



# OPEN Carbon dynamics of silvopasture systems in the Northeastern United States

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Silvopasture is increasingly recognized as a nature-based solution to climate change. However, few studies have quantified the total carbon storage potential of silvopasture in humid continental climates, complicating efforts to understand climate mitigation potential. In this study, we compared the carbon stocks of silvopastures established by afforestation of trees into pastures (silvopasture) with pasture that remained without trees (treeless pasture) on five farms in the Northeastern United States. Total carbon content was measured in the woody, herbaceous, and soil pools for silvopastures and treeless pastures. Results indicate that silvopastures stored 43% more total carbon (136.42 Mg C ha<sup>-1</sup>) than treeless pastures (95.47 Mg C ha<sup>-1</sup>), with tree carbon in silvopastures being the driving factor. No significant difference in soil carbon stocks were found between systems across all five study farms. Total carbon content of forages was generally lower in silvopastures (7.24 Mg C ha<sup>-1</sup>) when compared to treeless pasture (7.84 Mg C ha<sup>-1</sup>). These findings quantify the additionality of silvopasture as a nature-based carbon storage practice when trees are planted into pasture.

Silvopasture is an agroforestry practice that integrates tree, livestock, and forage management on the same piece of land. In the United States (U.S.), silvopasture management occurs across multiple geographic regions and climate zones with systems being established by planting trees into pasture, thinning trees in native forest or plantations and establishing forages, or integrating livestock into orchards or natural savannas<sup>1,2</sup>. The livestock used in U.S. systems are diverse, including cattle, goats, sheep, chickens, turkeys, horses, bison, pigs, geese, and ducks. However, cattle tend to be the most commonly used species<sup>1</sup>.

While great diversity exists when considering region, silvopasture establishment pathway, and livestock type; the benefits of silvopasture are consistent among producers in the U.S. Survey and case study research have found that producers most value silvopasture for shade and improved animal welfare<sup>1–4</sup>. Producer-reported benefits also include income diversification, increased forage availability and variety, decreased fertilizer inputs through enhanced nutrient cycling, and a wide range of ecosystem services<sup>1,5</sup>. Of the many ecosystem services silvopasture can provide, climate mitigation through carbon storage has received increased attention in the U.S. This is due to the ability of silvopasture systems to increase carbon stocks when planting trees into pasture<sup>6–10</sup>. This is especially true of silvopasture systems being established in pastures that were originally native forest. Converting native forests to agriculture can result in large losses of carbon from the vegetation itself and through increased mineralization of soil organic carbon<sup>11,12</sup>. As such, reintroducing trees into pastures through silvopasture, where appropriate, may help offset the climate impact from grazing-based livestock operations. In particular, the U.S. has over 159 million hectares (392,981,662 acres) of permanent pasture and rangeland<sup>13</sup>, where even a small percentage increase in silvopasture adoption may have a meaningful impact given the large land base.

When trying to identify the climate mitigation potential of silvopasture management through tree planting, there are a number of studies from which inferences can be made. However, research on this topic is predominantly from tropical environments<sup>14–18</sup>. Unfortunately, many of these studies may not be applicable to the climate conditions found within the U.S., which is predominately classified as temperate (Köppen climate classification C) and continental (Köppen climate classification D). In relation to studies from temperate regions, Amorim et al.<sup>19</sup> found that silvopastures in Arkansas, U.S. had 18% greater soil organic carbon than conventional pastures at the 0–15 cm soil sampling depth. This is in contrast to Beckert et al.<sup>20</sup> who found no significant difference in total soil carbon stocks between silvopastures and pastures in Scotland, though ecosystem carbon stocks were significantly higher in the silvopasture after accounting for aboveground and belowground tree biomass. Similarly, Adewopo et al.<sup>21</sup> found that a 22-year-old silvopasture in Florida, U.S. contained more ecosystem

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carbon in the silvopasture ( $144 \text{ Mg ha}^{-1}$ ) than sown pasture ( $83 \text{ Mg ha}^{-1}$ ) or native rangeland ( $69 \text{ Mg ha}^{-1}$ ), with soil organic carbon stocks down to 30 cm being significantly higher in silvopastures ( $69 \text{ Mg C ha}^{-1}$ ) than native rangeland ( $41 \text{ Mg ha}^{-1}$ ). Sharrow and Ismail<sup>22</sup> also found that an 11-year-old silvopasture in Oregon, U.S. stored  $5770 \text{ kg ha}^{-1}$  more ecosystem carbon than adjacent pasture controls. Further, Nair et al.<sup>10</sup> found that silvopastures contributed to more stable carbon within soil profiles when compared to treeless pastures in Florida, due to the presence of trees.

While data from previous studies provide a strong foundation for silvopasture systems in tropical, semi-tropical, and temperate Köppen climate zones, a noticeable gap exists in our understanding of how silvopasture management may impact ecosystem carbon stocks in continental climates. These climates are characterized as having significant annual variation in temperature and are most prevalent in the central and eastern parts of North America, Europe, and Asia<sup>23</sup>. The studies that have described the carbon storage potential of silvopastures from this climate type show promise<sup>24–26</sup>. For example, Baah-Acheamfour et al.<sup>24</sup> investigated silvopasture systems in Alberta, Canada and found that they stored more organic carbon in the bulk mineral soil than adjacent herblands without trees. However, the silvopastures in the three aforementioned studies were established by thinning an existing forest and did not originate from planting trees into treeless pasture.

While previous studies have demonstrated the carbon storage potential of silvopasture in their respective regions, there is a lack of data for silvopasture systems established by tree planting in continental climates. Further, few studies include carbon stocks beyond the soil pool. With climate type greatly influencing carbon storage rates<sup>14,27</sup>, it necessitates further studies to fill in regional and climatic gaps where data sources are minimal or unavailable. As such, the objectives of this study were to:

1. Quantify the carbon stocks between silvopastures and adjacent treeless pasture controls on farms within the northeastern United States. Carbon pools include soil, forage biomass (aboveground and belowground), tree biomass (aboveground and belowground), and their sum total (ecosystem).
2. Make inferences on the degree to which increased silvopasture adoption may impact the carbon balance of the region.

Data from this study fill an important gap in our understanding of silvopasture systems in continental climates, which is needed for carbon inventory efforts, both for reporting and potential incentive programs for producers utilizing silvopasture.

