Version of record at: https://doi.org/10.1002/saj2.70075

Check for updates

Received: 8 February 2025 | Accepted: 29 April 2025

DOI: 10.1002/saj2.70075

Soil Science Society of America Journal

ORIGINAL ARTICLE

Agricultural Soil and Food Systems

Evaluating routine agronomic soil tests for coastal soil salinity detection in the mid-Atlantic

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Assigned to Associate Editor Curtis Dell.

Funding information
USDA; NIFA, Grant/Award Numbers: 2022-68008-36647, 2018-68002-27915

Abstract

Coastal salinity is a growing concern for managing agricultural soils in the eastern United States, including the Delmarva Peninsula. The saturated paste (SP) extraction, which is the standard method for measuring soil salinity in arid climates, is not widely available in the eastern United States and its effectiveness in humid coastal soils is unknown. We evaluated the Mehlich-3 (M3) routine agronomic soil test as an alternative to SP and ammonium acetate (AA) extractions on samples from 13 Delmarva agricultural fields with known salinity issues. Soils were analyzed for electrical conductivity (EC) by SP extract (EC_e) or deionized water (1:2 and 1:5 soil-to-water ratios; $EC_{1:2}$ and $EC_{1:5}$). Extractable cations (Na, Ca, Mg, and K by SP, M3, and AA) were used to calculate exchangeable sodium percentage (ESP), sodium cation ratio (SCR), and sodium adsorption ratio (SAR). We noted significant positive relationships between SP-extractable Na and both M3-extractable and AA-extractable Na ($r^2 = 0.81$ and 0.77, respectively). Soil SCR values calculated from M3 and AA exhibited significant linear relationships ($r^2 = 0.82$–0.88) with ESP_{SAR} and SAR. Strong positive linear relationships were also noted between M3-extractable Na and EC_e ($r^2 = 0.81$). Reclassification of salinity using predicted EC_e from M3-Na and SCR_{M3} were similar to standard classification methods. We suggest M3 as a cost-effective and accessible option for salinity assessment in coastal soils of the Eastern United States. Further field studies linking soil salinity to crop health and yields are needed to validate soil salinity interpretations prior to widespread adoption of M3-based salinity assessments.

Abbreviations: AA, ammonium acetate; CEC, cation exchange capacity; EC, electrical conductivity; $EC_{1:2}$, electrical conductivity from 1:2 volumetric soil to water extraction method; $EC_{1:5}$, electrical conductivity from 1:5 volumetric soil to water extraction method; EC_e, electrical conductivity from saturated paste extract; ESP, exchangeable sodium percentage; ESP_{SAR}, exchangeable sodium percentage estimated from sodium adsorption ratio; NCDA&CS, North Carolina Department of Agriculture and Consumer Services; SAR, sodium adsorption ratio; SCR, sodium cation ratio; SCR_{AA}, sodium cation ratio from ammonium acetate; $SCR_{AA(acid)}$, sodium cation ratio from ammonium acetate for acidic soil; $SCR_{AA(alkaline)}$, sodium cation ratio from ammonium acetate for alkaline soil; SCR_{M3}, sodium cation ratio from Mehlich-3; SEC, sum of extractable cations; SLR, sea-level rise; SP, saturated paste; SSI, soluble salt index.

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1 | INTRODUCTION

Climate change is impacting worldwide crop production. One significant consequence of global climate change is the rising incidence of soil salinization in humid coastal regions (Tully et al., 2019). Landscapes that are situated along the coast in humid regions are vulnerable to salinization due to saltwater intrusion or tidal flooding (Epanchin-Niell et al., 2017). Saltwater intrusion and salinization that is driven by sea-level rise (SLR), stormwater surge, irrigation with saline groundwater, hydrologic connectivity to tidal channels, or a combination of these factors (Huang et al., 2019; Kaushal et al., 2021; Miller, 2024; Moftakhari et al., 2015; A. C. Ross et al., 2015; Tully et al., 2019) is increasingly affecting low-lying fields along the Delmarva Peninsula (i.e., Delaware and parts of Maryland and Virginia; Epanchin-Niell et al., 2017). When crops are cultivated in saltwater intrusion-affected fields, plants may experience sodium (Na^+), chloride (Cl^-), or boron (B) toxicity that disrupts plant cell functioning and plant growth (Munns, 2005). Along coastal edges, saltwater intrusion has led to the formation of ghost forests (Kirwan & Gedan, 2019) and barren salt patches within crop and pasture fields (Mondal et al., 2023; Tully et al., 2019).

Historically, soil salinity issues were most commonly experienced in arid soils. The saturated paste (SP) and ammonium acetate (AA) soil tests are commonly recommended to diagnose salinity issues in arid soils (Richards, 1954). The SP extraction involves the addition of deionized water until the soil-water mixture forms a paste (i.e., when 100% of pore space is filled with water); the exact soil to solution ratio used in the SP extraction varies based on soil physical properties. Suction is applied to the paste to remove the "pore water," which is then analyzed for soluble ions, typically calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and Na^+ (Butcher et al., 2016; Richards, 1954). Other ions, including Cl^-, sulfate (SO_4^{2-}), nitrate (NO_3^-), and bicarbonate (HCO_3^-), may be measured in the SP extract. Soil pH (pH_e) and total dissolved solids may also be measured following SP extraction, with the latter reported as electrical conductivity (EC_e), where the subscript "e" signifies the use of the SP extraction. Sodium adsorption ratio (SAR [$mmol_c\ L^{-1}]^{0.5}$); Equation 1) is calculated from Ca^{2+}, Mg^{2+}, and Na^+ concentrations (cations in meq $100\ g^{-1}$ or $cmol_c\ kg^{-1}$) following SP extraction. Exchangeable sodium percentage (ESP; Equation 2) is calculated using the Na^+ concentration and soil cation exchange capacity (CEC) as measured following AA extraction.

$$SAR = \frac{\left[Na^{+1}\right]}{\left(\left[Ca^{2+}\right] + \left[Mg^{2+}\right]/2\right)^{0.5}}. \quad (1)$$

Core Ideas

- Soil salinity assessments are needed to guide management in coastal regions of the Eastern United States.
- Saturated paste extractions are not offered as a routine agronomic soil test outside the Western United States.
- Mehlich-3 extractable Na and ammonium acetate extractable Na had a strong positive relationship with saturated paste extractable Na.
- Mehlich-3 extractable Na has potential to identify and classify the salinity on the Delmarva Peninsula.

$$ESP = \frac{\left[Na^{+1}\right]}{CEC} \times 100. \quad (2)$$

Soils containing excess salts are then classified as saline, sodic, or saline-sodic (DeSutter et al., 2024) based on pH_e, EC_e, SAR, and ESP. For example, soils are classified as saline when EC_e exceeds 4 dS m^{-1} and ESP is less than 15%. In contrast, a sodic soil has an ESP > 15% but lacks significant concentrations of other cations (Ca^{2+}, Mg^{2+}, and K^+) that contribute to salinity. Soils with high Na^+, Ca^{2+}, and Mg^{2+} concentrations (EC_e > 4 dS m^{-1}; SAR > 13%) and high ESP (>15%) are classified as saline-sodic. Soil salinity classification mainly addresses soil physical properties rather than salt sensitivity among different crops. Yet, plant growth can be adversely affected at EC_e levels that are significantly lower than the 4 dS m^{-1} threshold for salt-affected soils, particularly for crops with high economic value like corn (Maas & Hoffman, 1977). For example, corn yield reductions can begin at EC_e values of 1.7 dS m^{-1} (Tanji & Kielen, 2002).

