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Forage Performance and Soil Quality in Forage Systems under Organic Management in the Southeastern United States

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ABSTRACT

Interest is increasing in organic forage production and sod-based rotations in the southeastern United States, but research-based information is limited. A replicated field study was established to evaluate productivity and soil quality changes in five organically-managed forage systems over 2 yr. Systems included four regionally-adapted perennial systems and one warm- and cool-season annual rotation: (i) alfalfa (*Medicago sativa* L.), (ii) red clover (*Trifolium pratense* L.), (iii) alfalfa/orchardgrass (*Dactylis glomerata* L.), (iv) red clover/orchardgrass, and (v) an annual system of wheat (*Triticum aestivum* L.)/crimson clover (*T. incarnatum* L.) followed by sorghum–sudangrass [*Sorghum bicolor* × *S. bicolor* var. *sudanense* (Piper) Stapf.]. Soil quality was compared to two annual vegetable systems, one managed organically and one managed conventionally. Poultry litter was applied to organically-managed systems in September 2010 (9 Mg ha^{-1}) and in September 2011 (4.5 Mg ha^{-1}). Mean annual forage yield was greatest from wheat/crimson clover and sorghum–sudangrass (12.4 Mg ha^{-1} yr^{-1}), intermediate from red clover, red clover/orchardgrass, and alfalfa/orchardgrass (10.0–10.3 Mg ha^{-1} yr^{-1}), and least from alfalfa (7.6 Mg ha^{-1} yr^{-1}). Soil C (total and particulate organic matter-C) increased over 2 yr in all forage systems which were similar, and was in most cases significantly lower in vegetable systems. Soil N (total and particulate organic matter-N) increased in all forage systems and was highest in alfalfa and treatments containing red clover, and lowest in vegetable systems. Results suggest these short-term forage systems are viable options for regional organic rotations.

Improving soil quality is a central goal of sustainable crop production given the agronomic benefits of increased soil moisture retention, improved soil fertility, improved crop yield and improved yield stability, as well as potential global climate benefits from increased soil C sequestration (Lal, 2006; Karlen et al., 2001; Franzluebbers, 2010a; Powlson et al., 2011). In organic agriculture systems, the integration of perennial forages in crop rotations has potential to not only increase soil quality, but also to increase soil fertility (Cavigelli et al., 2008, 2013; Spargo et al., 2011), reduce weed pressure (Liebman and Dyck, 1993; Porter et al., 2003; Teasdale et al., 2004; Cavigelli et al., 2008, 2013), and reduce crop pests (Katsvairo et al., 2007) for subsequent crops as compared with crop rotations with only annual crops. These cropping system services may be especially important in organic cropping systems, which prohibit most synthetic inputs used to address these issues in conventional cropping systems. Annual forage crops also have potential as economically-valuable catch crops or break crops in organic rotations, can play a role in weed management (Schoofs and Entz, 2000), and could provide increased flexibility of management decisions in an organic crop rotation using cover crops.

Due to increased consumer demand for organic livestock products, especially dairy, and the USDA-National Organic Program rule requiring that 30% of a ruminant's dry matter intake must come from grazing during the grazing season (a period not less than 120 d and determined by site conditions and regional climate; USDA-AMS, 2014), a growing market exists for organic forages. At the same time, research-based information relating to the production of organic forages for organic dairy and other organic grazing livestock production is extremely limited and that available typically originates from production systems in continental or maritime temperate climates (e.g., Vinther and Jensen, 2000 [Denmark]; Kuusela and Khalili, 2002 [Finland]; Pietsch et al., 2007 [Austria]; Weller and Cooper, 2001 [United Kingdom]; Harrington et al., 2008; 2012 [New Zealand]). A number of studies have also evaluated organic production of perennial forages as a rotational component of organic grain cropping systems in the mid-Atlantic and Midwest, but these studies were generally not focused on the establishment and management of the forages as primary research objectives (e.g., Delate and Cambardella, 2004; Cavigelli et al., 2008). Information related to cool-season forage species selection and management from these regions may provide useful general strategies for organic forage production in diverse regions, but is of limited specific applicability in the humid, subtropical southeastern United States where climatic conditions and soil properties differ markedly (Bouton, 2007). While climatic conditions in the southeastern United States can provide the benefits of a lengthened grazing season, it can be difficult to produce forages of sufficient quality during the hot and periodically

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Abbreviations: POM-C, particulate organic matter-carbon; POM-N, particulate organic matter-nitrogen; POx-C, permanganate oxidizable-carbon.

droughty summer months and stand persistence of perennial cool-season forages can be limited. Additionally, given that soils in the southeastern United States are typically highly weathered and low in soil organic matter, forage productivity without conventional fertilizers can be low without sufficient N contribution from forage legumes and appropriate management of nutrient cycles (Franzluebbers, 2010b).

In the southeastern United States there is no published research relating to yields of organically established and managed perennial forages. While establishment of perennial forages without herbicides through the use of tillage combined with annual nurse crops was common historically (Miller and Stritzke, 1995), use of herbicides and various conventional fertility sources are ubiquitous in modern forage research. In organic forage systems, where producers cannot rely on herbicides for weed control for establishment and stand maintenance, or conventional fertility sources to optimize productivity, the vast majority of conventional forage research and extension materials are not transferable to organic production systems. Producers and agricultural professionals need research using organic management techniques to optimize methods of forage establishment and management to address organic system agronomic issues.

Perennial species commonly used in southeastern U.S. forage systems that could be integrated into organic production systems for grazing or mechanical harvest include alfalfa, red clover, and orchardgrass. Alfalfa is associated with high forage quality, long production season and drought resistance, and high protein production per land area (Barnes and Sheaffer, 1995; Ball et al., 2002). For organic producers, the high biological N fixation rate (Ledgard and Steele, 1992; Peoples et al., 1995) makes alfalfa a useful rotational crop for systems which are often limited by N availability (Berry et al., 2002). Red clover is a potentially attractive forage legume for organic producers due to fewer insect pest issues in the region as compared with alfalfa (e.g., alfalfa weevil [*Hypera postica*], potato leafhopper [*Empoasca fabae*], greater flexibility in time and method of establishment, and greater tolerance to subsoil acidity and poorly drained soils than alfalfa (Barnes and Sheaffer, 1995; Ball et al., 2002). Orchardgrass can be used to add functional diversity (e.g., diversity of N acquisition strategies; Tilman et al., 1997) to legume monocultures which can improve productivity (Sanderson et al., 2004; Picasso et al., 2011), better suppress weeds at establishment (Sanderson et al., 2012), reduce risk of bloat (Majak et al., 2003) and potentially improve soil organic matter gains due to differing root structure and distribution within the soil profile compared to legume monocultures (Bolinder et al., 2002). Orchardgrass is also high in forage quality if well-managed (Christie and McElroy, 1995) and unlike tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.], which is also well-adapted to the region, does not have issues with endophytic toxins (Sleper and Buckner, 1995) and may better allow for legume persistence in mixtures (Chamblee and Lovvorn, 1953; Sheaffer, 1989), an important consideration for organic management. Other perennial legumes (e.g., white clover [*T. repens* L.], alsike clover [*T. hybridum*] or birdsfoot trefoil [*Lotus corniculatus* L.]) or perennial grasses {e.g., Kentucky bluegrass (*Poa pratensis* L.), reed canarygrass (*Phalaris arundinacea* L.), timothy (*Phleum pratense* L.), perennial ryegrass (*Lolium perenne* L.), bahiagrass (*Paspalum notatum* Flugge) or bermudagrass [*Cynodon dactylon* (L.) Pers.]} are potentially useful for organic forage growers in at least some areas of the southeastern United States, but many are not as broadly adapted to regional climate and soil type (Ball et al., 2002), or have other limitations such as poor drought tolerance, poor persistence, low forage quality or potential to become weedy in rotation. While perhaps the most broadly-adapted perennial species for organic forage production in the region, no published research has evaluated the relative productivity or associated soil quality changes associated with alfalfa, red clover, or orchardgrass under organic management.

