Management Intensification Impacts on Soil and Ecosystem Carbon Stocks in Subtropical Grasslands

Proper management of grassland ecosystems for improved pasture productivity can also enhance their potential to serve as sinks for anthropogenic carbon (C). We assessed the long-term (>22 yr) effects of grassland intensification (conversion of native rangeland to slash pine-bahiagrass silvopasture or bahiagrass-sown pasture) on above- and belowground C stocks in a subtropical ecoregion. Soil cores (0- to 30-cm depth) were collected from five equidistant quadrats (20 × 20 m) established along a diagonal transect within each of the experimental units. Root and aboveground biomass responses to grassland intensification were also evaluated. Management intensification resulted in increased soil organic C (SOC) stocks from 41 Mg ha⁻¹ in the native rangeland to 62 and 69 Mg ha⁻¹ in sown pasture and silvopasture, respectively. Additional C storage occurred in the live biomass of slash pine trees in silvopasture (58 Mg ha⁻¹), while the C accruing to woody biomass in native rangeland (3 Mg ha⁻¹) was lost after conversion to sown pasture. Conversion to tree-integrated silvopastoral ecosystem favored the sequestration of a more stable mineral-associated C fraction (41.8 Mg ha⁻¹; ~200% increase) compared with the native rangeland. Ecosystem C was greater in silvopasture (144 Mg ha⁻¹) and in sown pasture (83 Mg ha⁻¹) relative to the reference native rangeland (69 Mg ha⁻¹). This research supports growing evidence that increasing intensity of grassland management is beneficial for soil and ecosystem C sequestration in the long term; however, shifts in the allocation of C into ecosystem pools will likely have implication for biochemical cycling within this subtropical ecoregion.

Abbreviations: POC, particulate organic carbon; PON, particulate organic nitrogen; SOC, soil organic C.
The objective of this study was to evaluate the long-term effects of grassland intensification on soil organic carbon (SOC) and overall ecosystem sustainability in a native subtropical rangeland. The study was conducted on adjacent fields of three management systems that were applied to optimize grassland productivity in relation to the broader context of grassland management systems. Most research studying the effects of grassland management on soil organic matter is limited to temperate regions (Batjes and Sombroek, 1997), but it is also crucial for the development of sustainable management strategies focused on maintaining and improving soil resources as well as overall ecosystem sustainability (Batjes and Sombroek, 1997).

A significant proportion (~30%) of the global soil organic C is sequestered in subtropical and tropical ecosystems (Dalal and Carter, 1999), and little is known about C and N dynamics in relation to the broader context of grassland management systems. Most research studying the effects of grassland management on soil organic matter is limited to temperate regions (Batjes and Sombroek, 1997; Silveira et al., 2013), often focused on individual management practices (Conant et al., 2001), and predominantly conducted as short-term experiments (Dubeux et al., 2006; Chan et al., 2010; Peichil et al., 2012; Silveira et al., 2013). Several researchers have attempted to elucidate changes in C and N stocks after land-use conversion (Corre et al., 1999; Guo and Gifford, 2002; Pucheta et al., 2004; Sharrow and Ismail, 2004; McLaughlin et al., 2006) but they focused primarily on transitions from broad agricultural or forest land-cover type to grassland pasture and vice-versa.

There is limited knowledge of the effect of land-use change on ecosystem C within grassland ecosystems, especially in relation to the increasing global trend of conversion of native grasslands to more intensively managed grassland ecosystems (White et al., 2000). Addressing this knowledge gap is not only critical for improved accuracy in modeling ecosystem C responses to global land-use changes (Batjes and Sombroek, 1997; Fynn et al., 2009), but it is also crucial for the development of sustainable management systems that can improve C sequestration and mitigation of atmospheric CO2 concentration (Sobecki et al., 2001). The objective of this study was to evaluate the long-term effects (20+ years) of grassland intensification on SOC and overall ecosystem C stocks, taking advantage of a unique long-term experimental setup in a native subtropical rangeland.