Because soil salinity issues were historically rare in humid regions, public and private soil testing laboratories outside the Western United States typically exclude soil salinity tests (e.g., SP extraction) from their standard offerings. Plus, there are several analytical challenges with the SP extraction. One key issue with the SP test is poor reproducibility, which is partly due to variability in the amount of deionized water needed to create the paste with soil texture (Aboukila & Norton, 2017). In addition, the SP extraction is labor-intensive and relatively more expensive to run than other routine agronomic soil tests (DeSutter et al., 2024). The accuracy of the SP method can also be compromised due to inconsistencies in measurement techniques between the labs and challenges in converting resistivity to conductivity when directly inserting electrical conductivity (EC) sensors into paste instead of

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extracting water from paste (DeSutter et al., 2024; Hogg & Henry, 1984). Consequently, the SP test is more often used as a research tool rather than as a routine agronomic soil test outside the Western United States (DeSutter et al., 2015; Monteleone et al., 2016). When salinity tests are available in other regions of the United States, they are often considered specialty or add-on services. As a result, farmers seeking to identify soil salinity issues (regardless of their location) must currently ship their samples to labs that routinely offer soil salinity tests; these options can be costly to growers.

Given the emerging salinity challenges in the humid coastal areas (such as the Delmarva Peninsula), it is essential to explore more accessible and regionally appropriate soil testing options. In the Northeastern United States, agronomic soil fertility assessments typically involve extraction of soils using the Mehlich-3 (M3) extraction (Mehlich, 1984; NECC, 2011). The acidic M3 extraction is considered a universal soil extractant because soil macronutrients (i.e., K, Ca, and Mg) and other elements (e.g., zinc [Zn], aluminum [Al], copper [Cu], and B) can be quantified in the M3 extracts. The AA extraction is also an approved soil test for base cations (i.e., K, Ca, and Mg) in the Northeastern United States and is sometimes used to yield a more accurate estimation of cation exchange capacity (CEC_{sum}) than is provided by the summation of cations following M3 extraction (D. S. Ross & Ketterings, 2011). In the Western United States, various extractions (e.g., Bray P-1, AA, modified Morgan, etc.) are recommended over the SP extraction for routine agronomic fertility analysis (Miller et al., 2013). For instance, the Bray P-1 extraction is commonly used to extract P in the Western United States (Bray & Kurtz, 1945), while other elements like K, Ca, Mg, and even Na are often analyzed in AA extracts (Merwin & Peech, 1951).

Some researchers have evaluated routine soil tests for their potential to replace the SP extraction for salinity assessments. For example, DeSutter et al. (2015) compared Na concentrations in North Dakota soils following the SP and AA extractions and found that AA-extractable Na had a positive, linear relationship with SAR. However, concentrations of other ions (i.e., Ca, Mg, and K) solubilized during AA extraction were higher than with SP because the AA extraction liberates both the soluble (i.e., SP-extractable nutrients) ions and those sorbed to the soil CEC (DeSutter et al., 2015). Similarly, researchers have examined relationships between EC_e and EC measurements using deionized water with fixed ratios (v:v) that are used widely across the United States (i.e., $EC_{1:1}$ and $EC_{1:2}$ v:v; Gartley, 2011; Miller et al., 2013; J. J. Wang et al., 2014; Whitney, 2015) and in Australia ($EC_{1:5}$; Rayment & Lyons, 2011). Researchers reported variable relationships depending on region and soil texture (Aboukila & Norton, 2017; Endo et al., 2021; Kargas et al., 2018; Sonmez et al., 2008). For example, Sonmez et al. (2008) observed a strong and significant relationship between EC_e and EC from different soil-to-water extraction ratios (1:1, 1:2.5, and 1:5), but the strength of these relationships varied by soil texture. Similarly, Endo et al. (2021) reported a strong correlation between EC_e and $EC_{1:5}$, although these relationships varied for soils collected from different geographical locations (i.e., China vs. Sudan). Yet, fixed soil to water ratio EC tests appear to have potential as a replacement for EC_e in soil salinity assessments.

In contrast, the potential for the M3 routine agronomic soil test to measure and classify soil salinity has not been widely explored. North Carolina Department of Agriculture and Consumer Services (NCDA&CS) researchers reported a strong relationship between M3-extractable Na and soluble salt index (SSI) that is based on $EC_{1:2}$. The NCDA&CS lab measures M3-Na concentrations and converts them to SSI based on the relationship SSI = 53.523 × M3-extractable Na in meq L^{-1} (r^2 = 0.97, n = 910); SSI values are then used to classify salinity issues and guide remediation (Ozlu et al., 2024). No other evaluations of M3 as an indicator of soil salinity were found in the literature. However, comparisons of the M3 soil test with the AA extraction (and other routine soil tests) using Delaware agronomic soils displayed strong linear relationships (e.g., r^2 = 0.93–0.99; Gartley et al., 2007). Researchers in the US Midwest have also shown M3 to be suitable for nutrient extraction, compared to AA and Bray methods (Culman et al., 2019), providing a solid foundation for further soil test comparisons. This study builds upon past research by evaluating the effectiveness of routine agronomic soil test methods that are commonly used in the Northeastern United States (e.g., M3, AA, and $EC_{1:2}$) for detecting salinity issues in Delmarva soils impacted by SLR and saltwater intrusion. While these methods are widely used for agronomic soil fertility assessments, their reliability in characterizing soil salinity in coastal environments remains uncertain. To address this gap, we compare mid-Atlantic routine agronomic soil tests to the standard salinity assessments that were developed for arid soil (e.g., SP). Our objective is to determine whether routine agronomic tests can provide accurate and practical indicators of salt-affected soils, thereby improving diagnostic tools for farmers and land managers in the region.

2 | MATERIALS AND METHODS

2.1 | Site selection and sample collection

We collected soil samples from 13 fields in coastal areas of the Delmarva Peninsula with known salinity issues affecting crop production between 2020 and 2023; all fields were within the Northern Tidewater Area (Major Land Resource Area 153D; Figure 1). Soils were mostly classified as Ultisols, with the exception of one Entisol (Soil Survey Staff, 2019). Information on general location, sampling year, and

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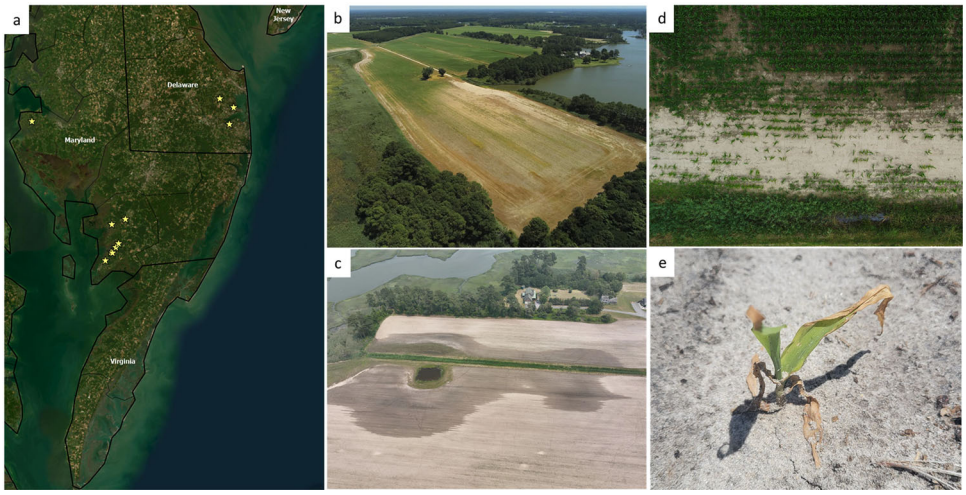

