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Temporal Stability of Spatial Patterns of Soil Salinity Determined from Laboratory and Field Electrolytic Conductivity

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We elaborated a procedure for the assessment of the temporal stability of soil salinity and the optimization of the sampling effort. Soil electrolytic conductivity data obtained from field electrode probes and laboratory analysis were compared and analyzed to check the temporal stability of salinity patterns. Sampling of 20 locations at different depths was repeated 19 times over a period from November 1994 to June 2001. Both methods showed a strong temporal stability. The Spearman rank correlation confirmed the persistence of the ranking of the different locations. Additionally, using the technique of relative differences, we identified three classes: (1) low saline locations, (2) locations which are representative of the average field soil salinity, and (3) high saline locations. Low saline locations were associated with the zones of waterlogging and/or salt leaching. High saline locations were exclusively in the zone of salt accumulation. Locations representative of the average soil salinity were found in all three possible zones. We investigated how precise the selected locations representing the average soil salinity can estimate this average. We found that using only two locations from the 20 available, the average was adequately estimated with a difference $<0.3\,dS\,m^{-1}$. *This representativeness was also checked by splitting the measurements into two temporal subsamples. For both subsamples the same locations were representative of the average soil salinity compared to when all measurement dates were considered.*

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In Hungary, salt-affected soils exceed one million hectares, covering more than 10% of the territory of the country. More than 95% of these soils are located in the Great Hungarian Plain (GHP). Hortobágy National Park, where our study area was located, forms a subregion of this plain. Hortobágy is a recharge area of saline groundwater originating from the northern mountains. This groundwater is the main source of salt accumulation in the area, so its dynamics strongly influences soil salinization (Tóth et al., 2002). Conventionally, soil salinity is determined in the laboratory by measuring the electrolytic conductivity of a solution extracted from a water-saturated soil paste (EC_e). Alternatively it can be measured in the field, and then it is called apparent electrolytic conductivity (EC_a), using electrode probes. This approach is easier, less time consuming and cheaper than the laboratory approach.

For an efficient management of salt-affected soils, we need to measure soil salinity which is spatially variable and dynamic. This variability is the outcome of different pedological factors like water table depth, topography, parent material, and so on. As a consequence of the spatial and temporal variability, we need measurements from numerous samples from different locations and during different times. However, as soil salinity does not change noticeably over short time periods in natural conditions, the observed spatial pattern could be time stable and can persist from one instant to another. If this is so, the sampling could be reduced to a limited number of locations representative of mean, low, and high saline conditions.

The concept of temporal stability, or persistence, has been used almost exclusively in the context of soil water content. Vachaud et al. (1985) were the first to introduce the concept. They analyzed the temporal stability of soil water for three crops (grass, olive trees, and wheat) to check if time-invariant characteristic statistical properties of the probability distribution functions can be assigned to individual locations. Comegna and Basile (1994) analyzed the temporal stability of soil water storage in a cultivated sandy soil in Italy. Grayson and Western (1998) defined the concept of Catchment Average Soil Moisture Monitoring (CASMM) sites using the approach of Vachaud et al. (1985). More recently, Gómez-Plaza et al. (2000) studied the temporal stability of the spatial pattern of soil moisture encompassing different scales from a semiarid region of Spain. Mohanty and Skaggs (2001) analyzed the influence of factors like soil, slope, and vegetation on the temporal stability of soil moisture within three remote sensing footprints. The temporal stability of soil water content and matric potential were investigated by Van Pelt and Wierenga (2001). The most recent work on time stability of soil moisture was done by Martínez-Fernández and Ceballos (2003).

All the previous studies focused on soil water. There is one exception (Castrignanò et al., 1993): the authors studied temporal persistence of three indicators of soil salinity: electrolytic conductivity (EC), Na content, and sodium adsorption ratio (SAR) of the soil saturation extract. They collected 28 soil samples from an agricultural field of 80 m × 350 m at three different depths at eight specific times over a period of two years.

The first objective of our research was to apply the concepts of temporal stability to soil salinity determined by two techniques (a field and a laboratory determination of electrolytic conductivity), at different depths sampled within a large field and repeated over a long temporal domain. The second objective was to study the relationship between the salt accumulation processes and their temporal stability. We also tried to find simple covariables (such as vegetation pattern or elevation) with soil salinity that would allow the identification of optimal sampling locations without an extensive sampling effort.

