Relationships Among Apparent Electrical Conductivity and Plant and Terrain Data in an Agroforestry System in the Ozark Highlands

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Research Article

Keywords: electromagnetic induction, proximal sensing, soil management zones, northwest Arkansas, soil moisture, transported material

Posted Date: February 7th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2550717/v1

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Abstract

Minimal research has been conducted relating apparent electrical conductivity (ECₐ) surveys to plant and terrain properties in agroforestry systems. Objectives were to identify i) ECₐ survey relationships with forage yield, tree growth, and terrain attribute within ECₐ-derived soil management zones (SMZs) and ii) terrain attributes that drive ECₐ variability within a 20-year-old, 4.25-ha, agroforestry system in the Ozark Highlands of northwest Arkansas. The average of 12 monthly perpendicular (PRP) and horizontal coplanar (HCP) ECₐ surveys (August 2020 to July 2021) and 14 terrain attributes were obtained. Tree diameter at breast height (DBH) and height (TH) measurements were made in December 2020 and March 2021, respectively, and forage yield samples were collected during Summer 2018 and 2019. Apparent ECₐ-tree property relationships were generally stronger within the whole site (averaged across tree property and ECₐ configuration, |r| = 0.38) than within the SMZs (averaged across tree property, ECₐ configuration, and SMZ, |r| = 0.27). The strength of the SMZs’ terrain-attribute-PRP-ECₐ relationships were 9 to 205% greater than that for the whole site. In whole-site, multi-linear regressions, Slope Length and Steepness Factor (10.5%), Mid-slope (9.4%), and Valley Depth (7.2%) had the greatest influence (i.e., percent of total sum of squares) on PRP ECₐ variability, whereas Valley Depth (15.3%), Wetness Index (11.9%), and Mid-slope (11.2%) had the greatest influence on HCP ECₐ variability. Results show how ECₐ relates to plant (i.e., DBH, TH, and forage yield) and terrain data within SMZs in agroforestry systems with varying topography and could be used to precisely manage agroforestry systems.

Introduction

Crop yield variability due to spatially heterogeneous soil properties has been well recognized. As a result, whole-field land management has increasingly been identified as inefficient, as whole-field land management causes the under- and over-application of resources in regions of high- and low-yield potential, respectively (Johnson et al., 2003). Intra-field management, the spatially directed management of pests, crops, and soils based on differing characteristics within a field, is a precision agriculture management approach that produces smaller management units and optimizes field production and sustainability (Cicore et al., 2019; Johnson et al., 2003). However, site-specific management requires the characterization of within-field variability and the identification of areas of homogeneous characteristics, or soil management zones (SMZs; Cicore et al., 2019).

Several methods have been used to map spatial variability and delineate management zones within a field. These methods include soil sampling for digital soil mapping, yield monitoring, and geophysical methods for proximal soil sensing, with electromagnetic induction (EMI)-based methods being the most frequently used for proximal soil sensing (Allered et al., 2016; Serrano et al., 2014; Soil Science Division Staff, 2017). Electromagnetic induction-based methods use ground conductivity meters, which are non-invasive, simple to implement, and are capable of measuring large areas relatively quickly (Corwin & Lesch, 2005a,b). Electromagnetic-induction sensors delineate spatial changes in belowground soil properties through proximally sensing the soil’s apparent electrical conductivity (ECₐ), which is the ability of a soil to conduct an electrical current. In-field measured ECₐ is the result of complex interactions of many soil properties [i.e., base saturation, bulk density (BD), cation exchange capacity, clay content and mineralogy, organic matter (OM), soil salinity, soil temperature, and soil water content (SWC)] and, in turn, can be used to help identify within-field soil property variability through correlations (Corwin & Scudiero, 2017).

Electromagnetic induction-ECₐ surveys have been used to help evaluate in-field variability within a variety of different land management systems and ecosystems across the world. In addition to soil properties, relationships between ECₐ survey and crop yield data have been assessed (Corwin et al., 2003; Johnson et al., 2003; Singh et al., 2016). Similarly, relationships between terrain attribute and ECₐ survey data have been evaluated, and both have been used to create management zones or functional units and for predictive mapping, individually or in combination (Altdorff & Dietrich, 2014; Beucher et al., 2020; Jiang et al., 2021; Kitchen et al., 2003; Pedrera-Parrilla et al., 2014; Robinson et al., 2010; Singh et al., 2016; Taghizadeh-Mehrjardi et al., 2014; Ylagan, 2022; Ylagan et al., 2022). However, minimal work has been conducted exploring ECₐ-forage yield, ECₐ-tree growth, and ECₐ-terrain attribute relationships in agroforestry (AF) systems, and no work has been conducted assessing the relationships in AF systems in environments similar to the Ozark Highlands. Further, the possibility of improving such relationships with ECₐ-derived SMZs has not been explored.

The Ozark Highlands is a region with unique characteristics that result in the area having increased potential for water conservation issues. Specifically, the Ozark Highlands is characterized by a relatively warm and wet climate, rolling topography, inclusions of shallow, cherty soils overlying karst limestone geology, rapid urbanization, and pastoral systems with repeated, excessive applications of poultry litter (PL). These characteristics, in turn, cause the Ozark Highlands to have an elevated potential for surface and sub-surface water quality degradation via nutrient-rich runoff to surface waters and leaching to shallow and/or easily accessed groundwater sources.
Considering the water conservation issues in the Ozark Highlands, AF systems may be beneficial due to the many potential ecosystem services that AF systems offer (i.e., reduced soil erosion and runoff and water and soil quality enhancement; Dollinger & Jose, 2018).

Considering the lack of information relating EC<sub>α</sub> surveys to plant characteristics and terrain attributes in a sloped, topographically variable AF system in the Ozark Highlands, the objectives of this study were to identify: i) correlations between EC<sub>α</sub> survey and forage yield, tree growth, and terrain attribute data at the whole-site and EC<sub>α</sub>-derived SMZs level, ii) correlations between EC<sub>α</sub> and forage yield per forage species and fertility treatments within the whole site, and iii) terrain attributes that drive EC<sub>α</sub> variations at a 20-year AF system in the Ozark Highlands of northwest Arkansas. It was hypothesized that EC<sub>α</sub> survey data are correlated with forage yield, tree growth characteristics, and terrain attributes, and that correlations among EC<sub>α</sub> survey and forage yield, tree growth data, and terrain attributes can be improved with EC<sub>α</sub>-derived SMZs. It was also hypothesized that terrain attributes would contribute to the EC<sub>α</sub> variability to varying degrees within the AF site and across the SMZs.