FIGURE 1 (a) Location of 13 salt-affected fields on the Delmarva Peninsula where soils were sampled between 2020 and 2023 to evaluate the use of routine agronomic soils tests to identify soil salinity issues. Soil salinity issues may be related to (b) proximity to brackish or saline waters like the Chesapeake Bay or (c) salt water entering through open ditch drainage, resulting in (d) visible salt patches and (e) crop growth issues.

soil taxonomy for each site is included in Supporting Information. Soil sampling points were identified along topographic or EC gradients within each field, resulting in 11–48 soil sample collection points per field in 2021 and 12 soil sampling collection points per field in 2022 and 2023. Detailed information on the identification of sampling points is included in the Supporting Information. At each sampling point, we collected approximately 12 soil cores (sub-samples) to a depth of 20 cm using a soil probe (7/8 in./2.22 cm); individual core samples were mixed to generate one composite sample per sampling point, resulting in a total of 291 composite soil samples collected across all 13 field sites. Soils were air-dried and ground using a Dyna-Crush Soil Grinder (Custom Laboratory Equipment Inc.) to pass through a 2-mm stainless steel sieve prior to analysis.

2.2 | Soil analysis

A subsample of each composite soil was sent to Brookside Laboratory (New Bremen, OH) for analysis of soluble ions (Ca, Mg, K, Na, Cl, and sulfur [S]) and soluble salts (EC_e) following SP extraction (Richards, 1954). SP data were reported in $cmol_c\ L^{-1}$ because the volume of water used to create the paste for each sample was not recorded. The lab calculated SAR (Equation 1) and estimated ESP (ESP_{SAR}), which is predicted percentage of soil's CEC occupied by Na calculated from SAR ($[mmol_c\ L^{-1}]^{0.5}$) derived from SP extract, based on the following equation as described by Richards (1954):

$$ESP = 100 \times \frac{-0.0126 + 0.0147 \times SAR}{[1 + (-0.0126 + 0.01475 \times SAR)]}. \quad (3)$$

Soil samples were also analyzed at the University of Delaware Soil Testing Laboratory for particle size by hydrometer method (Bouyoucos, 1962), pH ($pH_{1:1w}$; 1:1 v:v soil:deionized water), Adams-Evans buffer pH (Sims & Eckert, 2011), $EC_{1:2}$ and $EC_{1:5}$ (Gartley, 2011), and soil organic matter (loss on ignition; Schulte & Hoskins, 2011). In addition, samples were analyzed for Ca, Mg, K, and Na using inductively coupled plasma-optical emission spectroscopy following M3 extraction (Wolf & Beegle, 2011) and 1 M AA extraction (1:2 soil to solution; Warncke & Brown, 2015); AA and M3 data were reported in $cmol_c\ kg^{-1}$. Soil sodium cation ratio (SCR) (%) was calculated using M3 extractable elements and the sum of extractable cations (SEC; $cmol_c\ kg^{-1}$) by M3 or AA (alkaline soil and acidic soil) extractions (SCR_{M3} and SCR_{AA}, respectively; D. S. Ross & Ketterings, 2011). For AA-based SEC, we summed cations with and without an estimation of exchangeable acidity from the Adams-Evans lime requirement test (Equations 4 and 5, respectively) for use in SCR_{AA} calculations (Desutter et al., 2015; Gartley et al., 2007) because mid-Atlantic soils are typically acidic.

$$SEC_{acid} = [8 \times (8 - \text{AE Buffer pH})] + Ca + K + Mg + Na, \quad (4)$$

$$SEC_{alkaline} = Ca + K + Mg + Na. \quad (5)$$

This calculation follows the same methodology as conventional CEC estimation in the Northeast soils, though we recognize SEC may include some non-exchangeable cations in saline conditions. The approach remains valuable for comparative salinity assessments while acknowledging it does not represent true exchange capacity.

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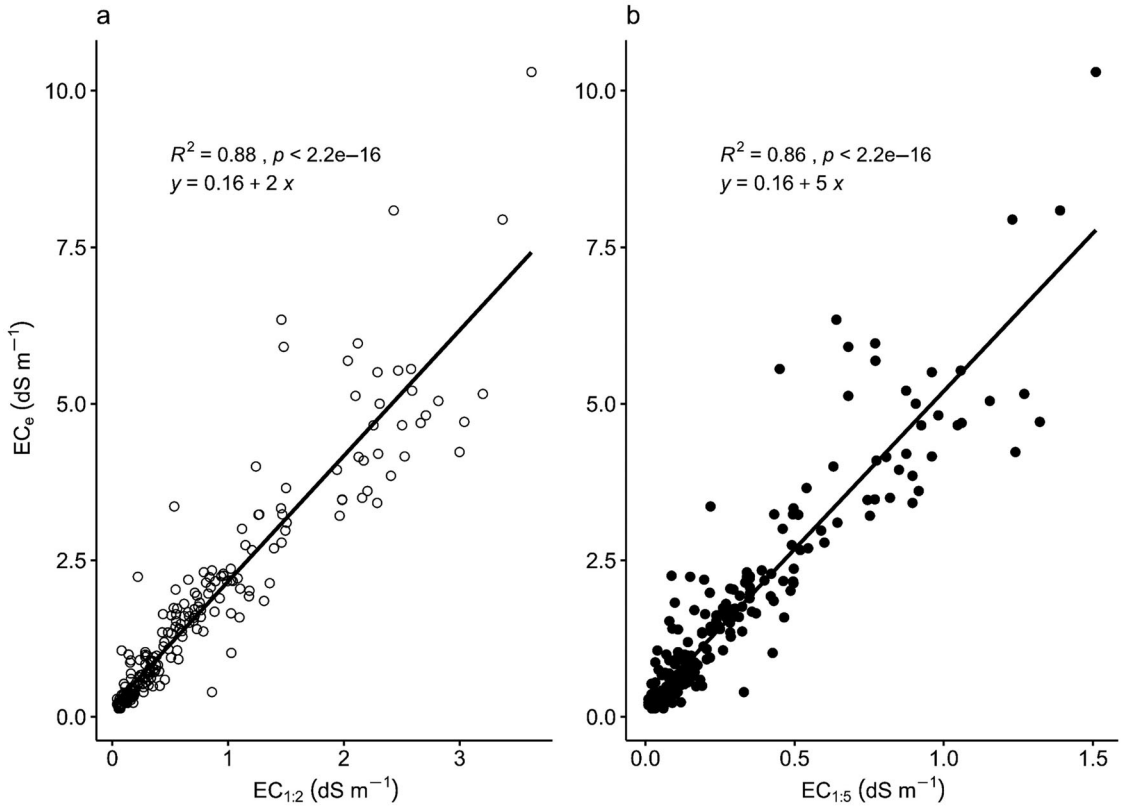

FIGURE 2 Comparison of soil electrical conductivity by saturated paste extraction (EC_e) with soil electrical conductivity by 1:2 and 1:5 soil to deionized water extraction ($EC_{1:2}$ and $EC_{1:5}$) for 291 coarse-textured soil samples collected from 13 salt-affected agricultural fields in Delaware and Maryland from 2021 to 2023.