Materials and Methods

Data Description

The study site covers an area of about 25 ha, located in the Hortobágy National Park, in eastern Hungary with central coordinates: 47°30″ N and 21°30″ E. Bulk soil, also called apparent, electrolytic conductivity (EC_a) was observed in the field at 413 locations according to a pseudo-regular grid of 25 m × 25 m. EC_a was measured using an electrolytic conductivity probe equipped with four electrodes (Rhoades & van Schilfgaarde, 1976). The electrodes were inserted in the soil to two depths: 8 cm and 13 cm. The corresponding EC_a measures are characteristic for the 0–20 and 0–40 cm soil depth, respectively. It is the first reported extensive use of such probes in native grasslands, which are characterized by heterogeneous vegetation and elevation, and which can undergo large fluctuations in soil moisture.

From these EC_a measurements, a subset of 20 locations (Figure 1) were selected according to a spatial site selection algorithm (Lesch et al., 1995). Soil samples from these locations were collected to a depth of 40 cm, at 10 cm increments, from bulk subsamples collected from two boreholes 50 cm apart. Samples were air dried and crushed to pass a 2-mm mesh. The 1:2.5 soil:water suspensions were left for 16 hours to equilibrate, then pH and electrolytic conductivity were measured ($EC_{2.5}$) and converted to a standard temperature of 25°C. $EC_{2.5}$ is a simple proxy for EC_e.

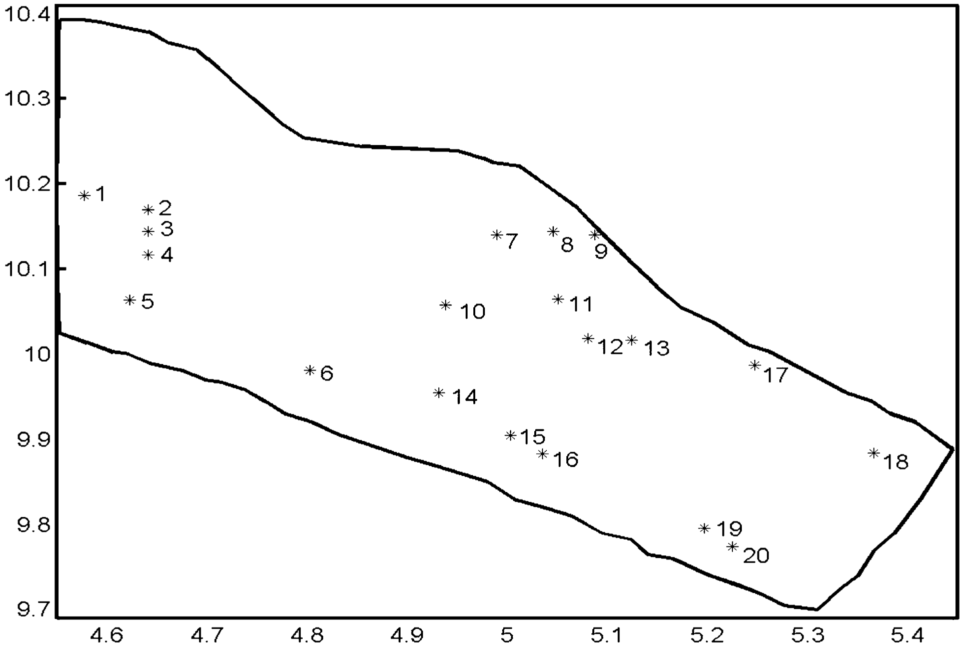

Figure 1. Spatial locations where soil was sampled for the determination of $EC_{2.5}$.

The sampling was repeated 19 times covering a period of about seven years, between November 1994 and June 2001 with an average temporal lag of three months.

Temporal Stability

The concept of temporal stability was introduced by Vachaud et al. (1985). They defined it as the time-invariant association between spatial location and statistical parameters of soil properties. They used two approaches to check for the existence of this temporal stability.

The first approach is based on the concept of the relative differences. Let EC_{ij} be EC_a or $EC_{2.5}$ at location i ($i = 1, \ldots, 20$) and time j ($j = 1, \ldots, 19$), then the relative difference δ_{ij} is defined as:

$$\delta_{ij} = \frac{EC_{ij} - \overline{EC_j}}{\overline{EC_j}},$$

with $\overline{EC_j} = \frac{1}{n}\sum_{i=1}^{n} EC_{ij}$ being the spatial average value for the time j with n the number of locations.

