Statistical Methods for Evaluating Soil Salinity Spatial and Temporal Variability

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Monitoring soil salinity requires knowledge of its magnitude and its spatial and temporal variability. To characterize the spatiotemporal variability of soil salinity in a native sodic grassland in the east of Hungary, we applied several statistical methods. Within a 25-ha study area, soil samples were taken repeatedly from 13 to 20 locations at 19 dates between November 1994 and June 2001 (with intervals between 2 and 9 mo). Electrical conductivity was measured both in the laboratory in a 1:2.5 soil/water suspension ($EC_{2.5}$) and in situ using a four-electrode probe (EC_a). These measurements were converted, via calibration regressions, into predicted $EC_{2.5}$*, which were compared with $EC_{2.5}$ in their ability to characterize the spatiotemporal variability of soil salinity. The temporal change in the mean soil salinity level between each subsequent two dates was evaluated using a paired ***t***-test, a test of significance of the regression parameters based on the concept of temporal stability, and a temporal mean shift test. The static–dynamic (uniform–nonuniform) nature of the temporal change in the spatial pattern of soil salinity between two dates was evaluated using the same concept of temporal stability and a spatial shift test. For either type of temporal change (mean level or spatial pattern), the methods agreed for some pairs of dates and did not for others, but these differences were partly due to differences in data input. The method to use depends on the data availability and the aim of the study. The joint use of temporal stability and temporal mean shift and spatial shift tests could result in a drastically reduced sampling effort.

Abbreviations: $EC_{2.5}$, soil electrical conductivity determined from a 1:2.5 soil/water suspension; $EC_{2.5}$*, electrical conductivity in a 1:2.5 soil/water suspension predicted from apparent electrical conductivity using calibration regression equation; EC_a, apparent soil electrical conductivity; EC_e, electrical conductivity of a water-saturated soil paste; MD, mean difference.

To control its harmful effects, soil salinity needs to be monitored in space and time. This requires knowledge of its magnitude, temporal dynamics, and spatial variability. The magnitude of soil salinity is conventionally assessed in the laboratory by determining the electrical conductivity of a water-saturated soil paste (EC_e), either in an extracted suspension or in the paste directly. This procedure, however, is time consuming and expensive.

Alternatively, soil salinity can be evaluated by measuring the apparent electrical conductivity (EC_a) in the field using electrode probes or a soil sensor like the EM38 (Geonics Ltd, Mississauga, ON, Canada). This approach is faster and cheaper, and allows a more intensive surveying. Nevertheless, it still requires the collection of soil samples for analysis in the laboratory to establish calibration equations linking EC_a to EC_e. Different approaches are used but the more statistically rigorous is the stochastic field-calibration technique (Rhoades et al., 1999). It is based on regression models linking EC_a to EC_e for areas uniformly managed and homogeneous for all but soil salinity factors. For example, Halvorson and Rhoades (1974) found a correlation coefficient between both variables of 0.98 when the soil profile was at or near field capacity, and of 0.96 when it was drier. More details about describing and interpreting soil salinity from EC_a can be found elsewhere (e.g., Rhoades et al., 1999). Clay et al. (2001) evaluated the spatial variability of EC_a and found that it was positively correlated to EC_e, soil water, and clay content. Corwin et al. (2006), studying the space–time variation of soil quality based on an EC_a directed sampling, found that salinity levels were reduced by 13% in the 0- to 60-cm depth from 1999 to 2002, mainly due to leaching. When dynamic soil properties, such as salt concentration or water content, dominate EC_a measurements, their spatial patterns are less time stable than EC_a measurements that are mainly influenced by static properties like soil texture (Corwin, 2005).

As soil salinity can be variable in space and time, monitoring requires a lot of measurements. The spatial pattern of soil salinity can persist with time (Castrignanò et al., 1994), however, so that locations can be identified where deviations of soil salinity from the field mean value are nearly constant at all times. This means that a reduced number of selected locations would suffice to characterize the mean soil salinity status of the field. In such a situation, the sampling effort could be reduced substantially (Vachaud et al., 1985). *Temporal persistence*, also known as *temporal stability*, is defined as the

Soil Sci. Soc. Am. J. 71:XXX-XXX
doi:10.2136/sssaj2006.0083
Received 22 Feb. 2006.
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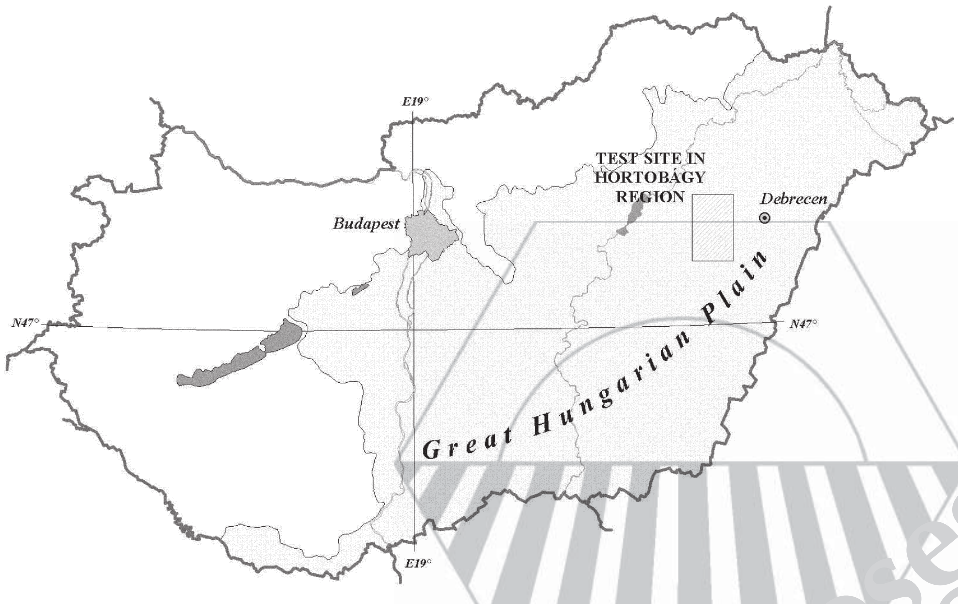