2.3 | Data analysis

Data were analyzed using JMP Pro 17 (SAS Institute Inc.) using simple linear regression to compare extractable elements, EC, SCR, and SAR. Comparisons of SP-derived data with M3- or AA-based data were based on trends in magnitude and direction because of differences in reported units, as described previously. Residual plots were evaluated to identify outliers and to verify that the normality assumption for the use of parametric statistical tests was valid. Outliers were removed only when an error in the data analysis was suspected. The α level of 0.05 was used to determine significance.

3 | RESULTS AND DISCUSSION

3.1 | Soil characterization

The study fields had soil textures classified as sand (7), loamy sand (18), sandy loam (49), sandy clay loam (13), loam (36), or silt loam (4) based on particle size analysis (Gee et al., 1986); these results are typical of the region (Daniels & Haering, 2006). Sand, silt, and clay content of samples ranged from 182 to 920, 0 to 557, and 2.1 to 296 g kg^{-1}, respectively; median sand, silt, and clay contents were 580, 261, and 151 g kg^{-1}, respectively. Soil organic matter content ranged from 5 to 47 g kg^{-1}, with a median of 17 g kg^{-1}. Only 17 of 291 samples had organic matter concentrations above 25 g kg^{-1}. Soils in the region typically have low organic matter content (<30 g kg^{-1}); however, some poorly drained soils or "black soils" may have organic matter contents ranging from 5 to 84 g kg^{-1} (Sims et al., 2002). Soil $pH_{1:1w}$ ranged from extremely acidic to neutral, with values that ranged from 4.1 to 7.3; the median $pH_{1:1w}$ was 6.0 (moderately acidic). SP pH_e ranged from very strongly acidic to moderately alkaline, with values that ranged from 4.9 to 8.4; the median pH_e value was 7.4 (slightly alkaline).

3.2 | Electrical conductivity

Soil $EC_{1:2}$ values ranged from 0.04 to 3.62 dS m^{-1}, with a median value of 0.38 dS m^{-1}, while $EC_{1:5}$ values ranged from 0.01 to 1.51 dS m^{-1}, with a median value of 0.27 dS m^{-1}. Soil EC_e values ranged from 0.13 to 10.30 dS m^{-1}, with a median of 0.82 dS m^{-1}. Soil EC_e measurements were an order of magnitude higher than $EC_{1:2}$ and $EC_{1:5}$ due to the reduced amount

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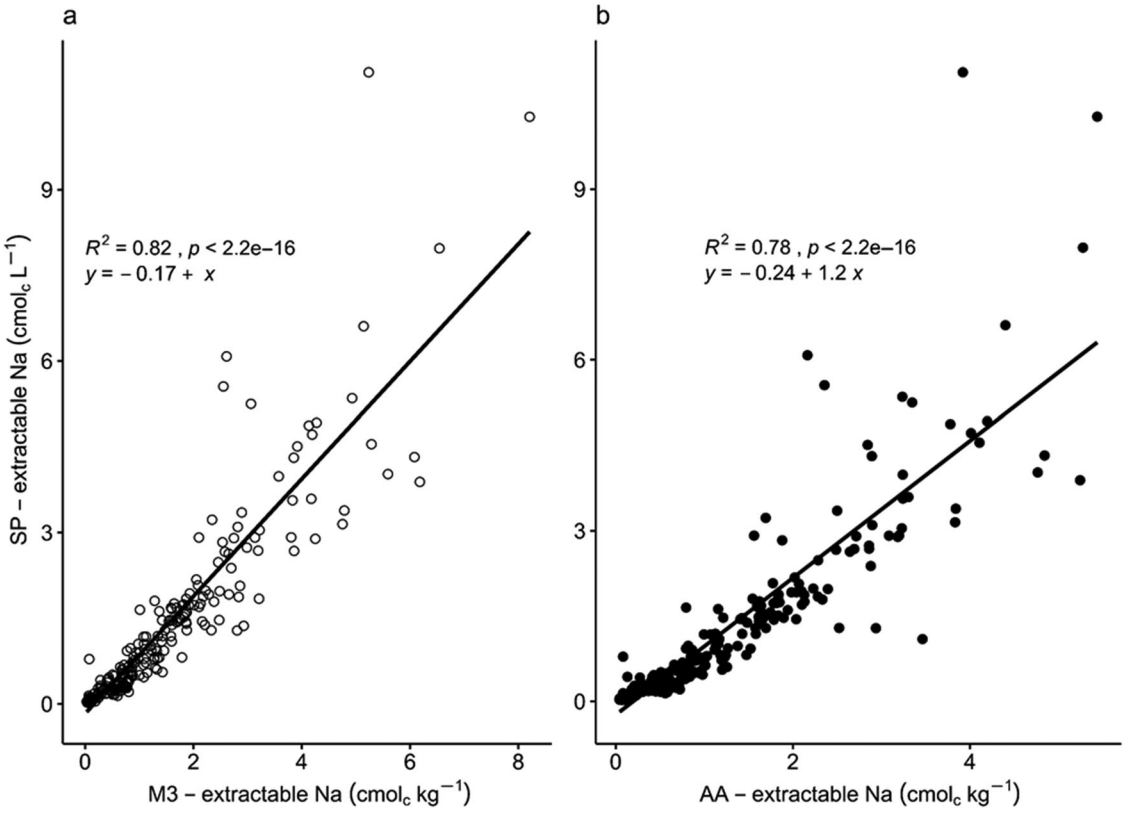

FIGURE 3 Linear regression comparison of Na concentrations as measured following saturated paste (SP) extraction with (a) Mehlich-3 (M3) and (b) ammonium acetate (AA) extractions for 267 soil samples collected between 2021 and 2023 from 13 salt-affected agricultural fields in Delaware and Maryland.

of water used in the SP extraction. Other researchers also noted a similar trend where EC_e values were higher than $EC_{1:2}$ or $EC_{1:5}$ (Chi & Wang, 2009; Endo et al., 2021; Sonmez et al., 2008; Zhang et al., 2005), as the fixed ratio water tests tended to have a higher soil to solution ratio than the SP extraction. Regression of EC_e with $EC_{1:2}$ and $EC_{1:5}$ showed strong, positive relationships ($p < 0.0001$; Figure 2). Other researchers also reported strong relationships between EC_e and EC values measured with a range of soil:water ratios (Aboukila & Norton, 2017; Endo et al., 2021; Kargas et al., 2020; Zhang et al., 2005). For example, Kargas et al. (2018) reported strong correlations between soil EC_e and $EC_{1:1}$ or $EC_{1:5}$ water extractions in coastal soils of Greece. Yet, many researchers noted variable relationships depending on region (i.e., arid vs. semiarid) and soil texture (Chi & Wang, 2009; Endo et al., 2021). Kargas et al. (2020) and He et al. (2013) also noted that the relationship between EC_e and water-based EC measurements became weaker as EC_e values increased; we noted a similar trend with our data (Figure 2). This data variability at higher EC_e values may be due to poor repeatability with the SP test. As such, Q. Wang et al. (2023) proposed standardized methods for water addition, equilibration, and centrifugation for the SP extraction. Researchers also observed better relationships between EC_e and water EC when soil to water ratios were lower, likely due to a soil texture effect; $EC_{1:1}$ interpretations vary by texture because less water will be extractable from the finer textured soils than when soil to water ratios are higher (e.g., $EC_{1:1}$ compared to $EC_{1:2}$ or $EC_{1:5}$; Sonmez et al., 2008; Whitney, 2015). Considering the variation in EC based on soil texture and regional conditions, selection of an EC measurement method should account for these factors to accurately assess salinity impacts.

