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Geophysical Quantification of Water Percolation Quotient in an Alluvial Agricultural Soil

Florence Cassel[1] & Shankar Sharma[2]

[1] California State University, Fresno, USA

[2] University of California, Merced, USA

Correspondence: Florence Cassel, Department of Plant Science, California State University Fresno, 2415 E. San Ramon Avenue, M/S AS 72, Fresno, California 93740, USA. E-mail: fcasselss@csufresno.edu

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Abstract

Efficient water use planning is crucial for the sustainability of irrigated agriculture in California, where alluvial geological materials with indigenous salts impinge on crop growth. To facilitate irrigation scheduling and cultivation planning, it is necessary to determine water percolation quotients (WPQ) required for removal of excess salts from the rhizosphere. In order to estimate real-time WPQ, we conducted electromagnetic geophysical surveys at a saline farmland followed by stochastic computations. Results showed a wide variability in salinity that reached 16 dS m^{-1} in some locations. About 95% of the surveyed samples surpassed 2 dS m^{-1}. Despite spatially dependent asymmetric variability and skewness (-0.13 to 1.90), the WPQ distribution patterns were consistently quantified with low errors (< 0.06). The sensor responses in the fields reached 100% cumulative frequency at a threshold of 13.6 dS m^{-1}. Up to 49% of WPQ data ranged from 0.1 to 0.2. The WPQ decreased with increasing salinity and the zones with low quotient values represented areas where plant growth could be impaired. High WPQ levels demarcated zones with potential solute dissolution and dispersion. Overall, evaluation of WPQ can benefit irrigation planning and crop management practices while enhancing water use efficiency for agricultural production in farms that have been affected by drought and water shortage, and crop growth can be sustained at WPQ level that maintains salts below the crop tolerance threshold.

Keywords: water use planning, percolation, salinity, alluvial, dual-dipole

1. Introduction

Geological parent materials in many agricultural lands of California are predominated by alluvial geomorphic structures that are primarily composed of shale and sandstone deposits containing elevated levels of indigenous salts (McNeal & Balisteri, 1989). High water tables, shallow clay layers and inadequate drainage in these areas result in reduced water percolation and salinity buildup that ultimately impair soil structure and crop growth (USGS, 2015). Agricultural productivity of these farmlands is heavily dependent on irrigation. However, extensive application of poor-quality water often exacerbates the salinity problem. Nearly 45% of irrigated agricultural lands in California are impacted by soil or water-induced salinity (Letey, 2000).

For mitigating these adverse conditions, it is necessary to develop a precise water percolation quotient (WPQ) in order to remove salts from the rhizosphere and maintain a tolerable salinity for plants. Application of irrigation water in excess of plant requirement can achieve this removal (Hanson et al., 2006). The percent of excess water flowing past the rhizosphere depends on several factors including soil texture and salinity, electrical conductivity of the applied irrigation water and salt tolerance of the planted crops. Subsequently, estimation of precise water quantity in field conditions is a challenging task for the growers as conventional measurement methods of using electrode probes and soil sampling are laborious, slow and costly (Davis et al., 1999). Under variable environmental conditions, the electromagnetic geophysical sensing (EGS) technique can be utilized for rapid and reliable quantification of WPQ over large areas. The sensing approach allows for real-time above-ground measurements and provides a better, rapid and economical option as compared to the invasive traditional methods (Hendrickx et al., 1992; Diaz & Herrero, 1992; McKenzie et al., 1997; Sudduth et al., 2003).

Versatility of the EGS technique has been reported for diverse environments. The sensing approach was found to be effective for assessing groundwater recharge (Cook et al., 1992), wetland (Paine et al., 2004), soil moisture in agroforestry (Huth & Poulton, 2007), and coastal agriculture (Yao et al., 2016). Cassel et al. (2015) already detailed the concept of applying electromagnetism for rapid and high-resolution assessment of salinity. The EGS techniques have been applied for salinity and water management across the globe including China (Yao et al., 2016), New Zealand (El-Naggar et al., 2017), Utah (Abdu et al., 2017), the Nile delta (Aboelsoud & Abdel-Rahman, 2017) and Spain (Pedrera-Parrilla et al., 2017). Lia et al. (2015) used EGS measurements for studying the impact of saline water irrigation on desert ecology. Huang et al. (2017a) predicted soil water dynamics using EGS and assimilating artificial neural network and physical model data. Recently, Cassel (2017) demonstrated the application of electromagnetism for site-specific yield optimization in central California. In another study, Cassel and Sharma (2017) described the application of electromagnetism for spatial analysis of salt heterogeneity in a grape field.