Fig. 1. Map of Hungary with the Great Hungarian Plain and the test site inside the Hortobagy region.

time-invariant association between spatial location and classic statistical parameters (Vachaud et al., 1985). To check for its presence, Vachaud et al. (1985) introduced two tests. The first one is based on the Spearman rank correlation. It consists of the determination of the rank correlation coefficient between sampling dates. The second test is based on the relative differences between sampling dates. Kachanoski and de Jong (1988) applied the second approach and showed that a good test for the temporal persistence was the significance and magnitude of the Pearson correlation coefficient and the parameters of a simple linear regression fitted to values observed at two consecutive dates. The significance test of the regression intercept is a check on whether the mean soil salinity level has changed (either increased or decreased) or not between two dates, while the test of significance of the regression slope is a check on whether the spatial pattern of soil salinity between two dates was static (uniform, i.e., changed by the same amount for all locations) or dynamic (nonuniform, i.e., the amount of change was different from one location to another). Although the temporal stability has been used by many researchers, most of their studies have been applied only to soil water properties (Van Wesenbeeck et al., 1988; Da Silva et al., 2001; Martínez-Fernández and Ceballos, 2003; Petrone et al., 2004). Castrignanò et al. (1994) evaluated the temporal stability of EC_e, the Na content, and the Na adsorption ratio from a field of 2.8 ha (at 28 locations) during 2 yr (at eight dates). They were able to identify a small number of sampling locations to estimate the mean soil salinity and sodicity at any time during the 2-yr period. Also, they found that the spatial pattern of these soil properties persisted during the time period considered.

The paired *t*-test, comparing the mean differences, is another way to check if the mean soil salinity level has significantly changed between two dates. This method, however, does not allow a check of the static–dynamic nature of the spatial pattern of soil salinity. This approach was used by Kenny et al. (2002) to check the temporal trend of the mean thickness of the Ap horizon.

There is a third way to check the significance of a temporal change in the mean soil salinity level as well as the static–dynamic nature of its spatial pattern. For this method, Lesch et al. (1998) introduced a different procedure by combining EC_a and EC_e. Their approach is based on two statistical tests and allows a check of two kinds of change. The first test, called the *temporal mean shift*, is used to check if the observed mean value at the second date and the mean of the estimated values (obtained from the calibration equation of the first date and EC_a measurements at the second date) are significantly different, i.e., if the mean soil salinity level has changed. The second test, called the *spatial shift*, allows detection of the existence of a dynamic (nonuniform) spatial variation, i.e., a change in soil salinity that is different from one location to another. Otherwise, the spatial variation was static, meaning either no change or a constant change that occurred for all locations between the two sampling dates.

The main objective of this research was to evaluate several statistical methods to characterize the spatiotemporal variability of soil salinity either by direct electrical conductivity measurements or from predictions obtained from EC_a observations. The specific objectives were to evaluate: (i) the temporal change in the mean soil salinity level between two sampling dates using a paired *t*-test, a significance test of the regression parameters based on the concept of temporal stability, and a temporal mean shift test; (ii) the static–dynamic (uniform–nonuniform) nature of the temporal change of the spatial pattern of soil salinity between two dates using the same concept of temporal stability and a spatial shift test; and (iii) the opportunity to reduce the sampling effort for monitoring soil salinity with time depending on whether the mean soil salinity level has changed or not and whether its spatial pattern is static or dynamic.

MATERIALS AND METHODS

Study Site

Our study site was a native sodic grassland of about 25 ha located in the Hortobagy National Park in eastern Hungary with central coordinates 47°30′ N and 21°30′ E (Fig. 1). This area has been described in several studies, providing details on soil properties (Tóth and Jozefaciuk, 2002) and the spatial and temporal variation of soil salinity (Douaik et al., 2004; Douaik, 2005; Tóth et al., 2002). Although it was not our aim to characterize the pedological or chemical aspects of the soil salinity of this area, some of its characteristics will be discussed briefly.

The study area is a part of the largest contiguous salt-affected landscape in central Europe. The topography is nearly flat, with a mean elevation of 89 m above sea level. The typical soils of the study site are classified as Typic Natrustolls and Typic Natraquolls according to Soil Taxonomy and they have a characteristic morphology. The A/E (eluvial) horizon is mostly salt free, with a pH of about 7. Its texture is loam with a weakly developed platy structure with many roots. In contrast, the B (illuvial) horizon is characterized by a strong alkalinity, a finer texture, typically clay loam, a columnar structure, and a very low hydraulic conductivity. The C horizon is less affected by salt accumulation, resembling the original loess parent material, but the Natraquolls show many redoximorphic features in this horizon.