3.3 | Extractable cations

Soil extractable Na concentrations ranged from 0.02 to 11.1 cmol$_c$ L^{-1} (median = 0.582 cmol$_c$ L^{-1}) for SP extraction. In comparison, Kargas et al. (2022) reported SP-extractable Na concentrations ranging from 0.11 to 33.5 cmol$_c$ L^{-1} (mean = 2.37 cmol$_c$ L^{-1}) in Mediterranean coastal soils with varying levels of salinity in Greece. Chi and Wang (2009) reported that SP-extractable Na ranged from 0.02 to 24.5 cmol$_c$ L^{-1} (median = 2.6 cmol$_c$ L^{-1}) in semiarid soils collected in China. Extractable Na concentrations using M3 and AA extractions were similar to concentrations in SP extracts with Na concentrations ranging from 0.03 to 8.21 and 0.04 to 5.43 cmol$_c$ kg^{-1} (median = 0.89 and 0.86 cmol$_c$

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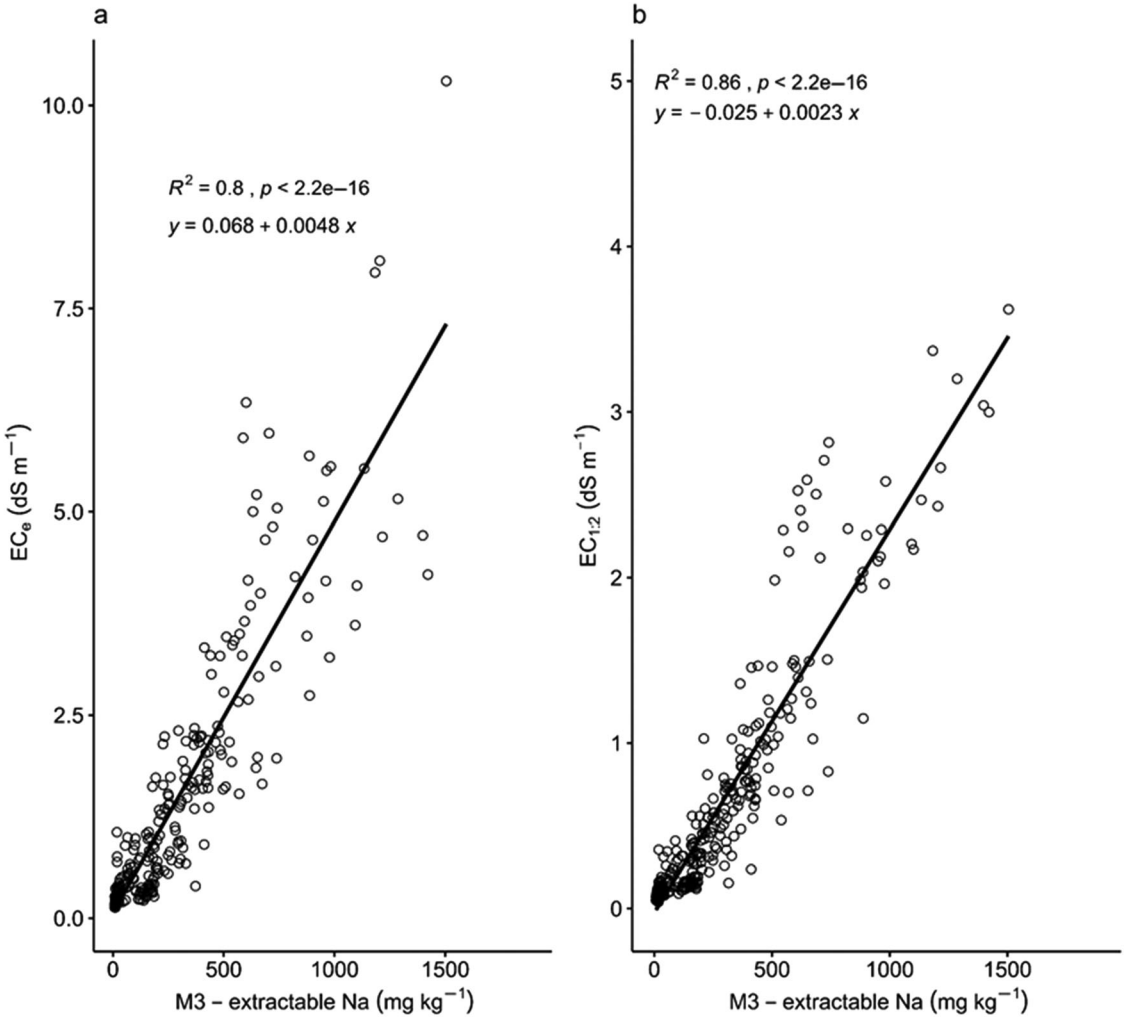

FIGURE 4 Relationship of (a) electrical conductivity (EC_e) from saturated paste (SP) extraction and (b) $EC_{1:2}$ by 1:2 volumetric soil-to-water extraction to Mehlich-3 (M3)-extractable Na from soil samples collected from 13 salt-affected agricultural fields in Delaware and Maryland from 2021 to 2023.

kg^{-1}, respectively) for M3 and AA extractions, respectively. Butcher et al. (2018) reported AA-extractable Na concentrations of 0.87−26.2 $cmol_c$ kg^{-1} (mean = 7.13 $cmol_c$ kg^{-1}) in the top 15 cm of arid, salt-affected sandy loam soils in North Dakota. Overall, our extractable Na concentrations were lower than reported in the literature for drier climates when high extractable Na concentrations were attributed to evapotranspiration-driven salt accumulation. In our study, soil Na concentrations were driven primarily by surface saltwater intrusion under humid climate conditions, which may have resulted in lower overall SP-extractable Na concentrations.

Soil Ca concentrations ranged from 0.02 to 1.73 $cmol_c$ L^{-1} following SP extraction and from 0.43 to 10.42 and 0.32 to 7.58 $cmol_c$ kg^{-1} for the M3 and AA extractions, respectively. Extractable Mg concentrations ranged from 0.01 to 2.50 $cmol_c$ L^{-1} by SP, and from 0.14 to 3.48 and 0.13 to 3.75 $cmol_c$ kg^{-1} for the M3 and AA extractions, respectively. Values for SP-extractable Ca and Mg reported by Chi and Wang (2009) for semiarid soils from China ranged between 0.08 and 4.28 and 0.00 and 4.22 $cmol_c$ L^{-1}, respectively. In contrast, Butcher et al. (2018) reported AA-extractable Ca and Mg concentrations of 82.0−282 and 29.4−113 $cmol_c$ kg^{-1} (mean = 210 and 6.2 $cmol_c$ kg^{-1}, respectively) in salt-affected arid soils in North Dakota (0−15 cm). Despite our soils being inundated by brackish waters, we did not reach the highest concentrations of Ca and Mg observed by Chi and Wang (2009), where salts accumulated due to evapotranspiration, or Butcher et al. (2018), where salts accumulated in the topsoil as a result of geology, shallow water table, and evapotranspiration.