**MATERIALS AND METHODS**

**Study Site**

The experimental site is located at the University of Florida Range Cattle Research and Education Center in Ona, Florida (27°23’76” N, 82°56¢11˝ W). The site is characterized by relatively homogenous slope (~5%), and subtropical climate with 10-yr average annual precipitation of ~1206 mm and temperature of ~21.5°C. The study was conducted on adjacent fields of three grassland management systems that have been established and consistently maintained for over 20 yr. The three management systems consist of a gradient of management intensities ranging from native rangeland (lowest), silvopasture (intermediate), to sown pasture (highest). Before the establishment of the adjacent silvopasture and sown pasture, the entire site was native rangeland for livestock grazing. Each collocated ecological unit was replicated twice (6 ha each; Fig. 1). The dominant soil series was the same across the sites and consisted of Ona and Immokalee fine sand (sandy siliceous, hyperthermic Typic Alaquods). This soil was developed on parent material of sandy marine deposits (Soil Survey Staff, 2013).

**Native Rangeland**

The native rangeland treatment consisted primarily of saw palmetto (*Serenoa repens* Bartr.) and a wide variety of grass genera including *Andropogon*, *Panicum*, * Aristida*, and *Schizachyrium* spp. (Kalmicher et al., 1984). The native rangeland was never fertilized, but it had been subjected to periodic burning (every 3 yr), occasional livestock grazing activities (~60 d yr-1), and herbivory by wildlife, all typical features of rangeland in this region. Each experimental unit was grazed only during winter at a rate of 125 animal days ha-1 yr-1. Each animal unit (average live weight = 500 kg) was fed a daily supplement of warm-season grass hay and sugarcane molasses at 1.5 to 1.9 kg cow-1 d-1 and 0.7 kg cow-1 d-1, respectively, throughout the grazing period.

**Silvopasture**

The silvopasture system has been managed for 22 yr and consists of slash pine (*Pinus Elliottii*) trees planted in double-rows (1.2 m along x 2.4 m between rows), and bahiagrass (*Paspalum notatum*) planted in alleys (12.2 m wide). The vegetation of the silvopasture was established in order of bahiagrass first, followed by slash pine, on a previously native rangeland. Native vegetation was suppressed by burning followed by plowing (~45 cm deep) and disking with a dual tandem disk harrow until there was no vegetation on the soil surface. These experimental units received periodic applications of 67 kg N ha-1 yr-1 as ammonium nitrate. No fertilizer was applied in the years of 1993 to 1997, 2000, 2002, 2008, 2009, and 2011. Grazing of the silvopasture began in March 1993, 18 mo after planting the trees, and has continued from March to September every year. Each experimental unit was rotationally stocked for 7 mo each year, with a 2-wk grazing period followed by a 5-wk resting period. Stocking rate was 207 animal days ha-1 yr-1. Animals were supplemented in the pasture with warm-season grass hay and sugarcane molasses at 1.5 to 1.9 kg cow-1 d-1 and 0.7 kg cow-1 d-1, respectively, from January to April. The management conditions that were applied represented limited inputs of fertilizer and moderate levels of biomass removal through grazing.

**Sown Pasture**

The sown pasture system consisted of 32-yr-old bahiagrass stand, which was managed to provide forage for grazing livestock. Each experimental unit was stocked at a rate of 360 animal days ha-1 yr-1. Grazing occurred on a rotational basis for 7 mo, with 1-wk residence period followed by 1-wk rest pe-
period between each grazing event. Each animal unit (average live weight = 500 kg) was fed a daily supplement of warm-season grass hay and sugarcane molasses at 1.5 to 1.9 kg cow\(^{-1}\) d\(^{-1}\) and 0.7 kg cow\(^{-1}\) d\(^{-1}\), respectively, from January to April. Ammonium nitrate fertilizer was applied at an annual rate of 67 kg N ha\(^{-1}\) yr\(^{-1}\) and dolomite was applied in 2001 and 2008 at a rate of 730 and 550 kg ha\(^{-1}\), respectively. These management conditions are typical of the beef cow–calf production system in Florida.

Experimental Design and Sampling Protocol

The study was based on a comparative-mensurative experimental design (Arevalo et al., 2009; Hurlbert, 1984) because the two replicate fields (6 ha each) of each management ecosystems are collocated; in other words, the treatment replicates are not spatially dispersed. This experimental design has an underlying assumption that the soil properties of the three ecosystems (native rangeland, silvopasture, and sown pasture) were similar before the conversion and designation of each ecological unit (Hurlbert, 1984; Arevalo et al., 2009). Factors such as the uniformity of initial land use, the flat terrain, and the limited potential for variation in the sandy textural class of the soils, which were all formed from the same parent material (Kalmbacher et al., 1984, 1993), lends credence to our assumption that the soils were similar before the management changes were imposed. However, similar to the general limitations of most long-term ecological studies (Janzen, 1995; Millar and Anderson, 2004), there were no data available on the soil properties before the land-use conversion (i.e., conversion to more intensively managed ecosystems), and some measure of spatial variability is bound to be inherent within the study area.

