Effects of Shallow Groundwater Management on the Spatial and Temporal Variability of Boron and Salinity in an Irrigated Field

P. J. Shouse,* S. Goldberg, T. H. Skaggs, R. W. O. Soppe, and J. E. Ayars

ABSTRACT

In some irrigated regions, the disposal of agricultural drainage waters poses significant environmental challenges. Efforts are underway to develop irrigation water management practices that reduce the volume of drainage generated. One such management strategy involves restricting flow in subsurface drains in an effort to raise the water table and induce the consumption of groundwater by crops. A potential complication with this management approach is that upward groundwater flow may salinize the soil and increase concentrations of phytotoxic elements such as B. In this study, salinity and B concentrations were monitored for 3 yr in a 60-ha agricultural field located in San Joaquin Valley, California. The irrigated field was managed according to a restricted drainage, shallow groundwater management technique. Salinity and B measurements were made biannually at approximately 75 sites within the field. Soil salinity and B concentrations were found to be highly correlated in the field. The observed spatial and temporal variability in B and salinity was largely a product of soil textural variations within the field and the associated variations in salt leaching. During the 3-yr study, the field changed very little from one year to the next, although within a given year there were fluctuations related to cropping and irrigation practices and to environmental conditions. However, any changes arising during the growing season were erased in the fallow season by winter rainfall and preplant irrigations that uniformly leached salts from approximately the top 1 m of the field. Overall, it appears that the shallow groundwater management program used in this study could be continued and sustained in this field without increasing soil salinity or B concentrations, and without decreases in yield.

Agricultural productivity in the semiarid western United States depends on irrigation, an agricultural practice beset by age-old salinity and drainage problems. Irrigation imports salts to the soil and dissolves native salts, both of which increase soil salinity and decrease crop yields. To reduce the buildup of soluble salts, excess irrigation water must be applied to leach the salts out of the root zone. Often it is necessary to install engineered subsurface drainage systems to facilitate leaching and prevent waterlogging. The water collected in these drainage systems is frequently saline and may contain agricultural chemicals or other contaminants (Banuelos, 1996; Goldberg et al., 2003). Disposing of the water has become a significant problem in irrigated agriculture, especially in San Joaquin Valley, California (Letey et al., 2002; Schoups et al., 2005).

Historically, agricultural drainage water in the western USA has been discharged into surface waters, mainly river systems (Schoups et al., 2005). During the 1970s and 1980s, drainage water in the San Joaquin Valley was used to replenish wetlands and other wildlife habitats (Schoups et al., 2005). Drainage waters in San Joaquin Valley carry significant concentrations of Se, As, B, and other trace elements (Letey et al., 2002). These potentially toxic constituents come from salts that occur naturally in the region's soils, which were derived from marine sediments. Irrigation dissolves and leaches these native salts. In habitats receiving drainage eventually it was discovered that trace elements were moving up the aquatic food chain and becoming more concentrated, resulting in high levels of exposure for those animals near the top of the food chain (Fan et al., 1988). In some habitats, reproductive failures and deformities were observed in waterfowl (Letey et al., 2002; Tanji et al., 1986).

Because of these adverse impacts on wildlife, disposal of agricultural drainage water into wetland refuges was halted, and alternative disposal solutions were sought. Proposed management options (San Joaquin Valley Drainage Program, 1990) included drainage source control (i.e., reducing the amount of drainage generated). One strategy for source control is to restrict outflow in field drains such that the height of the water table is maintained at a shallow depth that allows certain crops to utilize groundwater to satisfy a portion of their water requirements. Groundwater consumed by a crop is groundwater that no longer requires drainage and disposal. Hutmacher et al. (1996) showed that cotton (*Gossypium hirsutum* L.) crops can obtain 20 to 50% of their water requirement from shallow groundwater under the proper irrigation management. The timing and amounts of surface irrigation impact the extent to which crops will utilize shallow groundwater. Judicious use of deficit irrigation in combination with shallow groundwater management is necessary to achieve optimal results (Ayars et al., 1999).

One complication resulting from restricted drain flow is the potential for salinizing the soil profile (Hornbuckle et al., 2005). If root zone salinity increases significantly, there may be reductions in crop yield that would render the source reduction strategy unworkable. Another danger is increased root zone concentrations of phytotoxic trace elements such as B (Banuelos, 1996; Oster and Grattan, 2002). Indeed, it is possible that the accumulation of B may be more of a limiting factor than the total salt concentration (Ayars et al., 1993).

Boron is an essential micronutrient for plants, but it is toxic to many plants at higher concentrations. The optimum concentration range of plant-available B is very

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Abbreviations: EC, electrical conductivity.

narrow for most crops (Keren and Bingham, 1985; Grattan and Grieve, 1999). The B tolerance of crops is species dependent and can vary widely among cultivars within a given species (Benlloch et al., 1991). For example, cotton is considered very tolerant (no yield reduction when soil water B concentrations are <6–10 g m^{-3}) whereas tomato (*Lycopersicon esculentum* L.) is classified as tolerant (concentrations <5.7 g m^{-3}). In irrigated semiarid regions, excess B often occurs in association with moderate to high levels of soil salinity (Nicholaichuk et al., 1988). Thus B toxicity may be underreported, with B effects being confounded with the associated problems of salt accumulation (Grattan and Grieve, 1999). It has been suggested that a combination of stresses resulting from excess salt and B may have a negative synergistic effect on certain crops (Grieve and Poss, 2000).

Boron and salinity occur together in the landscape on the west side of the San Joaquin Valley, (Corwin et al., 2003) but their variability is as yet unknown. Significant changes in salt and B distributions could occur when a field is newly managed according to a shallow groundwater source reduction strategy. Water would be expected to move up from the water table as well as down from the soil surface. The parameters and processes controlling salt and trace element movement would likely vary in space and time. At present, predictive models can give us insight into the processes at work, but cannot predict the variability (Vaughan et al., 2004).

The objective of our study was to measure and describe the spatial and temporal variations in salinity and B content of an irrigated field in the San Joaquin Valley managed according to a shallow groundwater management drainage reduction strategy.

MATERIALS AND METHODS

Field Site

The field site is located at the SE quarter of Section 13, T13S, R13E, Mt. Diablo Baseline (36° 47.5′ N, 120° 29.6′ W) in the Broadview Water District on the west side of the San Joaquin Valley in California (Fig. 1). The designation for this field on maps of the Broadview Water District is 13-4, indicating Field 4 in Section 13. This convention is also used on the maps in this article. The field is a quarter-section with approximately 60 ha of drained land in production. The soil belongs to the Lillis soil series and is classified as very-fine, smectitic, thermic Halic Haploxerert.

Cropping Sequence

Cotton (cv. MAXXA) was grown during the 1995 and 1997 seasons (planted between 15 and 26 Apr. and machine-harvested from 30 Oct. to 2 Nov., depending on the year). Tomato (cv. Heinz 3044 hybrid, cv. La Rosa, and cv. Apex 1000) was