**Materials And Methods**

**Site Description**

The study site was located in the Ozark Highlands, Major Land Resource Area 116A (NRCS, 2006), at the University of Arkansas Milo J. Shult Agricultural Research and Extension Center (SAREC) in Fayetteville, AR (36.101002°N, 94.173728°W). The study site was a 4.25-ha paddock primarily mapped as Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults), but contains some Pickwick silt loam (fine-silty, mixed, semiactive, thermic Typic Paleudults), Nixa cherty silt loam (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults), Johnsburg silt loam (fine-silty, mixed, active, mesic Aquic Fragiudults), and Cleora fine sandy loam (coarse-loamy, mixed, active, thermic Fluventic Hapludolls; Fig. 1; Soil Survey Staff, 2019). The research area also contained a dissimilar soil inclusion that is consistently wetter and lower in elevation than the immediate surrounding areas at the site. The dissimilar inclusion within the study site is not captured in the formal soil mapping units across the site, but is classified as fine, mixed, active, thermic Typic Endoaqualfs (Ashworth et al., 2021). The AF site receives an average of 1176 mm of precipitation annually and has annual minimum, maximum, and average air temperature of 8.9, 20.3, and 14.6°C, respectively, based on 30-yr means (1991 to 2020; NOAA, 2022).

Sixteen rows of northern red oak (*Quercus rubra* L.), pecan (*Carya illinoinensis* Wangenh. K. Koch), and eastern black walnut (*Juglans nigra* L.) were established at the study site in 1999 in an east-west orientation with 15-m spacing between tree rows (Fig. 1). The eastern black walnut trees grew adequately on the east side, but struggled to grow in the central, wetter area and in the dry Nixa soil on the west side of the tree rows. Consequently, in 2014, the eastern black walnut trees were removed and replaced with three fast-growing tree species: pitch/loblolly pine (*Pinus rigida x Pinus taeda*) in the drought-prone portion, American sycamore (*Platanus occidentalis* L.) in the well-drained portion, and cottonwood (*Populus deltoides* W. Bartram ex Marshall) in the poorly drained portion of the study site (Fig. 1). Furthermore, two forage-species treatments were established in the tree-row alleys, which included a cool-season grass species [orchardgrass (*Dactylis glomerata* L., var. Tekapo)] that was seeded in Fall 2015 at 17 kg pure live seed (PLS) ha<sup>-1</sup>, and a native warm-season grass mix [8:1:1 big bluestem (*Andropogon gerardii* Vitman), little bluestem (*Schizachyrium scoparium* Michx. Nash), indiangrass (*Sorghastrum nutans* L.)] seeded in spring 2016 at 10 kg PLS ha<sup>-1</sup>.

(Fig. 1). To remove existing vegetation from the alleys before forage establishment, Cornerstone® Plus (N-phosphonomethyl) glycine, Winfield Solutions, St. Paul, MN) was applied at a 2.2 kg ha<sup>-1</sup> rate [41% active ingredient (ai)]. Additionally, a Haybuster 107C no-tillage drill (DuraTech, Jamestown, ND) was used to plant the alleys and Plateau™ (ammonium salt of imazapic) was applied after establishment at a rate of 0.28 kg ha<sup>-1</sup> (23.6% ai) to remove any remaining non-forage vegetation.

Native grass (NG) and orchardgrass (OG) forage treatments in the alleys between tree rows received 84 kg N ha<sup>-1</sup> (4.94 Mg ha<sup>-1</sup>, fresh weight basis) of locally sourced PL in March 2017 and 2018 and April 2019 (Fig. 1). The PL in the 2017 application had a chemical composition of 2.7, 0.7, and 1.1% N, P, and K, respectively, and had a pH of 6.1. The PL in the 2018 application had a chemical composition of 2.0, 0.6, and 1.0% N, P, and K, respectively, and had a pH of 6.2. The PL in the 2019 application had a chemical composition of 2.5, 0.7, and 0.9% N, P, and K, respectively, and had a pH of 5.2. After fertilization each year, heifers (*Bos taurus* L.) grazed the study site at a density of 1.9 animal units (AU) ha<sup>-1</sup> from May to June 2017, 2.2 AU ha<sup>-1</sup> from May to July 2018, and 2.4 AU ha<sup>-1</sup> from May to July 2019 (Ashworth et al., 2021; Gurmessa et al., 2021; Niyigena et al., 2021). On 30 March 2020 and 31 March 2021, urea (46-0-0) was applied to all alleys at a rate of 67.3 kg N ha<sup>-1</sup> with a fertilizer spreader (Willmar S500; Duluth, GA). Additional details about site history and management were previously described in Ylagan (2022), Ylagan et al. (2022), and Sauer et al. (2015).
**ECₐ Survey Equipment, Procedures, and Data Processing**

A Trimble R2 global positioning system (GPS) unit (Trimble Inc., Westminster, CO) and a DUALEM-1S sensor (DUAL-geometry Electro-Magnetic; Dualem Inc., Milton, ON, Canada) were used to collect the ECₐ survey data. The DUALEM-1S's perpendicular (PRP) and horizontal coplanar geometries (HCP) measure the bulk ECₐ of the 0 to 0.5-m depth and 0 to 1.6-m depth, respectively (Abdu et al., 2007, 2017). Furthermore, a Can-Am Side-by-Side utility vehicle (Defender, BRP US, Inc., Sturtevant, WI) was used to power and pull the DUALEM-1S on a sled during each survey in this study (Fig. 2). The DUALEM-1S's ECₐ measurements were obtained simultaneously with the GPS data thought a hand-held geoinformation system program (HGIS; HGIS version 10.90, StarPal Inc., Fort Collins, CO) on a Trimble Yuma 2 computer (Trimble Inc., Westminster, CO; Abdu et al., 2007, 2017). Fig. 2).

Between August 2020 and July 2021, 12 monthly ECₐ-surveys were conducted at the AF site. For each survey, the DUALEM-1S was pulled at a rate of 4.8 to 8.0 km hr⁻¹ in a looping pattern over two alleys at a time until four parallel, 2 to 5 m apart, drive paths per alley had been completed. Once each survey had been completed, a temperature-drift calibration line was driven over all subsequent survey drive paths so that any measurement drift that occurred during the survey period due to increases in internal sensor temperature could be assessed and accounted for. After each ECₐ survey was conducted, the PRP and HCP ECₐ of each survey underwent data cleaning, GPS-coordinate adjustment, outlier removal, temperature-drift calibration, temperature standardization to 25°C, averaging of coincidental points, experimental semi-variogram modeling, and universally-kriging to a 5-m grid. Specific details of the ECₐ survey equipment, procedures, and data processing techniques were previously described (Ylagan, 2022; Ylagan et al., 2022). The PRP and HCP ECₐ of the 12 monthly surveys conducted were averaged to produce a single ECₐ data file per configuration for the analyses. Hereafter, the mean PRP and HCP ECₐ of the 12 universally kriged surveys are referred to as PRP and HCP ECₐ, respectively.