Considering the multipurpose benefits of EGS, the current research concentrated on water quantity analyses with specific focus on water percolation to application ratio. Thus, the objective of this study was to estimate WPQ in some salt-affected alluvial agricultural soils in California. Based on the electromagnetic survey and stochastic computations, we quantified soil salinity distribution and WPQ in real-time despite high parametric variability. This approach can help growers and agricultural decision makers develop selective soil reclamation and irrigation management practices depending on specific crop tolerance levels.

2. Materials and Methods

2.1 Geophysical Survey

We performed an EGS survey in a Californian farmland with alluvial silty clay soils that had slowly degraded due to salt accumulation (USDA, 2006). The geomorphic feature included fan remnants with alluvial parent materials derived from sedimentary and igneous rocks. The land was characterized by flat topography with < 1% slope, alkaline soil pH (> 7.9), silty loam surface horizon and silty clay subsurface soils. In this area, occurrence of clayey and saline parent materials and inadequate drainage led to salt buildup that was exacerbated by intensive irrigation practices (Cal EPA, 2006; USDA, 2014). Typical vegetation comprised irrigated crops including tomato as well as salt-tolerant shrubs and grasses.

Our study concentrated on two 800 m × 800 m contiguous fields within the farm, designated hereafter as fields A_1 and A_2. In these fields, soils within a 1.2 m rhizosphere were investigated using dual-dipole electromagnetic sensors (38DD) aligned in perpendicular positions. The sensors were set to measure soil electrical conductivity at 14.6 kHz frequency across 0.8 and 1.5 m lateral and vertical depths, respectively. Potential signal interferences from terrestrial metals were eliminated by securing the sensors in a protective carrier-sled located about 3 m behind a tow-vehicle. Precise survey points were obtained using a global positioning system with differential correction capability at the sub-meter accuracy level. The real-time data were recorded using an on-board computer connected through digital interfaces.

2.2 Optimal Sampling and Laboratory Analyses

Following the EGS data recording, an optimal soil sampling plan with spatial characteristics of the whole survey area was devised using an ESAP analysis (Lesch et al., 2000). For subsequent calibration, the response sample design methodology was applied to select the survey locations that yielded minimal spatial auto-correlations and best described the spatial variability in apparent electrical conductivity. Within 48 hours of the survey, physical soil samples were collected at specific plan-defined points across the rhizosphere. Afterward, these soil samples were processed and analyzed for electrical conductivity (EC), volumetric water content (θ) and water saturation percentage (SP) using procedures described by Dane and Topp (2002) and Gavlak et al. (2003).

2.3 Stochastic Analyses and Mapping

Soil salinity and WPQ were determined based on electrical conductivity characterization by geophysical surveys, laboratory assay, as well as statistical and stochastic modeling analyses described by Lesch et al. (2000). The EGS response data were also analyzed for dispersion, variance, symmetry and distributions. For each field, the model that estimated WPQ was calibrated using the EGS response values as well as their mean and range across the rhizosphere. The principal component de-correlation analysis and validation routines were applied to expel the outliers, and center, scale and de-correlate the conductivity data. Results from the field surveys and the physical soil data were utilized for stochastic analyses, and EC, θ and SP data were integrated to compute WPQ. The signal and trend surface parameters were estimated using multi-linear regression analyses. The WPQ was then determined based on the estimated rhizosphere conductivity values by using a conversion routine available in Lesch et al. (2000). Next, raster maps of soil salinity and WPQ were plotted using ArcGIS (ESRI, 2012).