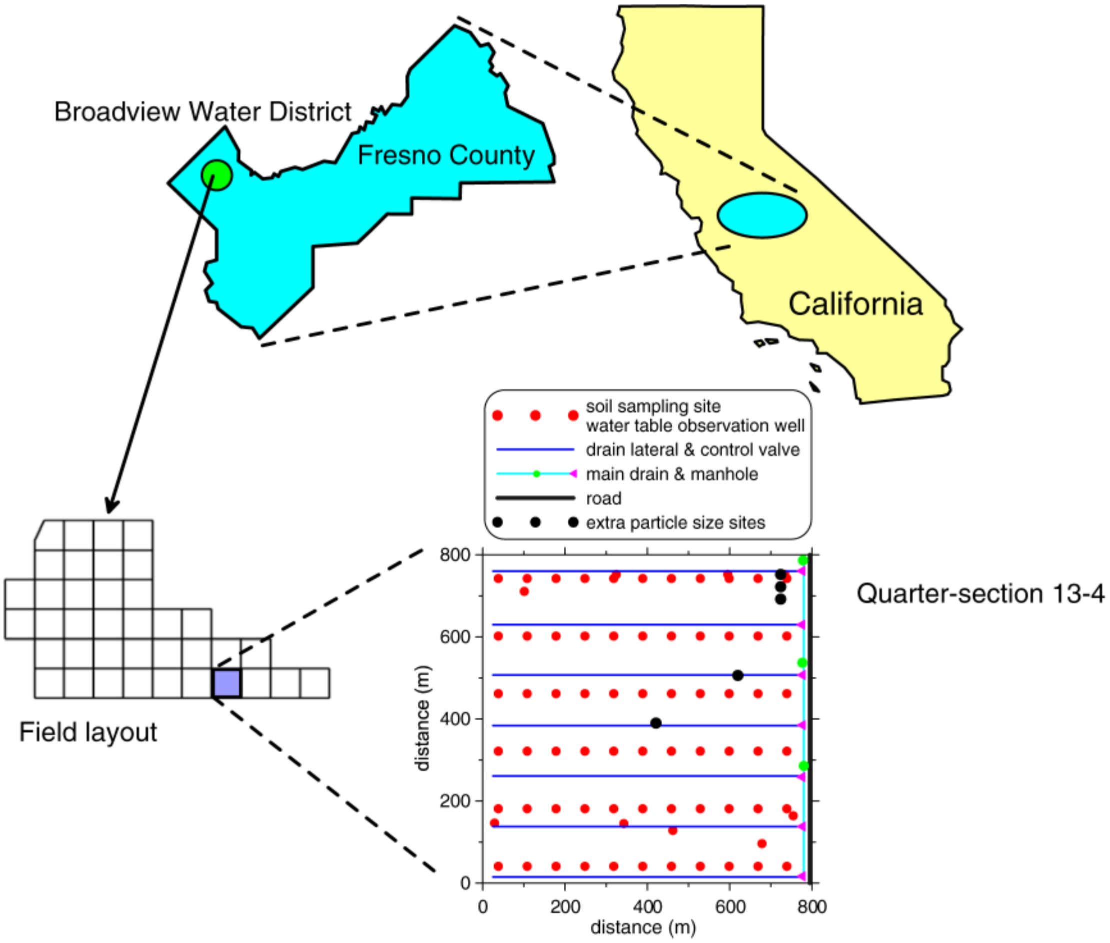


Fig. 1. Schematic map showing the relative location of the study site and the field infrastructure.

grown during the 1996 season (planted between 28 Jan. 1996 and 10 Mar. 1996 and harvested 1–17 July 1996, depending on the cultivar). Agronomy and pest management were the responsibility of our farmer cooperator.

Irrigation and Drainage

The field was irrigated using sprinklers and graded furrows. Sprinklers were used for germination and early season irrigation of tomatoes. Furrows were used later in the season for tomatoes, and for all irrigations of cotton. The field was divided into thirds for irrigating tomatoes. The upper third was irrigated using siphon tubes emanating from a ditch, while the remaining two-thirds were irrigated with gated pipe. Cotton was irrigated using two laterals, one a ditch and siphon tube and the other a gated pipe. Irrigation scheduling was the responsibility of the cooperating farmer. Rainfall in the area is approximately 25 mm yr^{-1}, but it occurs almost entirely in the fallow months between November and February.

Broadview Water District measured irrigation water quality on a monthly basis during our study. The electrical conductivity (EC) was always <0.8 dS m^{-1} and the B concentration <0.7 mg L^{-1}.

The field was drained by a subsurface drainage system consisting of seven laterals installed at a depth of 1.8 m and laid perpendicular to the furrow direction and the submain collector (Fig. 1). Drainage flow in individual laterals could be controlled with butterfly valves installed on the east side of the field where the laterals met the submain (Fig. 1). Three weir structures installed in manholes along the submain provided additional water table control (Fig. 1). Because drainage laterals were perpendicular to the slope, it was possible to maintain a relatively uniform water table depth under a large portion of the field using controls installed only on the east side. Ayars et al. (1996) gave a detailed account of the water table control methods. In 1995, 1996, and 1997 the butterfly lateral valves remained open for most of the growing season, but the weir structures were in place at a depth of 1.2 m below the soil surface. Generally, this meant that the water table would start the growing season at a depth of 1.2 m and then decline as the season progressed and crops consumed groundwater. At the end of each growing season, the weir boards were removed and the field was drained in preparation for harvest.

Data Collection

The shallow groundwater response to irrigation and drainage management was measured using observation wells constructed of 38-mm-diam. PVC pipe that had slits in the bottom meter. The observation wells were 3 m deep and were installed on a regular grid (Fig. 1). The soil surface and observation wells were surveyed and referenced to a common elevation. The depth to water table was measured weekly using a sounder attached to a tape measure. The shallow groundwater was sampled every other week using a suction tube connected to a sample bottle that was evacuated by a vacuum pump. Water samples were refrigerated and transported to the lab for chemical analyses. Boron concentrations were determined using a Lachat Quikchem AE Automated Ion Analyzer (Latchat Instruments, Loveland, CO) and the Azomethine-H method (Bingham, 1982; Sah and Brown, 1997). Sample EC was measured using a conductivity meter (U.S. Salinity Lab Staff, 1954).

We sampled soil twice per year, once in the spring (April–June) and once in the fall (August–November). The spring sampling followed planting, and was done as soon as the soil was dry enough to be accessed with a truck-mounted hydraulic drilling rig. Usually this occurred 2 to 3 wk after emergence. The fall sampling was done following completion of harvest, land preparation, and crop stubble management operations (usually within 3 wk of harvest). On a regular grid (Fig. 1) we used a nominal 4.76-cm-i.d. (2 inch) soil core probe to sample to a depth of 1.80 m or until hitting the shallow groundwater table, whichever came first. The soil cores were sectioned into 0.30-m increments, put into plastic bags, and transported in ice chests to a mobile laboratory at the edge of the field for preliminary processing, which included (i) weighing the total soil sample from each depth increment, (ii) mixing the soil in the plastic bag and removing a water content sample (300–500 g), (iii) weighing the water content sample, and (iv) packing both samples for transport back to the main laboratory. At the lab, the water content samples were put into a 105°C oven for 48 h and then reweighed. The remaining soil samples were stored in their plastic bags in a cold room (4°C) until an oversaturation paste (quantitative 1:1 water/soil) could be extracted using vacuum extraction procedures (U.S. Salinity Lab Staff, 1954). The samples did not dry while stored in the plastic bags and remained close to field water content until extracted. During the fall 1996 analyses, samples used for gravimetric water content determinations were saved and subsequently used to measure soil particle size distribution. Additionally, several soil samples (locations not shown in Fig. 1.) were gathered along a line from the southwest to northeast to further define the extent of an apparent old stream channel that traversed the field. A combination of hydrometer and wet sieving methods was used to provide a complete particle size distribution (Gee and Bauder, 1986; Skaggs et al., 2001). The total weight of the soil sample (measured in the field) and the water content were used to estimate soil bulk density (Grossman and Reinsch, 2002). Our 1:1 extraction method used a water balance procedure so that the total amount of water in the soil sample was known. This allowed us to calculate the total mass of all chemical constituents present in the soil. We compared the quantitative 1:1 (soil/water) extract method with other soil B extraction procedures and found that most other methods correlate well with the 1:1 extract method (Goldberg et al., 2002). Also, Goldberg et al. (2003) found that the 1:1 water extract was well correlated to plant B content in the leaves, stems, and fruits of melons.

Soil solution extract ECs and B concentrations were measured with the same analytical procedures used for the groundwater samples. Soil B concentrations are reported as the mass of B per volume of soil. Soil salinity is reported as EC_e, the electrical conductivity of the saturation paste extract, which was calculated from the EC of the 1:1 extract and an assumed saturation percentage of 62%. The apparent leaching fraction was estimated by dividing the long-term average irrigation water EC by the EC of the soil solution measured in the 1.2- to 1.5-m depth increment (Corwin et al., 2003; Rhoades, 1981), with the soil solution EC being determined from the EC of the 1:1 extract and the moisture content of the soil at the time of sampling (we assumed the extract was a simple dilution of the soil solution).

Spatial maps of the data were created using the Surfer graphics program (Golden Software, Boulder, CO). The maps were made using ordinary point kriging and a neighborhood of 300 m. All semivariograms were fit to an exponential model (Webster and Oliver, 2001). The method of Blackmore (2000) was used for analyzing the spatial trend and time stability of the EC and B data, as well as the calculated apparent leaching fractions. In this analysis, the spatial trend is a time-averaged spatial map obtained by calculating the mean value of a variable at each grid point in the field over all years, while the temporal stability is assessed by calculating the coefficient of variation at each grid point for the same time period.