Using δ_{ij} we can estimate, for each location i, the temporal average $\overline{\delta}_i$ and its corresponding temporal standard deviation $\sigma(\overline{\delta}_i)$:

$$\overline{\delta}_i = \frac{1}{m}\sum_{j=1}^{m} \delta_{ij} \quad \text{and} \quad \sigma(\overline{\delta}_i) = \sqrt{\frac{1}{m-1}\sum_{j=1}^{m} \left(\delta_{ij} - \overline{\delta}_i\right)^2},$$

where $m =$ the number of time instants.

A zero value for $\overline{\delta}_i$ indicates that the temporal average $\overline{EC_j}$ represents the average value over the whole study area at any time, and $\overline{\delta}_i < 0$ indicates locations where the values are less than the average of the study area while $\overline{\delta}_i < 0$ indicates the locations where the values are larger than the average.

The $\overline{\delta}_i$ values can be plotted against their rank with the corresponding temporal standard deviations. A small value of $\sigma(\overline{\delta}_i)$ indicates a time stable location while a large value indicates a site with values which are strongly time-variable.

The second method is based on the non parametric Spearman rank order correlation:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} \left(R_{ij} - R_{ik}\right)^2}{n(n^2 - 1)},$$

with R_{ij} being the rank of the soil EC at location i and time j and R_{ik}, the rank of the soil EC at the same location but for another time $k (k \neq j)$. This correlation is computed for all possible pairs of measurement times. A perfect temporal stability between time instants j and k is indicated by $r_s = 1$, and a lack of temporal stability implies that $r_s = 0$.

Results and Discussion

Exploratory Data Analysis

Basic statistics about the apparent (EC_a) and laboratory ($EC_{2.5}$) electrolytic conductivity, calculated using 20 locations and 19 time instants, are reported in Table 1.

Table 1. Descriptive statistics for EC_a and $EC_{2.5}$ measured at different depths

Property (dS m^{-1})	Depth (cm)	Mean	Median	Min[a]	Max[b]	SD[c]	CV%[d]
EC_a	0–20	1.40	0.90	0.02	9.19	1.64	117
	0–40	1.94	1.31	0.03	10.05	1.99	103
$EC_{2.5}$	0–10	1.29	1.02	0.10	13.50	1.29	100
	10–20	1.72	1.37	0.08	8.30	1.41	82
	20–30	2.33	1.92	0.07	13.70	1.77	76
	30–40	2.69	2.28	0.07	11.50	1.84	68
	0–40 (mean)	2.01	1.67	0.10	7.50	1.38	69

[a] minimum.
[b] maximum.
[c] standard deviation.
[d] coefficient of variation.

Since bulk soil electrolytic conductivity is affected by spatial variability of texture and soil moisture, EC_a has higher CV's compared to $EC_{2.5}$, and for both soil properties the CV decreased, and the mean value increased, with depth. Regarding the extreme values, there are some nonsaline locations (minimum of 0.02 to 0.10 dS m^{-1}) as well as some highly saline sites (maximum values ranging between 8.3 and 13.7 dS m^{-1}).

Temporal Stability Using the Spearman's Rank Order Correlation

As the Spearman rank order correlation is a nonparametric (free distribution) test, it is less restrictive than the Pearson linear correlation. It indicates the strength and the direction of a rising or falling relationship between two different variables, or the same variable observed at two different time instants.

Table 2 gives the rank correlation coefficients with regard to $EC_{2.5}$ for the 19 time instants. Rank correlation coefficients ranged between 0.46 and 0.96 and were generally greater than 0.85. Table 2 shows that $EC_{2.5}$ presented time-stable spatial patterns across the whole study period. This is indicated by the values of order correlation which were highly ($p \leq 0.01$) to very highly ($p \leq 0.001$) significant in most of the cases. For example, only one of the 171 coefficients was not significant ($p \geq 0.05$), whereas 153 coefficients were highly significant ($p \leq 0.01$). Also, the loss of information between two measurement times was small. The rank correlations of the other variables (results not shown) were mostly significant, although the number of nonsignificant coefficients was larger for some of the depths.

Temporal Stability Using the Mean Relative Differences

Using the Pearson linear and Spearman rank correlation coefficients, we were able to show that there was a strong temporal stability of the spatial pattern of soil salinity across the whole spatial domain and the whole study period. However we still need to quantify this temporal stability by identifying locations which are time-stable and simultaneously are representative of the mean and/or extreme saline conditions. Therefore, the concept of relative differences (Vachaud et al., 1985) was used.