**Tree and Forage Data Collection**

On 9 December 2020, the diameter at breast height (DBH) of the trees were measured at 137 cm above the soil surface (Ashworth et al., 2022; Jiang et al., 2021). Additionally, a hand-held clinometer (SS011096010; Suunto; Vantaa, Finland) was used 12.2 m from each tree trunk to measure the angle to the highest point on each tree on 15 March 2021. The angle's tangent was then used to calculate the vertical tree height (TH), with the clinometer operator's eye height added to Eq. (1):

$$\text{Treeheight} = (\tan(\text{clinometerangle}) \times \text{distancefromtrunk}) + \text{eyeheightofclinometeroperator}$$

1

During Summer 2018 and 2019, 4-m² cattle exclosures, three for each of the 2017–2019 forage species-fertility treatment combinations, were placed in alley centers to exclude forage areas from cattle grazing (Fig. 1; Ashworth et al., 2022; Jiang et al., 2021; Niyigena et al., 2021). Two, 0.25-m² forage total biomass subsamples were collected from each cattle exclosure on multiple occasions in 2018 and 2019 (Ashworth et al., 2022; Jiang et al., 2021; Niyigena et al., 2021). In 2018, forage biomass samples were collected on 25 May and 4, 15, and 29 June. In 2019, forage biomass samples were collected on 4 and 20 June and 3 July (n = 54 per timepoint). Forage samples were obtained by hand clipping aboveground biomass 6 cm above the soil surface (Ashworth et al., 2022; Jiang et al., 2021; Niyigena et al., 2021). Afterward, forage samples were geo-referenced, weighed, oven-dried at 70°C for 48 hr, and reweighed for moisture content and dry matter determinations (Ashworth et al., 2022; Jiang et al., 2021; Niyigena et al., 2021).

**Terrain Attribute and Soil Management Zone Data Collection**

Terrain attribute data for the study site were obtained from a bare-earth digital elevation model (DEM) that was originally derived from Light Detection and Ranging (LiDAR) imagery (Adhikari et al., 2018). The DEM had a 5-m grid spacing and was obtained from the United States Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) Geospatial Data Gateway (NRCS, 2022), where the DEM was used to extract 14 terrain attributes within in System for Automated Geoscientific Analysis (SAGA GIS; SAGA GIS version 7.9.0; Conrad et al., 2015) and ArcGIS platforms ArcGIS (ArcGISmap version 10.6.1, Esri, Redlands, CA; Adhikari et al., 2018). The 14 terrain attributes and their abbreviations, definitions, and summary statistics are presented in Table 1 and their spatial pattern across the AF site can be visualized in Fig. 3.

Furthermore, recently created ECₐ-derived SMZs (Ylagan, 2022; Ylagan et al., 2022) were used for this study. The same 12 ECₐ surveys used for the current study were used to create three precision SMZs at the AF site (Ylagan, 2022; Ylagan et al., 2022) using the k-means clustering algorithm (Hartigan, 1975) by overlaying and grouping HCP and PRP ECₐ surveys (Ylagan, 2022; Ylagan et al., 2022). Only the
SMZs created by the HCP EC<sub>a</sub> were used, as the SMZs created by the PRP EC<sub>a</sub> presented decreased manageability due to the PRP EC<sub>a</sub> SMZs possessing a less cohesive and more spatially erratic pattern than the HCP EC<sub>a</sub> SMZs. Of the three SMZs, SMZ 1 generally had the smallest mean EC<sub>a</sub> and EC<sub>a</sub> variability and was characterized as an area of shallower depth to bedrock, increased coarse fragment abundance, and an area of erosion rather deposition (Fig. 1; Ylagan, 2022; Ylagan et al., 2022). Additionally, SMZ 2 generally had the largest mean EC<sub>a</sub> and EC<sub>a</sub> variability of the three SMZs and contained the local drainageway and areas of potential subsurface water movement (Ylagan, 2022; Ylagan et al., 2022).

**Statistical Analyses**

Correlation analyses were conducted with the collected EC<sub>a</sub> and tree, forage, and terrain attribute measurements to identify potential linkages among variables within treatment combinations. Specific correlations conducted in this study were among 1) PRP and HCP EC<sub>a</sub> and TH, DBH, and total forage yield within the whole AF site and each SMZ, 2) correlations among PRP and HCP EC<sub>a</sub> and total forage yield within forage species and 2017–2019 PL/control treatment combinations within the whole AF site, and 3) correlations among PRP and HCP EC<sub>a</sub> and terrain attribute data within the whole AF site and each SMZ. Pearson correlations were performed between EC<sub>a</sub> and plant properties (i.e., total forage yield, TH, and DBH) because the plant properties were generally normally distributed, while Spearman correlations were conducted between terrain attributes and EC<sub>a</sub> because both EC<sub>a</sub> configurations were generally non-normally distributed. Additionally,