RESULTS AND DISCUSSION

As part of our fall 1996 field characterization, we measured soil bulk density and particle size distribution at every depth increment to 180 cm (Fig. 2). A section of the middle of the field, stretching from the southwest corner to the northeast corner, has high (40–60%) sand content down to about 120 cm (150 cm in the northeast corner). This coarse material is apparently related to an old stream channel that once bisected the field. The spatial patterns in the bulk density maps are similar to

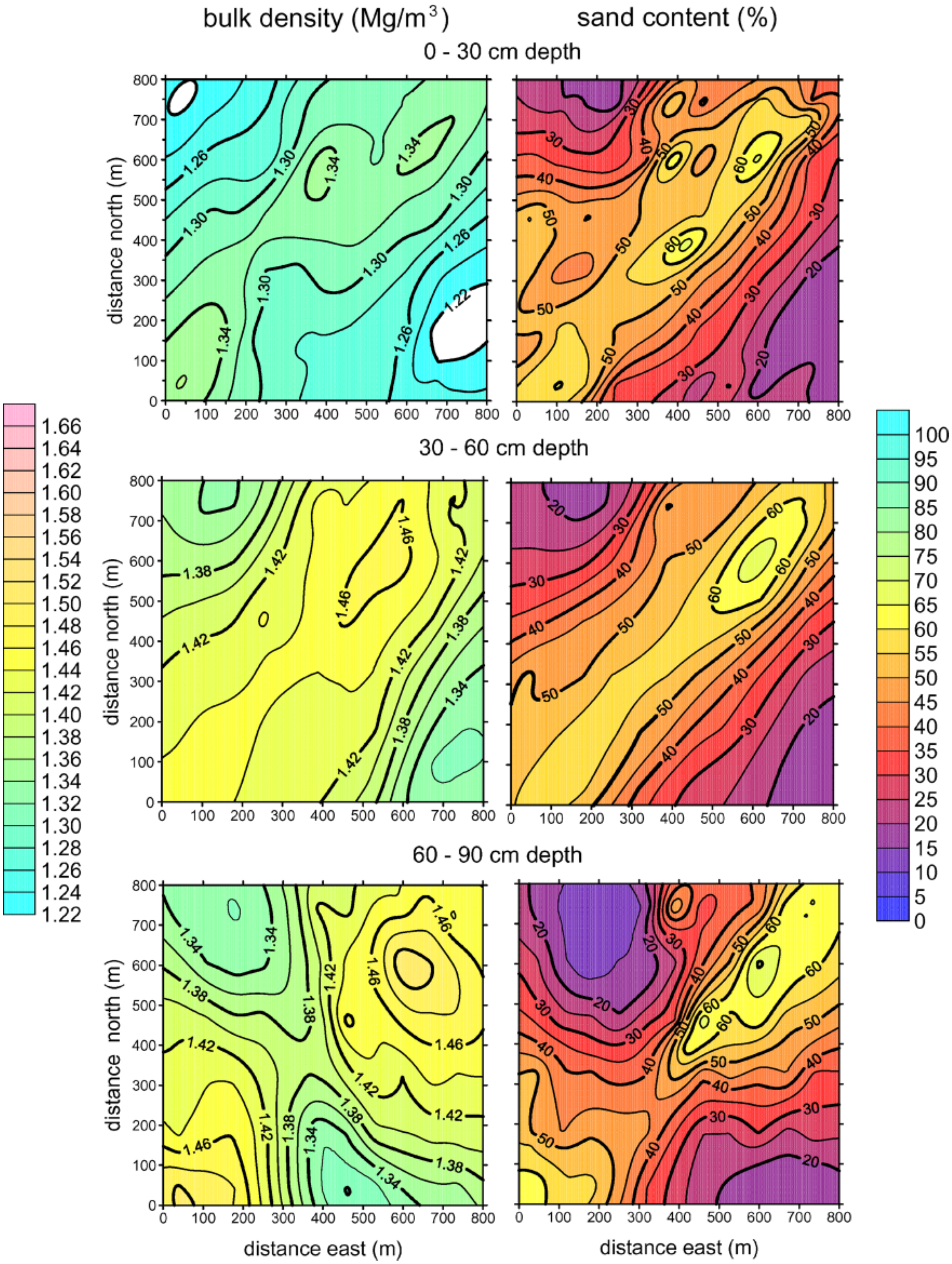
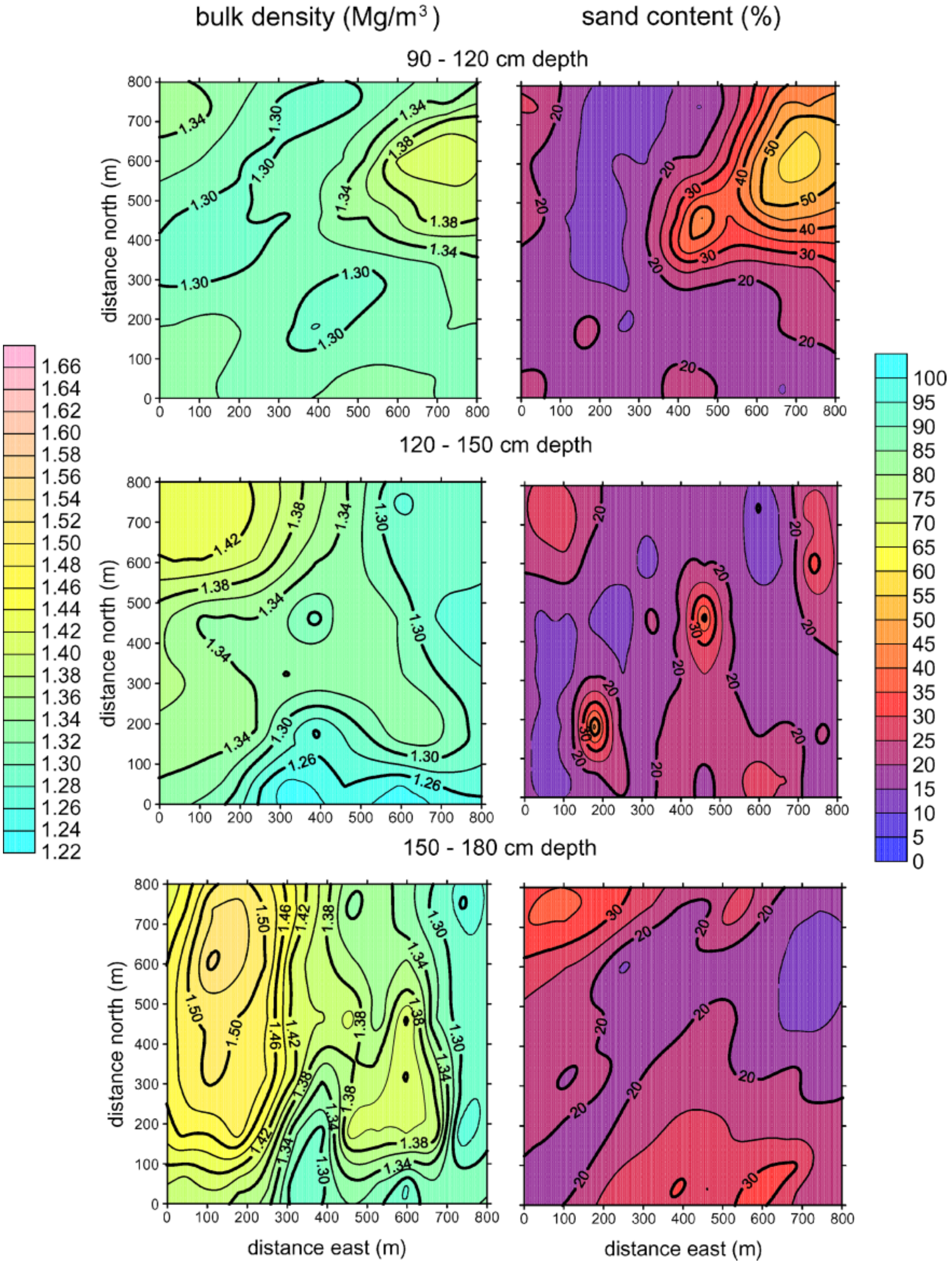


Fig. 2. Spatial distribution maps of soil bulk density and sand content at each depth in the field.



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those for the sand content, at least until 120 cm. The bulk density is larger in the areas with the higher sand content. The silt content of the field is fairly uniform throughout (data not shown), so in this field a high sand fraction corresponds to a low clay fraction, and vice versa. Areas with higher sand content had higher saturated hydraulic conductivities and lower soil water retention compared with the higher clay areas (data not shown).

