. However, we found that the strength of these correlations are affected by local conditions especially in the relationships between GT and SM and IRT and SM and most notably between IRT and SM in which the differences between sites were found in the range between −0.36 and −0.83 (Table 8).

Table 7
Pearson's correlation coefficients for IRT, GT and SM aggregated by sampling date. Values with $**$ and $*$ show correlations with statistical significance at the 0.01 and 0.05 probability level, respectively.

Date	GT–IRT	GT–SM	IRT–SM
03-11-2005	0.3**	−0.37**	−0.53**
03-28-2005	0.5**	0.16	−0.044
04-11-2005	0.5**	0.33**	0.67**
05-24-2005	0.2**	0.014	−0.20*
11-30-2005	0.45**	−0.25**	−0.33**
12-01-2005	0.45**	0.003	0.002
01-13-2006	0.314**	−0.25**	−0.204*
01-14-2006	0.754**	0.06	0.01

Table 8
Pearson's correlation coefficients for IRT, GT and SM aggregated by fields. Values with $**$ and $*$ are correlations with statistical significance at the 0.01 and 0.05 probability level, respectively.

Site	Land cover	Correlations		
		GT–IRT	GT–SM	IRT–SM
8	Grass	0.96**	−0.57**	−0.57**
16	Grass	0.92**	−0.51**	−0.36*
26	Row crop	0.98**	−0.75**	−0.824**
32	Grass	0.92**	−0.64**	−0.83**
40	Row crop	0.92**	−0.72**	−0.824**
50	Grass	0.81**	−0.63**	−0.79**
63	Grass	0.97**	−0.724**	−0.69**
66	Bare soil	0.94**	−0.65**	−0.73**

Comparison between Hydra-probe and Theta probe field readings

In the process of studying environmental variables using remote sensing data, retrieving algorithms are formulated and later validated using ground data measured from relatively homogeneous areas, where the accuracy of the estimates can be compromised when the ground area corresponding to an image pixel combines spectral information from different land covers (Kustas and Norman, 2000). Since energy fluxes in the soil–atmosphere interface do not exhibit a linear behavior in the scaling process assessing the extension of the field for which a point reading can be used as a valid predictor of local conditions is a critical task, especially when the validation process is attempted over heterogeneous landscapes (Chen et al., 2005).

Point data from the Hydra-probe in situ stations were compared to field data collected with the Theta probes from the 30 by 30 m adjacent plots. In general, the ground temperature readings from the 5 cm Hydra-probes for the eight sampled stations agree with the average GT and IRT of the readings obtained from the 30 by 30 m adjacent plots with a range of variation between <1 and

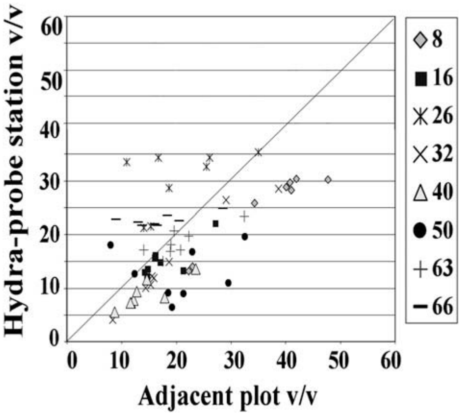

Fig. 2. Relationship between readings from Hydra-probe stations and hand carried devices for the variables SM.

Table 9
Analysis of variance of GT and IRT for landuse at the LRW.

Variable	Variation source	Sum of squares	df	Mean square	*F*	Sig.
Ground temperature (GT)						
11-30-2005	Between groups	759.8	4	189.963	2.866	.037
	Within groups	2386.4	36	66.290		
	Total	3146.2	40			
12-01-2005	Between groups	212.2	4	53.056	21.726	.000
	Within groups	87.9	36	2.442		
	Total	300.1	40			
01-13-2006	Between groups	179.8	4	44.974	35.919	.000
	Within groups	43.8	35	1.252		
	Total	223.7	39			
01-14-2006	Between groups	211.8	4	52.965	79.982	.000
	Within groups	23.1	35	.662		
Surface temperature (IRT)						
11-30-2005	Between groups	455.79	4	113.950	6.440	.001
	Within groups	636.95	36	17.693		
	Total	1092.75	40			
12-01-2005	Between groups	346.37	4	86.594	4.694	.004
	Within groups	664.06	36	18.446		
	Total	1010.43	40			
01-13-2006	Between groups	233.25	4	58.313	32.220	.000
	Within groups	63.34	35	1.810		
	Total	296.59	39			
01-14-2006	Between groups	607.63	4	151.908	41.614	.000
	Within groups	127.76	35	3.650		
	Total	735.39	39			

3.8 °C (Fig. 2). Seasonal or site specific effects did not influence this agreement. For soil moisture, five of the sampled stations' 5 cm Hydra-probe readings agreed with the average reading recorded with the portable Theta probe from the 30 by 30 m plot. Two of the stations (26 and 66) tended to overestimate field conditions while station 50 tended to underestimate them with no appreciable seasonal effect in these variations. The causes of under and overestimating field SM behaviors can be diverse including variation in the water table, equipment calibration or human errors suggesting the need to conduct a separate study that addresses this variation. Considering the long term goal for the Hydra-probe stations, the results of this analysis support the importance of replicating the field validation on the remaining stations of the network to find if variations also occur in other stations and explore suitable explanations.