## Methods

### Site description and experimental design

We sampled five silvopasture/treeless pasture pairs across five farms in the Northeastern U.S. Elevations between farms ranged from 101 to 476 m above sea level. Sites were chosen on farms where afforestation occurred on one portion of a pasture that did not have trees. Therefore, pairings on each farm included (1) a portion of formerly treeless pasture where trees had been afforested as silvopasture and (2) a treeless pasture control, which was the portion of the pasture that remained treeless (Fig. 1). Our sample focused on farms with active silvopastures that were beyond the tree establishment phase (Table 1), and all silvopasture sites included in this study originated from establishing trees into formerly treeless pasture. We used a network of practitioners and the assistance of agriculture extension centers to identify farms with actively grazed silvopasture and treeless pasture.

The selected farms have a broad array of acreage, livestock types, soil types, and tree stocking (Table 1). Livestock stocking density on the farms in this study was variable within and between years based on weather patterns, changing herd sizes, and farm management. However, both silvopasture/treeless pasture pairs on farms in this study were part of the same livestock herd grazing rotations. Forages in silvopasture and treeless pasture pairs included diverse mixtures of cool season grasses and legumes, including but not limited to *Dactylis glomerata*, *Agrostis* spp, *Phleum pretense*, *Festuca arundinacea*, *Trifolium pretense*, and *Trifolium repens*. Mean annual precipitation on farms in this study ranged from 864 to 1143 mm per year. The Köppen climate type is Dfb (warm-summer humid continental).

### Site and plot selection

The experimental design was a comparison of paired treeless pasture with silvopasture, with treeless pasture serving as the control. Each farm site had one silvopasture area and one treeless pasture area from which three sampling plot centers were established per treatment. These plot centers served as the basis for vegetation and soil sampling locations further described below.

On each farm, boundaries for pastures and silvopastures were identified through discussions with farmers about grazing management and using visual interpretation of Landsat 8 images in ArcGIS. Prior to identifying sampling plots, soil map units were compared for similarity between silvopasture and treeless pasture pairs, as described in Khaleel et al.<sup>28</sup> and Haile et al.<sup>29</sup>. Plot centers were randomly assigned for each treatment within ArcGIS, while maintaining a 15 m buffer from any pasture edge. To account for on-the-ground uncertainties, more plot centers were identified than needed for potential measurement. The first day of each farm visit included a tour, which allowed for non-pasture areas or areas that were not actively grazed in the last 2 years to be excluded from the study.

### Tree, forage, and soil sampling

Tree spacing was variable between and within sites, and fixed area plots were used to help account for this variability. All trees greater than 2.5 cm diameter at breast height (DBH) were inventoried in silvopasture areas using 0.081 hectare fixed area plots. DBH and species were recorded. Three 0.25 square meter ( $\text{m}^2$ ) subplots were established around plot centers in silvopastures and treeless pastures to conduct forage and soil sampling.



**Fig. 1.** Photos of a study site pairing of treeless pasture control on the left and silvopasture on the right on Farm A in New York State. This silvopasture was 33 years old at the time of the study and was comprised of mixed cool season grasses and legumes with a *Robinia pseudoacacia* and *Juglans Nigra* overstory.

| Farm | Location                      | Livestock | Years since tree establishment | Soil type  | Soil texture       | Tree composition          | Quadratic mean tree diameter at 1.3 m (cm) | Basal area (m <sup>2</sup> ha <sup>-1</sup> ) | Silvopasture trees per hectare |
|------|-------------------------------|-----------|--------------------------------|------------|--------------------|---------------------------|--------------------------------------------|-----------------------------------------------|--------------------------------|
| A    | Schuyler County, New York     | Cattle    | 33                             | Alfisol    | Gravelly Silt Loam | Black Locust/Black Walnut | 19.1                                       | 18.4                                          | 642                            |
| B    | Schuyler County, New York     | Cattle    | 33                             | Alfisol    | Gravelly Silt Loam | White Pine                | 24.7                                       | 13.4                                          | 280                            |
| C    | Addison County, Vermont       | Goat      | 18                             | Spodosol   | Fine Sandy Loam    | Mixed Softwood/Hardwood   | 21.2                                       | 5.2                                           | 148                            |
| D    | Dutchess County, New York     | Cattle    | 41                             | Inceptisol | Silt Loam          | Apple/Maple               | 42.8                                       | 16.5                                          | 115                            |
| E    | St. Lawrence County, New York | Cattle    | 21                             | Inceptisol | Fine Sandy Loam    | Black Walnut              | 14.5                                       | 15.6                                          | 939                            |

**Table 1.** Climatic, operational, and ecosystem characteristics of study farms.

Forage was sampled during the active grazing season between June and August of 2021. The forage pool being analyzed in this study was that which was consistent throughout the growing season, not the peak or total forage production. Therefore, we set a uniform forage height of 10 centimeters to utilize for our sample. Forage was first clipped to 10 cm heights to mimic a uniform grazing height, with excess material being analyzed separately. The forage was then clipped to ground level and placed in paper bags for drying and weighing. This 0–10 cm standardization was meant to reflect the carbon stored in aboveground herbaceous material on actively grazed pasturelands and allowed us to standardize forage height across all study sites for consistency. Rotational grazing on established perennial forages, such as those in this study, is determined by forage height and 10 cm is a common residual minimum height of cool season forages after grazing in this region<sup>30</sup>. This standardization was also needed because the regrowth time above 10 cm since last grazing period differed between sites. After collecting the aboveground forage samples, forage roots were collected to a depth of 30 cm, as described in López-Santiago<sup>31</sup>. Large rocks were collected to a depth of 30 cm for volume measurements to account for the heterogeneity of soils in the Northeastern U.S. Large rock volumes were later determined using the water displacement method.

Following forage root sampling, the subplots were widened to 1 m<sup>2</sup> for soil sampling via a soil pit. Soil samples were collected from the following soil depth ranges: 0–10 cm, 10–30 cm, 30–60 cm, 60–100 cm, or until an impermeable layer was reached. The soils of this area are of glacial origin, so it was not uncommon for soil depth to be stopped by ledge or glacial hardpan. The lowest uniform depth across all plots in a silvopasture/ treeless pasture pair was used for determining soil carbon content. For Farm A, this corresponded to 60 cm,

while Farm B was 30 cm, Farm C 60 cm, Farm D 10 cm, and Farm E 100 cm. The differences in soil depths make soil carbon comparisons between farms impractical but resulted in equitable comparisons between silvopastures and treeless pasture pairs within farms to assess treatment-level effects. Further, it is important to note that a litter layer was not present at the silvopasture sites in this study due to the intentional management of the system by participating farmers to maximize forage growth.