Rotations of annual forages are often utilized in dairy production systems due to ease of integration into crop rotations on high-value crop land, high productivity, as well as potentially high forage quality, especially for cool-season annuals such as small grains and annual clovers. Annual forage species can also help to extend the forage season, through greater early spring and mid-summer productivity compared with cool-season perennial forages (Rao and Horn, 1995; Ball et al., 2002). For organic systems, the rapid establishment of highly competitive annual forage species can also limit weed pressure (Forney et al., 1985; Schoofs and Entz, 2000), and potential tillage events at planting can help to limit establishment of perennial weeds. However, these tillage events may negate the beneficial effects of forages in crop rotation due to the negative impacts on soil organic matter accumulation associated with soil disturbance (Haynes, 1999). Cool-season annual grasses are typically very high in forage quality, and include annual ryegrass (*Lolium multiflorum* Lam.) and several species of small grains, including common wheat, cereal rye (*Secale cereale* L.), triticale (*X Triticosecale* Witmack), barley (*Hordeum vulgare* L.), and oat (*Avena* spp.). For organic producers rotating to non-forage crops, annual ryegrass may be less desirable due to its potential as a weedy species without herbicides for management. While winter cereal rye may be a good option where weed control is a primary objective due to allelopathic effects of rye root residues (Przepiorkowski and Gorski, 1994) which would remain following forage harvest, winter wheat or triticale may be an optimal balance between forage quality, cold-hardiness, and weed suppressive ability. Annual legume species commonly used in the southeastern United States include crimson clover, arrowleaf clover (*T. vesiculosum* Savi.), and ball clover (*T. nigrescens* Viv.), with crimson clover being the most reliably winter-hardy in the colder areas of the region (Hoveland and Evers, 1995). Warm-season annual grasses, such as forage sorghum, sudangrass and hybrids, and pearl millet [*Pennisetum glaucum* (L.) R. Br.] are well-adapted to southeastern U.S. climate and soils, suppress weeds through competition and in the case of *Sorghum* spp., allelopathic mechanisms (Weston and Duke, 2003), and improved forage cultivars are widely available.

Given the limited available data on biomass production and soil quality changes associated with management of organic forage systems in the southeastern United States our objectives were to evaluate (i) the productivity of five regionally-adapted forage systems under organic management during a 2-yr period and (ii) soil quality changes associated with short-term perennial forage systems under organic management during a 2-yr period as compared to an annual forage system and two annual vegetable production systems. Four perennial forage systems (two legume monocultures and two legume-grass mixtures) were selected for their potential adaptability to organic farming rotations in the southeastern United States. Perennial forage system productivity was compared to a rotation of annual forage species with biannual soil disturbance over a 2-yr crop rotation phase and relative contribution to soil quality was compared among forage systems and to two annual vegetable production systems. The hypotheses were (i) that the rotation of annual forage species would be most productive, but have the least impact on soil quality improvement of forage systems as indicated by measures of soil C and N in the 0- to 15-cm soil horizon and (ii) that of the perennial forage systems, legume-grass mixtures would be more productive compared to constituent legume monocultures and have a more positive impact on soil C and N than the annual forage system and both annual vegetable production systems.

MATERIALS AND METHODS

Experimental Design and Site Description

Beginning in September 2010, a randomized complete block experiment was established in four blocks at the Organic Crops Unit of the East Tennessee Agricultural Research and Education Center in Knoxville. Each block contained 10 plots (2.4 by 9.1 m) which were each randomly assigned 1 of 10 treatments; five of which corresponded to organic forage production systems and five of which corresponded to rotations of annual vegetable crops and winter cover crops. The experimental design was selected to evaluate the impact of sod-based rotations of perennial forages in organic vegetable production systems in future years (i.e., following 2 yr of perennial forages in a 4-yr rotation). This manuscript focused solely on forage crop performance in the five replicated organic forage systems during the period of 2010 to 2012 which represented the forage phase of the rotation, and soil quality changes among forage systems and compared to two replicated annual vegetable systems (one organically managed and one conventionally managed).

The soil at the site is a Dewey silt loam (fine, kaolinitic, thermic Typic Paleudult; soil pH 6.9, initial soil organic C of 10.9 g C kg^{-1} soil). The site was fallow during summer 2010, following a winter rye and crimson clover cover crop in winter 2009–2010. In August 2010, the entire site was plowed (2-bottom), disked (offset double disk), and harrowed (spring-tine with rolling basket) to terminate perennial weeds and create a seed-bed for establishment of forages. Weather conditions at the Organic Crops Unit were monitored and recorded every 30 min during the course of the study using an automated weather station (Vantage Pro2, Davis Instruments Corp., Hayward, CA) (Fig. 1).

Forage System Establishment and Management

In September 2010, stockpiled poultry (broiler) litter was applied to all forage plots at a rate of 9 Mg ha^{-1} (28% moisture content; 2.2 Mg C ha^{-1}, 68 kg total N ha^{-1}, 105 kg P ha^{-1}; 133 kg K ha^{-1}) to improve low soil P and K values and incorporated with a rotovator (RTC240, Bush Hog, Inc., Selma, AL). Forage stands were then established by broadcast seeding by hand, followed by rolling to establish seed to soil contact. Forage systems evaluated included four perennial mixtures and one mixture of warm- and cool-season annuals. Cultivars were chosen based on regional adaptation and relative performance in conventionally-managed University of Tennessee forage variety trials (e.g., Bates et al., 2010a, 2010b, 2011b). Forage treatments, cultivars, seeding rates, and dates were as follows: (i) alfalfa (cultivar Phoenix, fall dormancy rating 5, winter survivability rating 4, 22 kg ha^{-1}, 15 Sept. 2010) monoculture,