Belowground Sampling and Analysis

Soil sampling was conducted in June/July 2012 which corresponds to the period of maximum ecosystem productivity and biochemical cycling rates (decomposition/mineralization). A comparative-mensurative experimental design (Hurlbert, 1984; Arevalo et al., 2009) was adopted to assess above- and belowground biomass across the three ecosystems. The most important consideration for this design is to ensure that replicates are dispersed in space (or time) in a manner appropriate to the specific hypothesis being tested (Hurlbert, 1984). An initial offset (30 m) was established from the edge of each field to avoid potential edge effects, and five quadrats (20 × 20 m), spaced ~75 m apart, were marked out along a diagonal transect within the inner boundary (Fig. 1). Four randomly located soil cores (diameter of 2.2 cm) were sampled from each quadrat at soil depths of 0 to 10, 10 to 20, and 20 to 30 cm and composited within a depth for C and N analysis, while one random soil core was sampled in each quadrat for bulk density determination.

Soil samples were air-dried and sieved (2-mm-sized sieve), and the modified version of the procedure described by Cambardella and Elliott (1992) was adopted to separate SOC and N into two particle-size fractions: particulate organic C (POC) and N (PON) which corresponded to the >53-µm-sized particles, and mineral-associated C and N which corresponded to the <53-µm-sized particles. Carbon and N concentrations
were determined by dry combustion using a ThermoFlash EA 1112 elemental analyzer. Soil C and N stocks in each ecological unit were calculated based on the C and N concentration and the bulk density at each depth. For bulk density, the soil samples collected at each soil depth interval were dried at 105°C until constant weight and weighed. Bulk density was computed by dividing the dry weight by the soil core volume.

Belowground root biomass samples were collected using AMS hydraulic powerprobe (Arts Manufacturing and Supply, American Falls, ID) equipped with soil coring drills (diameter of 5 cm). Three soil cores were randomly sampled in each quadrat at the 0 to 10, 10 to 20, and 20 to 30 cm depths. Samples were air-dried and subsequently dispersed in water to separate roots from soil particles through sieving (sieve size = 250 µm). Root samples were dried to constant weight at 65°C, and final weight was recorded after 3 d. The dried root samples were combusted at 550°C for 5 h to determine ash concentration. Carbon and N concentrations were determined by dry combustion using a ThermoFlash EA 1112 elemental analyzer. Root biomass C presented here is expressed on an ash-free basis.

Aboveground Biomass Sampling

The aboveground biomass measurement was conducted in mid-summer, to estimate the biomass during the period of peak annual primary production. Sampling was strategically conducted to capture the peak production under each management system such that (i) sown pasture was sampled 5 d after the cows had been moved out of the pastures, i.e., 2 d before the next herd moved in; (ii) silvopasture was sampled ~4 wk after the cattle had been moved out; and (iii) native rangeland was sampled after ~3 mo of being ungrazed by cattle. Different sampling strategies were employed across the ecological units because of the different vegetation composition.

Aboveground Biomass C in Sown Pasture

A double-sampling method (Wilm, 1944) was adopted to quantify aboveground biomass in the sown bahiagrass pastures. The compressed vegetation height was estimated at 40 stratified random sampling locations (~30 m apart) using a disc meter (diameter = ~0.6 m), while double sampling included measurement of both disc height and biomass under the disc at 12 locations across the experimental units. At each double-sampling location, the biomass within the confines of the disc’s circumference was harvested with a cordless grass shear to soil level (Homelite, Anderson, SC), raked and collected into cloth bags. The collected biomass samples were oven-dried to constant weight (at 65°C for 5 d). The dry biomass was regressed on the disc height for all double samples from a given treatment to develop a calibration equation ($r^2 = 0.8$) for prediction of total aboveground biomass in each experimental unit based on the average of the 40 disc heights taken on that experimental unit. Biomass C was calculated by multiplying the biomass by a standard factor of 0.5 (Poorter et al., 1997)).