The region is characterized by a wide range in monthly average temperatures (23.6°C) and a mean annual precipitation of 524 mm. The wettest month is June (67 mm), while January is the driest (26 mm). The drought index, i.e., the ratio of potential evaporation to precipitation, exceeds unity for most of the year (March–October), hence the salinization susceptibility of the region. Since the region is a recharge area of saline groundwater originating from rock weathering in the surrounding mountains, the groundwater is the main source of salts.

Data Description

Field work was conducted at 19 dates between November 1994 and June 2001, with temporal intervals ranging from 2 to 9 mo. The EC_a was measured at up to 413 locations according to a pseudo-regular grid of 25 by 25 m, using the four-electrode probe apparatus of Rhoades and Miyamoto (1990). Based on the principles of the effect of inserting the electrodes (Rhoades et al., 1999) in the sodic soil, two insertion depths were initially used to characterize the 0- to 20- and 0- to 40-cm depths. Due to the temporally changing soil moisture content (ranging from puddles to cracking surface), however, instrumental data collected with 8-cm-deep insertion (measured from the air–litter contact of the grassland) showed great scatter and were ignored, whereas data obtained with 13-cm-deeper insertion showed significant correlation with the soil salinity of the 0- to 40-cm layer. An electric current with intensity Y is induced between the outer electrodes and the potential, E, is measured between the inner electrodes. The soil resistance R_s is obtained from

$$R_s = E/Y \qquad [1]$$

which was converted to EC_a using a cell constant determined experimentally.

Simultaneously, a limited number of soil samples, between 13 and 20 depending on the date, were collected following a spatial sampling algorithm (Lesch et al., 1995) (Fig. 2). Normally, 20 calibration locations were sampled but at seven dates, some of the calibration locations (1–7) could not be sampled due to water logging, instrument malfunction, or vandalism of the reference marks since the area is an open pasture. On these samples, $EC_{2.5}$ was measured in the laboratory in a 1:2.5 soil/water suspension and converted to a reference temperature of 25°C, which we considered as a simple proxy for EC_e (Soil and Plant Analysis Council, 1992). The sampling locations were selected following a spatial response surface sampling design (based on the 413 EC_a observations) and spanned the whole extent of the study area, which optimized the estimation of the calibration model. Soil samples were collected at four depths from 0 to 40 cm with an increment of 10 cm. In this study, we considered only the EC_a of the depth interval 0 to 40 cm and the mean $EC_{2.5}$ for the four depths. The average $EC_{2.5}$ values ranged between 1.6 mS m^{-1}, with a standard deviation of 0.63 mS m^{-1} (March 1997), and 3.3 mS m^{-1}, with a standard deviation of 2.17 mS m^{-1} (September 1998) (Douaik, 2005).

The $EC_{2.5}$ is reported at a standard temperature of 25°C, while EC_a was reported at the prevailing temperature in the field. To avoid a proportional shift due to differences in temperature and moisture content, however, EC_a was rescaled (using calibration equations) into a predicted $EC_{2.5}$* separately for each date (Table 1). Thus we could evaluate the characterization of the temporal stability of spatial patterns in the observed ($EC_{2.5}$) and predicted ($EC_{2.5}$*) soil salinity at the same 13 to 20 locations. This allowed us to evaluate how well the fast field method using electrodes can replace laboratory analyses in characterizing the temporal stability of soil salinity.

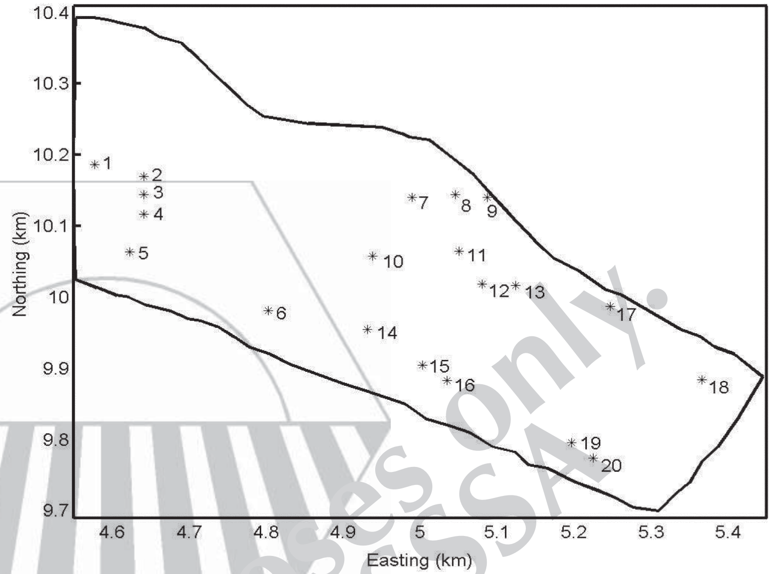

Fig. 2. Study area with locations where apparent electrical conductivity was measured and where samples were taken to determine electrical conductivity in a 1:2.5 soil/water suspension (in this figure all 20 locations are indicated, but due to practical limitations, Locations 1 to 7 could not be sampled at some of the 19 dates).

Maps of $EC_{2.5}$* at different dates have been reported elsewhere (Douaik, 2005).