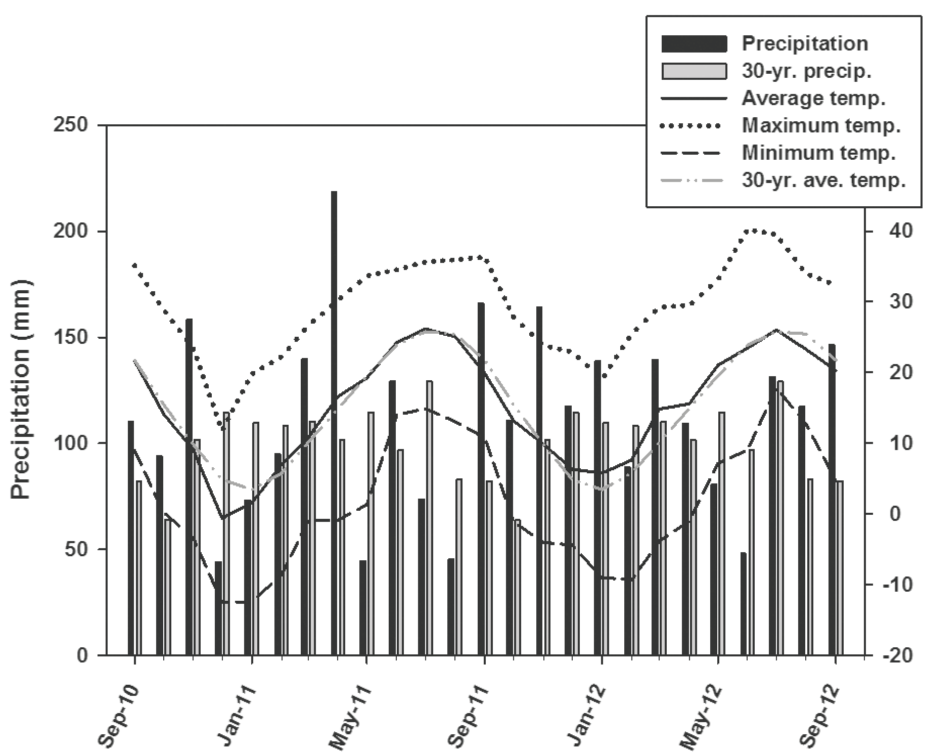

Fig. 1. Mean monthly precipitation, mean monthly air temperature, maximum monthly air temperature, and minimum monthly air temperature at the University of Tennessee Organic Crops Unit, Knoxville, September 2010 to September 2012, and 30-yr mean temperature and precipitation for Knoxville, TN.

(ii) red clover (cultivar Cinnamon Plus, 13 kg ha^{-1}, 15 Sept. 2010) monoculture, (iii) alfalfa (17 kg ha^{-1})/orchardgrass (cultivar Benchmark Plus, 6 kg ha^{-1}, 15 Sept. 2010) biculture, (iv) red clover (9 kg ha^{-1})/orchardgrass (6 kg ha^{-1}, 15 Sept. 2010) biculture, and (v) an annual forage system of soft red winter wheat [cultivar Haas Cover (2010) & cultivar ForageMax (2011), 168 kg ha^{-1}]/crimson clover (cultivar Dixie, 11 kg ha^{-1}) biculture seeded in fall (15 Oct. 2010 and 17 Oct. 2011) followed by sorghum–sudangrass (cultivar BlackHawk BMR, 56 kg ha^{-1}) monoculture seeded in spring (10 May 2011 and 11 May 2012). Stubble from each annual crop was incorporated with a rotovator following the final harvest and before planting of the following crop. With the exception of the sorghum–sudangrass which was produced organically, all other forage seed was conventionally-produced, untreated and uncoated; legume seed was inoculated at planting with appropriate rhizobia (alfalfa/true clover combination, *Sinorhizobium meliloti* and *Rhizobium leguminosarum* biovar *trifolii*). Borax (sodium tetraborate) was applied to alfalfa and alfalfa/orchardgrass treatments at establishment at a rate of 20 kg ha^{-1} (2.2 kg B ha^{-1}) as recommended by University of Tennessee Extension for alfalfa establishment (Bates, 1998), given prevalence of B deficiency for alfalfa in the region. Additional broiler litter was applied in September 2011 at half the establishment rate (4.5 Mg ha^{-1}, 43% moisture content; 0.88 Mg C ha^{-1}, 125 kg total N ha^{-1}, 56 kg P ha^{-1}; 51 kg K ha^{-1}). All forage plots were managed according to USDA-National Organic Program guidelines (USDA-AMS, 2014).

Alfalfa and red clover were harvested in the late-bud to early-bloom stage (Skinner and Moore, 2007) and were cut at an approximate 7.5-cm stubble height (18 Apr., 6 June, 7 July, and 3 Aug. 2011; 16 Apr., 29 May, and 20 Sept. 2012). The wheat–crimson clover biculture was harvested in the late-boot stage of the wheat component (Skinner and Moore, 2007) and was cut to a 7.5-cm stubble height (18 Apr. 2011 and 16 Apr. 2012). Sorghum–sudangrass was harvested in the late-boot stage (Skinner and Moore, 2007) and was cut to an approximate 15-cm stubble height (7 July, 3 Aug., and 20 Sept. 2011; 17 July and 19 Sept. 2012). All forage plots were harvested with a flail-type forage harvester [0.76-m cutting width, Swift Machine and Welding Ltd., Swift Current, SK, Canada, or 0.91-m cutting width, Carter Mfg. Co., Brookston, IN (16 Apr. 2012 harvest only)], equipped with an automated weigh system to determine moist forage biomass yield from the harvested strip (9.1-m length). Subsamples of harvested forage were collected and oven-dried (65°C for 48 h) to determine dry matter content. Immediately before forage harvest, an aboveground biomass sample was removed to within 2 cm of the soil surface from a 0.09-m^2 area outside of the harvested strip, separated as either sown legume, sown grass, or nonsown species (i.e., weeds) and then dried and weighed. Values were used to calculate weighted proportions of aboveground biomass represented as sown legume or grass, or nonsown species over the course of each season. Aboveground biomass was sampled from cover crops in vegetable crop systems using the same methodology. Samples were also used to estimate aboveground biomass productivity in all systems, and amount of stubble remaining by subtracting forage harvest biomass.

Vegetable System Establishment and Management

Stockpiled poultry litter was applied to the organically-managed vegetable system as described for forage systems, whereas no poultry litter was applied to the conventionally-managed vegetable system. The organically-managed system was planted with a cover crop mixture of wheat and crimson clover whereas the conventionally-managed vegetable system was planted to a cover crop of wheat (168 kg ha^{-1}) in the fall of each year. Seedbed preparation, cultivars, and establishment were as described for the annual forage system. Crimson clover was included in the cover crop mixture for the organic vegetable system to increase soil N through biological N fixation. Cover crops in the organically-managed vegetable plots were terminated with a flail mower (5 May 2011, 20 Apr. 2012) and cover crops in conventionally-managed plots were terminated with one application of a glyphosate [N-(phosphonomethyl)glycine] herbicide (Roundup [Monsanto Co., St. Louis, MO], 1.7 L ha^{-1}; 18 Apr. 2011 and 19 Apr. 2012). Before cover crop incorporation, fertility amendments were applied to conventionally-managed plots using ammonium nitrate (134 kg N ha^{-1} in 2011 and 2012), triple superphosphate (105 kg P ha^{-1} in 2011, 56 kg P ha^{-1} in 2012) and KCl (118 kg K ha^{-1}, 51 kg K ha^{-1}). Application rates of P and K were equivalent to that applied in poultry litter to organically-managed treatments in the previous fall of each season. Nitrogen rates were chosen to approximate standard recommendations given to conventional growers in the southeastern United States (Kemble, 2010). Terminated cover crop residue was incorporated using a rotavator, a drip irrigation line applied, and covered with black polyethylene mulch (11 May 2011, 24 Apr. 2012). All nutrient amendments were applied before vegetable planting, with no applications of soluble fertilizer through drip irrigation.