From each subplot, three replicates from three of the four side walls of the pit were sampled within each soil fixed depth layer and analyzed for carbon independently as described in Khaleel et al.<sup>28</sup>. Lastly, bulk density samples were obtained using the soil core method<sup>32</sup>. Horizontal soil cores were collected at 10, 30, 60 and 100 cm depths within the pit or until an impermeable layer was reached. There were three replicates taken from three of the side walls of the pit and put in plastic bags<sup>30,33</sup>.

### Processing and analysis

Herbaceous and root forage samples were dried at 70 °C for 24 h and weighed. Forage dry weights were then converted to carbon equivalents using carbon content percentages (42.45% for forage roots, and 44.73% for foliage) as described in Ma et al.<sup>34</sup>. Tree aboveground and belowground biomass values were estimated using biomass equations from Chojnacky et al.<sup>35</sup>. The equation used for aboveground tree biomass was:  $\ln(\text{biomass}) = \frac{1}{4} b_0 + b_1 \ln(\text{DBH})$ . In this equation DBH is in cm, biomass is in kg and  $b_0$  and  $b_1$  are genus-specific values from Chojnacky et al.<sup>35</sup>. Belowground tree biomass was a ratio of root component biomass to total aboveground biomass, and fine and coarse roots were quantified separately. The biomass equation used for belowground values was:  $\ln(\text{ratio}) = \frac{1}{4} b_0 + b_1 \ln(\text{DBH})$ . In this equation DBH is in cm and the ratio is defined as component biomass divided by total aboveground biomass,  $b_0$  and  $b_1$  are genus specific constants found in Chojnacky et al.<sup>35</sup>. From these values, carbon content in biomass was determined using carbon content percentages from Ma et al.<sup>34</sup>, with values of 47.69% carbon for aboveground biomass and 46.59% for belowground biomass.

Soil samples were air dried and processed through a two-millimeter (mm) sieve to remove all visible plant material. 12–13 g (g) of soil from each sample were added to scintillation vials and sent to North Dakota State University's Soil Lab for total organic carbon (TOC) analysis using the dry combustion method with a Skalar Primacs solid carbon analyzer. Samples were also checked for the presence of inorganic carbon, which were all negative. TOC therefore equals total carbon for these study sites. Bulk density was collected using the core method at each sampling depth and analyzed in the Yale-Myers Forest research lab using a drying oven at 105 °C for 24 h. Bulk density was used to convert TOC to total soil carbon. The calculation to determine total soil carbon was  $C (\text{Mg ha}^{-1}) = \text{BD} * \text{TOC} * \text{LT} * (1 - \text{RV}) * 10,000$  where BD denotes bulk density, TOC is percent total organic carbon, LT is layer thickness, RV is percent rock volume, and 10,000 is the unit conversion from cubic meters to hectare.

Total soil carbon was also analyzed using equivalent soil mass. von Haden et al.<sup>36</sup> provided Program R<sup>37</sup> code that we used for our analysis. We used the soil mineral mass conversion from McBratney and Minasny<sup>38</sup>, as suggested by Fowler et al.<sup>39</sup>, to convert total soil mass to mineral mass:  $M_M = M_T - (1 - k * \text{SOC})$ . As explained in Fowler et al.<sup>39</sup>:  $M_T$  is the soil total mass,  $M_M$  is the soil mineral mass, SOC is the percent soil organic carbon, and  $k$  is the van Bemmelen factor of which we used a value of 1.9. The only change made to von Haden's<sup>36</sup> Program R<sup>37</sup> script was to align the soil depth increments with those used in this study and described above. Each farm was analyzed separately with the treeless pasture acting as the "time 0" reference data and the silvopasture as "time 1." Soil organic carbon stocks were determined down to 100 cm when possible.

Ecosystem carbon was calculated by summing (1) tree aboveground and belowground carbon, (2) forage 0 to 10 cm aboveground carbon, and forage belowground carbon and (3) soil organic carbon, as done in Adewopo et al.<sup>21</sup>, and Aryal et al.<sup>14</sup>. The livestock contribution to ecosystem carbon was not investigated in this study, as that was considered as a constant since herd numbers were consistent between pasture and silvopasture treatments. Further, a litter layer and downed woody debris was not present at silvopasture sites due to management by producers to enhance forage growth, and hence was not measurable. Forage carbon above 10 cm in height was not included in the ecosystem carbon calculation.

### Statistical analyses

Due to the variability of the ages of silvopastures and treeless pastures and the heterogeneity of the study sites, each farm was analyzed independently. Variables were assessed for normality using a Shapiro Wilk test, and visually by using QQ plots, boxplots, and histograms. Carbon variables (soil, forage, tree, aboveground, belowground, ecosystem) were found to be normally distributed. These data were analyzed using a one-way ANOVA with silvopasture and treeless pasture as independent variables. Data from all farms were also analyzed together to assess overall trends using descriptive statistics, as treatment effects within farms were analyzed independently. Bulk density data were not normally distributed and were analyzed using a Wilcoxon Sign-Rank test. A comparison of total soil carbon between fixed depth and equivalent soil mass is included in Supplement Table 1 and was analyzed using a Welch two-sample t-test. All statistical analyses were conducted in Program R<sup>37</sup>.

## Results

### Soil carbon

Across farms, bulk density was generally lower in silvopastures (128 g/cm<sup>3</sup>) than adjacent treeless pastures (1.23 g/cm<sup>3</sup>), with significance occurring on Farms B, C and D (Table 2).