In arid and semiarid irrigated areas, high B concentrations in soils are often associated with high salt concentrations (Grieve and Poss, 2000; Nable et al., 1997; Dhankhar and Dahiya, 1980; Nicholaichuk et al., 1988). Figure 3a shows a graph of the soil B concentra-

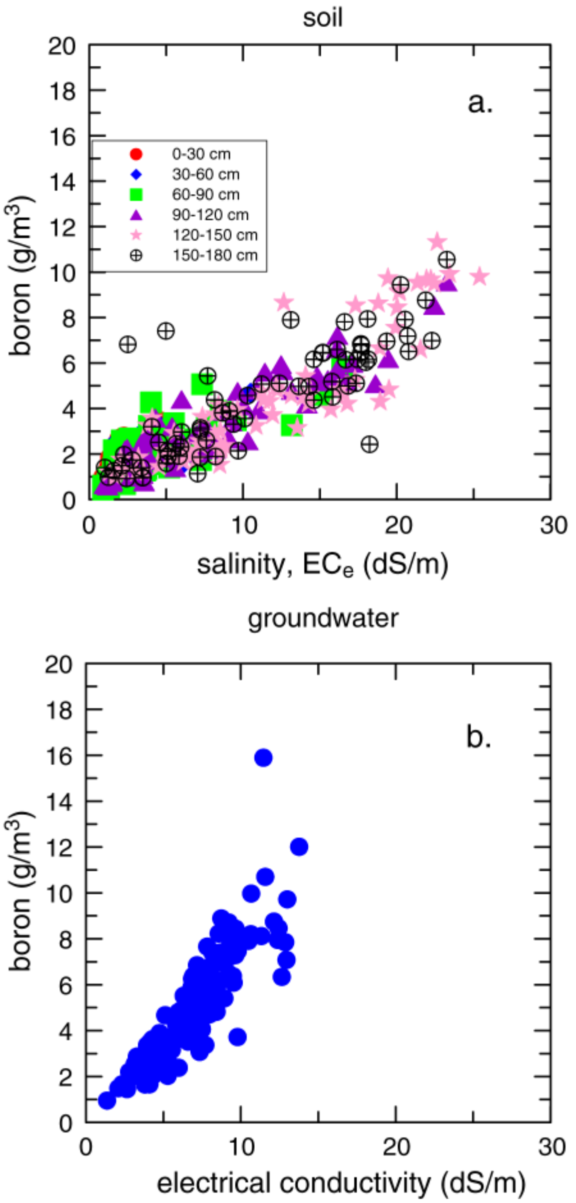

Fig. 3. **Relationship between (a) soil extract electrical conductivity and B concentration (mass per volume of soil), and (b) between groundwater electrical conductivity and groundwater B concentration (mass per volume of solution). Data is from the May 1995 sampling.**

tion vs. soil salinity (EC_e), and Fig. 3b shows the groundwater B concentration vs. the groundwater electrical conductivity. The data are from the spring (May) sampling in 1995. A linear relationship ($r^2 = 0.81$) between soil B content and soil salinity exists across all soil depths (Fig. 3a). Other sampling times show the same correlation with r^2 values between 0.8 and 0.9 (data not shown), and all of the sampling times fit essentially the same regression trend line. The linear correlation between salinity and B extends to the shallow groundwater (Fig. 3b, $r^2 = 0.75$). The correlation between salinity and B in this field probably exists because they share a common origin, namely the alluvium derived from sedimentary marine deposits of the Coast Range Mountains on the western side of the San Joaquin Valley (Letey et al., 2002). The correlation between B and salinity in soils and groundwater most likely exists throughout Broadview Water District and possibly extends to other fields in the western San Joaquin Valley (Corwin et al., 2003).

Field mean and variance for each sampling time are shown in Fig. 4 for soil B concentration and in Fig. 5 for soil salinity. Mean B concentration (Fig. 4a) and salinity (Fig. 5a) increase with depth at every sampling time. At the shallower soil depths the B concentration is between 1.0 and 2.0 g m^{-3}, and the salinity is <5 dS m^{-1}. If we take a soil volumetric water content of 0.25 to represent a middling field condition, then these shallow-depth B concentrations correspond to soil solution concentrations between 4 and 8 g m^{-3} (mg L^{-1}), which is right around the reported B threshold of 5.7 g m^{-3} for tomato

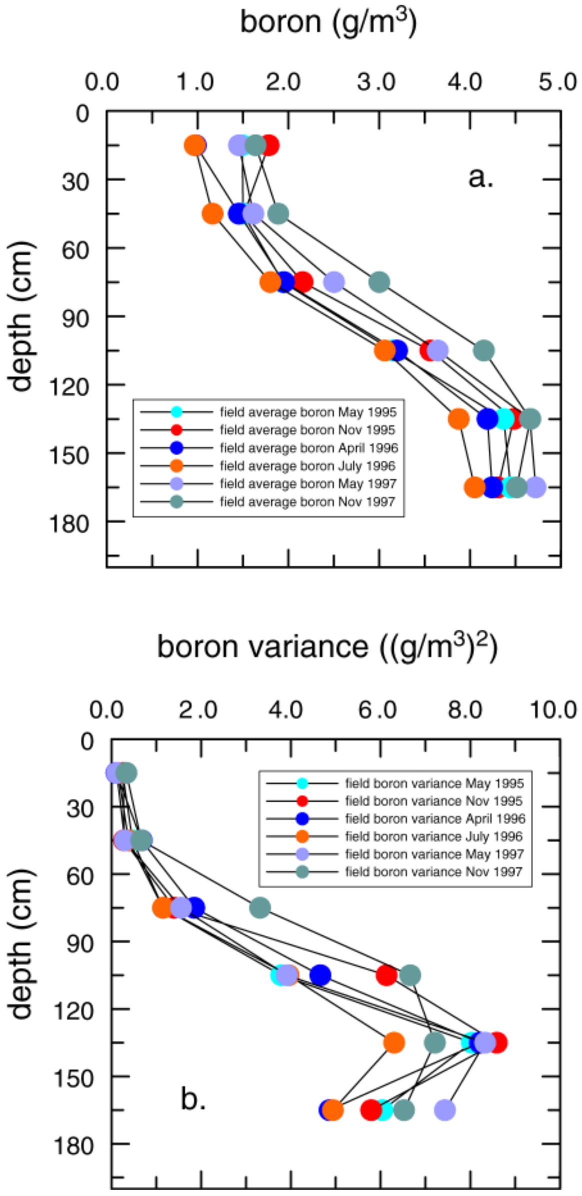

Fig. 4. **Depth distribution of the (a) mean and (b) variance of the soil B content measured at each sampling time.**

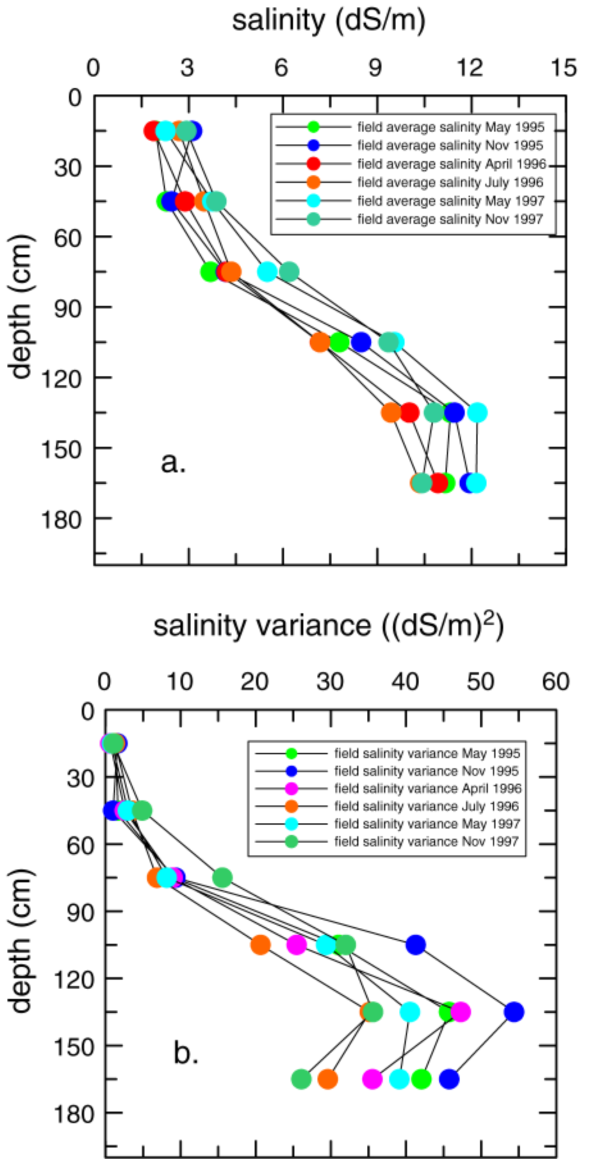

Fig. 5. Depth distribution of the (a) mean and (b) variance of the soil salinity measured at each sampling time.