Briefly, eggplant (*Solanum melongena* L.) transplants were planted in all treatments on 11 May 2011, in a single 9.1 m row in the center of each bed and 45-cm spacing between plants. Transplants were planted by hand into polyethylene-mulched treatments. Watermelon (*Citrullus lanatus* Thunb.) transplants were planted on 25 Apr. 2012 as described for eggplant, but with 76-cm spacing between plants. Pest management for all vegetable treatments utilized organically-approved methods (i.e., dusting with diatomaceous earth or physical exclusion with spunbonded polypropylene row cover for control of arthropod pests in early crop growth stages). Accordingly, differences between organically-managed and conventionally-managed vegetable systems were limited to (i) poultry litter application, (ii) cover crop selection, (iii) cover crop termination method, and (iv) inorganic fertilizer use. Vegetable crops were harvested using standard methodology (data not shown). At the end of the season, plastic mulch and aboveground crop residue was removed from all plots before tillage and cover crop establishment.

Soil Sampling and Analysis

At least three soil cores (0- to 15-cm depth, 1.75-cm internal diameter) were collected and composited for each plot (14 Sept. 2010) before litter application in 2010 and in spring and fall in 2011 and 2012 (16 May and 29 Aug. 2011; 15 May and 27 Aug. 2012). Soils were air-dried, large aggregates gently crushed with a mortar and pestle, and sieved (<2 mm) before soil nutrient analyses. Permanganate oxidizable carbon (POxC) was determined as described in Weil et al. (2003). Briefly, soil was reacted with 0.02 M $KMnO_4$ on a shaker for 2 min and then centrifuged (5 min at 3000 rpm). An aliquot of the supernatant was diluted and absorbance measured at 550 nm (Powerwave XS, BioTek, Winooski, VT) and compared with a standard curve of $KMnO_4$. Care was taken to minimize disturbance of sediment after centrifugation and to use the same batch of $KMnO_4$ for a given set of soil and standards. Particulate organic matter N (POM-N) and C (POM-C) were determined as described by Marriott and Wander (2006). Approximately 20 g of sieved (<2 mm), air-dried soil was placed in a vial covered with 53-mm mesh (Wildlife Supply Company, Yulee, FL) and shaken with 5% sodium hexametaphosphate followed by multiple deionized water washes until the rinse water was clear. Retentate was dried at 50°C and weighed, then homogenized in a ball mill (PowerGen, Thermo Fisher Scientific Inc., Waltham, MA) and combusted to determine total N and total C content of the <53 mm portion recovered as particulate organic matter (POM-N and POM-C, respectively), using a soil analyzer (Flash EA 1112 NC Soil Analyzer, Thermo Fisher Scientific Inc., Waltham, MA). Total N and C of bulk soils were similarly determined by combustion. Final concentration of C and N constituents in soils were calculated based on exact weight of analyzed soil.

Statistical Analysis

Data points at a distance greater than 1.5 interquartile ranges from either the first or third quartile were considered outliers and removed before analysis of variance. Data were subject to repeated measures analysis of variance using PROC MIXED in SAS software (version 9.3, SAS Institute Inc., Cary, NC) where block and the interaction of block and year were considered random effects, and sampling time was the repeated variable for treatments (forage system or management system) nested within blocks. Degrees of freedom were calculated according to a Satterthwaite approximation. Differences between means were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Forage Performance

Mean annual forage yield was significantly affected by forage system ($P < 0.01$), year ($P < 0.01$), and the interaction ($P < 0.05$; Table 1). The highest annual yields were observed from the annual system of wheat/crimson clover and sorghum–sudangrass in 2011 and 2012 (11.9 and 12.9 Mg ha^{-1}, respectively) and the alfalfa/orchardgrass mixture in 2012 (11.0 Mg ha^{-1}), which were statistically similar (Fig. 2). Percentage of nonsown species biomass was also low in these treatments (2, 7, and 0%, respectively; data not shown). The lowest annual yield was observed in the alfalfa monoculture in 2011 (6.0 Mg ha^{-1}), which is not surprising given slower establishment of alfalfa and disease pressure indicated by field symptoms and signs consistent with Sclerotinia stem and crown rot (Rhodes, 2015), resulting in minimal yield at first harvest (0.6 Mg ha^{-1}; data not shown). Over the course of the 2-yr study for all harvests in 2011 and 2012, mean total forage yield was greatest from the annual system of wheat/crimson clover and sorghum–sudangrass (24.8 Mg ha^{-1}), intermediate from red clover, red clover/orchardgrass, and alfalfa/orchardgrass systems (20.0–20.6 Mg ha^{-1}), and least from the alfalfa monoculture (15.1 Mg ha^{-1}; Fig. 3).

The higher forage yield from the annual system of wheat/crimson clover and sorghum–sudangrass compared with perennial systems can be at least partially explained by the slower establishment of perennial forages, which likely limited average aboveground productivity over the short 2-yr rotation phase studied here. Also, C4 species (e.g., sorghum–sudangrass) have greater productivity during hot and periodically droughty conditions (Fribourg, 1995). Whereas the mixture of red clover/orchardgrass did not improve productivity over the red clover monoculture, this was not the case for the alfalfa/orchardgrass mixture which did yield significantly more than the alfalfa monoculture (Fig. 2 and 3). It is possible that the orchardgrass component of the mixture had a compensatory effect on yield when alfalfa growth was limited by Sclerotinia stem and crown rot before the first harvest (which occurred in both treatments), an ecological mechanism that is often termed the "insurance effect" (Sanderson et al., 2004). The potential for greater losses to pests in organic systems as well as more heterogeneous environmental conditions (Lammerts van Bueren et al, 2011), implies the use of forage mixtures may be especially important for yield stability across varying environments. "Transgressive overyielding" has also been reported in mixtures of alfalfa/orchardgrass (i.e., yield of the mixture is greater than that of the highest yielding component in monoculture), resulting from facilitation effects (e.g., N contribution from the legume to the grass) and more efficient use of resources in space and time (Picasso et al., 2011). While fall-planted alfalfa in the southeastern United States is known to be susceptible to Sclerotinia stem and crown rot (e.g., Pratt and Rowe, 1995), fall planting of perennial forage crops is likely to best fit into organic cropping system rotations in the region as it prevents the additional establishment and management costs of a fall-planted annual cover crop following summer cash crop harvest and before spring forage crop establishment, and allows a greater time in rotation for forage establishment and production and the associated benefits of perennial forage systems in rotation to accrue.

Table 1. Repeated measures analysis of variance for response variables of forage and soil constituents as affected by management (or forage) system, time (year of sampling), and the interaction.

Response variable	Management system	Time†	Management system × time
		P value	
Forage constituents			
Yearly forage yield	<0.01	<0.01	0.05
Yearly aboveground biomass	<0.01	0.54	0.17
Soil constituents			
Total C	<0.01	<0.01	0.01
Particulate organic matter-C	<0.01	<0.01	0.19
Permanganate oxidizable-C	0.01	<0.01	0.14
Total N	<0.01	<0.01	<0.01
Particulate organic matter-N	<0.01	<0.01	<0.01

† Time = year of sampling.