Extractable K concentrations ranged from 0.00 to 0.35 $cmol_c$ L^{-1} in SP extracts and 0.05 to 0.84 and 0.05 to 0.96 $cmol_c$ kg^{-1}, respectively, in M3 and AA extracts. Both Chi and Wang (2009) and Zhang et al. (2005) reported that SP-extractable K concentrations in arid and semiarid soils were below detection. The presence of SP-extractable K in our

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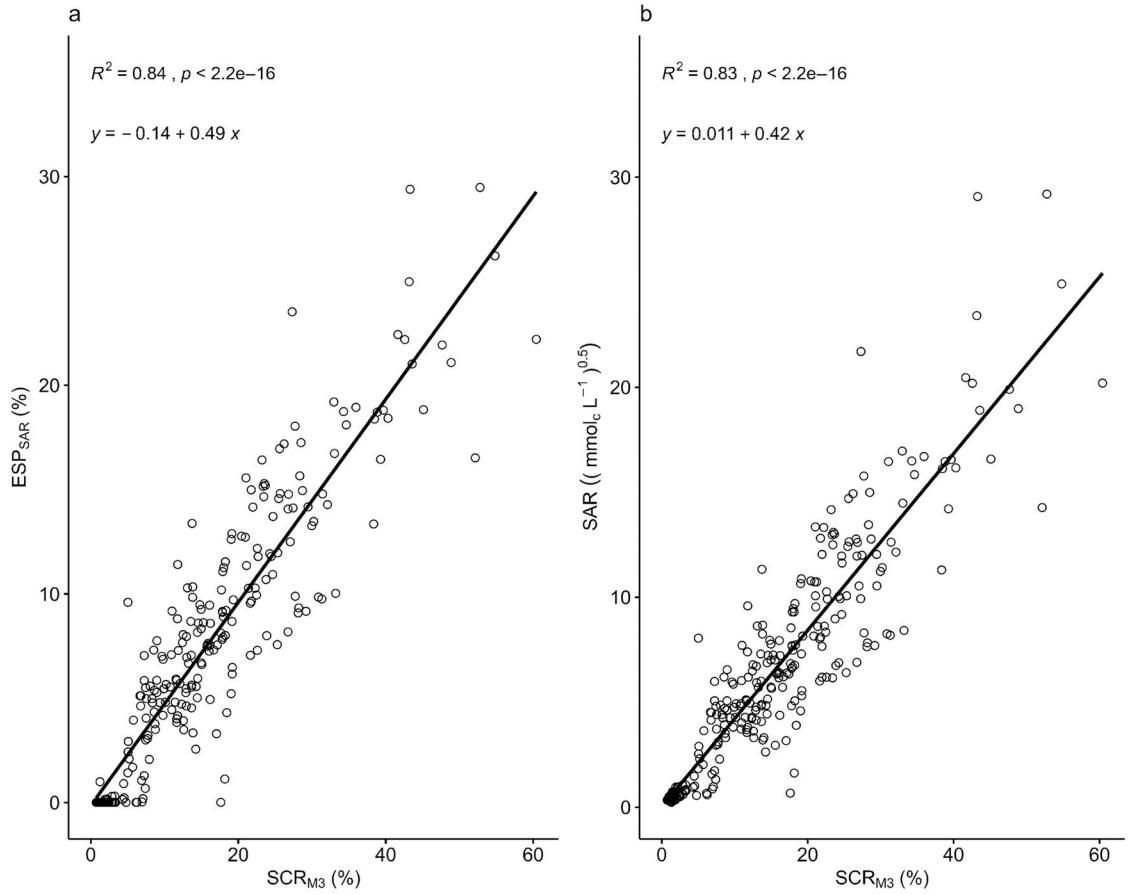

FIGURE 5 Relationship of (a) exchangeable sodium percentage exchangeable sodium percentage estimated from sodium adsorption ratio (ESP_{SAR}) (%) from saturated paste-extractable cations to sodium cation ratio from Mehlich-3 (SCR_{M3}) from Mehlich-3 (M3) cations, and (b) sodium adsorption ratio (SAR) from saturated paste extraction to SCR_{M3} from M3 in soil samples collected from 13 salt-affected agricultural fields in Delaware and Maryland from 2021 to 2023. The SAR value is expressed in units of $(mmol_c\ L^{-1})^{0.5}$. To convert it into $(cmol_c\ L^{-1})^{0.5}$, which is SI unit, the original values of SAR should be divided by 10.

study may be attributed to the significant release of K from the sand fraction in Delmarva soils, which are rich in feldspar minerals (Sadusky et al., 1987). In contrast, Butcher et al. (2018) reported AA-extractable K concentrations ranging from 29.4 to 113 $cmol_c\ kg^{-1}$ in salt-affected topsoil.

We observed a strong relationship between EC_e and M3-extractable Na ($mg\ kg^{-1}$; $r^2 = .80$, $p < 0.0001$; Figure 4a). Our directly measured EC_e values were comparable to predicted EC_e based on regression with M3-extractable Na ($mg\ kg^{-1}$); as such, M3-extractable Na concentration ($mg\ kg^{-1}$) can be used to estimate an EC_e equivalent.

$$EC_e = (0.0048 \times \text{M3}-\text{extractable Na}) + 0.068 \quad (6)$$

We also observed a strong relationship between $EC_{1:2}$ and M3-extractable Na ($mg\ kg^{-1}$; $r^2 = .86$, $p < 0.0001$; Figure 4b), which was similar to the findings of Ozlu et al. (2024), who reported even stronger correlation ($EC_{1:2}$ = 53.52 × M3-extractable Na; $r^2 = 0.97$). Rahman et al. (1993) also reported that Na was the strongest predictor of $EC_{1:1}$, accounting for 98% of its variability on salt-affected soils in Wyoming. As such, we feel confident in the use of M3-extractable Na concentrations to estimate EC_e or $EC_{1:2}$.

Comparisons between SP, M3, and AA extractions in our study revealed variable relationships. For example, SP-extractable Na (Figure 3) exhibited the strongest positive correlation with both M3 ($r^2 = 0.81$) and AA-extraction Na ($r^2 = 0.77$), whereas the relationship with other cations, such as Ca, Mg, and K, was considerably weaker (Figure S1). We did note some scatter in the data as extractable Na concentrations increased. Noting that the SP-extractable Na is reported as a solution concentration, we suggest that degradation of the linear relationship as extractable Na concentrations increase may indicate the possibility of sorbed phases for some samples when measuring the AA and M3 extracts. Faulkner et al. (2006) compared extractable cations by SP and AA extractions as part of a study looking to predict soil dispersion in the United Kingdom. The authors reported that AA extracted up to 1000 times more Ca, Mg, K, and Na than SP. Similarly, weak linear relationships between SP-extractable Ca,