Aboveground Biomass C in Silvopasture Field

Due to the morphological differences of the tree and grass components of the silvopasture fields, the biomass C content of these two components were quantified separately. To derive the biomass C content of the bahiagrass component, the same procedure adopted for the sown pasture (as described above) was applied. To estimate the biomass of the tree component, the diameter at breast height (DBH) of all trees in each field was measured with a girth tape. Published allometric equations that relate biomass to this parameter (Santantonio et al., 1977; Gonzalez-Benecke et al., 2010) were used to estimate the total aboveground biomass of the tree (Eq [1]), and the estimated biomass was corrected for logarithmic bias (Baskerville, 1972). The summation of the standing tree and the bahiagrass biomass C constituted the aboveground biomass C of each field. Biomass C was also calculated by multiplying the biomass by a standard factor of 0.5:

$$\ln(B_{AGT}) = -2.5563158 + 2.5209397 \times \ln(DBH)$$

$$CF = \exp (\text{MSE}/2)$$

where, $B_{AGT}$ = aboveground biomass of trees, DBH = diameter at breast height, CF = correction factor for logarithmic bias, and MSE = estimated mean square error of the allometric equation (Baskerville, 1972).

Aboveground Biomass C in Native Rangeland

We adopted a different double-sampling strategy to quantify aboveground biomass in native rangeland (Ebrahimi et al., 2008). Twelve quadrats (4 m²), 30 m apart, were sampled along the diagonal transect. The percentage of woody and nonwoody vegetation coverage in each quadrat was determined by visual-ocular observation, using a standard reference (Barry, 1998). To minimize estimation bias, two independent observers recorded the percent cover, and the final values were obtained by averaging the two observations for each quadrat. Percentage cover was adopted as the proxy (and high-frequency) sample, while vegetation biomass was quantified at every third quadrat along the sampling transect. The woody and shrubs biomass were stored in separate perforated polyethylene bags and dried (to constant weight) for 3 wk at 65°C. The period of drying was prolonged to ensure adequate drying of the woody biomass. Regression equations were developed to relate the weight of the dry biomass to the estimated percent vegetation cover (i.e., total, woody, and nonwoody). The equation ($r^2 = 0.7$) was applied to estimate the total biomass in each field based on the percent vegetation (woody and shrubs) coverage per quadrat. Biomass C was also calculated by multiplying the biomass by a standard factor of 0.5.

Statistical Analysis

Descriptive and statistical analyses were conducted using SAS 9.2 software (SAS Institute, 2001). The effect of grassland biome on above- and belowground C parameters was evaluated.
using the one-way ANOVA procedure. Grassland biomes were considered as the independent treatment effect while the bulk density, aboveground biomass, root biomass, SOC, and soil N stocks were the dependent response variable. Although multiple subsamples were collected within each experimental unit, values were averaged per field replicate within each grassland biome to avoid pseudo-replication bias. Treatments were considered different when F-test P values were <0.05. Mean separation was performed using Tukey studentized range test.

RESULTS

Soil Organic Carbon Stocks

Intensification of grassland by converting native rangeland to silvopasture and sown pasture had significant positive effects on SOC stock at all soil depth intervals (Table 1). In comparison with native rangeland, SOC under silvopasture was 38% higher but not different in sown pasture at the 0- to 10-cm soil depth interval. At 10- to 20-cm and 20- to 30-cm depth interval, SOC increased (88 and 68%, respectively) following conversion to sown pasture, while it increased to a greater degree following conversion to silvopasture (117 and 108%, respectively). The cumulative (0–30 cm) SOC stock also increased after conversion of native rangeland to sown and silvopasture (52 and 69% increase, respectively). However, the cumulative SOC was not different between sown pasture and silvopasture (62 and 69.2 Mg C ha⁻¹, respectively).

Differences in soil bulk density among the grassland biomes were observed at 0- to 10-cm depth but not at deeper (10–30 cm) soil depths (Fig. 2). Soil bulk density generally increased with increase in soil profile depth, and minimum and maximum values were observed in sown pasture, ranging from ~1.0 g cm⁻³ at 0 to 10 cm, to 1.5 g cm⁻³ at 20 to 30 cm.