There was no significant difference in soil carbon found between pasture systems within any of the farms when using fixed depth sampling (Table 3). Silvopastures averaged 87.82 Mg ha<sup>-1</sup> of soil carbon and treeless pastures averaged 87.63 Mg ha<sup>-1</sup>. We also calculated soil carbon using equivalent soil mass (ESM) for comparison to fixed depth sampling (Supplement Table 1). As with fixed depth sampling, there was no significant difference between

| Farm                     | Silvopasture (g/cm <sup>3</sup> ) | Treeless pasture (g/cm <sup>3</sup> ) | p-value          |
|--------------------------|-----------------------------------|---------------------------------------|------------------|
| A                        | 1.26 (0.02)                       | 1.28 (0.01)                           | 0.100            |
| B                        | 1.17 (0.01)                       | 1.23 (0.01)                           | <b>0.002</b>     |
| C                        | 1.21 (0.01)                       | 1.31 (0.01)                           | <b>&lt;0.001</b> |
| D                        | 1.17 (0.01)                       | 1.27 (0.01)                           | <b>&lt;0.001</b> |
| E                        | 1.27 (0.02)                       | 1.29 (0.01)                           | 0.134            |
| Average across all farms | 1.23 (0.01)                       | 1.28 (0.01)                           | <b>&lt;0.001</b> |

**Table 2.** Bulk density comparisons between silvopasture and treeless pasture within and across all farms. Statistical analyses were conducted using a Wilcoxon Rank Sum test. Average values listed with standard error in parentheses. Bold indicates significant difference at the 0.05 level or better.

| Farm                     | Pasture type | Total carbon (Mg ha <sup>-1</sup> ) |              |               |                  |                |                |
|--------------------------|--------------|-------------------------------------|--------------|---------------|------------------|----------------|----------------|
|                          |              | Soil                                | Forage       | Tree          | Aboveground      | Belowground    | Ecosystem      |
| A                        | Silvopasture | 118.83 (9.72)                       | 6.28 (0.18)  | 63.44 (0.61)  | 52.81 (0.44)     | 135.74 (9.74)  | 188.55 (9.79)  |
|                          | Treeless     | 122.37 (8.80)                       | 7.87 (0.05)  | 0.00          | 1.26 (0.04)      | 128.98 (8.79)  | 130.24 (8.83)  |
|                          | p-value      | 0.887                               | <b>0.001</b> | N/A           | <b>&lt;0.001</b> | 0.634          | <b>0.010</b>   |
| B                        | Silvopasture | 80.21 (6.20)                        | 7.70 (0.19)  | 33.97 (4.32)  | 29.04 (3.58)     | 92.83 (5.91)   | 121.88 (5.87)  |
|                          | Treeless     | 72.30 (5.31)                        | 8.26 (0.38)  | 0.00          | 1.33 (0.05)      | 79.22 (5.05)   | 80.56 (5.01)   |
|                          | p-value      | 0.722                               | 0.256        | N/A           | <b>0.001</b>     | 0.155          | <b>0.005</b>   |
| C                        | Silvopasture | 108.28 (13.04)                      | 6.71 (0.17)  | 13.81 (2.17)  | 12.37 (1.81)     | 116.43 (13.30) | 128.80 (14.19) |
|                          | Treeless     | 108.86 (28.43)                      | 7.63 (0.44)  | 0.00          | 1.11 (0.01)      | 115.39 (28.82) | 116.49 (28.83) |
|                          | p-value      | 0.986                               | 0.122        | N/A           | <b>0.003</b>     | 0.975          | 0.721          |
| D                        | Silvopasture | 35.44 (6.29)                        | 7.84 (0.11)  | 39.23 (10.40) | 33.37 (8.71)     | 49.13 (4.63)   | 82.51 (5.01)   |
|                          | Treeless     | 20.59 (5.18)                        | 6.99 (0.43)  | 0.00          | 0.95 (0.08)      | 26.63 (5.55)   | 27.57 (5.61)   |
|                          | p-value      | 0.143                               | 0.124        | N/A           | <b>0.020</b>     | <b>0.035</b>   | <b>0.001</b>   |
| E                        | Silvopasture | 96.35 (20.47)                       | 7.67 (0.65)  | 56.38 (15.64) | 47.01 (12.95)    | 113.39 (22.37) | 160.39 (34.59) |
|                          | Treeless     | 114.04 (15.54)                      | 8.47 (0.43)  | 0.00          | 1.37 (0.19)      | 121.14 (15.78) | 122.51 (15.96) |
|                          | p-value      | 0.529                               | 0.361        | N/A           | <b>0.024</b>     | 0.791          | 0.376          |
| Average across All Farms | Silvopasture | 87.82 (9.08)                        | 7.24 (0.20)  | 41.36 (5.71)  | 34.92 (4.67)     | 101.50 (9.26)  | 136.42 (11.69) |
|                          | Treeless     | 87.63 (11.61)                       | 7.84 (0.19)  | N/A           | 1.20 (0.05)      | 94.27 (11.71)  | 95.47 (11.74)  |

**Table 3.** Carbon content comparisons between silvopasture and treeless pasture within farms. Forage and tree carbon values presented in this table include both root and aboveground carbon. Total soil carbon values vary based upon depth in addition to treatment. However, these soil carbon numbers are based on the deepest common depth sampled between plots by farm (A to 60 cm, B to 30 cm, C to 60 cm, D to 10 cm, E to 100 cm). Note that each farm had at least one plot which could be sampled to 60–100 cm but soil depth to ledge varied between plots within each farm, therefore the numbers presented here are conservative to the shallowest sampling depth across all plots within a farm. This allowed for equal soil depth comparisons to be made between treatments. Statistical analyses were conducted within farms using one-way ANOVA. Average values are listed with standard error in parentheses. Bold indicates significant difference at  $\leq 0.05$ .

silvopasture and treeless pastures for soil carbon by farm when using ESM. There was also no difference in soil carbon stocks when comparing sampling methods.

### Forage carbon and biomass

Total forage carbon was significantly greater in treeless pastures for Farm A but was not significant for all other farms (Table 3). Differences in forage root carbon were only present for Farm A, while aboveground forage carbon was significant for Farms A and B (Table 4). Silvopastures had significantly less aboveground forage biomass (0–10 cm) than pasture controls for two of the five farms (Farm A and Farm B), while Farms C, D, and E showed no significance (Table 4).