<table>
<thead>
<tr>
<th>Terrain Attribute</th>
<th>Abbreviation</th>
<th>Definition</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect</td>
<td>Aspect</td>
<td>Direction of the steepest slope from the north</td>
<td>°</td>
<td>5.3</td>
<td>357.1</td>
<td>185.0</td>
</tr>
<tr>
<td>Elevation</td>
<td>Elevation</td>
<td>Height above sea level</td>
<td>m</td>
<td>379</td>
<td>387</td>
<td>382</td>
</tr>
<tr>
<td>Flow Accumulation</td>
<td>FlowAccum</td>
<td>Quantity of upland cells draining to a given cell</td>
<td>n&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25</td>
<td>21538</td>
<td>653</td>
</tr>
<tr>
<td>Slope-length Factor</td>
<td>LS-Factor</td>
<td>Calculates the slope length as used in the Universal Soil Loss Equation</td>
<td>m</td>
<td>&lt; 0.01</td>
<td>0.74</td>
<td>0.22</td>
</tr>
<tr>
<td>Mid-slope Position</td>
<td>MidSlope</td>
<td>Classifies the slope position in both crest and valley directions</td>
<td>index</td>
<td>&lt; 0.01</td>
<td>0.85</td>
<td>0.41</td>
</tr>
<tr>
<td>Multi-resolution Ridge Top Flatness Index</td>
<td>MRRTF</td>
<td>Identifies high flat regions at a range of scales</td>
<td>index</td>
<td>&lt; 0.01</td>
<td>4.86</td>
<td>1.34</td>
</tr>
<tr>
<td>Multi-resolution Valley Bottom Flatness Index</td>
<td>MRVBF</td>
<td>Identifies zones of deposited material in flat valley bottoms</td>
<td>index</td>
<td>&lt; 0.01</td>
<td>5.77</td>
<td>2.24</td>
</tr>
<tr>
<td>Normalized Height</td>
<td>NormHt</td>
<td>Assigns a value of 1 and 0 to the highest and lowest elevation, respectively</td>
<td>index</td>
<td>0.14</td>
<td>0.92</td>
<td>0.44</td>
</tr>
<tr>
<td>System for Automated Geoscientific Analysis Wetness Index</td>
<td>SAGAWI</td>
<td>A specific catchment area and slope-based wetness index</td>
<td>index</td>
<td>4.5</td>
<td>10.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Slope Height</td>
<td>SlopeHt</td>
<td>Relative height difference to the immediate adjacent crest lines</td>
<td>m</td>
<td>0.35</td>
<td>4.67</td>
<td>1.46</td>
</tr>
<tr>
<td>Slope Percent</td>
<td>SlopePer</td>
<td>Maximum rate of change between a cell and its neighboring cells</td>
<td>%</td>
<td>0.02</td>
<td>9.10</td>
<td>3.02</td>
</tr>
<tr>
<td>Topographic Position Index</td>
<td>TPI</td>
<td>+ and - values identify cells that are higher and lower than their surroundings, respectively</td>
<td>index</td>
<td>-1.27</td>
<td>2.39</td>
<td>0.04</td>
</tr>
<tr>
<td>Valley Depth</td>
<td>ValleyDep</td>
<td>Relative height difference to the immediate adjacent channel lines</td>
<td>m</td>
<td>0.00</td>
<td>3.23</td>
<td>1.18</td>
</tr>
<tr>
<td>Altitude Above Channel Network</td>
<td>VDistChn</td>
<td>Difference between channel base and surface elevation</td>
<td>m</td>
<td>0.00</td>
<td>2.28</td>
<td>0.21</td>
</tr>
</tbody>
</table>

<sup>a</sup> Degrees from true north (°); Number of pixels (n).
multi-linear regression (MLR) models were applied over the PRP and HCP ECₐ to identify terrain attributes that had an effect on PRP and HCP ECₐ, and to determine which terrain attributes contributed the most to overall PRP and HCP ECₐ variability using terrain attributes’ percent of total sum of squares within the MLR model. Significance in the MLR models were judged at $P \leq 0.05$ and all statistical analyses were conducted in R Studio (version 4.05, R Core Team, Boston, MA).

**Results And Discussion**

**PRP and HCP ECₐ**

Correlations ($P < 0.05$) were identified between measured ECₐ and tree growth (i.e., DBH and TH), forage yield, and terrain attributes for both configurations (HCP and PRP; Fig. 4). The PRP ECₐ ranged from 1.8 to 18.0 mS m⁻¹ and averaged 5.9 mS m⁻¹, while the HCP ECₐ ranged from 3.1 to 25.8 mS m⁻¹ and averaged 9.9 mS m⁻¹ (Fig. 4). For both the PRP and HCP ECₐ, maximum ECₐ occurred within the local drainageway or areas of potential groundwater movement (Ylagan, 2022; Ylagan et al., 2022), which was characterized by the trail of elevated ECₐ that started in the northwest corner, peaked in the center (Rows 5 to 7), extended eastward, and dissipated towards the bottom middle of the site (Figs. 1 and 4). The minimum ECₐ for both the PRP and HCP occurred within the areas of shallower depth to bedrock, increased coarse fragment abundance, and areas of erosion rather than deposition (Ylagan, 2022; Ylagan et al., 2022), which were characterized by reduced ECₐ occurring in the western/southwestern portion of the site (Fig. 4). Additional information regarding the experimental semi-variogram parameters, models, summary statistics, and spatial pattern of the 12 universally kriged PRP and HCP ECₐ surveys that were averaged and used to create PRP and HCP ECₐ maps in the present study are available in Ylagan (2022) and Ylagan et al. (2022).

**Correlations Among ECₐ and Forage and Tree Data**

**Whole-site Correlations**

Within the whole AF site, total forage yield did not have the same relationship to ECₐ as the tree data (Table 2). Forage yield was unrelated ($P > 0.05$) with either the PRP or HCP ECₐ.

<table>
<thead>
<tr>
<th></th>
<th>PRP Whole-Site</th>
<th>PRP SMZ 1</th>
<th>PRP SMZ 2</th>
<th>PRP SMZ 3</th>
<th>HCP Whole-Site</th>
<th>HCP SMZ 1</th>
<th>HCP SMZ 2</th>
<th>HCP SMZ 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH</td>
<td>417 0.34*</td>
<td>188 0.37*</td>
<td>82 0.15</td>
<td>147 -0.13</td>
<td>417 0.21*</td>
<td>188 -0.20*</td>
<td>82 0.11</td>
<td>147 -0.22*</td>
</tr>
<tr>
<td>Tree Height</td>
<td>421 0.54*</td>
<td>191 0.35*</td>
<td>81 0.26*</td>
<td>149 0.16</td>
<td>421 0.42*</td>
<td>191 -0.22*</td>
<td>81 0.12</td>
<td>149 0.05</td>
</tr>
<tr>
<td>Total Yield</td>
<td>84 0.01</td>
<td>39 -0.02</td>
<td>17 0.52*</td>
<td>28 -0.26</td>
<td>84 -0.04</td>
<td>39 0.07</td>
<td>17 0.54*</td>
<td>28 -0.51*</td>
</tr>
</tbody>
</table>

Correlations among ECₐ and forage and tree data within the whole-site and three ECₐ-derived soil management zones (SMZs). Ylagan (2022; Ylagan et al., 2022), at an agroforestry site in the Ozark Highlands of northwest Arkansas. The location of the trees, forages, yield samples, and SMZs are presented on Fig. 1.
DBH and tree height measurements were collected on 9 December 2020 and 15 March 2021, respectively.

Forage total yield measurements were collected on 25 May and 5, 15, 29 June 2018, and 4 and 20 June and 3 July 2019.

* Significant correlation at \( P < 0.05 \). (Table 2). However, both DBH (\( r = 0.34 \) and 0.21) and TH (\( r = 0.54 \) and 0.42) were moderately, positively (\( P < 0.05 \)) related with both the PRP and HCP EC\(_a\), respectively, where the PRP EC\(_a\) had stronger relationships with tree properties than the HCP EC\(_a\) (averaged across DBH and TH, \( r = 0.44 \) and 0.32, respectively; Table 2). Additionally, there were no relationships between forage yield and EC\(_a\) for any of the eight EC\(_a\) configuration (PRP or HCP), forage species (NG mix or OG), and 2017–2019 fertility (PL or no fertilizer control) treatment combinations.