The plots of the mean relative differences ranked in ascending order are shown in Figure 2 for EC_a, and in Figure 3 for $EC_{2.5}$. The corresponding temporal standard

Table 2. Spearman rank order correlation coefficients for $EC_{2.5}$ at the 19 time instants

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2	0.65																	
3	0.77	0.72																
4	0.89	0.71	0.94															
5	0.87	0.72	0.96	0.96														
6	0.69	0.66	0.94	0.92	0.94													
7	0.87	0.73	0.92	0.96	0.94	0.88												
8	0.59	0.71	0.85	0.88	0.85	0.89	0.83											
9	0.82	0.79	0.94	0.96	0.95	0.92	0.92	0.94										
10	0.79	0.71	0.89	0.94	0.92	0.91	0.92	0.89	0.95									
11	0.69	0.72	0.95	0.93	0.94	0.96	0.91	0.93	0.95	0.93								
12	0.76	0.67	0.86	0.84	0.87	0.85	0.80	0.85	0.88	0.89	0.88							
13	0.70	0.54	0.85	0.90	0.87	0.90	0.84	0.86	0.90	0.84	0.86	0.80						
14	0.46	0.74	0.88	0.86	0.85	0.78	0.87	0.86	0.93	0.84	0.84	0.71	0.85					
15	0.85	0.74	0.95	0.94	0.94	0.93	0.92	0.87	0.95	0.95	0.95	0.90	0.87	0.85				
16	0.77	0.73	0.92	0.93	0.93	0.91	0.91	0.89	0.96	0.95	0.94	0.90	0.90	0.89	0.95			
17	0.70	0.78	0.89	0.85	0.88	0.84	0.87	0.86	0.95	0.92	0.90	0.86	0.76	0.88	0.94	0.93		
18	0.91	0.64	0.90	0.94	0.95	0.89	0.92	0.80	0.90	0.90	0.89	0.85	0.86	0.82	0.91	0.91	0.79	
19	0.76	0.66	0.82	0.90	0.88	0.90	0.88	0.84	0.95	0.96	0.85	0.87	0.81	0.83	0.90	0.94	0.88	0.87

Note: 1 to 19 refer to: Nov 1994, March, June, Sept, and Dec 1995, March and June 1996, March, June, Sept, and Dec 1997, Sept 1998, Apr, Jul and Sept 1999, Apr and Dec 2000, March and June 2001, respectively.