3. Results and Discussion

Relevant soil physicochemical properties of the plan-defined locations within the rhizosphere of fields A_1 and A_2 are summarized in Table 1. The electrical conductivity (EC) values in the surveyed fields ranged from 1 to 26 dS m^{-1}, and were characterized by wide variations in salinity with 45 to 80% coefficient of variation (CV). The mean salinity levels were 9 and 6 dS m^{-1} in fields A_1 and A_2, respectively. In this farmland, most vegetable crops would be adversely affected by these levels of salinity. For example, tomato was reported to tolerate salinity up to a threshold of 2.5 dS m^{-1} (Hanson et al., 2006). Likewise, onions yields start decreasing when salinity reaches 1.2 dS m^{-1}. Even cotton, considered a salt-tolerant crop with a salinity threshold of 7.7 dS m^{-1}, would exhibit yield declines across most of field A_1 and in the north-west corner of field A_2. Average SP values ranged from 27 to 60% with the higher values suggesting more clayey soil texture. Greater average and maximum SP levels were observed in field A_1, which also exhibited the higher mean EC level. The soil water contents were near the field capacity conditions in both fields with levels ranging from 18 to 40%. Abdu et al. (2017) employed electromagnetic mapping at varied water contents of a fallow field with mostly homogeneous silt-loam alluvial soils under xeric moisture regime in Utah. By utilizing the geophysical method, the authors were able to determine the textural patterns and observed that the lowest electrical conductivity zone had high correlations with coarse geological materials.

Table 1. Summary statistics of soil physicochemical characteristics

	Field A_1			Field A_2		
	EC (dS m^{-1})	SP (%)	θ (%)	EC (dS m^{-1})	SP (%)	θ (%)
Mean	9	50	27	6	30	27
Standard Deviation	4	16	3	5	6	5
Minimum	2	27	18	1	21	20
Maximum	16	85	34	26	47	40
Coefficient of variation (%)	45	32	11	80	18	19
Confidence interval (%)	95	95	95	95	95	95

During the geophysical survey, the transmitter coil was used to apply an alternating electrical current to the ground and generate a primary magnetic field. The primary magnetic field induced circular eddy current flow loops, which created a secondary magnetic field. The receiver coil measured both of these magnetic fields. The total EGS response (R_{egs}) was directly proportional to the magnitude of the eddy current loops and expressed as depth (d) weighted apparent soil electrical conductivity (McNeill, 1992). The depth weighted responses for the vertical ($\phi_v(d)$) and lateral ($\phi_l(d)$) dipoles were computed as:

$$\varphi_v(d) = \frac{4d}{(4d^2+1)^{3/2}} \tag{1}$$

$$\varphi_l(d) = 2 - \frac{4d}{(4d^2+1)^{1/2}} \tag{2}$$

Considering multi-layer contributions from zero to infinity (∞), the cumulative response ($R(d)$) and the corresponding electrical conductivity (EC(d)) were integrated to determine the total EGS response (R_{egs}):