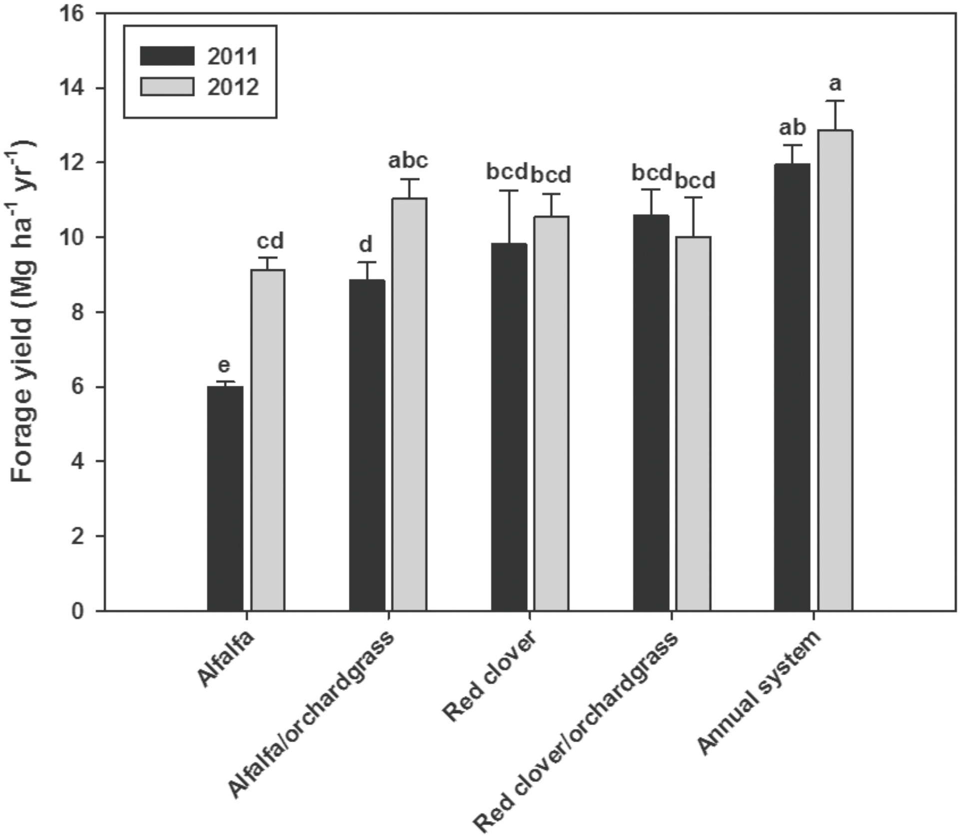

Fig. 2. Average annual forage dry matter yield as affected by forage system in 2011 and 2012. Bars indicated by the same letter are not significantly different, $P > 0.05$. Error bars represent standard error of the mean.

To our knowledge, there are no published studies focused on organic production of perennial or annual forages in the southeastern United States. However, higher yields have been reported for organically-managed sorghum–sudangrass (cultivar Haychow) as a cover crop (~10–14 Mg ha^{-1}) in North Carolina (Finney et al., 2009) compared to that in our study (4.8 Mg ha^{-1} in 2011 and 8.4 Mg ha^{-1} in 2012; data not shown). While environmental differences, management, and cultivar differences prevent direct comparisons to our study, it does suggest that sorghum–sudangrass potential yield may be greater than the realized yield in our study when coupled with observed N deficiency symptoms of late season sorghum–sudangrass and relatively low whole plant N concentration (average of 10 g kg^{-1} at final harvest; data not shown). The annual system in our study may have been improved by the inclusion of a warm-season annual legume (e.g., cowpea, *Vigna unguiculata* Walp.) in mixture with sorghum–sudangrass which may lead to increased overall summer forage yield. Wheat/crimson clover biomass of 7.1 Mg ha^{-1} in 2011 and 4.4 Mg ha^{-1} in 2012 in our study was within the range reported in regional cover crop studies (e.g., Ranells and Wagger, 1996; Parr et al., 2011) and conventional forage variety trials at the University of Tennessee (e.g., Bates and Beeler, 2008). There are a limited number of published studies relating to organic perennial forages from other regions in the United States. Primarily, published studies were designed to evaluate rotations for organic annual field crops in the Midwest or mid-Atlantic regions, with some treatments including a perennial forage or green manure crop in the rotation for a period of 1 to 3 yr for which yield was reported (Smolik et al., 1993; Hanson et al., 1997; Porter et al., 2003; Delate and Cambardella, 2004; Posner et al., 2008), but which did not include comparisons to other forage systems. These studies along with conventional variety trials at the University of Tennessee (e.g., Bates et al., 2011a, 2011b) suggest that productivity (and thus potential C inputs to soil) in our study was generally in the range of reported values from similar systems or environments.

Estimated annual aboveground biomass production was significantly affected by management system ($P < 0.01$), but not year or the interaction (Table 1). As expected considering forage yield, the highest yearly aboveground biomass was observed from the annual forage system (18.1 Mg ha^{-1} yr^{-1}), intermediate aboveground biomass was observed from all other forage systems and the cover crop in the organically-managed vegetable system (11.0–12.0 Mg ha^{-1} yr^{-1}), and the least biomass was observed from the cover crop in the conventionally-managed vegetable system (6.7 Mg ha^{-1} yr^{-1}). When compared to harvested biomass, estimated unharvested biomass (i.e., stubble) averaged 25% of total aboveground biomass, which was not significantly affected by forage system, time, or the interaction (data not shown). While the relatively small sample area as compared to forage harvest area and associated high variability in the data limits the use of stubble estimates, it does provide an estimate of the amount of aboveground biomass productivity left unharvested, which can provide insight into soil quality dynamics during the course of the study.

Control of nonsown species, whether weedy species or less desirable forage species for a given system, is a major consideration of organic producers when establishing perennial forages,