Statistical Methods

The difference in mean soil salinity level between two dates can be checked using three methods: the paired t-test, the significance test of the regression parameters of the relative differences based on the concept of temporal stability, and the temporal mean shift test. It is also interesting,

Table 1. Linear regression parameters of calibration equations relating apparent soil electrical conductivity (x) to soil electrical conductivity determined from a 1:2.5 soil/water suspension (y) for every sampling date to determine the predicted soil salinity.

Sampling date	Sample size n	Intercept	Slope	r^2†	RMSE
		dS m^{-1}			dS m^{-1}
9 Nov. 1994	13	0.81	2.56	0.72	0.26
2 Mar. 1995	20	1.29	0.54	0.83	0.36
12 June 1995	20	0.87	0.50	0.77	0.54
1 Sept. 1995	20	0.97	0.54	0.88	0.33
6 Dec. 1995	20	0.83	0.47	0.85	0.36
26 Mar. 1996	16	1.20	0.44	0.76	0.41
24 June 1996	20	0.87	1.35	0.76	0.45
25 Mar. 1997	20	0.82	0.41	0.79	0.28
4 June 1997	15	0.91	0.80	0.69	0.57
15 Sept. 1997	20	0.51	1.59	0.88	0.44
5 Dec. 1997	20	0.36	0.99	0.83	0.46
15 Sept. 1998	20	0.95	0.89	0.72	1.17
28 Apr. 1999	20	–0.10	0.62	0.86	0.66
15 July 1999	13	0.38	0.43	0.83	0.69
20 Sept. 1999	20	0.85	0.62	0.83	0.81
30 Apr. 2000	18	0.20	0.61	0.88	0.57
11 Dec. 2000	20	0.83	0.92	0.86	0.70
28 Mar. 2001	19	0.12	0.77	0.94	0.28
13 June 2001	20	0.70	0.86	0.74	0.92

† Coefficient of determination.

however, to evaluate the static–dynamic nature of the temporal change of the spatial pattern of soil salinity. Two evaluation methods are available for this: the same concept of temporal stability and the spatial shift test.

Temporal Change of the Mean Soil Salinity Level

Paired *t*-Test. The paired *t*-test (McClave and Sincich, 2000) tests if the mean difference (MD) is significant. Therefore the differences between the soil salinity (generally identified as EC) on two consecutive dates are calculated:

$$\mathrm{MD} = \overline{\mathrm{EC}}_{j+1} - \overline{\mathrm{EC}}_{j} \qquad [2]$$

with $\overline{\mathrm{EC}}_{j} = (1/n)\Sigma_{i=1}^{n}\mathrm{EC}_{ij}$ and EC_{ij} the EC measured at location i (i = 1, …, n) and date j (j = 1, …, l). Then, a *t*-test statistic is computed and compared with tabulated t values or the corresponding probability of the *t*-test statistic is compared with a given level of significance (generally 0.05) to check if the difference of the means is significant.

Temporal Stability Test. The concept of temporal stability was introduced by Vachaud et al. (1985). It refers to the tendency of measurements of a soil property at different locations in space to maintain their relative ranking with time. One way to evaluate this temporal stability is to calculate the relative difference (δ_{ij}):

$$\delta_{ij} = \frac{\mathrm{EC}_{ij} - \overline{\mathrm{EC}}_{j}}{\overline{\mathrm{EC}}_{j}} \qquad [3]$$

Kachanoski and De Jong (1988) refined the definition of temporal stability by showing that it exists if the relative differences remain constant between two dates. This implies that

$$\mathrm{EC}_{ij+1} = \frac{\overline{\mathrm{EC}}_{j+1}}{\overline{\mathrm{EC}}_{j}}\mathrm{EC}_{ij} \qquad [4]$$

Thus, to evaluate the temporal stability of soil salinity, a linear regression between EC at two different dates can be modeled with an intercept I, and a slope S given by

$$S = \frac{\overline{\mathrm{EC}}_{j+1}}{\overline{\mathrm{EC}}_{j}} \qquad [5]$$

The temporal change in the mean soil salinity level can be checked by testing if I = 0. If this hypothesis is rejected, we can assume that the mean soil salinity level has increased (I > 0) or decreased (I < 0) between the two dates. On the other hand, if the hypothesis can't be rejected, the mean soil salinity is considered unchanged between these dates.

Temporal Mean Shift Test. The temporal stability test investigates the temporal changes of $\mathrm{EC}_{2.5}$ and $\mathrm{EC}_{2.5}$* (and thus indirectly EC_{a}) separately. Lesch et al. (1998) discussed another approach that can test the change in the mean soil salinity level, as well as the static–dynamic nature of the change in the soil salinity spatial pattern between two sampling dates, by integrating both soil properties. Their approach is based on the estimation of the regression parameters (intercept I_j and slope S_j) of the model

$$\mathrm{EC}_{2.5}{*}_{j} = I_{j} + S_{j}\mathrm{EC}_{\mathrm{a}\,j} \qquad [6]$$

using the data from date j (j = 1, …, l) observed at n locations. Next, the $\mathrm{EC}_{2.5}$ of date j+1 is predicted from EC_{a} measurements at m locations (i = 1, …, m), with $m \le n$, using the regression parameters of the previous date:

$$\mathrm{EC}_{2.5}{*}_{i,j+1} = I_{j} + S_{j}\mathrm{EC}_{\mathrm{a}i,j+1} \qquad [7]$$

Then, the MD is obtained between these predictions and the observed $\mathrm{EC}_{2.5}$ at the m locations of the second date:

$$\mathrm{MD} = \overline{\mathrm{EC}_{2.5}}_{\,j+1} - \overline{\mathrm{EC}_{2.5}{*}}_{\,j+1} \qquad [8]$$

with $\overline{\mathrm{EC}_{2.5}}_{\,j+1} = (1/m)\Sigma_{i=1}^{m}\mathrm{EC}_{2.5i,j+1}$, and similarly for the predicted value.