$$R(d) = \int_0^\infty \varphi(d)\,\delta d \tag{3}$$

$$R_{egs} = \int_0^\infty \varphi(d)\,EC(d)\,\delta d \tag{4}$$

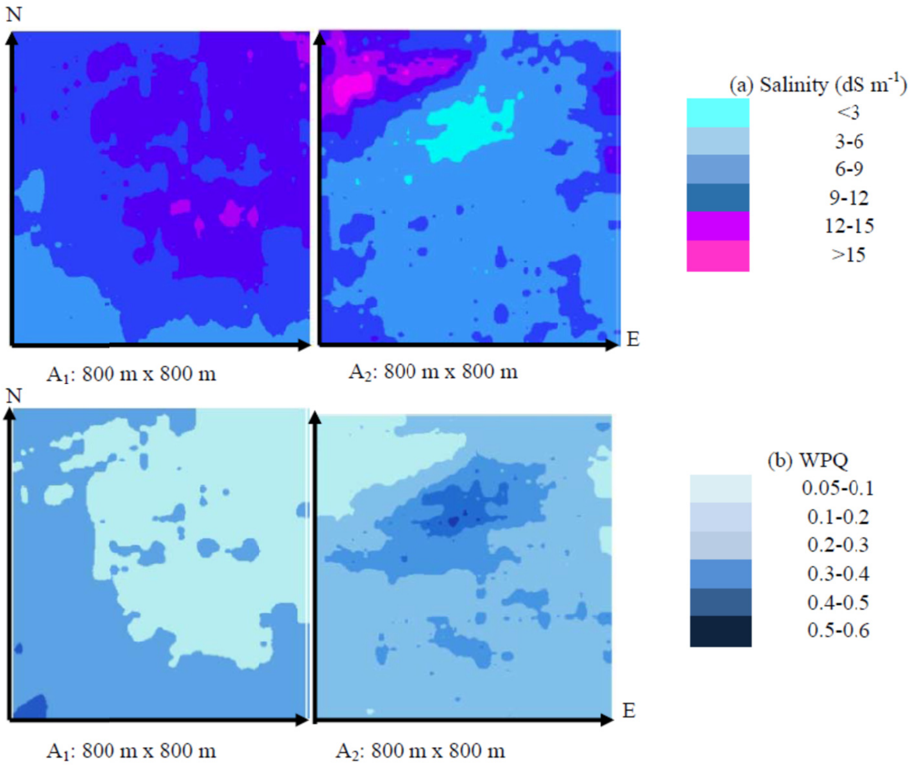

Figure 1. Raster maps of (a) soil salinity and (b) water percolation quotient (WPQ)

Spatial variations in soil salinity and water percolation quotient for fields A_1 and A_2 are presented in Figure 1. The raster maps indicated that soil salinity was elevated across the fields with levels mostly above 2.5 dS m^{-1}. Only the north-central part of field A_2 had low salinity (< 3 dS m^{-1}). Some locations in both fields exceeded 15 dS m^{-1}. The raster maps also show the spatial distributions of WPQ within the soil rhizosphere. The WPQ at the surface was generally elevated and gradually decreased with depth. In A_1, the WPQ values primarily were less than 0.1, while the majority of A_2 had ratios above 0.3. The maps also showed that the zones with relatively elevated salinity had low WPQ levels thereby suggesting the need for greater water volume for soil reclamation. The areas with low salinity were typically characterized by elevated WPQ. Thus, high WPQ was indicative of less salt accumulation plausibly due to greater dissolution and transport of ions from the surface to subsurface zone. The overall results indicated that the reclamation and salt management would be primarily necessary for field A_1 and the north-western part of field A_2. These findings are critical to identify the parts of the fields that would affect plant growth and need management practices aimed at water percolation beyond the rhizosphere to maintain salt levels within crop tolerable limits. In a study of a farm cultivated with ryegrass and clover in New Zealand, El-Naggar et al. (2017) applied electromagnetic imaging to estimate water content in fluvial soils. These authors observed that EGS accurately estimated water content with closer correlations under homogeneous clay content, and both variables followed similar trends across the soil profile depths. Huang et al. (2017b) applied conductivity imaging for three-dimensional assay of soil water balance in the context of real-time irrigation management. The authors predicted soil water dynamics from the electromagnetic data and a physical model fitting. They demonstrated that the water distribution and drying cycles would depend on soil physical texture and irrigation scheduling. Water drying in the loamy soil was fast due to deep drainage and preferential flow. At the early stage of irrigation cycles, the soil water dried very rapidly and then the drying process declined with time and soil profile depth.