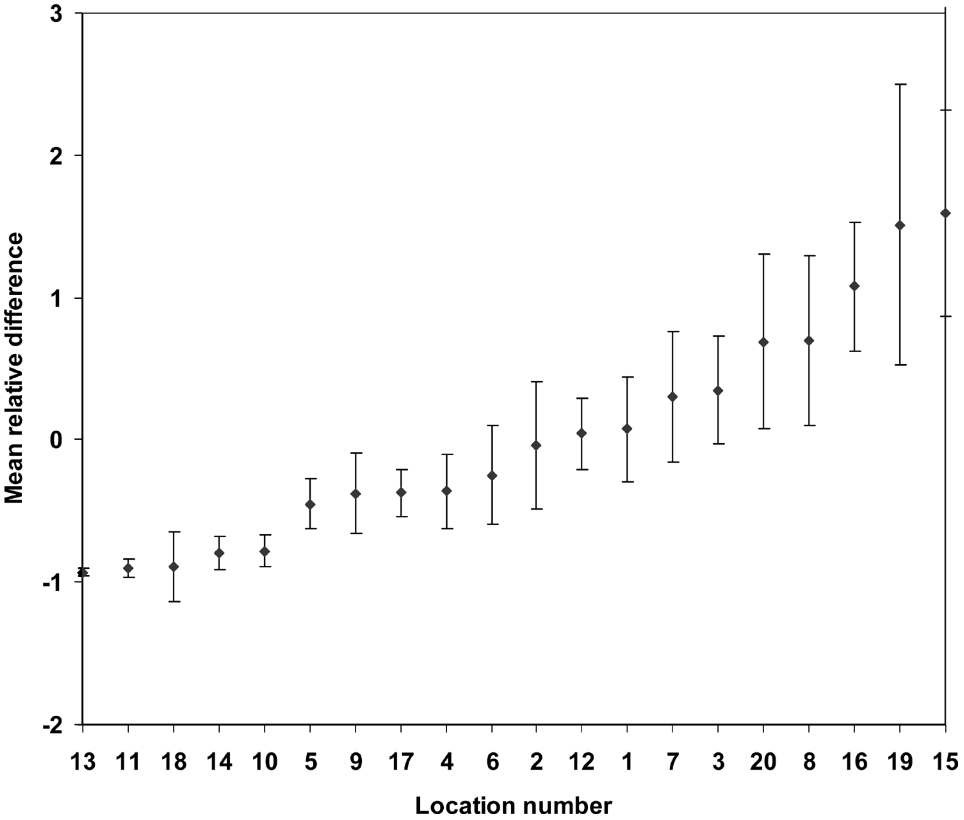

Figure 2. Mean relative differences for EC_a. Locations are ranked from the lowest to the highest mean relative differences. Vertical bars represent +/− one standard deviation.

deviations (vertical bars represent +/− one standard deviation) were also drawn to indicate the dispersion around the mean relative differences.

Figure 2 shows that at locations 1, 2, and 12 the mean field EC_a was observed consistently within +/− 0.1 dS m^{-1} at any time instant. At the locations 10, 11, 13, 14, and 18 this mean was systematically underestimated by more than 0.5 dS m^{-1}. Of these locations 11, 13, and 18 were the least saline. On the other hand, at locations 8, 15, 16, 19, and 20 the spatial mean EC_a was overestimated by more than 0.5 dS m^{-1}, with locations 15, 16, and 19 being the most saline. The temporal stability, indicated by the vertical bars corresponding to +/− one temporal standard deviation, is strong for the locations with low salinity, intermediate for locations representative of the mean field EC_a, and low for locations with high salinity. The locations representative of the least saline conditions in terms of $EC_{2.5}$ were identified from Figure 3. These are locations 11, 13, and 18. They maintain their temporal stability, although these locations were less time stable as the temporal standard deviations were respectively, 0.06, 0.02, and 0.25 dS m^{-1} for EC_a, and 0.21, 0.19, and 0.30 dS m^{-1} for $EC_{2.5}$.

When the locations representative of the most saline conditions, based on $EC_{2.5}$, were selected from Figure 3, the same locations were obtained as for EC_a except one (location 8). Also, as for EC_a, they displayed a weak temporal stability although the