Together with the regression model design matrix, an approximate *t*-test (with $n-2$ degrees of freedom) can be derived to test if MD = 0, i.e., if there is a change in the mean soil salinity level (Lesch et al., 1998).

Static–Dynamic Nature of the Temporal Change of the Soil Salinity Spatial Pattern

Temporal Stability Test. If there is no, or uniform, change in the EC of all the locations between two sampling dates, we expect that S = 1 (Eq. [5]; Kachanoski and de Jong, 1988). Then, the magnitude of the change is given by I, so when I = 0 there is no change. In this case, the spatial pattern of the soil salinity is said to be static. On the other hand, if S is significantly different from 1, the spatial pattern of the soil salinity can be considered to be dynamic, i.e., the magnitude of change in the soil salinity between two dates is nonuniform and is different from one location to another.

Spatial Shift Test. The nature of the spatial variation of the temporal change (static–dynamic) is tested by computing a statistic φ, which is a function of the normalized squared differences, the design matrix, and the regression model mean squared error estimate. The statistic φ is compared to an F distribution with $m-1$ and $n-2$ degrees of freedom (Lesch et al., 1998).

Combining Tests for Mean Level and Spatial Pattern of Soil Salinity

Temporal Stability Test. Based on whether I is significantly different from 0, S is significantly different from 1, or both, four possible scenarios can be distinguished (Grant et al., 2004):

- *Scenario* 1 (I = 0 *and* S = 1): there is no net change between the two sampling dates
- *Scenario* 2 ($I \neq 0$ *and* S = 1): the mean soil salinity level has changed and there is a static (uniform) change in the soil salinity spatial pattern
- *Scenario* 3 (I = 0 *and* $S \neq 1$): the mean soil salinity level has not changed and the change in the soil salinity spatial pattern is dynamic (nonuniform) but, when averaged, this change is not significant
- *Scenario* 4 ($I \neq 0$ *and* $S \neq 1$): the mean soil salinity level has changed and the change in the soil salinity spatial pattern is dynamic (nonuniform)

Temporal Mean Shift and Spatial Shift Tests. Again, four scenarios are possible:

- *Scenario* 1 (MD = 0 *and* φ = 0): there is no net change with time in the soil salinity
- *Scenario* 2 (MD ≠ 0 *and* φ = 0): the mean soil salinity level has changed and there is a static (uniform) change in the soil salinity spatial pattern
- *Scenario* 3 (MD = 0 *and* φ ≠ 0): the mean soil salinity level has not changed and the change in the soil salinity spatial pattern is dynamic (nonuniform); again, when averaged, this change is not significant
- *Scenario* 4 (MD ≠ 0 *and* φ ≠ 0): the mean soil salinity level has changed and the change in the spatial pattern of the soil salinity is dynamic (nonuniform)

The usefulness of the temporal mean shift and spatial shift tests lies in the possibility of using only the pairs of EC_{a}–$\mathrm{EC}_{2.5}$ values from the first sampling date, along with the $\mathrm{EC}_{2.5}$ values from the second date. If it is found that there was no or a static (uniform) change between the two dates, then the regression equation computed using the data from the first date can be used to predict $EC_{2.5}$* for the second date using a larger EC_a survey data set. If a dynamic spatial variation was detected, however, then a new regression equation should be estimated using the EC_a–$EC_{2.5}$ pairs of values from the second date.

The paired *t*-test and the temporal stability test were performed for both $EC_{2.5}$ and $EC_{2.5}$*, while the temporal mean shift (significance of MD) and the spatial shift tests (significance of φ) were applied only to $EC_{2.5}$, as these tests integrate the EC_a.

RESULTS AND DISCUSSION

Calibration Equations

All the coefficients of determination (r^2) of the calibration equations, $EC_{2.5} = I + S(EC_a)$, for each of the observed dates (Table 1) were highly significant and ranged between 0.69 and 0.94, indicating that the regression explained between 69 and 94% of the variance within the data. The intercept (*I*) values ranged between –0.10 and 1.29 dS m^{-1}, while the slope (*S*) values varied between 0.41 and 2.56. These fluctuations reflect the differences in field conditions (temperature and moisture content) when EC_a was observed, but no clear seasonal effect could be found. Also, the RMSE, reflecting the deviation from the regression line, was generally small. It varied between 0.26 and 1.17 dS m^{-1}. Therefore, it could be concluded that, generally, EC_a was found to be closely and linearly linked with $EC_{2.5}$.

It was assumed that $EC_{2.5}$ could be used as a simple proxy of EC_e, reflecting soil salinity. Since $EC_{2.5}$ was determined in the laboratory for each date, we considered this soil property to be the reference. The predicted soil salinity ($EC_{2.5}$*) was obtained from field measurements of EC_a using an electrode configuration and a fitted calibration curve. The goodness-of-fit of the calibration equations (Table 1) indicate that generally there was a strong relationship between both variables and that $EC_{2.5}$ could be reliably predicted from EC_a.