Ground and infrared temperature variation within different LULC

ANOVA analysis for GT and IRT showed significant difference between landuses at the probability level of 0.01 for both variables. High values in the between groups analysis imply different behavior between the landuses while the differences in the within groups section of the analysis suggest higher variation in the individual behavior within a given landuse. The differences between groups and within group were greater for the values of IRT than for GT (Table 9) suggesting a more stable behavior of GT than IRT within a given landuse. These properties are important when selecting either GT or IRT to characterize environmental conditions of the landscape.

The Tukey groups of similarity showed that while grass and peanuts demonstrated the most similar behaviors for IRT and GT, the landuses grass and bare soil have a less similar behavior for both variables. The two agriculture landuses studied here, peanuts and cotton showed similar GT and IRT values and a loose association with other vegetated landuses. A possible explanation for this association is that the soil under both landuses suffered a similar disturbance and alteration by agriculture equipment during the sowing process and growing period. Cotton showed a low association with the landuse grass for the variable IRT since they shared only a single similar group, while the perennial landuse orchard did not show a particular trend that differentiates it from other vegetated landuses such as cotton or grass for both variables. Orchard was clearly differentiated from the non-vegetated landuse, bare soil, for the variable GT. Overall the results suggest that vegetated landuses differ from bare soil in GT and IRT since bare soil show the lower similarity with other landuses for GT (only 2) and for IRT (7) (Table 10).

Pearson's correlations between soil water and soil temperature in different landuse transects

A positive linear association was found between IRT and GT for each one of the landuses studied here (Fig. 3a). This positive association was stable through the four reading dates for which data were collected (Fig. 3b). A less clear correlation was found between the temperature variables and SM for all the four landuses studied here (Table 11). Significant negative correlations at the 0.01 probability level were found between SM and temperature only for bare soil and a negative correlation at the 0.05 significant level was found between SM and GT in the landuse cotton. The results found

Table 10
Tukey groups of similar GT and IRT at the 0.05 probability level.

Transects	Grass	Peanut	Cotton	Orchard	Bare soil	Total
Ground temperature (GT)						
Grass		4	3	2	0	9
Peanut	4		3	2	0	9
Cotton	3	3		3	1	10
Orchard	2	2	3		1	8
Bare soil	0	0	1	1		2
Total	9	9	10	8	2	
Surface temperature (IRT)						
Grass		4	1	2	0	7
Peanut	4		3	2	2	11
Cotton	1	3		2	3	9
Orchard	2	2	2		2	8
Bare soil	0	2	3	2		7
Total	7	11	9	8	7	

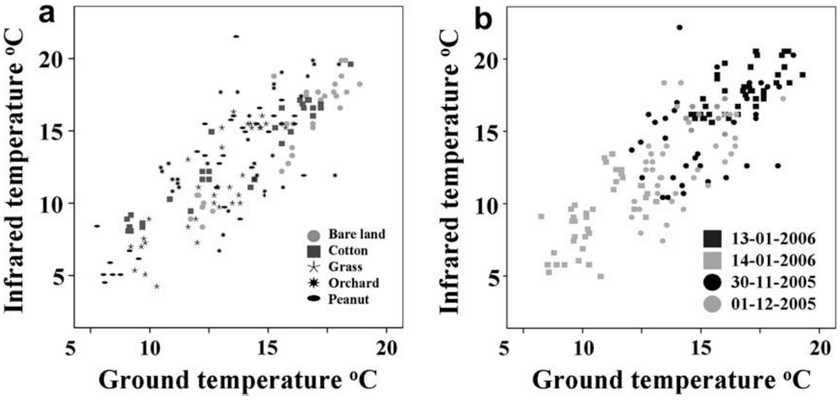

Fig. 3. Relationship between GT and IRT for (a) five landuse transects and (b) four reading dates.

Table 11
Pearson's correlation coefficients for IRT, GT and soil moisture (SM) for different landuses. Values with ** and * are correlations with statistical significance at the 0.01 and 0.05 probability level, respectively.