(Maas and Grattan, 1999). At deeper depths (120–180 cm), the salt and B concentrations reach a maximum. The field average B concentration near the bottom of the soil profile exceeds the threshold value for tomato. The salinity at the same depths exceeds the threshold level (7.7 dS m^{-1}) for cotton, a salt tolerant crop (Maas and Grattan, 1999). This high salinity at depth is probably due to the influence of shallow groundwater and root water extraction patterns. The July 1996 sampling found relatively low B concentrations and salinities; this is due to late spring rainfall and the irrigation schedule used to grow tomato. November 1997 saw the highest B concentrations and salinities, possibly because of a long period with no irrigation or rain at the end of the cotton growth cycle.

The variances for B (Fig. 4b) and salinity (Fig. 5b) are quite small in the upper reaches of the soil profile, indicating considerable uniformity to a depth of about 0.90 m. This is indicative of a water management regime that leaches B and salt uniformly across the field near the soil surface. However, B variances increase with depth and reach maximums between 1.20 and 1.50 m. This indicates a variation in the leaching fraction at depth. At the deepest depth in the profile, there is a decrease in the variance that could be related to the influence of the shallow groundwater table.

While the statistical analysis indicates variability across the field in the B and EC$_e$ profiles at depth, inspection of the data shows that the variability was mostly comprised of two distinct salinity and B profiles. In one, the concentration of salt and B was low and uniform throughout the profile. In the other, concentrations increased with depth to a maximum level and then decreased slightly at the deepest depth. The uniform profiles were located in areas associated with higher leaching: the sandy areas of the field, areas near drain laterals, and

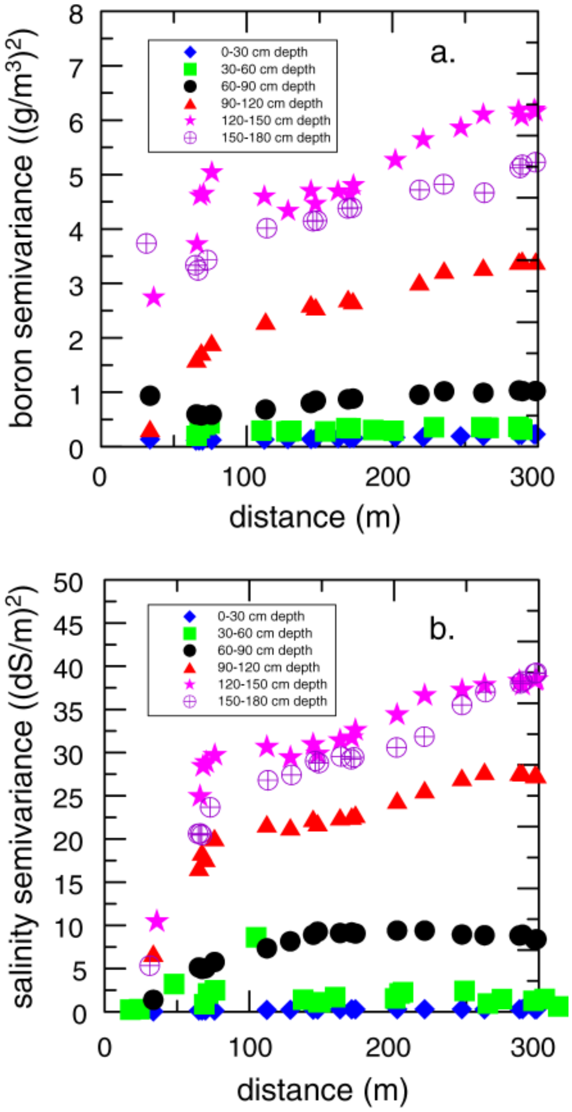

Fig. 6. (a) Semivariograms of the soil B content for each depth measured in May 1995. (b) Semivariograms of the soil salinity for each depth measured in May 1995.

the head end of the field (which receives more irrigation water). In the more clayey areas and near the tail end of the field, leaching was lower and the profiles exhibited a maximum concentration between the depths of 0.9 and 1.5 m.

Figure 6 shows the experimental semivariograms of salinity and B with depth for the May 1995 sampling time (other times show the same trends, data not shown). The semivariance increases with lag distance, indicating that near neighbors are similar and that there is some structure to the variance. The semivariances follow the population variances for the field B, increasing with depth to 1.5 m and then decreasing down to 1.8 m. Consistent with the previous analysis, this indicates that concentrations across the field become less homogeneous with increasing depth. Also, the slopes of the

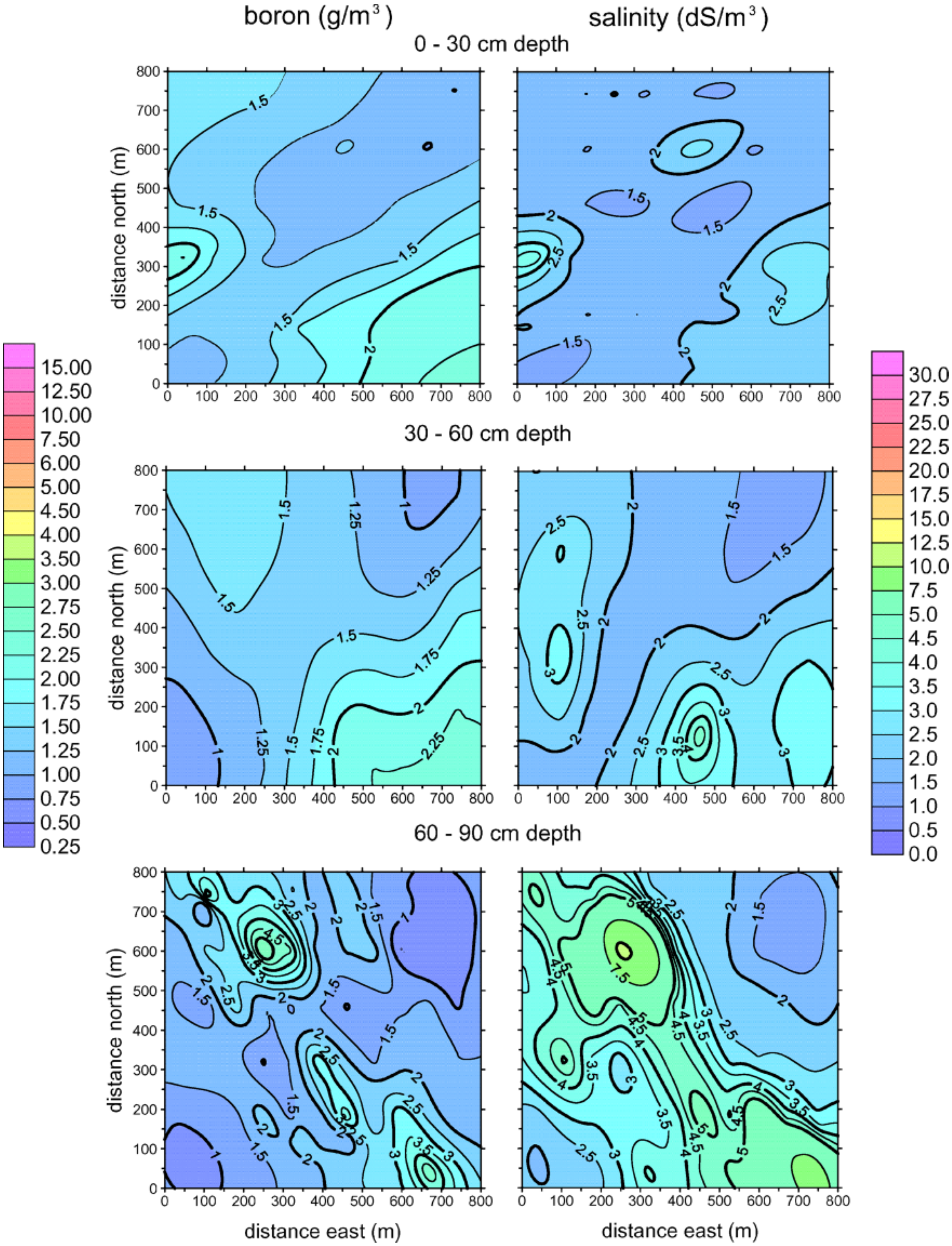

Fig. 7. Spatial distribution of soil B and salinity for each depth measured in May 1995.

variograms are steep at short lag distances, indicating that while there is similarity at short lags, the transition to dissimilarity at longer lags is fairly abrupt (Webster and Oliver, 2001).