Soil N Stocks

Comparison of the three management systems showed differences in soil N stock in the upper 0- to 10-cm and 10- to 20-cm soil depths (Table 1). At both depth intervals, higher N stock was observed in the sown pasture (2.01 and 1.02 Mg N ha⁻¹, respectively) and silvopasture (1.93 and 1.13 Mg N ha⁻¹, respectively), compared with native rangeland (1.36 and 0.45 Mg N ha⁻¹, respectively). Similar results were obtained for the cumulative N across the sampled soil profile (0–30 cm) where higher N stock was observed in both sown pasture and silvopasture (3.83 Mg N ha⁻¹ and 3.94 Mg N ha⁻¹, respectively), compared with the native rangeland (2.40 Mg N ha⁻¹).

Soil C to N ratios ranged between 14 (in native rangeland at 20- to 30-cm soil depth) to 21 (in native rangeland at 10- to 20-cm soil depth). Soil C to N ratio reduced in sown pasture at upper 0- to 10-cm while it reduced in silvopasture at 10- to 20-cm soil depths, relative to native rangeland. However, there was no significant difference in the mean C to N ratio of all ecosystems across the sampled soil depth (0–30 cm; Table 1).

Particulate and Mineral-Associated Organic C and N

The quantity of POC only increased in sown pasture but not in silvopasture, compared with the reference native rangeland (Table 1). Particulate organic carbon fraction in the sown

<table>
<thead>
<tr>
<th>Management system</th>
<th>Depth 1, 0–10 cm</th>
<th>Depth 2, 10–20 cm</th>
<th>Depth 3, 20–30 cm</th>
<th>Cumulative Depth, 0–30 cm</th>
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<td></td>
<td>SOC, Mg C ha⁻¹</td>
<td>Soil N, Mg N ha⁻¹</td>
<td>Soil C to N ratios</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Mineral fraction</td>
<td>POC†</td>
<td>Total</td>
</tr>
<tr>
<td>Native rangeland</td>
<td>23.8b§</td>
<td>7.96b (33.5)</td>
<td>15.9b (66.5)</td>
<td>1.36b</td>
</tr>
<tr>
<td>Silvopasture</td>
<td>32.9a</td>
<td>12.9a (39.2)</td>
<td>20.0b (60.6)</td>
<td>1.93a</td>
</tr>
<tr>
<td>Sown pasture</td>
<td>31.5ab</td>
<td>8.31b (26.4)</td>
<td>23.2a (73.6)</td>
<td>2.01a</td>
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<td>0.013</td>
<td>0.006</td>
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<td>Native rangeland</td>
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<td>6.75 (79.9)</td>
<td>1.70 (20.1)</td>
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<td>2.54 (14.2)</td>
<td>0.87</td>
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<td>11.3 (79.6)</td>
<td>2.94 (20.4)</td>
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<td>1.32b (55)</td>
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<td>Silvopasture</td>
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<td>28.1b (45.3)</td>
<td>33.9a (54.7)</td>
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<td>P-value</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

† POC, particulate organic C.
‡ PON, particulate organic N.
§ Means followed by the same letter within column (by depth) are not significantly different according to Tukey studentized range test (α = 0.05); ns, not significant.
pasture increased at 0- to 10- cm and 10- to 20-cm depths (7.3 and 4.5 Mg C ha$^{-1}$ increase, respectively), but there was no difference at 20 to 30 cm. Across all depths (0–30 cm), POC in native rangeland (21 Mg C ha$^{-1}$) does not differ significantly from silvopasture (27 Mg C ha$^{-1}$) but it was higher in sown pasture (34 Mg C ha$^{-1}$). Sown pasture and silvopasture were not different at all depth intervals (Table 1). Similar to POC, the PON content and the relative percentage to total N decreased with depth across all ecosystems (Table 1). Sown pasture contained the highest PON at 0- to 10-cm and 10- to 20-cm depths (1.47 and 0.45 Mg N ha$^{-1}$, respectively), and across the sampled soil depth (2.09 Mg N ha$^{-1}$; Table 1).

The quantity and relative percentage of C and N associated with the mineral fraction increased in the silvopasture ecosystem at upper (0–10 and 10–20 cm) soil depth intervals, but did not change in sown pastures, compared with the reference native rangeland (Table 1). In contrast to the sown pasture which contained the highest POC at all depths (except 20–30 cm), silvopasture contained highest quantity and percentage of mineral-associated C and N fraction at all soil depth intervals (up to 15.1 Mg C ha$^{-1}$, and 86% of SOC at 20- to 30-cm depth).