Correlation Coefficients

The Pearson correlation coefficients (*r*) between consecutive sampling dates for both $EC_{2.5}$ and $EC_{2.5}$* were generally quite strong and all values were significant (Table 2). They ranged from 0.58 to 0.94 for $EC_{2.5}$ and from 0.81 to 0.98 for $EC_{2.5}$*. These values indicate the presence of moderate to strong temporal stability across the observed time intervals. The correlation coefficients of both variables were very similar and the differences were negligible except for the first pair of dates, where the difference was moderate (0.27).

Temporal Change of the Mean Soil Salinity Level

Paired *t*-Test. The paired *t*-test was applied to both $EC_{2.5}$ and $EC_{2.5}$* (Table 2). The MD in $EC_{2.5}$ between two consecutive dates (Eq. [2]) was significantly different from zero for only four out of the 18 pairs of dates. Of these four pairs, the mean value decreased only once (by 1.46 dS m^{-1}), while it increased for the other three pairs (by 0.27–1.70 dS m^{-1}). The results were strongly different for $EC_{2.5}$*. For this variable, the hypothesis that the mean difference was equal to zero was rejected for 11 pairs of dates. The significant mean differences decreased for seven pairs and increased for four pairs. The decrease ranged from 0.18 to 1.45 dS m^{-1}, while the increase varied between 0.15 and 1.70 dS m^{-1}. The four pairs of dates where the mean difference in $EC_{2.5}$ was significant are included in the case of $EC_{2.5}$* and the magnitudes of the mean differences of both variables were very similar.

Temporal Stability. From the four possible scenarios of the temporal stability test, the second and the fourth represent the cases where the mean change is statistically significant, whereas for the first and third scenarios, it is not. Regarding $EC_{2.5}$ (Table 3), the mean level changed significantly for seven pairs of dates, all showing an increase between 0.37 and 1.05 dS m^{-1}, except one pair for which there was a decrease of 0.57 dS m^{-1}. The mean $EC_{2.5}$* level changed significantly for nine pairs of dates, with an increase between 0.44 and 0.77 dS m^{-1} for six pairs and a decrease between 0.57 and 0.88 dS m^{-1} for the remaining three pairs of dates. Again, as with the paired *t*-test, all the pairs of dates for which the mean $EC_{2.5}$ level has changed also have changed $EC_{2.5}$* values.

Temporal Mean Shift Test. The temporal mean shift test compared the mean value for the observed $EC_{2.5}$ of one date to the mean of the predicted values based on the regression modeling between $EC_{2.5}$ and EC_a from the previous date (Table 1). The obtained MDs (Eq. [8]) were computed, together with their probability of significance (second and third columns of Table 4). The MD was significantly different for only three pairs of dates, with a decrease of 1.45 dS m^{-1} for one pair and an increase of 0.37 and 1.70 dS m^{-1} for the other two pairs of dates. These correspond to the same pairs of dates (no. 1, 11, and 12) for which the MD, based on the paired *t*-test, was found to be significant (Table 2), but this

Table 2. Pearson correlation coefficients (*r*) and results of the paired *t*-test of the observed ($EC_{2.5}$) and predicted ($EC_{2.5}$* derived from calibration equations relating apparent electrical conductivity to $EC_{2.5}$) electrical conductivity in a 1:2.5 soil/water suspension for 18 pairs of observation dates (significant values are in italic and the level of significance was 0.05).

Pair of sampling dates	$EC_{2.5}$			$EC_{2.5}$*		
	r	MD†	*P*(MD = 0)‡	*r*	MD	*P*(MD = 0)
		dS m^{-1}			dS m^{-1}	
1: Nov. 1994, Mar. 1995	*0.58*	*0.37*	*0.01*	*0.85*	*0.41*	*0.00*
2: Mar. 1995, June 1995	*0.78*	–0.27	0.09	*0.87*	*–0.27*	*0.02*
3: June 1995, Sept. 1995	*0.93*	–0.01	0.97	*0.91*	0.00	0.97
4: Sept. 1995, Dec. 1995	*0.92*	–0.17	0.06	*0.93*	*–0.18*	*0.04*
5: Dec. 1995, Mar. 1996	*0.93*	0.11	0.24	*0.98*	*0.15*	*0.04*
6: Mar. 1996, June 1996	*0.84*	–0.17	0.20	*0.96*	*–0.22*	*0.00*
7: June 1996, Mar. 1997	*0.78*	–0.22	0.09	*0.88*	*–0.22*	*0.02*
8: Mar. 1997, June 1997	*0.92*	*0.27*	*0.03*	*0.88*	*0.22*	*0.05*
9: June 1997, Sept. 1997	*0.93*	–0.17	0.25	*0.92*	*–0.27*	*0.04*
10: Sept. 1997, Dec. 1997	*0.90*	–0.03	0.83	*0.88*	–0.03	0.84
11: Dec. 1997, Sept. 1998	*0.90*	*1.70*	*0.00*	*0.86*	*1.70*	*0.00*
12: Sept. 1998, Apr. 1999	*0.82*	*–1.46*	*0.00*	*0.94*	*–1.45*	*0.00*
13: Apr. 1999, July 1999	*0.94*	0.08	0.72	*0.94*	0.21	0.30
14: July 1999, Sept. 1999	*0.91*	0.32	0.26	*0.81*	0.07	0.82
15: Sept. 1999, Apr. 2000	*0.94*	–0.29	0.10	*0.87*	–0.18	0.40
16: Apr. 2000, Dec. 2000	*0.94*	0.33	0.06	*0.94*	0.29	0.08
17: Dec. 2000, Mar. 2001	*0.79*	–0.58	0.06	*0.83*	*–0.56*	*0.03*
18: Mar. 2001, June 2001	*0.85*	0.22	0.33	*0.86*	0.22	0.26

† MD = mean difference according to Eq. [2].