Contour maps of the spatial distributions of salinity and B based on point kriging are shown in Fig. 7. The maps are consistent with the preceding statistical and geostatistical discussion: the B and salinity distributions are more uniform at shallower depths than at deeper depths, the complexity of the spatial distribution increases with depth, and B and salinity are colocated in the field. A look back at the soil physical properties maps (Fig. 2) shows that the areas of high salt and B content coincide with the areas of low sand–high clay content and

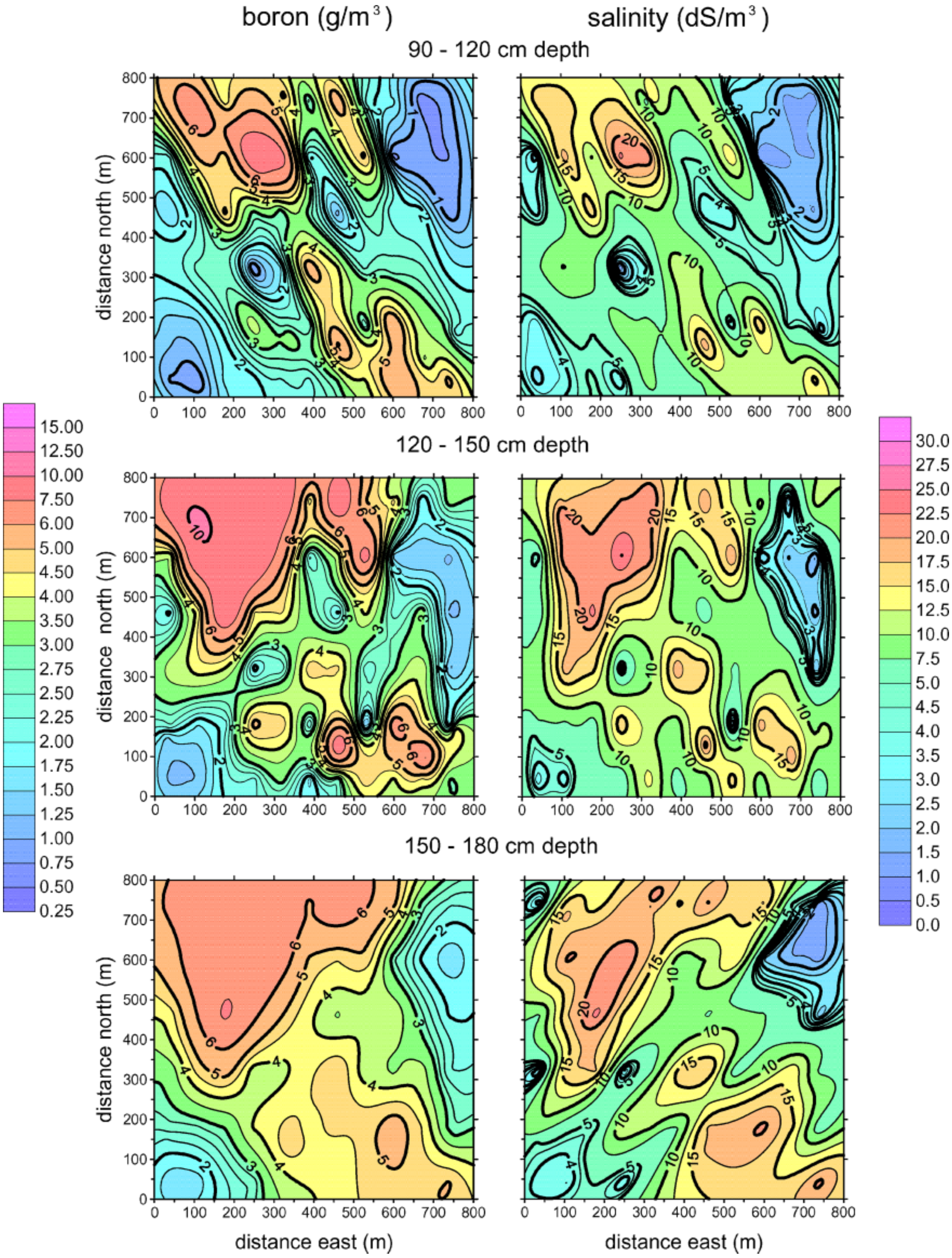

Fig. 7. Continued.

low bulk density. At the deeper depths (90–180 cm), salt and B continue to be colocated, with the highest concentrations being in areas that are low in sand and high in clay. The water movement through these areas is slower, and there is greater B adsorption because of the clay. However, despite the high salinities and B concentrations, the high clay content sections produced better crop yields (evidenced by visual inspection). Greater upward water flow, higher water retention, and perhaps greater nutrient retention and availability in the clayey areas may have increased water consumption and crop growth, with the corresponding decrease in leaching leading to the buildup in salts. Data from other sampling times show the same spatial trends and are not shown here.

According to Rhoades and Loveday (1990), crop plants respond to root zone average salinity, and we assume the same is true for B. Figure 8 shows the semivariograms for profile-averaged B and salinity at each sampling time. The B (Fig. 8a) and salinity (Fig. 8b) semivariograms (i.e., the variability) generally increased from spring to fall, and then decreased again by the next spring sampling. The more homogeneous conditions in the spring can be attributed to winter rainfall (≈0.25 m yr^{-1}) and increased leaching during preplant irrigations (≈0.2 m yr^{-1}). The data for the November variograms showing the highest variability were collected after cotton harvests. In a nearby field, Corwin et al. (2003) found cotton yield to be highly variable. Since cotton yield is directly related to water use, soil water use by cotton is presumably highly variable also, and this variability in water uptake would lead to variations in leaching and concentrations of salt and B across the field, consistent with the higher semivariances seen at the end of the cotton rotations.

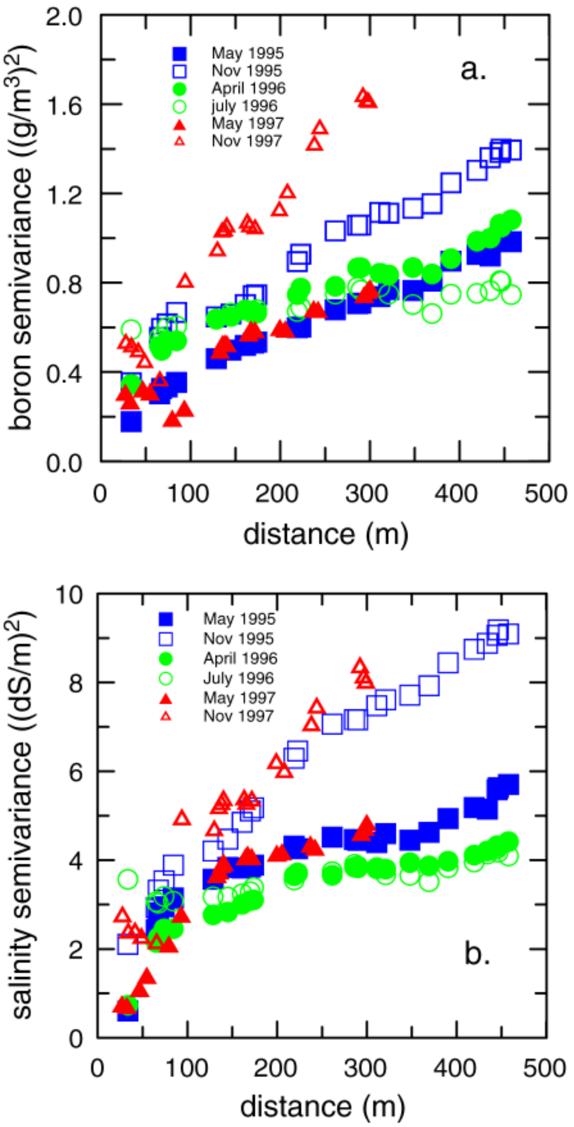

Fig. 8. (a) Semivariograms of the root zone averaged soil B content for each sampling date. (b) Semivariograms of the root zone averaged soil salinity for each sampling date.