**Root Biomass C**

Root biomass C decreased at deeper soil depth (10–30 cm) as management intensity increased (Fig. 3). At the 10- to 20-cm depth, greatest root biomass C was associated with the native rangeland (7.1 Mg C ha$^{-1}$) as compared with the sown pasture (3.1 Mg C ha$^{-1}$) and silvopasture (2.8 Mg C ha$^{-1}$). A similar trend was observed at the 20- to 30-cm depth. Across the sampled soil profile (0–30 cm), relative to root C in native rangeland (23.9 Mg C ha$^{-1}$), root biomass C in sown pasture (18.8 Mg C ha$^{-1}$) was not different, while it was lower (15.4 Mg C ha$^{-1}$) in silvopasture (Fig. 3). However, root C in sown pasture and silvopasture was similar. Generally, the highest proportion of the total root biomass C in all ecosystems accrued in the 0- to 10-cm depth and declined at lower depths.

**Aboveground Biomass C**

The total aboveground biomass C (woody + nonwoody) was significantly greater in silvopasture (59 Mg C ha$^{-1}$) compared with native rangeland and sown pasture (4.2 Mg C ha$^{-1}$ and 2.1 Mg C ha$^{-1}$, respectively; Fig. 4). Woody vegetation components of the native rangeland (saw palmetto) and silvopasture (slash pine) accounted for 70 and 98% of their total aboveground vegetation biomass, respectively.

**Ecosystem C**

Total ecosystem C was 69 Mg C ha$^{-1}$ in native rangeland, 83 Mg C ha$^{-1}$ in sown pasture, and 144 Mg C ha$^{-1}$ in silvopasture (Fig. 4). Soil organic C constitutes a larger percentage (~75%) of total ecosystem C in sown pasture but constitutes a lesser proportion in native rangeland and silvopasture (~59 and ~48%, respectively; Fig. 4). Belowground C (root C and SOC) accounted for ~95% of ecosystem C in both native rangeland and sown pasture, and ~59% of ecosystem C in silvopasture. The total belowground C stocks were comparable in silvopasture (85 Mg C ha$^{-1}$ in) and sown pasture (81 Mg C ha$^{-1}$) but relatively higher than the reference native rangeland (65 Mg C ha$^{-1}$).

**DISCUSSION**

We evaluated the effect of grassland management intensification on soil and ecosystem C grasslands on biomes that have been established and consistently managed for over 22 yr. Despite the limitations associated with our experimental approach (i.e., lack of...
randomization and limited number of replicates), the long-term nature of this study offers a unique opportunity to assess the effect of only management system changes on ecosystem C stocks without the influence of varying site or environmental factors such as elevation, climate, or soil properties at the field scale. In addition, our approach was based on changes in management systems rather than the conventional approach of focusing on individual management practices. Although assessing effects of different management practices (such as stocking rate, fertilizer application, and fire) separately on ecological properties are often beneficial within the context of a specific management system, comparison of distinctly different management systems often preclude the possibility of determining the effect of individual management practices, as was the case in this study. This is because each management system was characterized by different combinations of management practices which likely interacted to uniquely influence SOC and N dynamics. For instance, in intensively managed pastures, grazing and fire interact to facilitate nutrient cycling in soils, even though they have distinctly different pathways and magnitudes of influence when their effects on grasslands are isolated (Hobbs et al., 1991; Johnson and Matchett, 2001).

**Effect of Grassland Intensification on Soil Organic C Stocks and Soil Bulk Density**

According to a review of studies focused on SOC changes due to application of different management practices or conversion from native vegetation (Conant et al., 2001), more intensive management practices have been documented to enhance SOC sequestration at a rate of 0.11 to 3.04 Mg C ha$^{-1}$ yr$^{-1}$. Our study showed that conversion of native rangeland to sown pasture and silvopasture enhanced total SOC sequestration to a depth of 30 cm at a rate of 0.66 and 0.88 Mg C ha$^{-1}$ yr$^{-1}$, respectively. The SOC sequestration rate observed in this study, which is at the lower end of reported sequestration rates, may be attributed to the potential influence of the biome and climate (Conant et al., 2001) and the long-term duration of the study. It should be recognized that potential for high SOC sequestration is limited under the joint influence of sandy soil texture, high rainfall, and high temperature within the ecoregion of our study (Silveira et al., 2013), all of which favor fast processing of SOC and prevent large amounts of C accumulation. Hence, our overall reported SOC values are at the lower end of their reported range (within similar soil depth) for grassland ecosystems in subhumid southeastern Australia (Chan and McCoy, 2010), as well as in humid tropical Panama Canal Island (Schwendenmann and Pendall, 2006).

