Soil Aggregation and Glomalin under Pastures in the Southern Piedmont USA

A. J. Franzluebbers,* S. F. Wright, and J. A. Stuedemann

ABSTRACT

Soil aggregation is important for maintaining soil surface integrity and allowing water to infiltrate, rather than runoff and cause erosion. The effect of grazing animals on soil aggregation compared with other conservation management strategies in the Southern Piedmont USA is not well known. We tested a hypothesis that grazing animals might negatively affect soil aggregation characteristics. Water-stable macroaggregates (>0.25 mm), mean-weight diameter, and their stabilities were (i) similar between conservation-tillage cropping and tall fescue (*Festuca arundinacea* Schreb.)–common bermudagrass (*Cynodon dactylon* L.) pasture; (ii) similar between 15- to 19-yr-old grazed and hayed hybrid bermudagrass; (iii) 7 to 14% greater in 30-yr-old than in 10-yr-old grazed tall fescue and hybrid bermudagrass pastures; (iv) similar among long-term grazingland, hayland, and forestland; and (v) 5 to 11% lower under cattle grazing than under monthly haying or unharvested management during the first 4 yr following conversion of cultivated cropland to pastureland. Water-stable aggregate distribution at a depth of 0 to 50 mm was 0.30 ± 0.07 g g^{-1} in the 1.0- to 4.75-mm class, 0.46 ± 0.07 g g^{-1} in the 0.25- to 1.0-mm class, 0.15 ± 0.02 g g^{-1} in the 0.05- to 0.25-mm class, and 0.07 ± 0.01 g g^{-1} in the <0.05-mm class, averaged across management systems and replications (n = 56). Total glomalin of the 1.0- to 4.75-mm dry-stable aggregate class was highly related to whole soil organic C content, but neither of these properties was particularly well related with water-stable macroaggregation, mean-weight diameter, or their stabilities. We conclude, overall, that grazing of pastures in the Southern Piedmont USA has little detrimental effect on soil aggregate distribution and stability and is comparable in soil conservation with other land conservation strategies.

Soil aggregation is important for the stabilization of land surfaces and the ability of soils to remain productive. Soils of the southeastern USA are particularly susceptible to erosion because of the frequency of high-intensity thunderstorms that can wash away exposed soil by overland flow of water on gently to steeply sloping land. Conversion of tilled cropland to perennial grasses and legumes has been shown to increase soil organic matter and aggregation (Drury et al., 1991; Angers, 1992) and may be an effective means of controlling erosion in the southeastern USA. However, relatively little is known about the effect of a variety of widely used pasture management strategies on soil aggregation (Harris et al., 1966). Typical variations in pasture management that might affect soil aggregation include species of grass, grazing pressure, and stand age. Animal grazing of pastures raises concerns of increased erosion because of the potential for reducing vegetative cover by soil trampling (Trimble and Mendel, 1995), but the long-term effect of grazing vs. haying on soil aggregation has not been well documented.

Aggregation is a dynamic process involving soil physical, chemical, and biological processes (Kemper and Koch, 1966; Juma, 1993; Monreal et al., 1995). Soil aggregation has been conceptualized as a hierarchical system of primary particles forming microaggregates (<0.25 mm), which then become the basis for formation of macroaggregates (>0.25 mm) of varying sizes (Tisdall and Oades, 1982). Microaggregates are considered cemented by persistent, aromatic humic material in association with amorphous Fe and Al and polyvalent metals. The binding agents holding together macroaggregates are considered either transient (i.e., biochemicals such as microbial- or plant-derived polysaccharides) or temporary (i.e., roots and fungal hyphae) (Tisdall and Oades, 1982). Glomalin, a glycoprotein produced by arbuscular mycorrhizal fungi, may be an important specific cementing agent involved in the aggregation process (Wright et al., 1996; Wright and Upadhyaya, 1996). The harsh treatment (i.e., autoclaving with 20–50 m*M* citrate buffer necessary to extract glomalin from soil suggests that it is a stable compound resisting decomposition. Immunoreactive glomalin represents a more freshly deposited source of glomalin that has not undergone biochemical transformations in soil (Wright et al., 1996).