Figure 9 shows the spatial distributions for root zone–averaged B, apparent leaching fraction (Corwin et al., 2003), and salinity at every sampling period. Several basic characteristics are evident from the figure. Profile average B and salinity are associated with each other, as before (Fig. 3.). Areas with an apparent leaching fraction of <0.2 were the areas with the highest B and salinity contents. Recall that the apparent leaching fractions were calculated based on the salinities measured at the 1.2- to 1.5-m depths, and thus the leaching fraction maps are not independent of the salinity maps. However, the leaching fraction maps give some quantitative insight into the amount of leaching that was occurring in various parts of the field. Areas with the highest apparent leaching were also the areas with the highest root zone average sand content (Fig. 2).

According to Blackmore (2000), the time average of a spatial variable can give insight into the spatial trend of that variable, and the corresponding CV can give insight about the time stability of this trend. We created time-averaged salinity, B, and leaching fraction maps (Fig. 10). The time-averaged maps all have similar spatial patterns. Again, the highest B and salt concentrations (and lowest leaching) are found in the northwest and southeast corners of the field, the areas with the highest clay content. The highest concentrations of B and salinity correspond to an apparent leaching fraction of 0.1 or less, whereas the lowest concentrations correspond to a leaching fraction >0.2.

Temporal stability maps were produced by calculating the CV at each grid point (Blackmore, 2000). The leaching fraction stability map shows that the leaching fraction was relatively stable (low CV) in zones where leaching was lower (Fig. 10). In areas with high sand content and high leaching, the leaching fraction was less stable (high CV). Salinity had the highest CV, between 50 and 90%. The least stable zones for salinity were along the north, south, and west edges of the field, where salinity increased slightly during the study (Fig. 9). Boron showed greater time stability than salinity. The areas with the highest B time stability coincided with the areas of greatest salinity stability.

Figure 11 shows the spatial distribution of groundwater salinity and B concentrations from June 1995. Com-

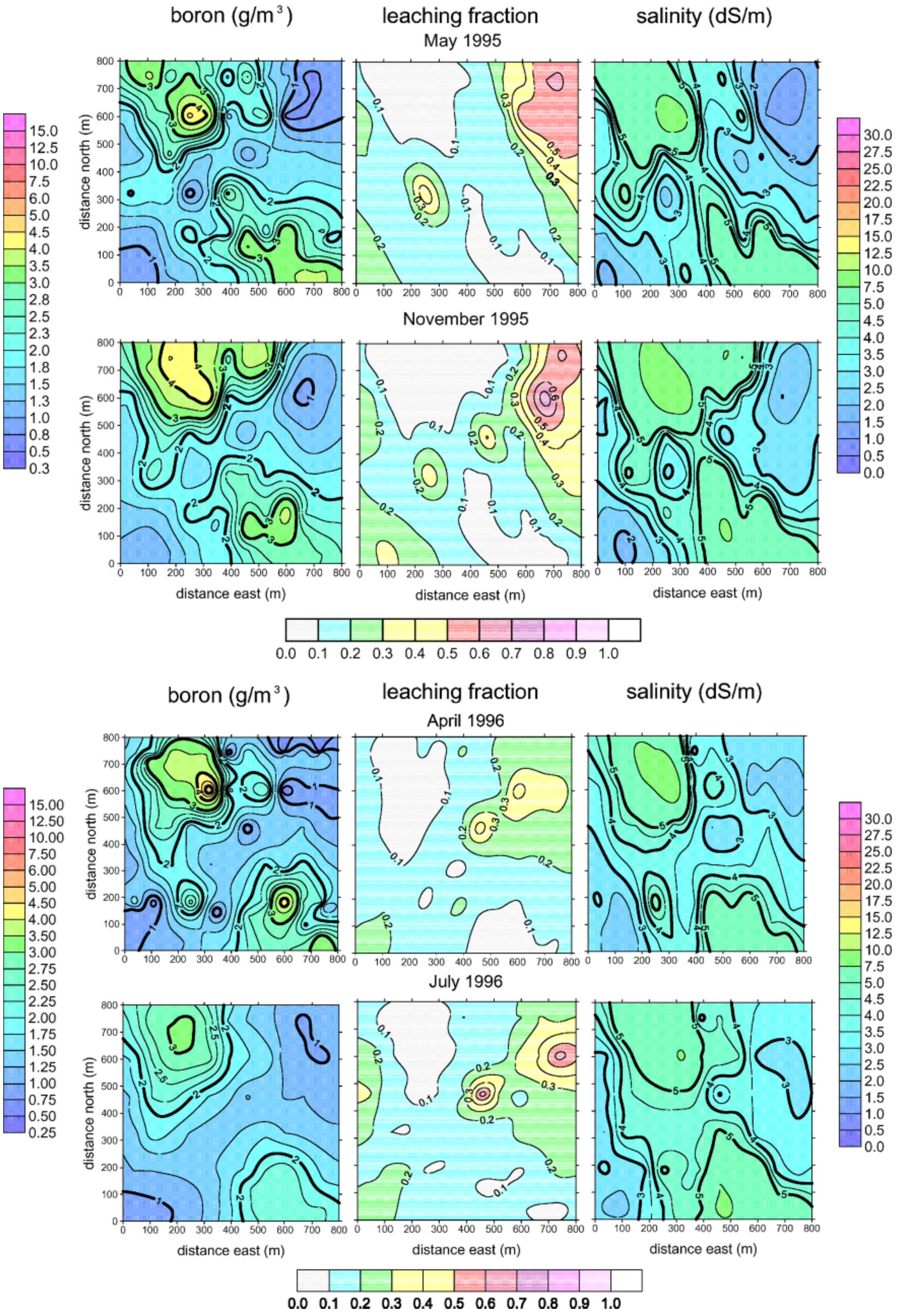

Fig. 9. Spatial distributions of the root zone averaged B content, salinity, and leaching fraction for each sampling date.

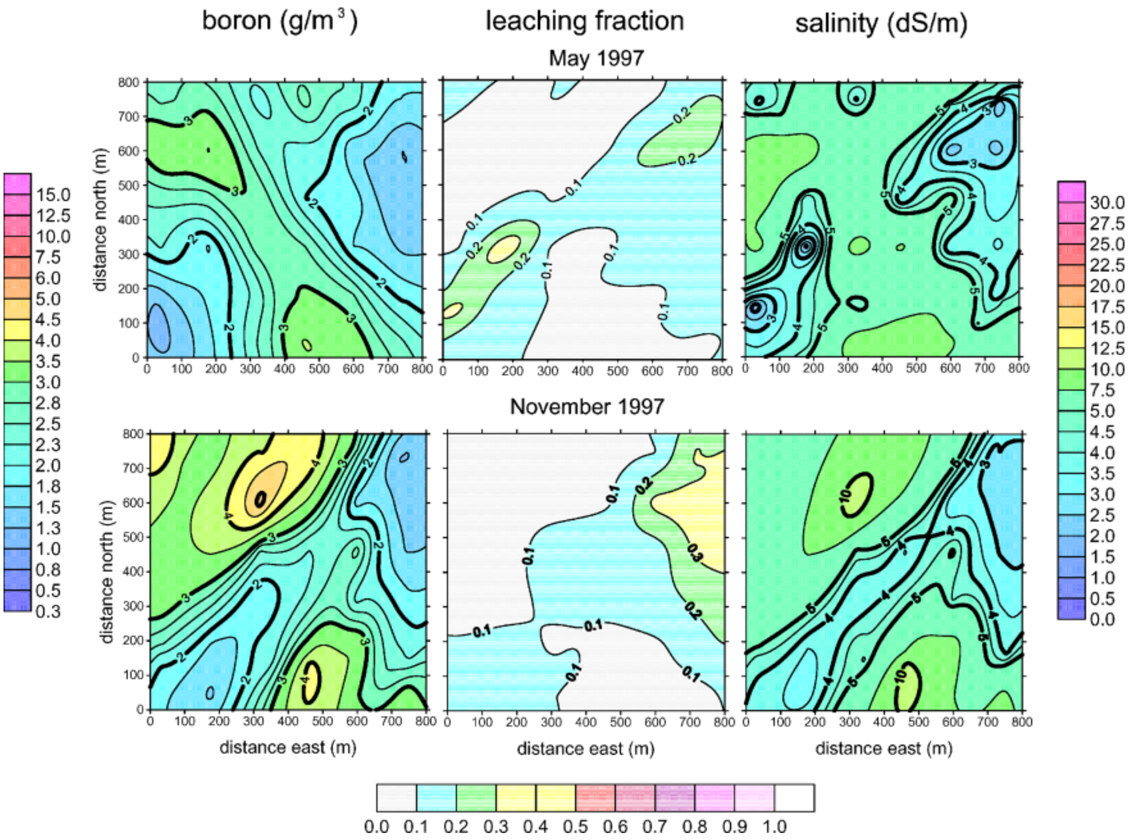

Fig. 9. Continued.

paring the distributions with those shown for the deeper soil depths in Fig. 7, it is clear that patterns for soil concentrations and groundwater concentrations are very similar for both B and salinity.