| Farm                     | Pasture type     | Forage biomass (Mg ha <sup>-1</sup> ) | Forage root carbon (Mg ha <sup>-1</sup> ) | Forage aboveground carbon (Mg ha <sup>-1</sup> ) |
|--------------------------|------------------|---------------------------------------|-------------------------------------------|--------------------------------------------------|
| A                        | Silvopasture     | 1.81 (0.04)                           | 5.47 (0.19)                               | 0.81 (0.02)                                      |
|                          | Treeless pasture | 2.82 (0.08)                           | 6.61 (0.25)                               | 1.26 (0.04)                                      |
|                          | <i>p</i> -value  | <b>&lt;0.001</b>                      | <b>0.003</b>                              | <b>&lt;0.001</b>                                 |
| B                        | Silvopasture     | 2.36 (0.11)                           | 6.64 (0.17)                               | 1.06 (0.05)                                      |
|                          | Treeless pasture | 2.97 (0.10)                           | 6.93 (0.33)                               | 1.33 (0.05)                                      |
|                          | <i>p</i> -value  | <b>0.016</b>                          | 0.489                                     | <b>0.016</b>                                     |
| C                        | Silvopasture     | 2.28 (0.17)                           | 5.69 (0.24)                               | 1.02 (0.08)                                      |
|                          | Treeless pasture | 2.47 (0.03)                           | 6.52 (0.43)                               | 1.11 (0.01)                                      |
|                          | <i>p</i> -value  | 0.339                                 | 0.162                                     | 0.339                                            |
| D                        | Silvopasture     | 2.09 (0.21)                           | 6.91 (0.03)                               | 0.94 (0.09)                                      |
|                          | Treeless pasture | 2.11 (0.18)                           | 6.04 (0.37)                               | 0.94 (0.08)                                      |
|                          | <i>p</i> -value  | 0.950                                 | 0.085                                     | 0.950                                            |
| E                        | Silvopasture     | 2.05(0.20)                            | 6.75 (0.63)                               | 0.92 (0.09)                                      |
|                          | Treeless pasture | 3.07 (0.42)                           | 7.09 (0.24)                               | 1.37 (0.19)                                      |
|                          | <i>p</i> -value  | 0.096                                 | 0.632                                     | 0.097                                            |
| Average across all farms | Silvopasture     | 2.12 (0.07)                           | 6.28 (0.19)                               | 0.94 (0.03)                                      |
|                          | Treeless pasture | 2.69 (0.12)                           | 6.63 (0.15)                               | 1.20 (0.05)                                      |

**Table 4.** Forage biomass and carbon between silvopasture and treeless pastures. Statistical analyses were conducted using one-way ANOVA within each farm. Average values listed with standard error in parentheses. Bold indicates significant difference at  $\leq 0.05$ .

### Tree carbon

Across farms, silvopastures contained an average of 41.36 Mg C ha<sup>-1</sup> in the aboveground and belowground tree component. However, this value varied greatly with carbon values ranging between 13.81 Mg C ha<sup>-1</sup> for Farm C to 63.44 Mg C ha<sup>-1</sup> for Farm A (Table 3). Trees per hectare ranged from 115 to 939 trees per hectare, with quadratic mean diameters ranging from 14.5 to 42.8 cm (Table 1). Additionally, the basal area of the silvopasture sites ranged from 5.2 to 18.4 m<sup>2</sup> ha<sup>-1</sup>. The wide range in carbon content can be attributed to variation in species composition and how each producer manages stand density over time within their silvopastures.

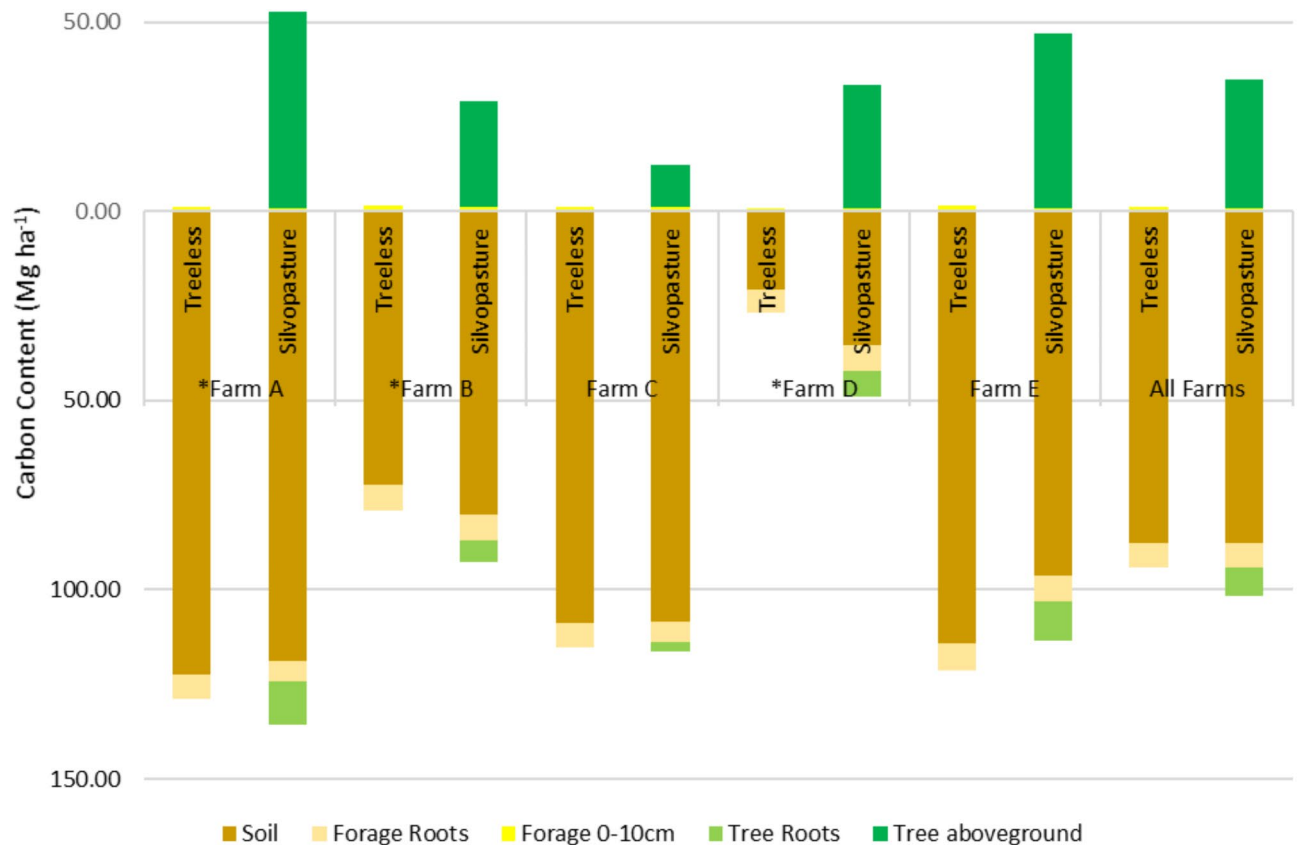
### Ecosystem carbon

Overall, silvopasture systems trended toward more carbon (136.42 ± 11.69 Mg C ha<sup>-1</sup>) than treeless pastures (95.47 ± 11.74 Mg C ha<sup>-1</sup>) when aggregating all farms together (Table 3). For the three farms (A, B, D) where ecosystem carbon was significantly higher in the silvopasture, differences were primarily attributed to tree biomass, since soil carbon was similar between the two management systems and differences in total forage carbon were minimal (Fig. 2). It should also be noted that Farm C was the youngest silvopasture (18 years) with the lowest basal area (5.2), which may help explain the lack of significant difference in carbon with the adjacent treeless pasture control.