The observed similarity in SOC between sown pasture and silvopasture across the sampled soil depth (0–30 cm) is consistent with the findings of other studies that indicated comparable short- and midterm C storage of silvopasture and sown pasture systems after conversion from or to an integrated tree–grass ecosystem (Sharrow and Ismail, 2004; Peichl et al., 2012), but contrasts the findings of Haile et al. (2008) and Martens et al. (2004) who reported that silvopasture and forested pastureland accreted higher SOC compared with a baseline sown pasture. Disparity with the findings of these studies may be related to the difference in the management strategies applied, soil type, and duration of the study.

Research has shown that land-use conversion and intensification of grassland management affects SOC chemical composition, physical structure, stability, and function (Bruce et al., 1999; Conant et al., 2001; Huang et al., 2011). The similarity of soil bulk density across the study site (except at 0- to 10-cm soil depth) suggested that observed changes in SOC stocks reflected changes in C stocks rather than soil compaction. The dominant soil series of the study site, mainly composed of fine sand, may have limited the possibility of soil compaction (and its confounding influence on interpreting SOC changes), which is often associated with increased stocking rate in high clay content soils. Generally, our observed bulk density values are similar to previously reported values under different grazing management practices on sandy soils (Tate et al., 2004) and under slash pine plantation in Florida (Gholz and Fisher, 1982).

**Changes in Soil Organic C Fractions and their N Content with Management Intensification**

The particle-size SOC fractions unveil a contrasting mechanism of SOC sequestration in silvopasture and sown pasture after conversion from native rangeland. Relative to the native rangeland, the accretion of a higher proportion of POM (i.e., POC and PON) in sown pasture at 0 to 20 cm and overall (0–30 cm), and the converse accretion of a higher proportion of mineral-associated SOM (i.e., C and N) in the silvopastoral ecosystem at 10 to 20 cm and overall (0–30 cm) suggests that the conversion of native rangeland to sown pasture favors the accumulation of the labile SOC pool, while the silvopastoral ecosystem favors greater accretion of the stable pools (mineral-associated SOC). Our findings are in accordance with the conclusions of researchers (Feller and Beare, 1997; Desjardins et al., 2004; Schwendenmann and Pendall, 2006) who have reported that SOC was accreted to a greater degree in the coarse (>53 μm) POC fraction under converted or sown grasslands. Fertilizer application and greater fecal
deposition associated with higher stocking rate in the sown pasture can potentially drive higher net primary production of the constituent bahiagrass and, consequently, favor more allocation of C to the POC fraction (Batjes and Sombroek, 1997).

The similarity in chemical and structural composition (lignified woody C$_r$ species) of the vegetation in both native rangeland and silvopasture may not suffice to elucidate similarity in the allocation of C into the POC fraction. However, the formation of more stable mineral-associated C in silvopasture is likely attributable to complexing of organic matter with tree-derived phenolic compounds (Jastrow et al., 2007) and potential in situ modification of microclimate under the tree stands which could favor abiotic humification. Research into potential influence of in situ microclimate and the influence of tree-derived phenolic compounds may be helpful to unravel the process of stable C formation under silvopasture.

As expected, the similarity between the trend of changes in soil N stocks and SOC reflected the coupled response after land-use conversion. Intensification of grassland increased soil N stocks due to higher quantity of applied fertilizer and increased potential for animal derived N deposition. The observed soil N stock (0- to 30-cm depth) across the treatments (ranging from 2.4 Mg N ha$^{-1}$ to 3.94 Mg N ha$^{-1}$) was in contrast with other studies in temperate and tropical regions but comparable to studies conducted under similar subtropical conditions. For example, Peichl et al. (2012) reported ~7.5 Mg N ha$^{-1}$ under 5-yr-old forest and adjacent grassland in Ireland, and Schwendemann and Pendall (2006) reported 9 and 8 Mg N ha$^{-1}$ in a 90-yr-old tropical forest (0–50 cm) and a converted grassland, respectively, while Silveira et al. (2013) reported a range of 1.4–1.7 Mg N ha$^{-1}$ under different pasture grazing and fertilization regimes in central Florida. Typically, a greater C to N ratio in particulate fractions and a lower C to N ratio in the heavier, mineral-associated fraction would indicate stronger resistance to decomposition (Sollins et al., 1984; Martens, 2000). As a result, the resistance or ease of decomposition of the SOC fractions was altered after conversion from native rangeland to tree-integrated silvopasture or more intensively managed sown pasture, but the effects were generally limited to the top 0 to 20 cm of soil.