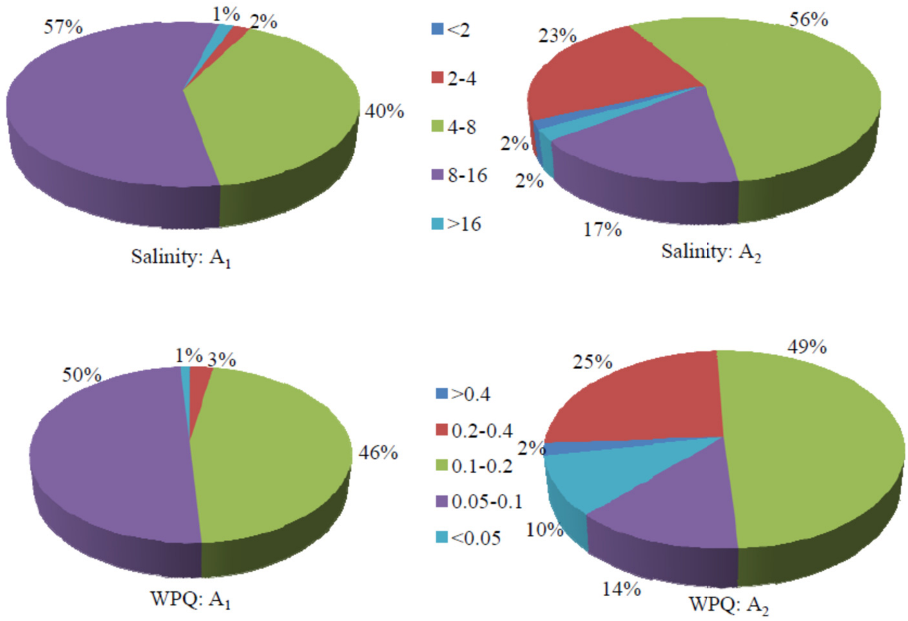

Figure 2. Partitioning of soil salinity (dS m^{-1}) and water percolation quotient (WPQ)

The partitioning of salinity and WPQ across the fields is shown in Figure 2. Over 95% of the salinity values surpassed 2 dS m^{-1}. About 40 and 56% of the salinity values in fields A_1 and A_2, respectively, remained between 4 and 8 dS m^{-1}. Furthermore, 57 and 17% of salinity data in A_1 and A_2, respectively, ranged from 8 to 16 dS m^{-1}. The overall WPQ increased with decreasing salinity. Nearly 46 and 49% of WPQ data in fields A_1 and A_2 were in the 0.1-0.2 range. About 50% of WPQ levels in A_1 remained between 0.05 and 0.1, whereas only 14% data in A_2 were in this range. The lower quotient values within the profiles suggested greater salt accumulation in soils that could impair plant growth and would need more intense management approach. The WPQ range of 0.2-0.4 was observed for 3 and 25% of data in A_1 and A_2, respectively. Also, as compared to 10% WPQ in A_2, only 1% WPQ in A_1 remained below the level of 0.05. These results indicated that WPQ distributions were highly variable and dynamic functions even within the contiguous areas. Such randomness in WPQ conformed to the wide variability in salinity within the fields. These variations could be attributed to the changes in ion concentrations of the soil pore water. Soil salinity can be sustained to acceptable crop growth levels if the percolation maintains salts below the crop tolerance threshold. With the challenge of agricultural water shortage, the growers can resort to innovative reuse of drainage and waste waters. Such adaptation may alleviate the need for additional irrigation water supplies and improve on farm water use efficiency. Thus, appreciation of WPQ can benefit the growers in planning water conservation measures while maintaining the soil salinity balance within the crop tolerance ranges. Pedrera-Parrilla et al. (2017) studied spatio-temporal characteristics of soil water content in an olive orchard in Spain and observed close correlation in the temporal stability of sensor response and water data. Within the field areas with high conductivity response, the soil water content showed non-linear behavior. Linearity was generally detected within conductivity zones characterized by below-average values. Dry zones with below-average field water content were identified with 89% chance within the segments of low conductivity response. Huang et al. (2017a) applied a two-dimensional algorithm to convert EGS response data to conductivity that was subsequently used to compute water content. These authors reported high predictive concordance of water content values based on the response data.