The importance of trees to ecosystem carbon is clear when looking at the aboveground carbon analysis, where silvopastures had 34.92 ± 4.67 Mg C ha<sup>-1</sup> and treeless pastures had 1.20 ± 0.05 Mg C ha<sup>-1</sup>. We found no clear trend in the belowground carbon pools when aggregating farms, where silvopastures had 101.50 ± 9.26 Mg C ha<sup>-1</sup> and treeless pastures had 94.27 ± 11.71 Mg C ha<sup>-1</sup> ( $p = 0.632$ ). All farms but Farm E trended toward greater belowground carbon stocks in silvopasture compared to treeless pasture (Fig. 2).

### Discussion

The lower bulk density of silvopasture soils compared to treeless pasture soils in this study is consistent with previous studies<sup>20,24,25,40</sup>. Because soil type and animal stocking were consistent between treatments, one explanation for lower bulk density in silvopastures is due to root exudates and tree roots that penetrate the soil<sup>20</sup>. Tree root respiration and activity may also stimulate the biological soil community in silvopastures more than that of treeless pastures. This can affect bulk density by enhancing nutrient cycling and increasing available carbon, which is converted by microbial activity into soil organic carbon. For example, Poudel et al.<sup>41</sup> found that soil microbial biomass was 45–60% greater in a temperate hardwood silvopasture compared to treeless pasture. Tree roots may also play a role in mitigating the physical impact of livestock hooves on pasture soils, potentially contributing to the lower bulk density of silvopasture soils compared to treeless pastures. Additionally, management practices of treeless pastures with a longer history of grazing and higher stocking rates may have resulted in higher soil compaction when compared to silvopastures<sup>40</sup>. However, in contrast to our study, Upson et al.<sup>42</sup> found that a 24-year-old silvopasture in England had higher soil bulk density than adjacent treeless pasture. The authors speculated that soil compaction may have occurred during the tree planting activities on the clay soil, leading to increased bulk density in the silvopasture treatment<sup>42</sup>. In contrast, Sharrow and Ismail<sup>22</sup> did not find a difference in bulk density between an 11-year-old silvopasture and treeless pastures in Oregon, USA. Likewise, Poudel<sup>41</sup> did not report a difference in bulk density between 28-year-old silvopastures and treeless



**Fig. 2.** Comparison of carbon stocks within farms for silvopasture and adjacent treeless pasture. Carbon pools include soil, forage (roots and 0–10 cm aboveground), and tree (roots and aboveground). Significant differences of  $p \leq 0.05$  for ecosystem carbon stocks between treeless pasture and silvopasture within farms are indicated by a \* next to the farm label. Note that data from “All Farms” were not analyzed for significance because each farm was analyzed independently and comparisons were not made between farms. Note that soil carbon accounts for the majority of ecosystem carbon on all farms, while tree carbon accounts for additionality between silvopasture vs. treeless pasture. Forage carbon is a relatively small pool of carbon when compared to soil or tree carbon content.

pastures in Virginia, USA. However, the relatively young age of that system may have been a contributing factor. Variation in studies suggests numerous factors are at play, ranging from underlying soil type, management intensity, to system age for tree roots to spread.

### Soil carbon

Across all five farms, soil carbon did not differ between silvopastures and treeless pastures when using fixed depth sampling (Table 3) or ESM (Supplement Table 1). These findings are like those reported by Upson et al.<sup>42</sup> and Amézquita et al.<sup>43</sup>. However, they are in contrast with several studies that reported increased soil carbon in planted silvopastures when compared to treeless pasture<sup>14,29,31,41</sup>. Given the complexity of silvopasture systems, which vary based on species composition, tree arrangement and stocking, age, management, and land use history, it is not surprising that there is disagreement between studies, and this is supported by variation between farms within our study (Fig. 2). For example, Poudel et al.<sup>41</sup> found that soil carbon was higher in silvopasture treatments with honeylocust (*Gleditsia triacanthos*) when compared to treeless pasture controls. However, silvopasture treatments with black walnut (*Juglans nigra*) had similar total carbon levels as treeless pastures, illustrating a species effect for silvopastures of the same age and growing on the same site. Beckert et al.<sup>20</sup> reported similar variability in soil carbon for three different tree species growing in a planted silvopasture in Scotland. Silvopastures also vary in tree arrangement, with some silvopastures consisting of tree rows with alleys of forage in between, or scattered trees with forage below, or small patches of trees surrounded by forages<sup>2</sup>.

Tree stocking also has an impact on soil carbon, with some studies sampling systems more akin to a savanna<sup>44</sup>, while others are more similar to a forest<sup>45</sup>. Such variation in tree arrangement and stocking likely impact carbon dynamics and the ability to easily compare studies. Furthermore, management has been found to affect carbon dynamics. Nyakatawa et al.<sup>46</sup> found that silvopasture treatments with more intensive management (i.e., enhanced forage plots with more soil disturbance during establishment) had lower total soil carbon accumulation than other treatments. Pinheiro et al.<sup>47</sup> also found that silvopastures had less SOC than pasture treatments and suggested that tilling the silvopasture during establishment may have reduced carbon stocks due

to the disturbance. Silveira et al.<sup>48</sup> also described how management may have affected the comparison between silvopasture and native rangeland in their study since the silvopastures were seeded with more productive warm-season grasses.