CONCLUSIONS

Salinity and B concentrations were measured for 3 yr in a field that was managed according to a shallow groundwater management strategy designed to reduce drainage volumes and induce the consumption of shallow groundwater by crops. Our objective was to characterize the spatial and temporal distributions of salinity and B, and to assess whether the groundwater management program was having an impact on soil salinity or concentrations of the phytotoxic trace element B.

A large section in the middle of the field found was found to have a much coarser soil texture in the upper 1 to 1.2 m than the rest of the field, and this texture variability proved to be critical to understanding the observed salinity and B distributions. Salinity and B were highly correlated in the field—areas with high salinity had high B content. During the 3 yr, salinity and B concentrations were relatively uniform across the field at shallow depths (<1 m), but exhibited greater variability at depth.

Inspecting the data, it was possible to discern two distinct salinity–B profiles in the field, one in which the salinity–B content was uniform and relatively low throughout the profile, and one in which the salinity–B content gradually increased with depth and reached a maximum between 1 and 1.5 m. The uniform profiles were located where leaching was highest (and net upward groundwater flow lowest): in the sandy areas, near the head of the field that received more irrigation water, and in the vicinity of drain laterals. The profiles showing increasing concentrations with depth were found in fine textured areas where there was less leaching and more upward flow. The salinity and B concentrations in these latter profiles were at or above levels where, according to published tolerances, it is expected that there would be some decrease in yield. However, these fine textured areas actually produced greater yields, presumably because of greater water and nutrient availability.

During the 3-yr study period, the field changed very little from one year to the next, although within a given year there were fluctuations related to the cropping and irrigation practices utilized and to environmental conditions. For example, the field variability was relatively low during the second year due to atypical rainfall in the late spring, whereas the field variability was greatest near the end of the third year when there was a lengthy period with no rainfall or irrigation at the end of the cotton growing season. However, any changes or increases in variability arising during the growing season were erased in the fallow season by winter rainfall and preplant irrigations that leached salts from the top ≈1 m of soil.

Overall, we find that the shallow groundwater management program used in this study could be continued

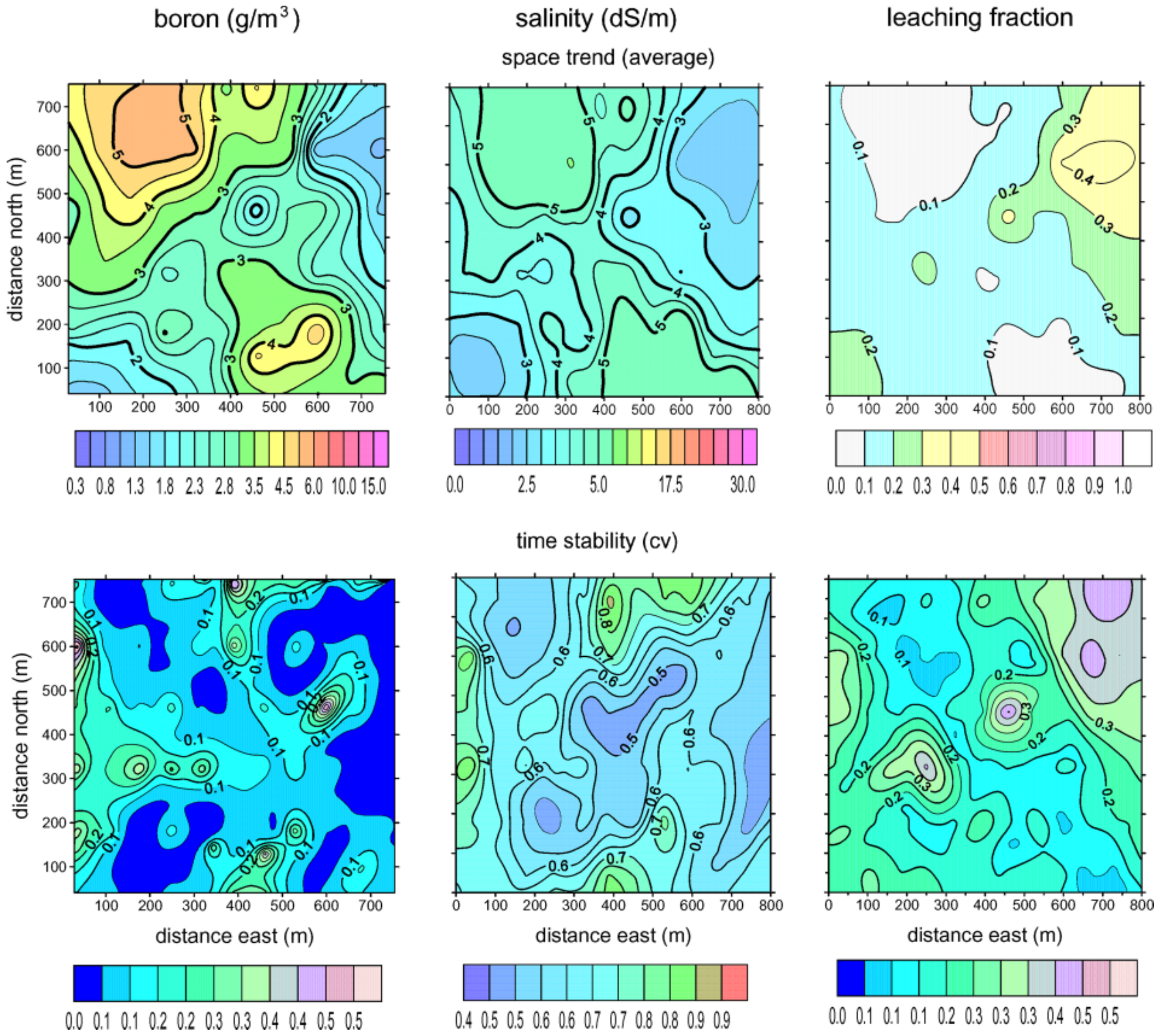

Fig. 10. Spatial distributions of space trends and time stabilities for root zone averaged B content and salinity and leaching fraction.

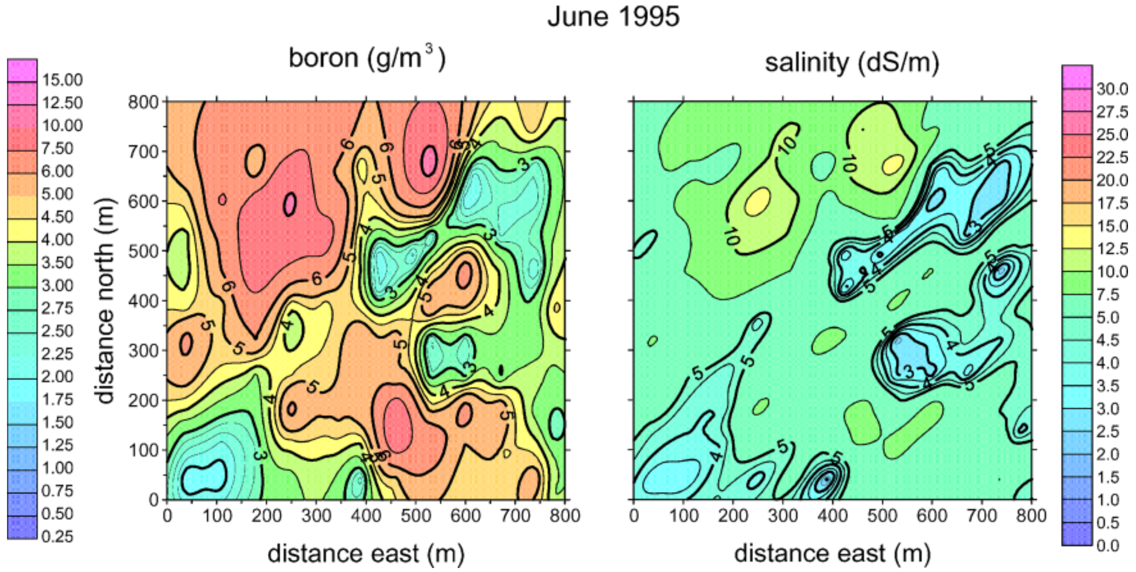

Fig. 11. Spatial distribution of shallow groundwater salinity and B concentration measured in June 1995.

and sustained in this field without increasing soil salinity or B concentrations, and without decreasing yield.

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