The positive relationship between the EC\(_a\) and tree properties at the whole-site level were likely the result of factors that increase EC\(_a\) and plant productivity (Table 2). Specifically, some of the largest measured EC\(_a\) values occurred within the local drainage way of the AF site (Ylagan, 2022; Ylagan et al., 2022) and were likely the result of the accumulation of transported water, nutrients/salinity, OM, and sediment from overland flow over time (Corwin & Scudiero, 2017). Increases in the SWC, nutrients, and OM also have the potential to increase plant productivity. Thus, increases in soil properties, such as SWC, nutrients, and OM, likely resulted in the positive relationship between the EC\(_a\) and DBH and TH for both EC\(_a\) configurations (Table 2).

**Soil Management Zone Correlations**

Within a SMZ, relationships among EC\(_a\) and forage and tree data were generally similar between both EC\(_a\) configurations (Table 2). The weak to moderate, positive correlations between PRP EC\(_a\) and DBH (\( r = 0.37 \)) and TH (\( r = 0.35 \)) in SMZ 1, the PRP EC\(_a\) and TH (\( r = 0.26 \)) and forage yield (\( r = 0.52 \)) in SMZ 2, and the HCP EC\(_a\) and forage yield (\( r = 0.54 \)) in SMZ 2 were potentially the result of topographic features and soil properties that increase EC\(_a\) and plant productivity (Table 2). Soil Management Zone 1 contains the greatest change in slope (Figs. 1 and 2) and SMZ 2 includes the local drainage way at the site. Overland flow causes water and transported materials (i.e., sediment, nutrients, and OM) to be deposited downslope and in depressional areas. Accumulation of transported material over time can result in increased soil moisture, nutrient, clay, and OM contents, all of which can increase measured EC\(_a\) and can increase plant productivity (Corwin & Scudiero, 2017). Thus, the positive relationships between EC\(_a\) and DBH, TH, and forage yield in SMZ 1 and 2 were likely the result of transported materials increasing both EC\(_a\) and plant growth (Table 2).

It is unclear why there was a negative correlation between the HCP EC\(_a\) and DBH (\( r = 0.21 \)) and TH (\( r = -0.22 \)) within SMZ 1, as the PRP EC\(_a\) and DBH and TH within SMZ 1 were positively correlated (Table 2). However, Jiang et al. (2021) collected 51, 0-15-cm soil core samples from the alleys at the same AF site as used in the current study using a 3.3-cm-diameter soil core. Jiang et al. (2021) then used the Soil-Land Inference Model (SoLIM) with the soil core sample data to create interpolated maps of different soil properties across the AF site. The BD map that Jiang et al. (2021) created displayed more elevated BDs (1.5 to 1.7 g cm\(^{-3}\)) in SMZ 3 than the other SMZs (Table 2; Fig. 1). Elevated BD can cause increased EC\(_a\) through increased soil conducance pathways and can cause decreased plant productivity, as increased BD decreases soil water-holding capacity, air and water movement, microbial activity, and restricts root growth (Corwin & Scudiero, 2017). Thus, the elevated BD within SMZ 3 likely resulted in the negative correlations between HCP EC\(_a\) and DBH and forage yield (Table 2).

Although tree growth properties and forage yield were not correlated to EC\(_a\) in all correlation groups evaluated (i.e., within the whole-site, SMZs, and species and fertility treatments), EC\(_a\)-tree and EC\(_a\)-forage correlations were established. Thus, the hypothesis that EC\(_a\) survey data will be correlated with forage yield and tree growth characteristics was confirmed within some, but not all correlation groups. Additionally, the EC\(_a\)-tree and EC\(_a\)-forage correlations demonstrated that relationships between EC\(_a\) and plant growth properties can vary from whole-site relationships and become explanatory (i.e., forage yield) when separated into SMZs (Table 2). As a result, using EC\(_a\) to describe plant growth variability in AF systems is potentially more effective within SMZs because more accurate EC\(_a\)-plant relationships can be established within sub-regions at a site that contain specific landscape features, soil properties, or EC\(_a\) ranges. However, the relationship strength (i.e., \(| r |\)) of the whole-site, EC\(_a\)-tree property relationships, averaged across tree property (DBH and TH) and EC\(_a\) configuration, \( r = 0.38 \), was stronger than the relationship strength of SMZ EC\(_a\)-tree property relationships, averaged across tree property, EC\(_a\) configuration, and SMZ, \( r = 0.27 \) (Table 2). Thus, the hypothesis that correlations among EC\(_a\) survey and total forage yield and tree growth data can be improved with EC\(_a\)-derived SMZs was confirmed for forage yield in some SMZs, but not for tree growth in any SMZ.
Correlations Among EC and Terrain Attributes

Whole-site Correlations

Most terrain attributes had correlations ($P<0.05$) with both EC configurations and the majority of the relationships can be described by surface processes (Table 3). Specifically, both NormHt and TPI identify areas of higher or lower relative elevation, and SlopeHt and VDistChn identify areas of increased height of above modeled drainage accumulation or channel network, respectively (Table 1). Additionally, LS-factor, which incorporates SlopePer, identifies areas of increased erosion potential, FlowAccum identifies where runoff accumulates, MRVBF identifies depositional areas, and SAGAWI identifies areas in valley floors with an increased potential of water accumulation (Table 1). Soil constituents (i.e., sediment, OM, nutrients, and water), which greatly contribute to EC (Corwin & Scudiero, 2017), are eroded and/or transported from upslope positions and are deposited downslope in valley, depressional, and flow accumulation areas over time. The accumulation of soil constituents downslope and in depressional areas often results in these areas having greater EC than higher elevation areas and/or areas with increased erosion (Ylagan, 2022; Ylagan et al., 2022; Zhu et al., 2010).

Thus, the negative relationships that NormHt ($r = -0.20$), TPI ($r = -0.21$), and SlopeHt ($r = -0.13$) had with the PRP EC, the negative relationships that LS-Factor ($r = -0.38$ and $-0.20$, respectively), SlopePer ($r = -0.43$ and $-0.23$, respectively), and VDistChn ($r = -0.33$ and $-0.22$, respectively) had with the PRP and HCP EC; and the positive relationships that FlowAccum ($r = 0.14$ and 0.07, respectively), MRVBF ($r = 0.33$ and 0.10, respectively), and SAGAWI ($r = 0.36$ and 0.16, respectively) had with the PRP.