Authors of several studies suggested that land use history likely impacts soil carbon dynamics between silvopasture and adjacent pasture controls. Amorim et al.<sup>19</sup> found that soil organic carbon content was 18% greater in silvopastures compared to treeless pasture at a depth to 15 cm, but the silvopasture had been fertilized with poultry litter during the first 7 years of establishment, while the treeless pasture was treated with urea during the first two years, and both were treated equally 15 years later. Fertilization differences can impact soil organic carbon in ways that mask the treatment effect of establishing trees. When the treeless pasture control contains well-established perennial forages, there is less likelihood to find significant differences in soil organic carbon with conversion to silvopasture due to relatively high initial carbon stocks in perennial pasture systems, as compared to converting a continuously grazed pasture<sup>49</sup> or annually tilled cropland<sup>50,51</sup> to rotational grazing or silvopasture. Lack of significant differences between soil carbon in silvopasture vs. treeless pasture in this study may have been due, in part, to pasture systems being well-managed on the five farms sampled. This is likely as all farms in this study utilized some form of managed rotational grazing in both silvopastures and treeless pastures.

Variation between studies may also be due to the sampling approach. For example, there is a wide range of depths used for soil sampling in silvopasture studies, ranging from 10 cm<sup>24</sup> down to 125 cm<sup>29</sup>. As described in Cardenas et al.<sup>52</sup>, the quantification of SOC to varying depths likely impacts whether differences are significant. However, as illustrated in our study, if sampling occurs on numerous farms, the depth to which soil sampling can occur will likely vary based on ledge, bedrock or hardpan.

### Forage carbon and biomass

Across all five study farms, total forage carbon was generally lower in silvopasture treatments (7.24 Mg C ha<sup>-1</sup>) than in adjacent treeless pastures (7.84 Mg C ha<sup>-1</sup>) (Table 3). Aboveground forage carbon (0–10 cm) also trended lower in silvopastures than in treeless pastures, though only significant for two of the five farms (Table 4). These trends are consistent with other studies. For example, Aryal et al.<sup>14</sup> reported aboveground forage carbon of 0.78–1.91 Mg C/ha for silvopastures and 1.80–2.66 Mg C/ha for open pastures. While not reporting forage carbon specifically, several studies have also reported lower forage biomass in silvopastures than adjacent treeless pasture controls<sup>53–58</sup>. For example, Sharrow et al.<sup>55</sup> found that silvopastures had roughly 12% less forage biomass than treeless pastures in Oregon, USA. Similarly, Orefice et al.<sup>57</sup> reported 38% less aboveground forage biomass for silvopastures in the Northeastern U.S. during the first year after establishment, but no significant difference in forage biomass during the second year after establishment. Amorim et al.<sup>19</sup> found similarly variable results with no significant difference at the system level for silvopastures vs. treeless pastures, but an interaction between forage species and time of year regarding forage production in silvopasture compared to treeless pasture.

Forage carbon in roots was generally lower in silvopastures than that of treeless pastures on 4 of 5 farms in this study, though only significant for Farm A (Table 4). This may suggest that silvopastures have less belowground resources per unit area to use for recovery from overgrazing. From a management perspective, forage data from this study suggests that carrying capacities of some silvopastures may be less than those of treeless pastures. However, this also depends on other factors of these systems which we did not account for, such as grazing season length, seasonal differences in forage production, and forage composition. Other factors in a silvopasture may not lead to greater forage biomass but may lead to greater forage health or quality throughout the year, such as reduced drought stress and potential fertilization from leaf fall during the autumn. For several of the farms in this study, grazing durations per unit area used in treeless pastures would likely result in overgrazing if directly applied to the silvopastures. These results indicate a need for grazing management to be customized to silvopasture conditions because forage biomass differs in amount and likely seasonality, when compared to treeless pastures.

A primary reason why some silvopastures have lower levels of aboveground and belowground forage carbon and biomass compared to treeless pastures may be due to a combination of factors, such as reduced solar radiation reaching the understory, competition for water, nutrients, and growing space, potential allelopathy, and species of tree<sup>55,56,58</sup>. Tree species in silvopasture can be strategically selected based on growth rate, crown shape, and leaf morphology to better manage light interception and forage growth. Producers can also manage light levels through periodic thinning to maintain desired forage growth conditions. For example, Bird et al.<sup>53</sup> investigated net primary productivity of silvopastures vs. treeless pastures and found no significant difference when trees were widely spaced (4.17 t ha<sup>-1</sup> vs. 4.83 t ha<sup>-1</sup>). However, as tree density increased, forage production decreased significantly, a finding also reported in Fernandez-Nunez et al.<sup>59</sup>. These studies, along with ours, illustrate a potential tradeoff between the tree and forage components for both biomass and carbon, which can be modified through management.

While total forage carbon and total forage biomass in this study were 7.65% and 21.18% lower in the silvopastures than treeless pastures across farms, the reduction compared to treeless pasture controls was not as large as reported in other studies. One possible reason is that the forages in this study were diverse mixtures of native and non-native cool-season grasses, which are typical for temperate pasturelands and are more tolerant of shaded conditions than warm-season forage<sup>60</sup>. This tolerance to shade may be one reason why we found total forage carbon in silvopastures to only be slightly less than total forage carbon in treeless pastures. Lin et al.<sup>61</sup> found that some forages grown in shade adapt their aboveground morphology to increase their leaf area. Additionally, the microclimate provided by tree canopies in silvopastures may allow cool season forages to buffer losses in biomass due to light competition by reducing moisture stress during the day<sup>62</sup>. Since cool season grasses are C3 plants, a more humid environment during the day will allow them to photosynthesize during times when forages in treeless pastures must stop due to heat stress<sup>62</sup>. Amorim et al.<sup>19</sup> documented this in a study of 20-year-

old silvopastures where orchardgrass (C3) produced more in silvopastures, while southeastern U.S. native warm season grasses (C4) had instances of being more productive in treeless pastures.

It is important to note that forage carbon content in this study was based on forage biomass below 10 cm in height. While this height was set as a standard to avoid sampling timing issues with time since last grazing period, it limits the study to providing a conservative estimate of aboveground forage biomass. Future research would have improved results if researchers can sample total forage biomass throughout the year, and that would require regular sampling periods during the active and inactive grazing seasons. It would also be important to monitor forage biomass over multiple years as moisture during the grazing season, and wind exposure during the winter, can significantly change total aboveground forage biomass.