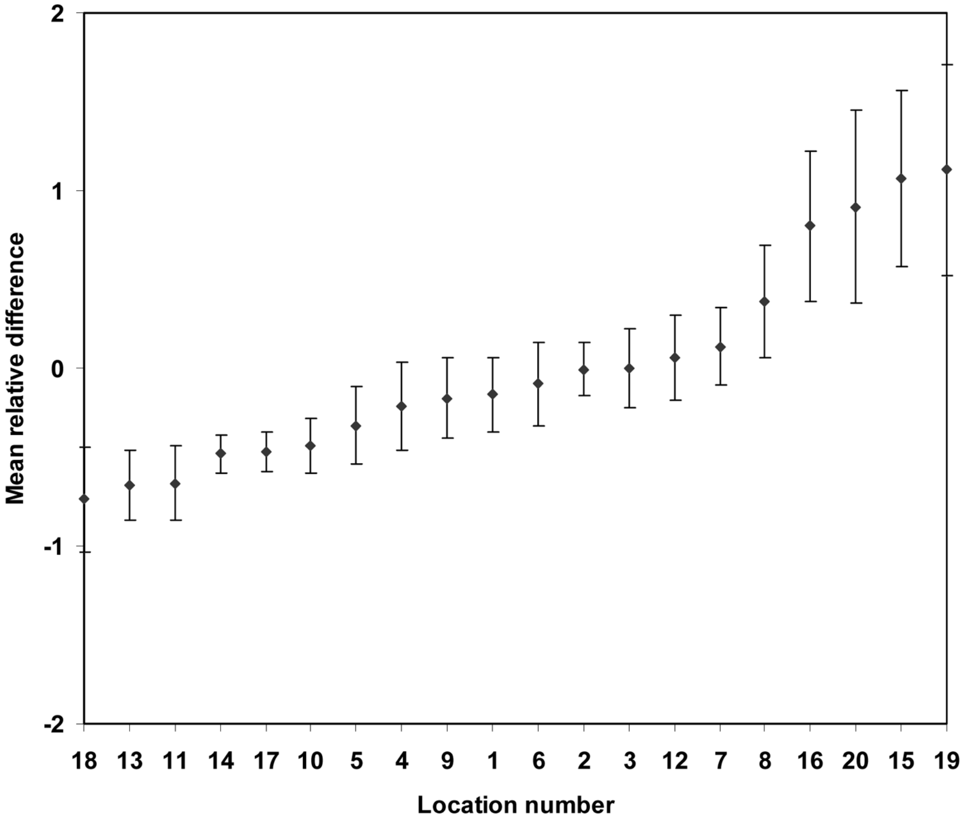

Figure 3. Mean relative differences for $EC_{2.5}$. Locations are ranked from the lowest to the highest mean relative differences. Vertical bars represent +/− one standard deviation.

standard deviations were smaller (e.g., the temporal standard deviation for location 15 is 0.73 for EC_a, and 0.50 for $EC_{2.5}$). The locations most representative of the average field salinity were 2, 3, 6, and 12.

Classification of the Locations as Low, Average, or Highly Saline

Analyzing maize yield data, Taylor et al. (2000) considered locations with a temporal standard deviation smaller than the mean relative difference to be consistently different from the mean. They further subdivided this group by separating locations for which the mean relative difference is negative from those for which this mean is positive. Also, they distinguished a third group, locations similar to the mean, for which the temporal standard deviation is larger than the mean relative difference and overlapped with the mean value (illustrated in Figures 2 and 3 by the x axis intersecting with the vertical bars). Based on these definitions, we classified the locations as low, average, or highly saline (Table 3).

These groups contain more locations than when we used a restrictive criterion, like +/− 0.1 $\mathrm{dS\,m^{-1}}$ for the mean and +/− 0.5 $\mathrm{dS\,m^{-1}}$ for the extreme values. We included almost the same locations for the three classes. For example, the low saline class (0.89 $\mathrm{dS\,m^{-1}}$) contained locations 5, 10, 11, 13, 14, 17, and 18; the average

Table 3. Location membership to low, average, or high salinity groups

Property	Low salinity	Average salinity	High salinity
EC_a	4, 5, 9, 10, 11, 13, 14, 17, 18	1, 2, 3, 6, 7, 12	8, 15, 16, 19, 20
$EC_{2.5}$	5, 10, 11, 13, 14, 17, 18	1, 2, 3, 4, 6, 7, 9, 12	8, 15, 16, 19, 20

salinity class (1.89 dS m^{-1}) grouped locations 1, 2, 3, 6, 7, and 12; and locations 8, 15, 16, 19, and 20 belonged to the high salinity class (3.77 dS m^{-1}). The proportion of locations classified as highly saline fluctuates between 15% and 25%, while this proportion ranges between 25 and 45% for the low saline class, and 30 and 60% for the average saline class. Consequently, most of the 20 locations were classified as average saline, followed by low saline and lastly highly saline.

Salt Accumulation Processes and Temporal Stability

The geology, the natural vegetation, and a conceptual model of salt accumulation of the study site were described in Tóth et al. (2002). In the study area, the maximal difference in elevation is 1.76 m. Although this difference is small, it was found that elevation is a major factor in soil salinization. The other factors are groundwater depth and its chemical composition, related to the elevation. All three factors contribute to the mosaic distribution of the natural vegetation.

Tóth and Kuti (2002) used a *k*-means clustering procedure described by Burrough (1989) to classify the 413 locations where EC_a was measured into one of the three strata of salt accumulation. These strata were identified as waterlogging, salt accumulation, and salt leaching (Tóth et al., 2001). For three locations (numbers 8, 10, and 11) a morphologic description and horizon-wise sampling for laboratory analysis was carried out as a way for validation. The waterlogged zone corresponds to the wet area with the lowest elevation, the natural vegetation is a meadow, and location 10 represents a typical profile. The zone of salt accumulation is intermediate in elevation, is the most sodic and saline, and is covered with short grass. Location 8 can be considered as a typical profile. The salt leaching zone has the highest elevation, is the least sodic, the natural vegetation is a tall grass, and location 11 is a typical profile. All the 413 locations were subjected to a *k*-means clustering, but only the membership of the 20 locations considered in this study was reported (Table 4). From Tables 3 and 4 we can conclude that the locations classified as low saline belong to the zones of waterlogging or leaching, the latter being more frequent than the former. Locations classified as highly saline originate exclusively from the accumulation zone while locations representative of the average field salinity encompass the three possible zones with the predominance of the accumulation zone, leaching and waterlogging zones are equally represented but less than the accumulation zone.