Management Intensification Effect on Live Biomass and Ecosystem C

Despite the similarity in the root biomass C and grass-derived biomass C after conversion from native rangeland to sown pasture, the contribution of the woody biomass (2.9 Mg C ha$^{-1}$) offers an advantage for aboveground ecosystem C sequestration in native rangeland. Consistent with the similarity of SOC in silvopasture and sown pasture, similarity in biomass C levels further suggests that the bahiagrass component may have a strong effect on SOC though it constitutes a marginal percentage (3%) of aboveground biomass in the silvopasture treatment (De Groot, 1990; Sharrow and Ismail, 2004). The observed similarity in grass-associated biomass C may be attributed to the relatively lower grazing pressure in silvopasture, which allowed the tree-based system to accrue similar quantity of grass biomass despite the higher potential for livestock-mediated nutrient cycling and greater forage production in the sown pasture ecosystem.

Compared with trees or woody vegetation, grass species generally develop shallow root systems or alternatively allocate the main root biomass to the uppermost soil layers, even though single roots can reach depths of several meters (Haile et al., 2010). The native rangeland ecosystem is dominated by rhizomatous saw palmetto species which have roots concentrated around the rachis, the plant part that is developed ~30 cm beneath and above soil surface (Fisher and Jayachandran, 1999; Duever, 2011). Although, the slash pine trees in the silvopasture ecosystem are also characterized by shallow rooting with about 85% of the total root C accruing to the 0- to 30-cm soil depth (Tang and Tang, 1989), limitations of our sampling technique (core diameter = 5 cm) may favor sampling of fine roots over large-diameter tree roots and possibly influence the representation of tree-derived root biomass C under silvopasture, especially at the lower 10- to 30-cm soil depth. However, the limited potential for tree-assocated fine root contribution at the upper (0–30 cm) soil depth (Jackson et al., 1997) may allow for dominance of the shallower bahiagrass roots on the belowground processes (within the sampled depth) thereby leading to the observed similarities with sown pasture. This may potentially translate into similarity in root turnover within silvopasture and sown pasture and overall accretion of comparable total SOC in both ecosystems in the long term. Further study on root turnover will be beneficial to elucidate the role of roots in regulating the long-term C sequestration within these ecosystems.

Generally, ecosystem C stocks include the aboveground woody and nonwoody biomass C, root biomass C, and SOC. Increase in ecosystem C after converting native rangeland to silvopasture (108%) and sown pasture (20%) indicates that the C sink capacity of grasslands can be greatly enhanced in the long term through improved management systems (Conant et al., 2001; Sharrow and Ismail, 2004). Similar to the findings of Arevalo et al. (2009) in a trajectory of land-use changes, including grasslands, it is interesting to note that the overall difference in belowground C stock (root C + SOC) between sown pasture and silvopasture was apparently marginal, but the dynamics are different in terms of the contribution from root C and SOC. The disparate biomass allocation into these ecosystem pools may have implications for modeling biogeochemical processes (including turnover of C, N, and other nutrients) and accurate assessment of ecosystem C balance in response to changes in management system (Sharrow and Ismail, 2004; Peichl et al., 2012). Also, the understanding of management-induced shifts in biomass allocation is important for strategic adoption of management approaches that enhance C sequestration opportunities and reduce potential losses in grassland ecosystems.

CONCLUSIONS

The findings from this study suggested that after >22 yr, conversion from native rangeland to tree-integrated silvopasture or more intensively managed sown pasture increased ecosystem C stocks due to increases in SOC, while silvopasture offered the
additional benefit of aboveground woody biomass sequestration within this subtropical ecoregion. Results provided evidence of long-term allocation of a higher quantity of stable SOC in silvopasture compared with baseline native rangeland suggesting a long-term C sink. Data suggested that increasing intensity of grassland management is beneficial for soil and ecosystem C sequestration in the long term; however, shifts in the allocation of C into ecosystem pools will likely have implications for biochemical cycling within this subtropical ecoregion.

However, it should be reckoned that our findings may be most applicable to ecological sites with similar site conditions, due to the constraints associated with the nondispersal of replicates in space under the studied long-term ecological units.

REFERENCES