### Table 3

Summary of the number of observations (n) and resulting correlation coefficients (r) from Pearson linear correlations evaluating the relationship between the perpendicular (PRP) and horizontal coplanar geometry (HCP) apparent electrical conductivity (EC) and 14 terrain attributes, within the whole-site and three EC-derived soil management zones (SMZs) (Ylagan, 2022; Ylagan et al., 2022), at an agroforestry site in the Ozark Highlands of northwest Arkansas.

<table>
<thead>
<tr>
<th>Terrain Attribute</th>
<th>Whole-site</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>PRP</td>
<td>HCP</td>
<td>n</td>
</tr>
<tr>
<td>Aspect</td>
<td>1836</td>
<td>0.22*</td>
<td>0.23*</td>
<td>691</td>
</tr>
<tr>
<td>Elevation</td>
<td>1836</td>
<td>&lt; 0.01</td>
<td>0.27*</td>
<td>691</td>
</tr>
<tr>
<td>FlowAccum</td>
<td>1836</td>
<td>0.14*</td>
<td>0.07*</td>
<td>691</td>
</tr>
<tr>
<td>LS-Factor</td>
<td>1836</td>
<td>-0.38*</td>
<td>-0.20*</td>
<td>691</td>
</tr>
<tr>
<td>MidSlope</td>
<td>1836</td>
<td>-0.09*</td>
<td>-0.21*</td>
<td>691</td>
</tr>
<tr>
<td>MRRTF</td>
<td>1836</td>
<td>0.01</td>
<td>0.14*</td>
<td>691</td>
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<tr>
<td>MRVBF</td>
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<td>0.33*</td>
<td>0.10*</td>
<td>691</td>
</tr>
<tr>
<td>NormHt</td>
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<td>0.06*</td>
<td>691</td>
</tr>
<tr>
<td>SAGAWI</td>
<td>1836</td>
<td>0.36*</td>
<td>0.16*</td>
<td>691</td>
</tr>
<tr>
<td>SlopeHt</td>
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<td>-0.13*</td>
<td>0.11*</td>
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<tr>
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<td>691</td>
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<tr>
<td>TPI</td>
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<td>-0.21*</td>
<td>0.02</td>
<td>691</td>
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<tr>
<td>ValleyDep</td>
<td>1836</td>
<td>-0.02</td>
<td>-0.25*</td>
<td>691</td>
</tr>
<tr>
<td>VDistChn</td>
<td>1836</td>
<td>-0.33*</td>
<td>-0.22*</td>
<td>691</td>
</tr>
</tbody>
</table>

* Significant correlation at $P<0.05$.\n
and HCP $E_a$ within the whole AF site were likely the result of the terrain attributes identifying areas where increased soil erosion and deposition/accumulation occur, which decreased and increased $E_a$ measurements, respectively (Tables 1 and 3).

Other explanations for the relationships between terrain attributes and $E_a$ were not as obvious. Specifically, the weak, positive correlations between Aspect and both PRP and HCP $E_a$ ($r = 0.22$ and $0.23$, respectively) were unexpected, as the mean and median slope aspect of the AF site were $185$ and $189^\circ$, respectively, making the AF site primarily south facing (Tables 1 and 3). Additionally, it is unclear why there were weak, positive correlations between Elevation ($r = 0.27$), NormHt ($r = 0.06$), and SlopeHt ($r = 0.11$) and HCP $E_a$, and a weak, negative correlation between ValleyDep and HCP $E_a$ ($r = -0.25$; Tables 1 and 3). Specifically, it can be expected that $E_a$ will likely decrease with increasing elevation and distance from valleys and drainage ways, as there would be decreasing $E_a$-contributing soil properties (i.e., clay, OM, nutrients, and water content, soil water-holding capacity, and soil depth) from erosional forces removing and depositing soil constituents downslope and in depositional areas (Ylagan, 2022; Yлаган et al., 2022; Zhu et al., 2010). However, the weak, positive correlations between Aspect and both the PRP and HCP $E_a$ and between Elevation and HCP $E_a$ within the whole AF site (Table 6) were similar to the result of Kitchen et al. (2003). Kitchen et al. (2003) conducted an $E_a$ survey on a 13-ha field in Boone County, Missouri that had been previously planted with corn ($Zea mays$ L.) and soybean ($Glycine max$ L. Merr.) and was mapped as Mexico (Aeric Vertic Epiqualfs) and Adco (Vertic Albaqualfs) soil series. The shallow $E_a$ (0–30 cm) had a positive relationship with aspect ($r = 0.41$), while the deep $E_a$ (0-100 cm) had a positive relationship with aspect and elevation ($r = 0.26$ and $0.37$, respectively; Kitchen et al., 2003).

The terrain attribute MidSlope identifies the mid-slope position between the greatest and lowest elevation in the defined landscape (Table 1). The weak, negative correlation between the MidSlope and both PRP and HCP $E_a$ ($r = -0.09$ and $-0.21$, respectively) was a potential indication that $E_a$ decreased with increasing distance from the mid-slope position, vertically up- or down (Tables 1 and 3). However, the negative relationship between the MidSlope and $E_a$ was likely a result of some of the largest $E_a$ values at the AF site occurring within the local depressional area in the drainage way, which was located within or just around the mid-slope position of study site (Figs. 3 and 4; Table 3).

Soil Management Zone Correlations

Correlations between $E_a$ and terrain attributes within the SMZs differed from the whole-site results and varied between SMZs and $E_a$ configuration (Table 3). Specifically, no terrain attribute had a consistent relationship with the HCP $E_a$ across all three SMZs, whereas eight terrain attributes had consistent relationships with PRP $E_a$ across all three SMZs (i.e., Elevation, LS-Factor, MRVBF, NormHt, SlopeHt, SlopePer, TPI, and ValleyDep; Tables 1 and 3). The PRP $E_a$ had 4 to 10 more significant correlations to the terrain attributes than the HCP $E_a$ in each of the SMZs (Tables 1 and 3). Additionally, all 15 correlations between terrain attributes and HCP $E_a$ within SMZs were weak ($|r| < 0.30$), whereas 75% of the 36 significant correlations between the terrain attributes and the PRP $E_a$ within the SMZs were moderate ($|r| \geq 0.30$; Tables 1 and 3). In all instances where both the PRP and HCP $E_a$ had a significant relationship with the same terrain attribute within the SMZs, the absolute value of the correlation coefficient was numerically greater from the PRP than the HCP $E_a$ (Tables 1 and 3). The increased quantity and strength of correlations between the terrain attributes and PRP $E_a$, compared to HCP $E_a$, was likely a result of the 0-0.5 m soil depth and its properties being more associated with the surface terrain attributes and the landscape-level process that they influence (i.e., overland flow, erosion, deposition, accumulation, and sunlight exposure) than the 0-1.6 m soil depth. The differences between the terrain attributes’ relationships with the PRP and/or HCP $E_a$ across SMZs, and between the SMZs and whole site, were likely a result of different terrain attributes affecting the soil and its properties, including $E_a$, to different degrees and depths within the configuration boundaries.