Transect	Correlations		
	GT–IRT	GT–SM	IRT–SM
Bare soil	0.92^{**}	-0.56^{**}	-0.59^{**}
Cotton	0.95^{**}	-0.12	-0.09
Peanut	0.83^{**}	-0.37^{*}	-0.35
Orchard	0.56^{**}	-0.33	0.08
Grass	0.84^{**}	-0.02	-0.10

in this section showed that landuse has an important influence in the relationship between GT–IRT and SM. Peanuts and bare soil that present a low vegetation cover and exposed soil negatively affects SM–GT relationship, while landuses such a grass, orchard or cotton had no significant effect on such relationship. Also high correlations between GT–IRT showed in Table 11 suggest that homogenous behavior can be found within small fields regardless of vegetation cover as it is shown by high correlation values for these variables (> than 0.8) in vegetated landuses except orchard and even as high as those presented by bare soil (0.92). This result support our original hypothesis of the possibility of identifying fields with homogeneous conditions within the landscape.

Discussion and conclusions

Landscape fragments are spatial units with unique combinations of physical characteristics such as landuse-land cover, soil and terrain where biophysical processes are expected to have similar behavior. With increasing landscape complexity, fragments tend to be smaller in size and a higher diversity of combined environmental conditions even under similar land covers (Giraldo, 2007). This variability presents a challenge to routine monitoring of soil moisture in a spatially distributed manner. At the LRW, this research showed that within 30 by 30 m landscape fragments it is possible to find high spatial homogeneity in the GT and IRT response independent of seasonal variation suggesting that 30 by 30 m plot size are an appropriate landscape spatial unit to study energy fluxes under this complex landscape condition.

The greater standard deviations of the IRT compared with the GT indicates that regardless of seasonal variation or vegetation cover, there is a level of uncertainty in the assessment of IRT, even within small spatial areas. Rapid changes in local conditions such as atmospheric state, canopy resistance to transpiration, cloud cover or wind speed are mentioned as its possible causes (Goward et al., 1985). This variability may cause errors when point field measurements are used for the ground validation of remote sensing data, or when indirect estimations of soil moisture conditions are calculated using radiometric surface temperature (T_R) from satellite thermal data (Carlson et al., 1990; Kustas et al., 2004). In this case by collecting more than one reading for a single point location, the variability can be decreased, since their average values will better reflect the conditions at that particular location.

The statistical differences among plots for GT and IRT were found to be: (1) seasonally independent; (2) associated with the in situ characteristics of the landscape fragments; and (3) only partially explained by landuse conditions. In this case, plots under similar land covers (Table 1) presented both similar (plots 26 and 40) and different (plots 8 and 50) behavior. In the same way, the study of variation among landuse transects showed strong differences only between the bare soil and the vegetated transects and only small differences with weak trends within the vegetated transects, in spite of their different vegetation type (grass, orchard, low crops). These observations suggest that other factors such as soil physical properties in addition to vegetation cover strongly influence the SM response and its correlation with GT and IRT supporting the hypothesis that in studying soil moisture conditions, vegetation cover is not sufficient to define a homogeneous landscape fragment.

In this regard, under a landscape approach, a broader concept of fragment should be considered that incorporates, in addition to vegetation cover, variables such as soil, topography and climate when defining the limits of the landscape fragment. Methodologies that consider the indirect estimation of soil moisture conditions based on vegetation component and surface temperature (Kustas et al., 2004), can benefit from an approach that incorporates ancillary information from soil and topographic characteristics since their estimates can be improved while accounting for the loss of in-field variability.

The wide range of values for the correlation between SM and temperature among the eight plots suggest that a site specific approach is recommended to decrease the errors of using these correlations to estimate biophysical values at the local level. Considering the long term goal for the Hydra-probe stations, the seasonal independent agreement between the station and the readings from Theta probes at the 5 cm depth demonstrate the reliability of the sampled stations SM and GT data for soil moisture studies. Under and over-estimation of field SM behaviors shown by three stations suggest the need to conduct field validation on the remaining stations of the network to find potential disagreements and suitable explanations.

As a general strategy to incorporate landscape analysis within environmental remote sensing, our results suggest that future research in the remote sensing of soil moisture should consider methodologies in which landscape fragments extracted from high spatial resolution remote sensing data are associated with biophysical processes using the quantitative methods of landscape ecology metrics as a way to link landscape pattern to process while considering the limitations of complexity within ecosystem analysis.

Acknowledgements

This research was funded by an agreement between United States Geological Survey, Rolla, Missouri (USGS), United States Department of Agriculture, Agriculture Research Service-South East Water Research Laboratory, Tifton, Georgia (USDA–ARS-SEWRL) and National Environmental Sound Production Agriculture Laboratory, University of Georgia (NESPAL-UGA). The authors express their gratitude to the personnel of the precision agriculture laboratory at NESPAL for their help in the field data collection, to Ms. Laura Marshal (USDA–ARS-SEWRL), and to personnel of the SEWRL that administrate the Hydra-probe network.

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