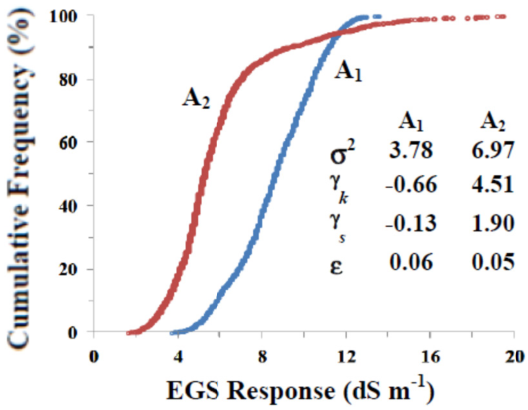

Figure 3. Variation in cumulative frequency with EGS response

The cumulative frequencies (CF) of the total EGS responses, R_{egs}, in fields A_1 and A_2 and the symmetry of the distributions are described in Figure 3. The R_{egs} distribution in A_1 was nearly symmetrical with diminutive skewness (γ_s) tailing negatively toward -0.13. Slightly negative kurtosis value (γ_k = -0.66) was indicative of nearly flat distribution within this field. As compared to A_1, notably greater asymmetry and sharpness of the distribution were observed in field A_2 that was characterized with γ_s and γ_k of of 1.90 and 4.51, respectively. Thus, the asymmetry of the distribution in A_2 was an order of magnitude higher than that in A_1. The response variance (σ^2) in A_2 was nearly twice of that in A_1 with magnitudes of 6.97 and 3.78, respectively. The local attributes of the two fields were significantly different, and field A_2 had greater variability and asymmetry in response distributions than field A_1. Subsequently, 100% CF was reached at the threshold R_{egs} of 13.6 and 19.5 dS m^{-1} in fields A_1 and A_2, respectively. At low R_{egs} ranges, the CF between the two fields had wide gap. The magnitude of this difference (ΔCF) narrowed down with increase in R_{egs} values. Thus, at R_{egs} of 5 and 10 dS m^{-1}, field A_2 showed correspondingly 13 and 1.25 times higher ΔCF than field A_1. The gradient ($\Delta CF/\Delta R_{egs}$) of both curves varied continuously with changing R_{egs} values. In low R_{egs} range (0.05-50 dS m^{-1}), the curves had comparable gradients with A_2 having slightly steeper (1.4 times) slope than A_1. In higher R_{egs} range (50 - 100 dS m^{-1}), the trend reversed and A_1 had about 2.8 times steeper gradient than A_2. At the intersection response level of 11.7 dS m^{-1}, both A_1 and A_2 reached around 95% CF. It was noteworthy that despite difference and variability between the two fields, the patterns in salinity and WPQ distributions were consistently quantified by the EGS measurements. Notably, the EGS responses in both fields were characterized by low standard error (ε) values of 0.06 and 0.05 in A_1 and A_2, respectively. Thus, our study demonstrated that for agricultural management purposes, results of geophysical measurements would be statistically reliable for land and water management in diverse and vast areas. Aboelsoud and Abdel-Rahman (2017) applied the electromagnetic technique for rapid salinity estimation in the Nile delta and employed exhaustive quadratic and multiple regression modeling. The authors observed that the conductivity response from the geophysical measurements were strongly correlated with salinity and could be applied with statistical confidence for mapping salinity in various profile depths and establishing control measures in irrigated agriculture. Altdorff et al. (2017) studied a forest ecosystem to determine catchment-wide soil water content by utilizing the electromagnetic technique. The authors applied linear and nonlinear regression models to relate sensor response and water content and observed strong spatial resemblance between these variables. Both models showed high prediction accuracy that was relatively improved with nonlinear modeling.

4. Conclusion and Implications for Water Use Planning

Water shortage and terrestrial upsurge of salts are persistent problems around the globe including in Californian agricultural lands (FAO, 2011; Howitt et al., 2014). Our geophysical method offered non-invasive estimation of soil salinity and WPQ with high resolution, and the results showed their spatial distributions and frequencies within the rhizosphere. The salinity and WPQ measures were widely dispersed from their mean values and characterized by wide range of coefficient of variation. The maps identified isolated zones of salt build up and water percolation-application gradients. The study area is part of the farming heartland of California that produces over 250 crops (CDFA, 2017). The information on salinity and water percolation to application balance can benefit agronomic decisions for sustaining crop production and concurrently implementing water conservation. Dynamic nature of soluble salts in the rhizosphere results in variability in soil salinity and WPQ. The electromagnetic measurements can benefit water budgeting by identifying dry and wet zones and mapping the areas exposed to deep drainage risks. The geophysical assessment can help growers in understanding the soil water dynamics for farm management planning. The spatial distribution of WPQ can assist evaluating soil water storage and hydraulic transport processes and the overall approach can be applied to a wide range of agricultural operations including irrigation scheduling, water budgeting and site-specific crop selection. Efficient use of water resources is crucial for the sustainability of irrigated agriculture in California and many parts of the world, where continuous droughts have accentuated the need to conserve water and improve on-farm water application. The study pertains to critical challenges in California including limited water supplies for agricultural industry and declining water and soil quality. Evaluation of WPQ can facilitate development of crop water requirements and optimization of water use efficiency under integrated irrigation scheduling. The WPQ evaluation can be integrated with agricultural monitoring methods and precise data acquisition processes to provide real-time plant water utilization data that can subsequently enhance efficient irrigation planning decisions to sustain crop productivity and implement soil reclamation strategies. The overall approach of this study can benefit decision support tools for planning water-related farming practices.

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