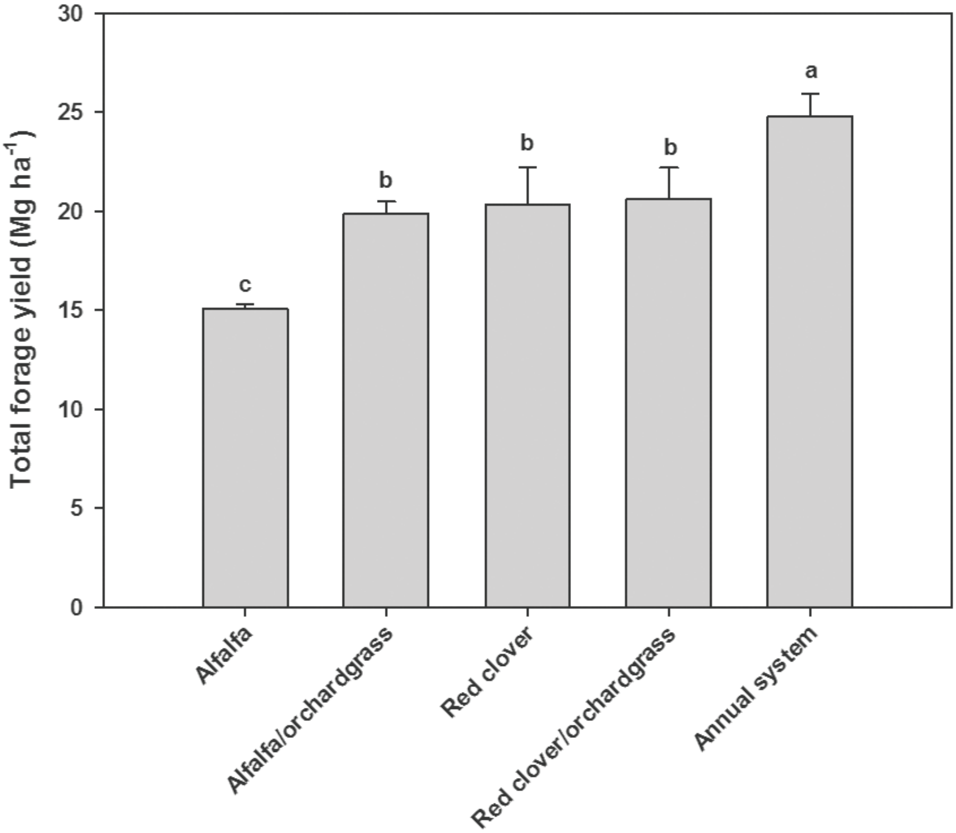

Fig. 3. Average total forage dry matter yield as affected by forage system over the course of the study. Bars indicated by the same letter are not significantly different, $P > 0.05$. Error bars represent standard error of the mean.

due to their slower establishment and limited competitiveness in the seedling stage as compared to many annual forage crops. In our study, the proportion of nonsown species in aboveground biomass was similar among perennial mixtures at the first harvest, with 36 to 52% of dry matter accounted for by nonsown species (data not shown; primarily annual ryegrass). By July 2011 harvests, the proportion of nonsown species was low in all treatments, averaging <5% of aboveground biomass. By the second year, with the exception of the red clover monoculture (31% nonsown species), the percentage of nonsown species was <10%. This pattern is similar to that reported in a New Zealand trial, where Harrington et al. (2008; 2012) reported that while weeds in organic dairy pastures were typically greater than conventional pastures at establishment, these differences were no longer apparent in subsequent years. It is likely that the combination of mowing (harvest) management, competitiveness of established forage stands and lessened seedling recruitment from the weed seedbank due to lack of disturbance led to reduced presence of annual nonsown species during the course of our study (Liebman and Davis, 2000), and prevented additional seeds of these annual species from being added to the seedbank. The red clover treatment was likely negatively impacted by the very hot and periodically droughty conditions in summer 2012 (Fig. 1), allowing for establishment of large crabgrass (*Digitaria sanguinalis* L.) from the seedbank.

Soil Quality

Maintaining or increasing soil quality in organic farming systems is critical for sustaining productivity without synthetically-derived fertility inputs (Cavigelli et al., 2008; Ugarte and Wander, 2013). Total soil C was significantly affected by management system ($P < 0.01$), year ($P < 0.01$), and the interaction ($P = 0.01$; Table 1). After 1 yr of organic forage management, total soil C was significantly higher than at the initiation of the study in all forage systems except the red clover monoculture, and unchanged in the organic and conventional vegetable systems (Fig. 4). Following 2 yr of management, total soil C was significantly higher in all forage systems compared to that at study initiation. On average across forage systems, total soil C was 14.5 g C kg^{-1} soil (30.9 Mg C ha^{-1}) in 2012, compared to 10.9 g C kg^{-1} soil (23.2 Mg C ha^{-1}) in 2010. This represents a 33% increase in total soil organic C (from 23.2 to 30.9 Mg C ha^{-1}) during the 2 yr of the study. The differences in soil C reported in long-term studies for annual cropping systems vs. those in perennial forages in the southeastern United States [31.1 compared to 47.4 Mg C ha^{-1}, respectively, as reviewed by Franzluebbers (2005)] suggests that this result is not inconsistent with other studies in the region, but this increase was more rapid than the reported long-term sequestration rates under perennial forages which average 1.03 (± 0.90) Mg C ha^{-1} yr^{-1} in the region (Franzluebbers, 2005). While the application of poultry litter can be expected to increase annual total organic C in southeastern U.S. soils by ~17% (± 15%) of the amount of C applied (Franzluebbers, 2005), especially with fall applications (Hernandez-Ramirez et al., 2009), our total rates of C application in manures (2.2 Mg C ha^{-1} in Year 1 and 0.88 Mg C ha^{-1} in Year 2) were not high enough to account for the differences observed in total soil C at the 0- to 15-cm depth (7.7 Mg C ha^{-1} mean increase over 2 yr). Likewise, total soil C in the organically-managed vegetable system, with the same manure application

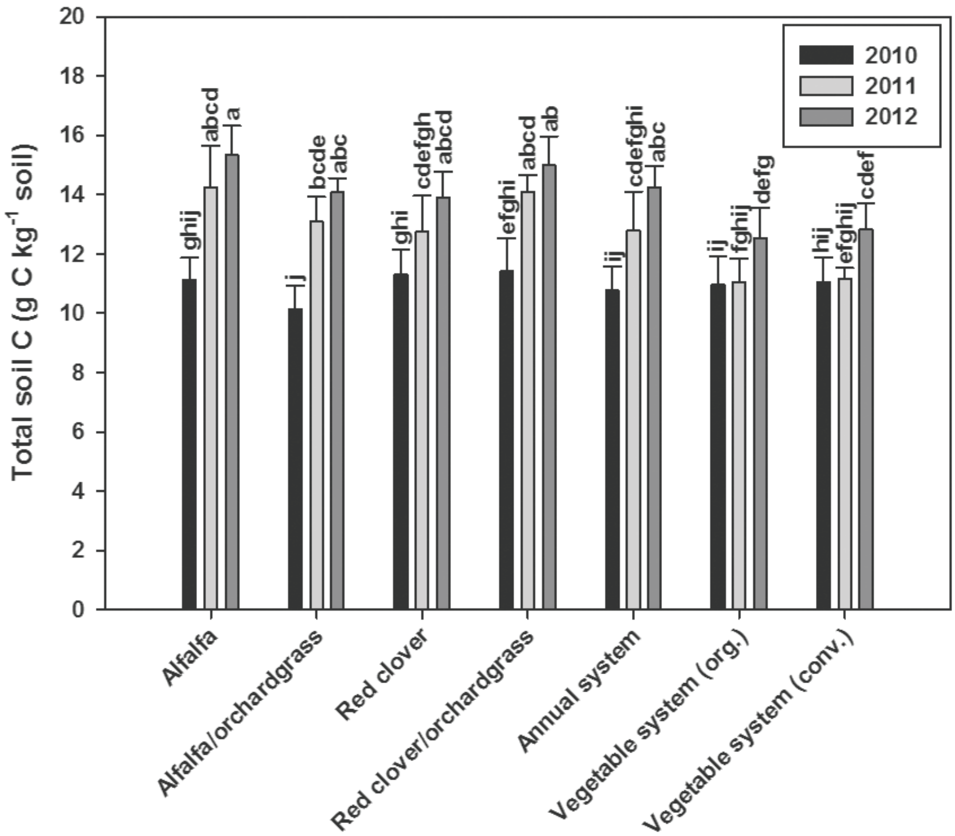

Fig. 4. Soil total C as affected by management system at study initiation (2010) and in the fall of each production year. Bars indicated by the same letter are not significantly different, $P > 0.05$. Error bars represent standard error of the mean.