Because terrain-attribute-$E_a$ correlations were established within both the whole-site and SMZs, the hypothesis that $E_a$ survey data are correlated with terrain attributes was confirmed. Additionally, when terrain attributes had a relationship with PRP $E_a$ for the whole-site and all SMZs (i.e., LS-Factor, MRVBF, NormHt, SlopeHt, SlopePer, and TPI), the strength of the relationships between the terrain attributes...
and the PRP ECa were 9 to 205% greater for the SMZs than for the whole-site (Table 3). Thus, the hypothesis that correlations among ECa survey and terrain attribute data can be improved with ECa-derived SMZs was confirmed.

**Terrain Attribute Multi-linear Regression Model on ECa**

**Whole-site Multi-linear Regression Models**

The relationships among the terrain attributes and ECa in the MLR models varied between ECa configurations and among the whole-site and SMZs (Tables 1 and 4). Within the whole-site, all terrain attributes were significant (P<0.05) in the models for both the PRP and HCP ECa; however, the degree to which the terrain attributes influenced (i.e., percent of total sum of squares) the whole-site PRP and HCP ECa variability varied (Table 4). Thus, the hypothesis that different terrain attributes would contribute to the ECa variability to different

<table>
<thead>
<tr>
<th>Percent of Total Sum of Squares</th>
<th>Soil Management Zone</th>
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<tbody>
<tr>
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<td><strong>Terrain Attribute</strong></td>
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<td>ValleyDep</td>
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<tr>
<td>VDistChn</td>
<td>0.2*</td>
</tr>
</tbody>
</table>

* Terrain attribute was significant (P<0.05) in the multiple regression model to explain ECa variations.

a Aspect (Aspect); Elevation (Elevation); Flow Accumulation (FlowAccum); Slope-length Factor (LS-Factor); Mid-slope Position (MidSlope); Multi-resolution Ridge Top Flatness Index (MRRTF); Multi-resolution Valley Bottom Flatness Index (MRVBF); Normalized Height (NormHt); System for Automated Geoscientific Analysis Wetness Index (SAGAWI); Slope Height (SlopeHt); Slope Percent (SlopePer); Topographic Position Index (TPI); Valley Depth (ValleyDep); Altitude Above Channel Network (VDistChnTerrain).
degrees within the AF site was confirmed. The terrain attributes LS-Factor, MidSlope, and ValleyDep had the greatest influence (i.e., largest percent of total sum of squares) on the PRP ECa variability (10.5, 9.4, and 7.2%, respectively), with MRVBF and SAGAWI following closely behind (7.1 and 6.1%, respectively; Tables 1 and 4). Alternatively, ValleyDep, SAGAWI, and MidSlope and the greatest influence on the HCP ECa variability (15.3, 11.9, and 11.2%, respectively; Tables 1 and 4).

With exception of MidSlope, the terrain attributes that had the greatest influence on the ECa variability across the whole AF site were likely due to the effect of topography and climate and the properties the terrain attributes describe (Table 4). The study site has variable topography (8-m elevation change and < 9.1% slope gradient) and receives a large amount of precipitation annually [1,176 mm, 30-yr means (1991 to 2010)] (NOAA, 2022). As a result of the AF site’s elevation change and level of precipitation, it can be expected that some of the largest contributors to the development of soils and their properties, including ECa, are or may be dominated by alluvial- and colluvial-related processes (i.e., erosion upslope and translocation and deposition downslope) within the local scale. Thus, because LS-Factor depicts erosional areas and MRVBF, SAGAWI, and ValleyDep depict depositional and water accumulation areas, it was expected that LS-Factor, MRVBF, SAGAWI, and ValleyDep be large contributors to the ECa variability at this AF site (Tables 1 and 4).

Soil Management Zone Multi-linear Regression Models

Unlike the whole-site MLR models, neither ECa configuration was influenced (P < 0.05) by all terrain attributes in any of the three SMZs (Tables 1 and 4). Additionally, the terrain attributes that had a significant influence on the ECa variability varied across the SMZs and between the ECa configurations (Tables 1 and 4). Thus, the hypothesis that different terrain attributes would contribute to the ECa variability to different degrees across the SMZs was confirmed.

The terrain attributes that were the largest contributors to the ECa variability in the SMZs included those that identified areas of higher and/or lower elevation (NormHt, TPI, and SlopeHt), depositional/accumulation (MRVBF, FlowAccum, SAGAWI, and ValleyDep), and increased erosion potential (LS-Factor and SlopePer; Tables 1 and 4). The terrain attributes that had no or minimal influence on the PRP or HCP ECa variability within the SMZs were likely the result of those terrain attributes having minimal variability within the SMZs, or due to different terrain attributes, other than the ones evaluated, being the dominant factor(s) influencing ECa within SMZs (Tables 1 and 4). Furthermore, Elevation, FlowAccum, LS-Factor, MRVBF, and SlopeHt had a consistent influence on the PRP ECa variability across the SMZs, whereas Elevation, FlowAccum, MidSlope, SlopePer, and ValleyDep had a consistent, significant influence on the HCP ECa variability across the SMZs (Tables 1 and 4). Additionally, unlike the whole-site MLR models, the terrain attributes that had a significant effect on the ECa’s in the SMZ MLR models were able to describe 10.2 to 17.9% more of the PRP variability than the HCP variability (Tables 1 and 4). Alternatively, in the whole-site MLR models, the terrain attributes were able to describe 10.3% more of the HCP ECa variability than the PRP ECa variability (Tables 1 and 3).

Practical Implications

The ECa-tree and ECa-terrain attribute correlations and MLR models provided useful information on using ECa surveys to describe and contextualize field variability in AF systems. Specifically, the stronger relationships between the PRP ECa and tree properties at the whole-site level, compared to the HCP ECa, are a potential indication that AF managers could describe the relationship between ECa and tree growth variability to a greater extent using the PRP rather than the HCP ECa. Additionally, the increased number and strength of significant terrain-attribute-PRP-ECa relationships suggest that the ECa variability, thus soil variability, in the 0-0.5-m soil depth can be better described by terrain attributes in AF systems with variable topography than in the 0-1.6-m soil depth. Furthermore, because the terrain attributes significantly related to the PRP ECa generally had stronger relationships in the SMZs than the whole-site, AF managers can potentially better describe 0-0.5-m ECa and soil variability with terrain attributes using ECa-derived SMZs.