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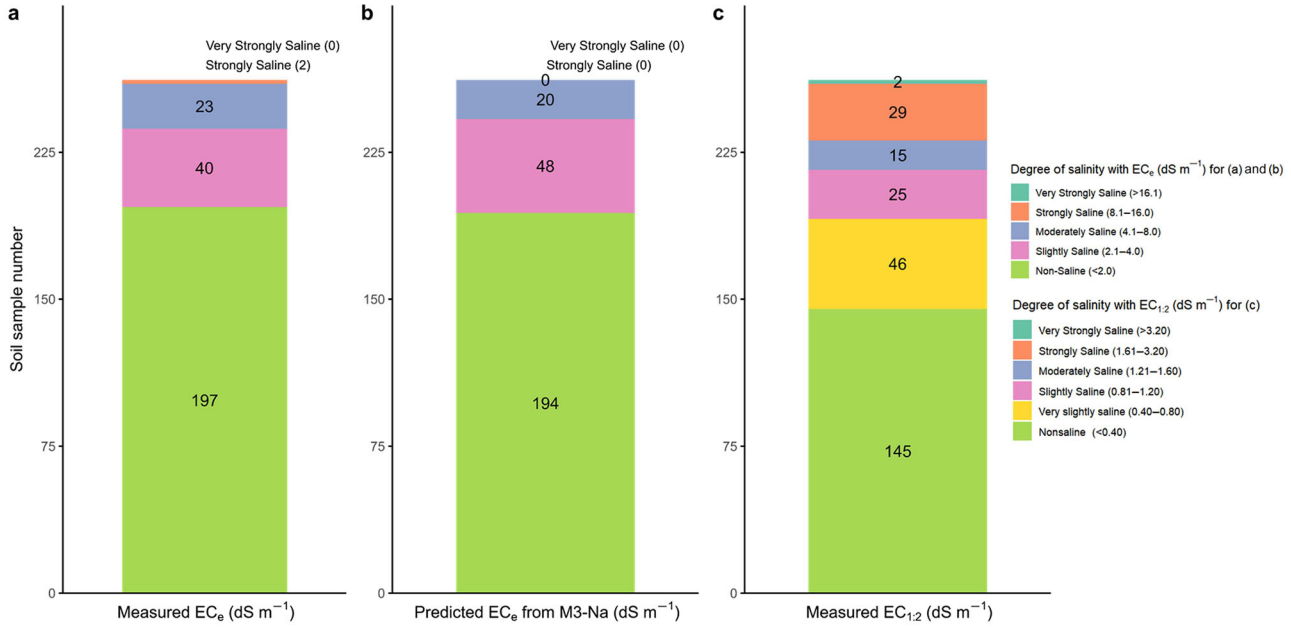

FIGURE 6 Comparison of soil salinity interpretations when (a) electrical conductivity from saturated paste extract (EC_e) was measured directly (Whitney, 2015) or (b) derived from regression relationships for samples where EC was determined from Mehlich-3 (M3)-extractable Na or (c) $EC_{1:2}$ (electrical conductivity from 1:2 volumetric soil to water extraction method) was measured directly (Ross & Ketterings, 2011).

Mg, and K and M3- or AA-extractable cations in our study could be due to extraction of sorbed phases with the M3 or AA extraction. The variability in extractable elements may also point toward poor reproducibility of the SP test, which may be attributed to the subjectivity and error associated with the SP test (Faulkner et al., 2006).

3.4 | Relationships between Mehlich-3 and ammonium acetate SCR versus SAR

Soil SAR values for our coastal soils ranged from 0.23 to 29.2 ($mmol_c\ L^{-1})^{0.5}$ (median = 5.96 $[mmol_c\ L^{-1}]^{0.5}$). Rahman et al. (1993) reported SAR values ranged from 0.9 to 10.10 $(mmol_c\ L^{-1})^{0.5}$ for salt-affected soils from Wyoming. In the coastal soils of Greece, SAR values ranged from 0.5 to 50.6 $(mmol_c\ L^{-1})^{0.5}$ (Kargas et al., 2018). Chi and Wang (2009) reported SAR values between 0.1 and 4040 $(mmol_c\ L^{-1})^{0.5}$, which at the higher end of the range were much higher than those SAR values observed in our fields.

Soil ESP_{SAR} values for our coastal soils ranged from < 0.010% to 29.5% (median = 6.68%); SCR_{M3} values ranged from 0.78% to 6.4% (median = 15.1%); $SCR_{AA(acid)}$ for acidic soil values ranged from 0.67% to 5.1% (median = 11.5%); and $SCR_{AA(alkaline)}$ for alkaline soil values ranged from 0.72% to 64.2% (median = 16.8%). Endo et al. (2021) reported ESP ranged from 0.50% to 16.27% for soils collected in China and 2.61% to 37.59% for soils from Sudan; ESP for the Chinese soils (Inceptisols and Entosols) was slightly lower than for our soils, while ESP of the Sudanese soils (Aridisols) was higher compared to our field sites.

The relationship between ESP_{SAR} and SCR_{M3} was strong (r^2 = 0.84; p < 0.001; Figure 5a). Relationships between SAR and $SCR_{AA(acid)}$ for acidic soil (r^2 = 0.89; p < 0.001; SAR = 0.26 + 0.53 $SCR_{AA(acid)}$ for acidic soil), $SCR_{AA(alkaline)}$ for alkaline soil (r^2 = 0.87; p < 0.001; SAR = −0.91 + 0.47 $SCR_{AA(alkaline)}$ for alkaline soil), and SCR_{M3} (r^2 = 0.83, p < 0.001; Figure 5b) were also strong. These findings align with the general linear relationship between SAR and %Na (equivalent to $SCR_{AA(alkaline)}$) as reported by Desutter et al. (2015; SAR = 1.15 × $SCR_{AA(alkaline)}$ − 0.91) that was based on nearly 2000 samples; Desutter et al. (2015) reported increased scatter when SCR_{AA} for alkaline soils was above 20%. We reported a shallower slope (0.4) compared to that reported by Desutter et al. (2015; slope of 1.15), which possibly reflects differences in the salt source. For example, Butcher et al. (2018) indicated the dominance of sulfate salts in North Dakota saline soils. In contrast, our soils had SP-extractable Cl concentrations of 0.00–19.3 $cmol_c\ L^{-1}$ (median = 0.31 $cmol_c\ L^{-1}$) and SP-extractable SO_4^{2-}–S of 0.00–0.67 $cmol_c\ L^{-1}$ (median = 0.04 $cmol_c\ L^{-1}$); therefore, our soils appear to be dominated by Cl originating from brackish waters. Regardless, we suggest that SAR can be predicted based on SCR calculations using M3 or AA extractable cations. Kalu et al. (2025) reported mean SAR values (based on M3-extractable ions) of 0.05 $(mmol_c\ L^{-1})^{0.5}$ for an agricultural soil in North Carolina that was not impacted by