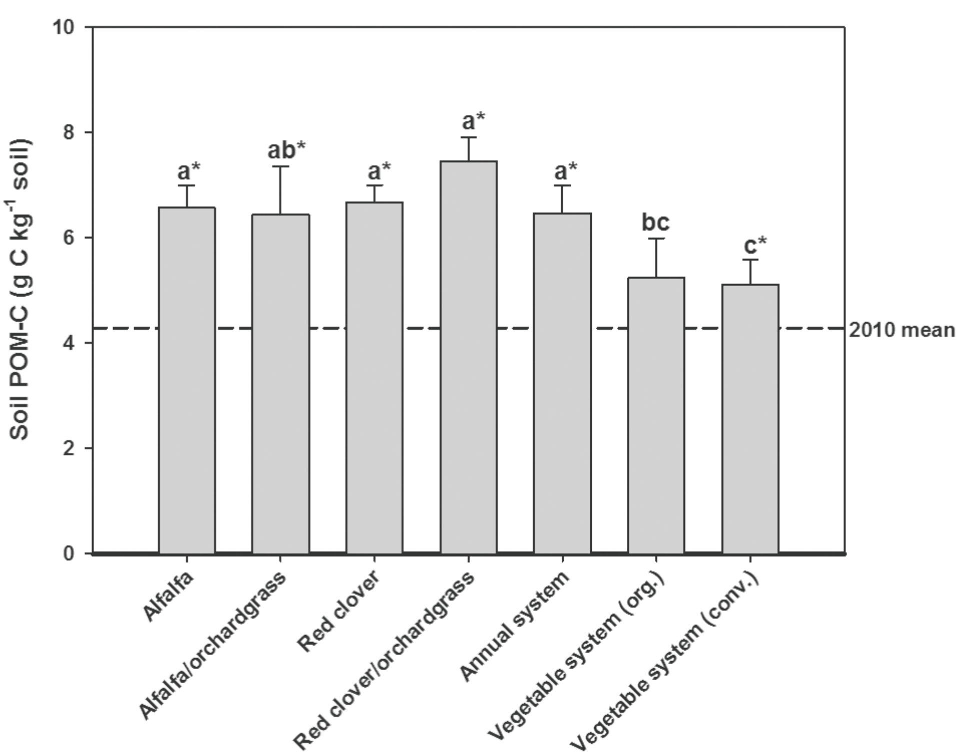

Fig. 5. Particulate organic matter carbon (POM-C) as affected by management system at the end of the study, fall 2012. Bars indicated by the same letter are not significantly different, $P > 0.05$. Bars indicated by an asterisk are significantly different from respective treatment values in fall 2010. Error bars represent standard error of the mean.

rates and similar soil disturbances as the annual forage system (i.e., biannual tillage), did not increase significantly over the course of the study (Fig. 4). Total soil C in the organically-managed and conventionally-managed vegetable treatments was also similar, despite no manure application in the conventionally-managed system. However, Kong et al. (2005) reported that quality of C inputs can be an important determinant of sequestration rates and reported greater relative sequestration for a system receiving plant residues and composted manure vs. only plant residues, suggesting that the interaction of organic amendment and forage-derived C inputs in the forage systems may have been an important driver of the soil C increases observed.

Total measured soil C in our study was likely comprised to a large extent by partially decomposed plant matter in soil samples (e.g., roots, incorporated senesced leaves, incorporated unharvested stubble) and enhanced by maintenance of perennial forage regrowth following the final fall harvest in September of each year, which was not harvested to promote stand winter survival. Given the total harvested forage productivity observed in our study (15.1–24.8 Mg ha^{-1} or 6.1–10.0 Mg C ha^{-1}; based on measured biomass C, data not shown), it is reasonable to estimate that belowground productivity (i.e., living and sloughed roots, root exudates) of these forage crops was similar to harvested biomass C totals, especially for the perennial crops (Gill and Jackson, 2000; Kuzyakov and Domanski, 2000; Bolinder et al., 2002; Rasse et al., 2005; Bolinder et al., 2007). When we also consider unharvested stubble (average of 25% of total aboveground biomass, data not shown), unharvested fall regrowth (in fall 2011) and senesced leaves, total C remaining in the field is estimated to surpass the total C harvested. These rapid rates of increase in soil C associated with annual cropland conversion to perennial forages would likely taper off with decomposition of these relatively unprocessed plant materials, given that approximately 10 to 35% of residue C can be expected to be stabilized in passive soil organic matter pools (Rasmussen and Collins, 1991).

Soil POM-C and POx-C were significantly affected by year ($P < 0.01$) and management system ($P \leq 0.01$), but not the interaction (Table 1). At the end of the study in 2012, POM-C did not differ among forage systems, but was higher in all forage systems than in the conventionally-managed vegetable system (Fig. 5). Soil POM-C was also higher in forage systems than the organically-managed vegetable system, with the exception of the alfalfa/orchardgrass mixture. Soil POM-C significantly increased in all forage systems over the 2 yr of the study from 4.3 to 6.8 g C kg^{-1} soil on average (58% increase). Similar to forage system effects on soil POM-C, soil POx-C also did not differ among forage systems (Fig. 6), but was in general more variable than POM-C. Only the red clover/orchardgrass system was significantly higher than both the organically-managed and conventionally-managed vegetable systems, where the lowest soil POx-C was observed.

Labile fractions of soil organic matter, POM-C and POx-C, which may be especially useful in monitoring soil quality changes in organic farming systems (Ugarte and Wander, 2013; Culman et al., 2013), increased in most forage systems during the 2 yr of the study (Fig. 5 and 6) and may be better indicators of soil C changes induced by forage system management and manure application than total soil C. Soil POM-C in our study was 6.8 g C kg^{-1} soil after 2 yr of forage management. Interestingly, there were no significant differences in POM-C or POx-C between the perennial forage systems and the annual system of wheat/crimson clover and sorghum–sudangrass with more frequent soil disturbance, which would be expected to reduce labile soil C through increased soil respiration.