Conclusions

Electromagnetic induction-ECa surveys and terrain attribute data have been used to assess field variability within a variety of land management systems and ecosystems across the world. However, no research has been conducted exploring relationships between ECa surveys and pasture forage yield, tree growth, and terrain attributes within an AF system, or whether the relationships could be improved with ECa-derived SMZs in an environment similar to the Ozark Highlands. Due to this lack of information, the objectives of this study were to: i) identify correlations between ECa survey and forage yield, tree growth, and terrain attribute data within the whole site and three ECa-derived SMZs, ii) identify correlations between ECa and total forage yield within forage species and fertility treatment combinations,
and iii) identify terrain attributes that contribute to EC\textsubscript{a} variations at a 20-year AF system in the Ozark Highlands of northwest Arkansas. Results partially supported the hypothesis that EC\textsubscript{a} survey data are correlated with total forage yield and tree growth characteristics and supported the hypothesis that EC\textsubscript{a} survey data are correlated with terrain attributes. However, results did not support the hypothesis that correlations among EC\textsubscript{a} survey and tree growth data can be improved with EC\textsubscript{a}-derived SMZs. Results supported the hypothesis that correlations among EC\textsubscript{a} survey and total forage yield and terrain attribute data can be improved with EC\textsubscript{a}-derived SMZs. Results also supported the hypothesis that different terrain attributes would contribute to the EC\textsubscript{a} variability to different degrees within the AF site and across the SMZs.

Results demonstrated that EC\textsubscript{a} survey relationships exist between forage yield, tree growth, and terrain attributes in AF systems, albeit they can vary with soil depth and SMZs. Results also demonstrated that the largest contributors of EC\textsubscript{a}/soil variability (i.e., terrain attributes) can vary with soil depth and when separated into EC\textsubscript{a}-derived SMZs. Additionally, results demonstrated PRP EC\textsubscript{a} can potentially have stronger and additional relationships with tree, forage properties, and/or terrain properties in AF systems when compared with HCP EC\textsubscript{a}. Additionally, results demonstrated terrain attributes that identify areas of higher and/or lower elevation, deposition/accumulation, and increased erosion potential are necessary to include when developing yield-soil-terrain variability models in AF systems with variable topography and increased precipitation. Results of this study provided further evidence on the potential versatility, applicability, and usefulness of EC\textsubscript{a} surveys for assessing and contextualizing in-field variability in a variety of ecosystems with different land management systems.

**Declarations**

**ACKNOWLEDGMENTS**

Authors are thankful to Taylor Adams with the USDA-ARS for field and laboratory assistance and Watson Dunn for coding assistance. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. Funding was provided by Foundation for Food and Agriculture Research (Grant No. 0000000025).

**FUNDING**

This research was in part supported by the Foundation for Food and Agriculture (Agreement 58-6022-9-002).

**AUTHOR CONTRIBUTIONS**

S.Y. conducted the EC\textsubscript{a} surveys, data processing, data analyses, and prepared the manuscript. A.J.A. and P.R.O were responsible for conception of the research and securing and allocating funds in support of this research. H.S. and A.M.P provided support in the use of R and GIS programs and in data processing procedures and analyses. K.R.B., A.J.A., and P.R.O provided support, guidance, and consultation throughout research. K.R.B., A.J.A., P.R.O., A.M.P., T.J.S., A.L.T., and D.P. reviewed and edited the manuscript. A.L.T. collected and provided tree property data. All authors have read and agreed to the published version of the manuscript.

**Conflict of Interest**

The authors declare no conflict of interest.

**References**


Figures

Figure 1

The agroforestry (AF) site in the Ozark Highlands of northwest Arkansas is organized into 16 rows, where Row 1 starts at the northern most row. Rows 1-5 consist of the northern red oak; the western, central, and eastern portion of Rows 6-10 consists of the pitch/loblolly pine, cottonwood, and American sycamore; and Rows 11-16 consist of pecan. The soils at the AF site include Captina silt loam (CaB), Pickwick silt loam (PsC2), Nixa cherty silt loam (NaC), Johnsburg silt loam (Js), and Cleora fine sandy loam (Cr; Soil Survey Staff, 2019) and the alleys between the tree rows consist of either orchardgrass or a native grass mix forages (big bluestem, little bluestem, and Indiangrass). The forage total yield samples were collected from within cattle exclosures on 25 May and 5, 15, 29 June 2018, and 4 and 20 June and 3 July 2019. The alleys between the tree rows consist of either orchardgrass or a native grass mix (big bluestem, little bluestem, and Indiangrass).}


The apparent electrical conductivity (EC\textsubscript{a}) survey setup included a DUALEM-1S sensor (DUAL-geometry Electro-Magnetic; Dualem Inc., Milton, ON, Canada) that was suspended on a sled that was tied to a Side-by-Side utility vehicle, a Trimble R2 global positioning system unit (Trimble Inc., Westminster, CO) mounted in-side of the Side-by-Side, and both the DUALEM-1S and Trimble R2 were connected to a Trimble Yuma 2 field computer inside the Side-by-Side that interpolated the data in a hand-held geoinformation system.
Figure 3

The spatial pattern of the 14 terrain attributes of the agroforestry site in the Ozark Highlands of northwest Arkansas. The terrain attributes included Aspect, Elevation, Flow Accumulation (FlowAccum), Slope-length Factor (LS-Factor), Mid-slope Position (MidSlope), Multi-resolution Ridge Top Flatness Index (MRRTF), Multi-resolution Valley Bottom Flatness Index (MRVBF), Normalized Height (NormHt), System for Automated Geoscientific Analysis Wetness Index (SAGAWI), Slope Height (SlopeHt), Slope Percent (SlopePer), Topographic Position Index (TPI), Valley Depth (ValleyDep), and Altitude Above Channel Network (VDistChnTerrain). The terrain attribute data were obtained from the USDA-NRCS Geospatial Data Gateway (NRCS, 2022) and are derived from a Light Detection and Ranging (LiDAR)-based, 5-m bare earth digital elevation model (DEM). Maps were created in ArcGIS (ArcGISmap version 10.6.1, Esri, Redlands, CA)
Figure 4

The overall mean of 12 perpendicular (PRP) and horizontal coplanar geometry (HCP) apparent electrical conductivity (ECa) surveys after universal kriging at the agroforestry site in the Ozark Highlands of northwest Arkansas. Maps were created in ArcGIS (ArcGISmap version 10.6.1, Esri, Redlands, CA)