### Tree carbon

Results from this study indicate that total tree carbon was a major contributor to the difference in total system carbon between silvopastures and treeless pastures, accounting for an average of 30% of the ecosystem carbon in silvopastures (Table 3). This is notable because forage carbon was generally lower in silvopastures and soil carbon was statistically similar between the two systems, indicating that tree carbon more than compensated for reduced forage carbon in silvopastures. Similar results were reported for a temperate silvopasture system in England, where the tree component compensated for carbon losses in other pools<sup>42</sup>. Tree carbon also varied greatly between farms due to system age, species composition, and stem density managed by each producer. This finding is consistent with the variability found on silvopasture sites in the region<sup>2</sup>. It should be noted that the total tree carbon reported in this study may also be an underestimate, due to the use of allometric equations, which can lose accuracy when applied to silvopasture systems<sup>63</sup>. These equations are typically derived from trees grown in forests, rather than in lower tree density systems like silvopastures. Competition for light and space in forests promotes height growth, which decreases diameter growth and live crown ratio<sup>64</sup>. For example, Dube et al.<sup>65</sup> found that allometric equations underestimated carbon for *Pinus ponderosa* grown in a silvopasture by 15–30% when compared to measured biomass data from destructive sampling. In contrast, Dold et al.<sup>45</sup> did not find a meaningful difference between allometric equations and measured biomass for *Quercus rubra* grown in a silvopasture, though the tree density of the silvopasture was high, with the authors suggesting that the planting may have been closer to a forest on the continuum of silvopasture systems. Therefore, it is likely that some of the tree biomass results from this study are an underestimation of carbon, especially for the silvopastures being managed with lower stocking levels to keep consistent light levels for forage growth. One additional limitation with the allometric equations used in this study is that they were based only on species and DBH measurements. Carbon content quantification of trees in silvopastures would be improved if researchers would develop allometric equations for trees in the United States that include tree height and canopy size, in addition to DBH.

While developing agroforestry-specific allometric equations would be beneficial for more accurate determination of carbon stored in tree biomass, it would be a difficult task, given the range of tree species used in silvopasture systems. For example, there were 10 different tree species used across the five farms in this study. Additionally, there is great variability in how many trees per hectare producers manage for in their silvopasture over the course of a rotation. In silvopasture systems that prioritize tree products, the stocking may be managed to near-forest levels, while other systems may prioritize forages and maintain more openly grown trees in a savanna-like system. Such a wide continuum of management poses challenges for developing silvopasture-specific allometric equations for tree carbon. Regardless, trees were found to be a major driver of ecosystem carbon in silvopasture systems in our study. When compared to treeless pastures, the tree component of silvopastures serves as a clear and reliable form of additionality in ecosystem carbon content.

### Ecosystem carbon

Overall, ecosystem carbon in silvopastures (136.42 Mg C ha<sup>-1</sup>) trended greater than treeless pastures (95.47 Mg C ha<sup>-1</sup>). The carbon stock values for the silvopastures in this study are slightly lower than northern hardwood forests in this region. More specifically, Catanzaro and D'amato<sup>66</sup> reported ecosystem carbon values of 190 Mg C ha<sup>-1</sup> for 80–100-year-old northern hardwood forests in the region, while Hoover, et al.<sup>67</sup> reported average total carbon stocks of 216 Mg C ha<sup>-1</sup> for old-growth northern hardwood forests. While these studies both found higher ecosystem carbon stocks, differences can be attributed to the older trees in more heavily stocked stands. Additionally, ecosystem carbon values in this study are conservative estimates because of previously mentioned issues with tree allometric equations, and our method for quantification of soil carbon to a shallower uniform sampling depth between paired silvopasture/treeless pastures. It should be noted that if the silvopastures in this region are maintained as a true silvopasture, the carbon pool in live trees should not near, or exceed, forest-like conditions due to shade inhibition of forages. Hence, the ecosystem carbon values described in the previous two studies on regional forest carbon content are not likely attainable in silvopastures.

This study found that silvopasture establishment increased ecosystem-level carbon stocks by 43% in the northeastern U.S. when compared to treeless pasture. Given that there are 291,662 ha of permanent pasture and rangeland in the study region<sup>13</sup>, there is potential to increase carbon storage on these grazing lands by transitioning treeless pasture to silvopasture where appropriate. For context, if 10% of these treeless pastures were instead silvopastures of the same average age and type of those in this study, they would store 1,194,355 megagrams of additional carbon when compared to their current treeless condition. This additional carbon would be primarily in the form of tree biomass. Conversion of treeless pasture to silvopasture through tree planting could also improve other ecosystem services, such as wildlife habitat, water infiltration rates, and nutrient cycling<sup>1</sup>, while providing economic diversification for the producer and improved welfare for the livestock. However, upfront costs of establishment are a key barrier to silvopasture adoption in the U.S.<sup>1</sup>.

## Conclusions

As illustrated in this study, carbon stocks varied greatly from farm to farm with forage carbon accounting for only a small portion of total stocks and tree carbon serving as clear additionality (Fig. 2). Furthermore, while this study assessed carbon stocks from an ecosystem perspective, it did not investigate fluxes between the various pools of the ecosystem or how potential changes in management (i.e., livestock stocking rates) may vary between the two management systems. One shortcoming of this study was that it was a snapshot in time on each farm. Future studies would do well to monitor carbon pools throughout the year in silvopasture systems since grazing season, animal stocking rates, and leaf and forage senescence all fluctuate through the year. While previous studies have found lower CO<sub>2</sub> and N<sub>2</sub>O fluxes in silvopasture systems when compared to treeless pastures<sup>26</sup>, additional research is needed to understand the degree to which silvopasture is a climate-mitigating management practice and how that may vary between operations. Still, this research illustrates that silvopasture systems originating from tree establishment into treeless pastures are capable of storing large quantities of additional carbon while providing producers with numerous co-benefits.

## Data availability

Data is provided within the supplementary information files for this paper.

Received: 12 November 2024; Accepted: 19 February 2025

Published online: 27 February 2025

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## Acknowledgements

We would like to thank the Yale Forests and Yale School of the Environment for providing space to process samples. Our most sincere thank you goes out to the farmers who so willingly allowed this research to occur on their farmland. This work was supported in part by the U.S. Department of Agriculture, Forest Service. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

## Author contributions

J.O. developed the research design with M.M.S. W.C.W. conducted the research as a Master's student mentored by J.O. and M.M.S. W.C.W. conducted the preliminary data analysis and wrote an early draft of the manuscript. J.O. M.M.S. and M.B. conducted the final analyses, developed the final figures, and wrote the final draft of the manuscript.

## Declarations

### Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-91268-6>.

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