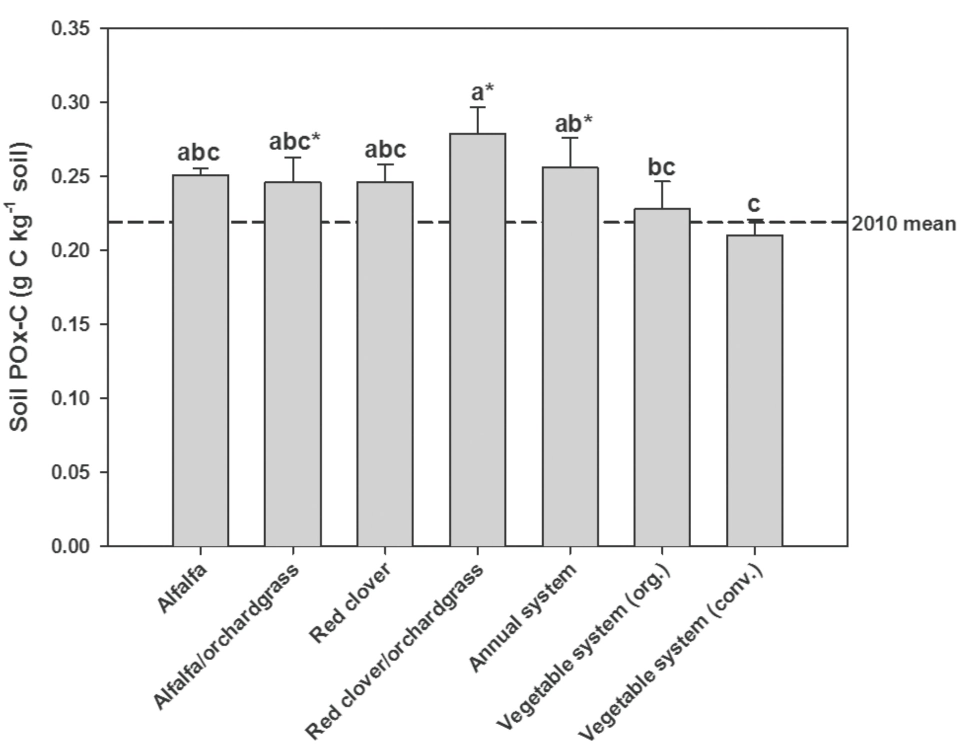

Fig. 6. Permanganate-oxidizable carbon (POx-C) as affected by management system at the end of the study, fall 2012. Bars indicated by the same letter are not significantly different, $P > 0.05$. Bars indicated by an asterisk are significantly different from respective treatment values in fall 2010. Error bars represent standard error of the mean.

Table 2. Mean total soil N and particulate organic matter-nitrogen (POM-N) as affected by management system and time (year of sampling). Within soil N constituent, means indicated by the same letter are not significantly different, $P > 0.05$.

Management system	2010	2011	2012
	mg N kg^{-1} soil		
	Total N		
Alfalfa	930f	1353ab	1438a
Alfalfa/orchardgrass	895f	1205bc	1208bc
Red clover	938ef	1215bc	1303ab
Red clover/orchardgrass	955def	1328ab	1359ab
Annual system	908f	1166bc	1238b
Vegetable system (organic)	920f	945def	1065cd
Vegetable system (conventional)	910f	943def	1058cde
	POM-N		
Alfalfa	204jk	444bcd	491abc
Alfalfa/orchardgrass	212ijk	277ghi	380def
Red clover	245hi	344efg	500ab
Red clover/orchardgrass	212ijk	392de	543a
Annual system	207jk	289fgh	395cde
Vegetable system (organic)	216ijk	225hijk	310efgh
Vegetable system (conventional)	215ijk	172h	279fghij

Belowground biomass and unharvested stubble produced by the rapidly growing species in this annual system of wheat/crimson clover and sorghum–sudangrass (which had the greatest yield) may be sufficient to maintain and improve labile pools of soil C (often comprised primarily of partially-decomposed plant root biomass; Cambardella and Elliott, 1992) when used in rotation even with biannual tillage and forage removal. At the same time, the large residue inputs from winter cover crops in the vegetable production systems (aboveground biomass average of 12 and 6.7 Mg ha^{-1} yr^{-1} in the organically- and conventionally-managed treatments, respectively) were not sufficient to increase POM-C to that observed in the annual forage system. Soil C sequestration should be further evaluated at greater depths to account for potentially greater soil C at depth in perennial forage systems with deeper rooted species (e.g., alfalfa; Bolinder et al., 2002). In general, soil POx-C in our study averaged near the minimum of that reported in other studies across the United States (means from 0.38 to 0.81 g C kg^{-1} across 12 sites; Culman et al., 2012). This likely reflects differences in soil types from our site compared to that of many of the other studies conducted on soils with higher native fertility and soil organic matter.

Total soil N and POM-N responded similarly to respective C constituents in soil; both were significantly affected by year ($P < 0.01$), management system ($P < 0.01$), and the interaction ($P < 0.01$; Table 1). On average, total soil N in forage systems increased from 924 mg N kg^{-1} in 2010 to 1297 mg N kg^{-1} soil in 2012 (Table 2). Following 1 yr of organic forage management, mean total soil N was significantly higher in all forage systems (1251 mg N kg^{-1} soil) than in the vegetable management systems (944 mg N kg^{-1} soil). At the final sampling, total soil N was highest in the alfalfa system and systems containing red clover, and lowest in vegetable production systems. Averaged over all forage systems, soil POM-N more than doubled from 218 mg N kg^{-1} soil in 2010 to 460 mg N kg^{-1} in 2012 (Table 2). Similar to POM-C, the highest POM-N after 2 yr of management was observed in soils in the alfalfa monoculture and treatments containing red clover, and the lowest in the vegetable management systems, the annual forage system and the alfalfa/orchardgrass system. The N fraction of POM following 2 yr of forage management was generally higher than that reported in other organic systems, although initial values from our study were similar to those reported elsewhere (~ 200 mg POM-N kg^{-1} soil; reviewed by Ugarte and Wander, 2013). These increasing values of POM-N are promising for regional organic production systems which could utilize N accumulated in labile soil organic matter during forage production phases to support most of the subsequent agronomic or horticultural crop's N needs, given the correlation between POM-N and soil N mineralization (Willson et al., 2001). However, while this relationship has not been well explored for soils and climate in the southeastern United States, the potential for sod-based rotations to reduce responsiveness of subsequent crops to applied N fertilizer (Giddens et al., 1971; Franzluebbers and Wilkinson, 2003) is well documented.

SUMMARY AND CONCLUSIONS

As demonstrated by total soil C and the labile soil organic matter fraction of POM-C at the 0- to 15-cm depth, soil quality can be increased significantly within 2 yr of organically-managed forage production (including an annual system of wheat/crimson clover and sorghum–sudangrass) as compared to initial soil C and soil C dynamics in similarly managed vegetable systems. This suggests that adding short-term forages to crop rotations has potential to benefit organic farms or farms transitioning to organic production in the southeastern United States. Annual forage systems may be especially useful in this transitional period due to rapid establishment and highly competitive growth habits and relatively high yields of harvestable biomass, while also leading to improved soil C stocks. While total soil N and POM-N trends were similar to soil C constituents, the annual forage system in general did not improve soil N storage to the same extent as most perennial forage systems. Mean annual yields of organic perennial forage systems evaluated did not differ for the alfalfa/orchardgrass, red clover, and red clover/orchardgrass systems over the 2-yr period of the study, although yields were less than the annual system. Organic farmers must consider trade-offs between potentially greater yields of annual forage systems and potentially greater cropping system services (such as increased soil N) provided by perennial forage systems in short rotation, in addition to management costs associated with each system.

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