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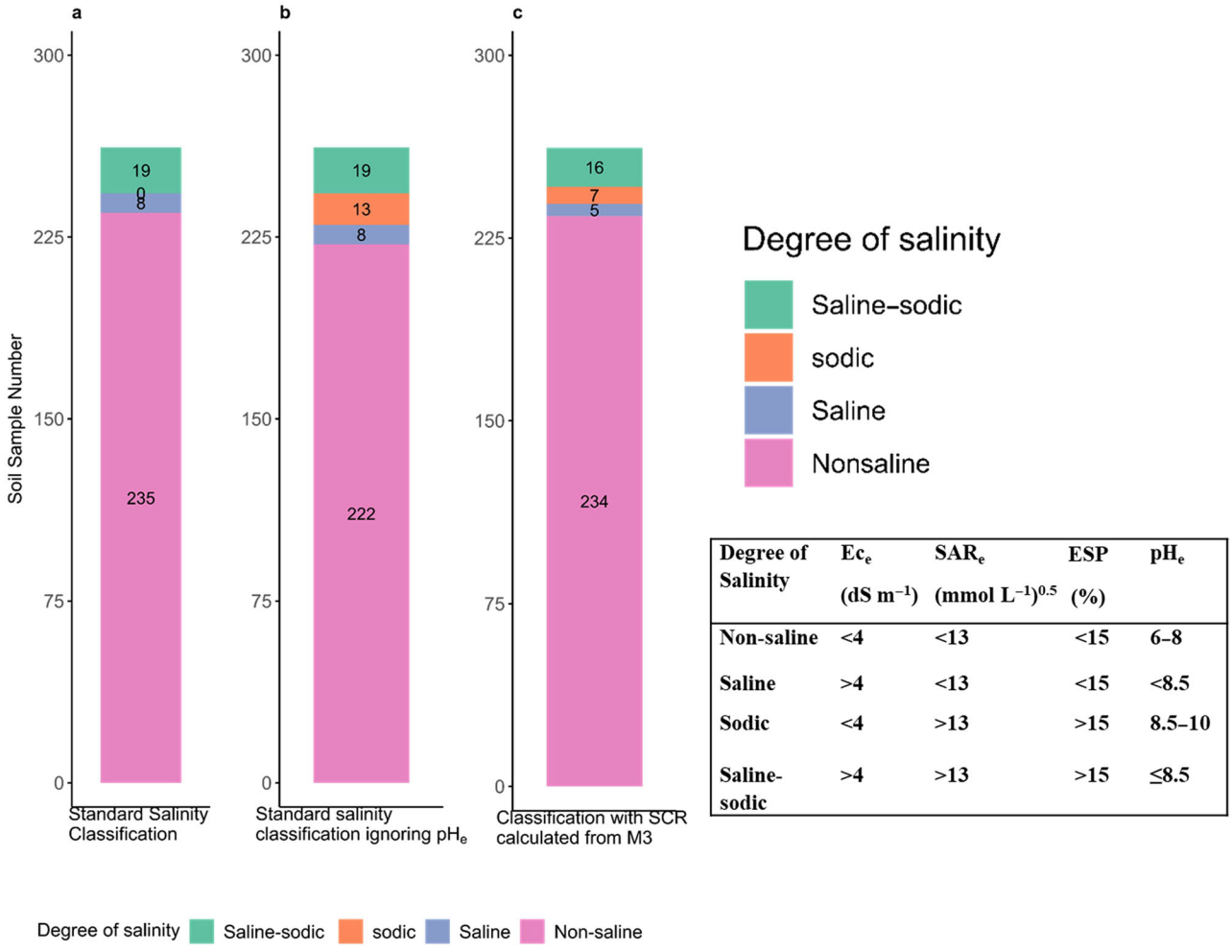

Degree of Salinity	Ec_e (dS m^{-1})	SAR_e (mmol $L^{-1})^{0.5}$	ESP (%)	pH_e
Non-saline	<4	<13	<15	6–8
Saline	>4	<13	<15	<8.5
Sodic	<4	>13	>15	8.5–10
Saline-sodic	>4	>13	>15	≤8.5

FIGURE 7 Comparison of standard classification of salt-affected soil by the US Regional Salinity Laboratory (Richards, 1954) for soil salinity interpretations when (a) electrical conductivity from saturated paste extract (EC_e), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and soil pH (pH_e) were considered for classification and (b) when pH_e was excluded for the classification as none of soil samples had pH > 8.5, and (c) classification with sodium cation ratio (SCR) calculated from Mehlich-3 (M3) extraction and excluded pH_e in 262 samples collected in Maryland and Delaware from 2021 to 2023.

saltwater intrusion. In contrast, fields with varying degrees of saltwater intrusion had mean SAR values of 0.06, 0.20, 0.30, 0.87, 1.89, and 2.36 $(mmol_c\ L^{-1})^{0.5}$; marsh soils had SAR of 14.20 $(mmol_c\ L^{-1})^{0.5}$.

3.5 | Soil salinity interpretations

When soil salinity was classified directly using EC_e values, 75% of our soil samples fell into the nonsaline (<2 dS m^{-1}) category (Figure 6a; Whitney, 2015). Similarly, when M3-extracted Na concentrations were converted to an EC_e equivalent (based on Equation 6), 74% of the samples were classified as nonsaline, indicating that the two methods provided very similar classification of soils. In contrast, 55% of samples were classified as "nonsaline" based on direct $EC_{1:2}$ measurements (Figure 6c). The $EC_{1:2}$ interpretations include a "very slightly saline" category, which is not included in the EC_e classification system; 18% of our samples were classified in this category, all of which would be considered "nonsaline" based on EC_e. When soil salinity was classified using EC_e, SAR, ESP_{SAR}, and pH_e (Richards, 1954), 90% samples were classified as nonsaline (Figure 7a). Additionally, 6.9% samples were classified as "saline-sodic" and there were no samples in the "sodic" classification, probably because the pH_e of all our samples was below 8.5 (Richards, 1954). Some researchers have suggested excluding pH_e for sodic classification. When reclassified ignoring pH_e, 85% of our samples were classified as nonsaline, 5% of samples were then classified as sodic (Figure 7b). Similarly, when reclassified ignoring pH_e and using ESP calculated from M3, 89% of our soils were classified as nonsaline, 3% were classified as sodic, and 6% were classified as saline-sodic (Figure 7c). Our results indicate that there is little difference in salinity

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classifications using SCR_{M3} when compared to ESP, SP-based measurements, as only one sample was reclassified as nonsaline when using interpretations based on SCR_{M3}. Yet, 51% of our sampling points exhibited signs of salt stress based on imagery and visual confirmation of plant stress (data not shown); many of the sampled areas exhibiting visual salt stress were classified as nonsaline by all the classification methods used in this study. These results are concerning and suggest that current soil salinity interpretations may underestimate salinity-related issues in humid-coastal areas affected by saltwater intrusion.

3.6 | Conclusions and recommendations

We demonstrated the potential of the M3 extraction method as an efficient approach for salinity assessment in the mid-Atlantic region, which eliminates the need for either SP or EC testing. The strong, linear relationship between M3-extractable Na and EC_e suggests that laboratories using M3 as their routine soil test could convert M3-extractable Na to an EC_e equivalent for salinity classifications. We also recommend converting standard M3-extractable cations into SAR equivalent and using existing interpretations for salinity. Converting M3 data to EC_e and SAR will facilitate rapid and cost-effective soil salinity assessments in the mid-Atlantic region due to the widespread use of M3 in agronomic soil testing. However, there is a risk that some soils that could exhibit salt stress would be characterized as nonsaline using existing SP-based interpretations. Further validation is needed to determine the accuracy of EC_e ratings in diagnosing salinity stress impacted by inundation or sea levels. Consequently, we recommend that future research should focus on completing correlation and calibration studies to develop a direct interpretation for M3-based data without converting to an SP equivalent. Additionally, relating M3-based salinity interpretations to field EC to create salinity maps for guiding remediation actions is essential. Incorporating texture or other field conditions into M3-based interpretations and conducting field trials to test remediation based on these interpretations would further strengthen this approach. Additional testing under diverse field and plant growth conditions is also essential, particularly for soils with higher OM content, which were not included in this study.

AUTHOR CONTRIBUTIONS

Sapana Pokhrel: Formal analysis; software; validation; visualization; writing—original draft; writing—review and editing. **Willow Blew**: Data curation; formal analysis; visualization; writing—original draft. **Jarrod O. Miller**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing. **Amy L. Shober**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing—review and editing.

ACKNOWLEDGMENTS

We thank Shawn Tingle for assisting soil sample collection and University of Delaware soil testing laboratory staffs for processing and analyzing samples. We also acknowledge the work of Georgia Angeletakis and Duke Williams who assisted in sample preparation and laboratory analysis as undergraduate student interns. We thank all the farmers for granting permission to collect soil samples from their fields. This project is funded by USDA NIFA award #2022-68008-36647 and 2018-68002-27915.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pokhrel, S., Blew, W., Miller, J. O., & Shober, A. L. (2025). Evaluating routine agronomic soil tests for coastal soil salinity detection in the mid-Atlantic. *Soil Science Society of America Journal*, *89*, e70075. https://doi.org/10.1002/saj2.70075

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