Table 4. *k*-means membership of the locations to the three salt accumulation strata

Salt accumulation stratum	Waterlogging	Salt accumulation	Salt leaching
Location number	2, 10, 14, 17	1, 3, 7, 8, 12, 15, 16, 19, 20	4, 5, 6, 9, 11, 13, 18

The A horizon of the salt accumulation zone (location 8) had a very limited hydraulic conductivity compared to the waterlogged zone (location 10) and the salt leaching zone (location 11). Also, the range of soil moisture change is the largest for the accumulation zone. The region is characterized by sudden rain during summer with a large amount of precipitation. The soil shows swelling/shrinking properties resulting in cracking. The cracks, open on the dry surface, allow a sudden leaching of salts. Consequently, it can be expected that the large temporal deviations (less time stable) for locations in the accumulation zone are related to the cracking and the subsequent leaching processes.

Waterlogged and leaching zones showed soil patterns which are strongly time-stable. During the wet season, in the leaching zone, the changes in soil salinity occur at greater depth because the groundwater table is deep, and during the warm season, there is no change in salinity as the groundwater is too deep. However, in the waterlogged zone the changes occur at depth during the wet season because waterlogging keeps salinity low, while during warm season there is no change because the groundwater rise is controlled by strong rain infiltration.

Based on the description above, it is possible to optimize the selection of locations used to monitor future salinity. The selection of the locations should consider the three salt accumulation zones, which can be identified considering the elevation and the vegetation pattern. The characterization of low saline areas will be based on samples taken from the lowest locations covered with meadow (waterlogged zone) or from the highest zones covered with tall grass (leaching zone) while the investigation of highly saline areas considers the locations with intermediate elevations and covered with short grass (accumulation zone). However, if we are interested in characterizing the average field salinity, we will need to obtain samples from all three zones.

How Good are the Selected Sites in Representing Average Salinity?

To investigate how good the selected sites represent the average salinity, we focused on $EC_{2.5}$. The average salinity is an important input parameter for salinity predictive models. For example, the model SALTMOD (Oosterbaan, 1997) requires the use of the cumulative Gumbel distribution which is assumed to fit the cumulative probability distribution of the root zone salinity. This distribution requires the average salinity and the standard deviation which is a function of the average salinity.

Locations 2 and 3 had a mean relative difference approaching zero and the smallest temporal standard deviation. The mean relative difference and its corresponding standard deviation were $-0.01\,\mathrm{dS\,m^{-1}}$ and $0.15\,\mathrm{dS\,m^{-1}}$ for location 2, and $0\,\mathrm{dS\,m^{-1}}$ and $0.22\,\mathrm{dS\,m^{-1}}$ for location 3.

Comparing the two series of means for using either all 20 locations or only locations 2 and 3, we found that they agreed in most of the 19 cases. For example, allowing for a difference of $\pm 0.3\,\mathrm{dS\,m^{-1}}$, they agreed for 14 out of the 19 cases, and in all the cases the difference was not more than $0.5\,\mathrm{dS\,m^{-1}}$. The differences would be smaller if locations 2 and 3 had reduced temporal standard deviations, that is, if they were more time stable.

To explore the possibility of using only a limited number of locations to estimate the average $EC_{2.5}$ instead of using all 20 locations, we split our data set into two subsamples (Grayson & Western, 1998): the first subsample involving only the nine