‡ *P* value of the test if MD = 0.

Table 3. Regression parameters between consecutive values of the observed ($EC_{2.5}$) and predicted ($EC_{2.5}$* derived from calibration equations relating apparent electrical conductivity to $EC_{2.5}$) electrical conductivity in a 1:2.5 soil/water suspension for 18 pairs of observation dates (significant values are in italic and the level of significance was 0.05).

Pair of sampling dates	$EC_{2.5}$				$EC_{2.5}$*			
	I†	***P***(***I*** = 0)‡	***S***§	***P***(***S*** = 1)¶	***I***	***P***(***I*** = 0)	***S***	***P***(***S*** = 1)
	dS m^{-1}				dS m^{-1}			
1: Nov. 1994, Mar. 1995	*1.05*	*0.01*	*0.52*	*0.05*	*0.64*	*0.02*	0.83	0.31
2: Mar. 1995, June 1995	−0.28	0.56	1.00	1.00	−0.46	0.21	1.08	0.58
3: June 1995, Sept. 1995	0.33	0.09	0.84	0.06	0.24	0.28	0.88	0.23
4: Sept. 1995, Dec. 1995	0.15	0.43	0.84	0.07	0.18	0.32	*0.82*	*0.04*
5: Dec. 1995, Mar. 1996	*0.54*	*0.01*	*0.78*	*0.02*	*0.63*	*0.00*	*0.75*	*0.00*
6: Mar. 1996, June 1996	−0.18	0.64	1.00	0.98	*−0.57*	*0.01*	1.17	0.07
7: June 1996, Mar. 1997	*0.59*	*0.01*	*0.55*	*0.00*	*0.44*	*0.01*	*0.64*	*0.00*
8: Mar. 1997, June 1997	−0.24	0.38	*1.34*	*0.05*	−0.01	0.97	1.15	0.40
9: June 1997, Sept. 1997	*−0.57*	*0.04*	1.23	0.13	*−0.66*	*0.03*	1.22	0.14
10: Sept. 1997, Dec. 1997	*0.37*	*0.05*	*0.76*	*0.01*	*0.44*	*0.02*	*0.71*	*0.01*
11: Dec. 1997, Sept. 1998	0.32	0.45	*1.86*	*0.00*	0.61	0.18	*1.68*	*0.01*
12: Sept. 1998, Apr. 1999	−0.33	0.45	*0.66*	*0.01*	*−0.88*	*0.00*	*0.83*	*0.02*
13: Apr. 1999, July 1999	*0.69*	*0.01*	*0.72*	*0.01*	*0.77*	*0.01*	*0.73*	*0.01*
14: July 1999, Sept. 1999	−0.20	0.68	1.23	0.22	−0.15	0.82	1.10	0.69
15: Sept. 1999, Apr. 2000	0.24	0.27	*0.78*	*0.01*	0.43	0.17	*0.73*	*0.02*
16: Apr. 2000, Dec. 2000	0.02	0.93	1.15	0.17	−0.02	0.93	1.15	0.16
17: Dec. 2000, Mar. 2001	*0.63*	*0.04*	*0.49*	*0.00*	*0.53*	*0.05*	*0.54*	*0.00*
18: Mar. 2001, June 2001	−0.25	0.54	1.27	0.17	−0.01	0.98	1.13	0.45

† *I* = intercept.

‡ *P* value for the test *I* = 0.

§ *S* = slope.

¶ *P* value for the test *S* = 1.

test indicated one more pair (no. 8) with a significant change in the mean soil salinity level.

Static–Dynamic Nature of the Temporal Change of the Spatial Pattern of Soil Salinity

Temporal Stability Test. The first and second scenarios of the temporal stability test indicate the presence of a static (uniform) change in the soil salinity spatial pattern between two sampling dates, while the third and fourth scenarios indicate a dynamic (nonuniform) change. It can be observed (Table 3) that the spatial pattern of $EC_{2.5}$ was static for eight pairs of dates, whereas it was dynamic for the remaining 10 pairs of dates. The spatial pattern of $EC_{2.5}$* was static and dynamic for the same number of pairs of dates (nine). The spatial pattern of both variables agreed for 15 pairs of dates, with a static spatial change for seven pairs and a dynamic spatial change for eight pairs.

Spatial Shift Test. As for temporal stability, in the first and second scenarios of the spatial shift test, the change in the soil salinity spatial pattern can be considered static, whereas the third and fourth scenarios show a dynamic soil salinity spatial pattern. The φ statistic was found to be significant, thus the spatial pattern of $EC_{2.5}$ was dynamic (nonuniform) for only three pairs of dates (the last two columns of Table 4, no. 8, 11, and 18). For the remaining pairs (15), the spatial pattern can be considered static, i.e., had not changed or changed uniformly by the same amount for all locations.