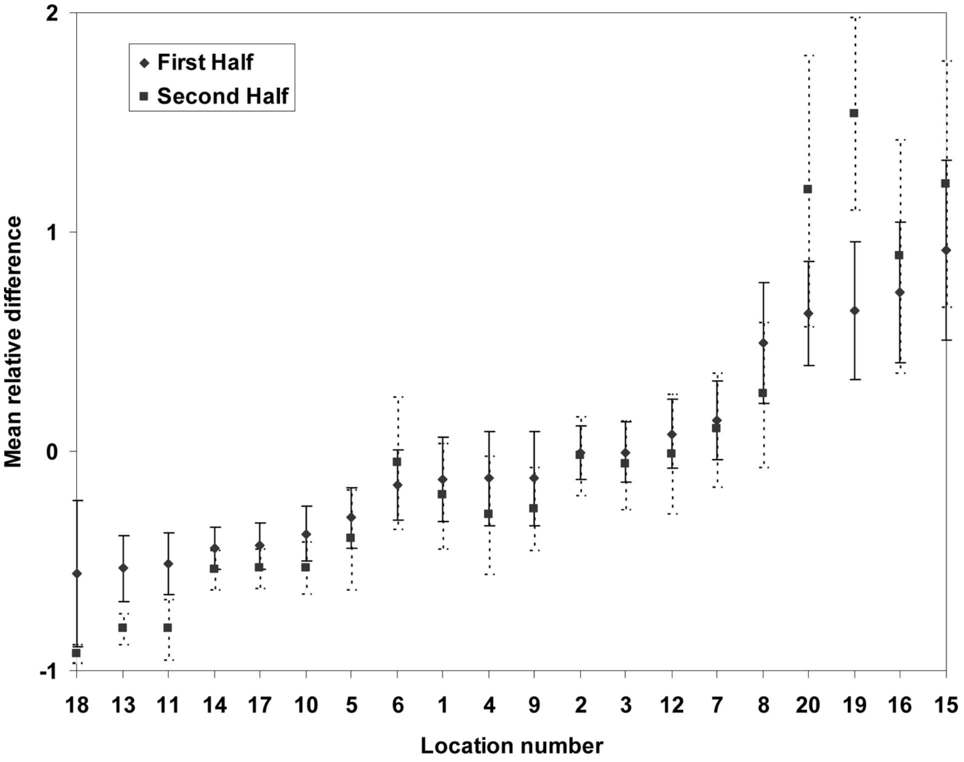

Figure 4. Mean relative differences for $EC_{2.5}$ for the first half of the data, the equivalent values for the second half are overlaid. Locations are ranked from the lowest to the highest mean relative differences. Vertical bars represent +/− one standard deviation.

first measurement times (excluding November 1994), and the second subsample covering the last nine sampling times. We computed the relative differences, means, and standard deviations for each subsample separately. Then, we plotted the average relative differences corresponding to the first subsample ranked from the smallest to the largest difference (Figure 4) and overlaid the corresponding differences computed from the second subsample. We note from this figure that, using only half-time coverage data, we reached the same locations representative of the average $EC_{2.5}$ for both halves; these locations were also selected using the whole data set (Figure 3). This result provided more confidence in the ability of the method of relative differences to identify and select consistently locations which seemed representative of the average field $EC_{2.5}$.

Conclusions

We applied the concept of temporal stability to soil salinity measurements provided by laboratory analysis ($EC_{2.5}$) and field probes (EC_a). The samples were collected from 20 locations at four depths while EC_a was measured at two depths. Additionally, we analyzed the mean $EC_{2.5}$ over the four depths. The sampling was repeated 19 times over seven years. The Spearman rank order correlation showed a temporal persistence of the spatial pattern of both properties at all depths. It indicated the strength and the direction of a rising or falling relationship between measurements made at two different time instants. As the Spearman correlation measures only the degree of concordance between two rankings and to find out the locations which were time-stable, we applied the technique of relative differences. We found no temporal stability of the complete soil salinity pattern. However, the low saline conditions were more time-stable while the locations representative of the average soil salinity had an intermediate time stability and the high saline locations were the least time-stable. Also, the low saline locations were related to zones of waterlogging and/or salt leaching while the high saline locations were related to the zone of salt accumulation. The locations representative of average soil salinity were present in the three zones: salt accumulation, salt leaching, and waterlogging. The concept of temporal stability allowed us to select a limited number of locations (as few as two), which were used to estimate the average soil salinity instead of using the 20 initial locations. This technique can be used to select the locations representative of average and extreme saline conditions, which will be used as "ground truth" data for the calibration and the validation of remote sensing data for determining, for example, a soil salinity index. According to the results on the temporal stability of soil salinity in the native solonetzic landscape studied, the zonation of the toposequence (vegetation pattern and elevation) was a good indicator of the differences in soil salinity and its temporal stability and supports the previous/ongoing soil mappings based on vegetation type.

The procedure presented in this work is a general one and could be used in different ecosystems (agricultural field, and native vegetation such as grassland, bushland, and forest), for different soil proprieties (moisture, salinity, soluble nutrients), and under different climatic zones (semihumid, arid, semiarid).

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