There was a clear difference in the ability of the different methods to characterize the spatiotemporal variability of the observed ($EC_{2.5}$) and predicted ($EC_{2.5}$*) soil salinity. These differences are mainly due to different data input and data modeling. Regarding the data input, the observed soil salinity was measured directly in the laboratory following standard methods, whereas the predicted soil salinity was obtained from rescaling of EC_a into soil salinity using calibration equations. Since the EC_a is a function of many soil properties such as clay content, water content, and total soluble salts, the predicted electrical conductivity ($EC_{2.5}$*) is only an indirect measurement of soil salinity and may fluctuate depending on the level of the clay and water content of the study site. This fluctuation is rather limited within our study area, so it can be expected that salinity dominates the EC_a measurements.

Regarding the data modeling, the paired *t*-test compared the means of either the observed or the predicted soil salinity data between two sampling dates. The temporal stability test determined the slope and the intercept of the measured data at two consecutive dates and tested if these parameters were significantly different from one and zero, respectively. The temporal mean shift and the spatial shift methods integrated soil salinity and EC_a data measured at a first date by determining the calibration equation linking these two soil properties, then used this regression to convert EC_a into predicted soil salinity, and finally computed the differences between the predicted values and those observed at the second date. Although the data input and modeling are different for the methods, there was some

Table 4. Test of significance of the temporal mean shift and the spatial shift in the observed electrical conductivity in a 1:2.5 soil/water suspension for 18 pairs of observation dates (significant values are in italic and the level of significance was 0.05).

Pair of sampling dates	MD†	*P*(MD = 0)‡	Statistic φ	*P*(φ = 0)§
	dS m^{-1}			
1: Nov. 1994, Mar. 1995	*0.37*	*0.04*	1.95	0.13
2: Mar. 1995, June 1995	−0.28	0.16	2.19	0.05
3: June 1995, Sept. 1995	0.00	0.99	0.58	0.88
4: Sept. 1995, Dec. 1995	−0.18	0.32	2.18	0.05
5: Dec. 1995, Mar. 1996	0.15	0.42	1.40	0.24
6: Mar. 1996, June 1996	−0.17	0.40	0.65	0.81
7: June 1996, Mar. 1997	−0.22	0.31	1.09	0.43
8: Mar. 1997, June 1997	0.22	0.22	*2.52*	*0.03*
9: June 1997, Sept. 1997	−0.17	0.59	1.12	0.43
10: Sept. 1997, Dec. 1997	−0.03	0.90	1.42	0.23
11: Dec. 1997, Sept. 1998	*1.70*	*0.00*	*9.62*	*0.00*
12: Sept. 1998, Apr. 1999	*−1.45*	*0.01*	0.80	0.68
13: Apr. 1999, July 1999	0.21	0.51	0.66	0.76
14: July 1999, Sept. 1999	0.32	0.48	2.06	0.11
15: Sept. 1999, Apr. 2000	−0.18	0.63	1.02	0.48
16: Apr. 2000, Dec. 2000	0.33	0.27	1.57	0.18
17: Dec. 2000, Mar. 2001	−0.56	0.16	1.88	0.10
18: Mar. 2001, June 2001	0.23	0.38	*10.84*	*0.00*

† MD = mean difference according to Eq. [9].

‡ Achieved *P* value for the test MD = 0.

§ Achieved *P* value for the test φ = 0.

agreement, since some pairs of dates were identified by all methods as dates with a significant temporal change in the mean level and in the spatial pattern.

CONCLUSIONS

A strong relationship was found between $EC_{2.5}$ and EC_a for all 19 measurement dates, with large and significant r^2 values and small RMSEs. This confirms the potential of the four-electrode probe to monitor the temporal change in soil salinity in native sodic grassland in every season. When EC_a was converted into $EC_{2.5}$*, however, some differences with $EC_{2.5}$ were found.

The concept of temporal stability requires a moderate number of measurements, but once it is checked, the number of future measurements can be reduced to locations with measurements representing important statistics such as the average value. Likewise, based on the spatial shift test, if it was found that there was a static (uniform) spatial variation between two dates, the sampling effort could be limited to the EC_a survey for the first date, while the laboratory analysis could be done for two dates but at a reduced number of locations. So the joint use of the concept of temporal stability and the temporal mean shift and spatial shift tests could result in a drastically reduced sampling effort. In another study using the same data, Douaik et al. (2006) found that it was sufficient to measure soil salinity at just two locations and nine dates to characterize reliably the average field soil salinity of this area.

The statistical method to use will depend on the data availability and the aim of the study. If only soil salinity or EC_a data are available, there is only one possibility for checking the spatial pattern of the soil salinity: the concept of temporal stability. For checking the temporal change in the average soil salinity, there is a choice between the paired *t*-test and the concept of temporal stability. If, on the other hand, both soil salinity and EC_a data are available, there are more options: the paired *t*-test and the concept of temporal stability for checking the temporal change in the average level separately for both soil properties or the temporal mean shift test for checking the temporal change in the average level combining both soil properties. Regarding the check of the temporal stability of the spatial patterns, the same choices are available except for the paired *t*-test. Finally, the results of this work can be extended to evaluate the temporal change (in the mean level as well as in the static–dynamic nature of the spatial pattern) of any other soil property related to EC_a, such as water content or organic matter content.

ACKNOWLEDGMENTS

A. Douaik was financially supported by the Ministry of the Flemish Community (Belgium) through his Ph.D. scholarship. T. Tóth acknowledges the material assistance of the Bilateral Flemish–Hungarian Research Foundation and the grants HNSF T37731 and OM-00124/2001.-NKPF/4. The linguistic improvement of David Simpson, Ghent University, is acknowledged.

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