Our objective was to evaluate the effect of grazed pasture on soil aggregation compared with other conservation management strategies in the Southern Piedmont USA. We also investigated relationships between clay content, soil organic C, glomalin, aggregate distribution, and aggregate stability.

MATERIALS AND METHODS

Site Descriptions

Fourteen fields located on the J. Phil Campbell Sr. Natural Resource Conservation Center (33° 52′ N, 83° 25′ W) were sampled in early May 1997 for Contrasts 1 to 4 described below (Table 1). Soils were predominantly Cecil, Madison, and Pacolet series with sandy loam, loam, or sandy clay loam texture (fine, kaolinitic, thermic Typic Kanhapludult). Generally, surface soils were once low in clay content (<15%), but now commonly contain a greater percentage due to erosion that has exposed clayey subsoil. The location is characterized by mean annual temperature of 16.5°C, mean annual precipitation of 1250 mm, and mean annual potential evaporation of 1560 mm. Fields were selected to contrast grazing with other conservation land management systems typical of the region.

Contrast 1: Pasture vs. Conservation-Tillage Cropland

Prior to 1974, a single field was managed under conventional-tillage cropping. From autumn of 1974 onwards, one portion was managed with conservation-tillage. The other portion continued to be managed with conventional-tillage crop-

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Table 1. Management characteristics and soil physical and chemical properties to a depth of 200 mm.

System	Management	Clay	Sand	Bulk density	Soil organic C	Soil total N
		g kg^{-1}		Mg m^{-3}	g kg^{-1}	
	Contrast 1: Pasture vs. conservation-tillage cropland					
1-Cropped	24-yr conservation tillage after conventional tillage	151 ± 30	686 ± 66	1.57 ± 0.04	7.8 ± 1.2	0.56 ± 0.08
2-Pasture	20-yr tall fescue–common bermudagrass pasture	220 ± 25	610 ± 25	1.48 ± 0.05	10.9 ± 0.9	0.79 ± 0.09
	Contrast 2: Grazed vs. hayed hybrid bermudagrass					
3-Grazed	19-yr Tifton 44 bermudagrass	290 ± 22	558 ± 17	1.48 ± 0.03	12.9 ± 1.4	1.18 ± 0.19
4-Grazed	15-yr Tifton 44 bermudagrass after forest	222 ± 54	583 ± 51	1.39 ± 0.05	16.8 ± 2.7	1.26 ± 0.20
5-Grazed	15-yr Tifton 44 bermudagrass after cropping	118 ± 14	726 ± 42	1.60 ± 0.02	9.1 ± 1.5	0.58 ± 0.08
6-Hayed	19-yr Tifton 44 bermudagrass	187 ± 56	564 ± 167	1.42 ± 0.07	13.2 ± 4.1	0.98 ± 0.31
7-Hayed	15-yr Coastal bermudagrass after forest	284 ± 24	568 ± 18	1.50 ± 0.04	9.1 ± 0.9	0.58 ± 0.06
8-Hayed	15-yr Coastal bermudagrass after cropping	235 ± 43	585 ± 28	1.50 ± 0.01	9.6 ± 1.0	0.70 ± 0.08
	Contrast 3: Stand age of hayed bermudagrass and grazed tall fescue					
9-Bermuda	6-yr hayed Coastal bermudagrass after cropping	233 ± 128	592 ± 116	1.64 ± 0.12	8.5 ± 1.2	0.61 ± 0.13
8-Hayed	15-yr Coastal bermudagrass after cropping	235 ± 43	585 ± 28	1.50 ± 0.01	9.6 ± 1.0	0.70 ± 0.08
10-Bermuda	40-yr hayed Coastal bermuda after cropping	125 ± 17	694 ± 25	1.52 ± 0.02	10.4 ± 1.1	0.71 ± 0.06
11-Fescue	10-yr grazed tall fescue	147 ± 29	692 ± 36	1.52 ± 0.04	10.0 ± 1.5	0.64 ± 0.07
12-Fescue	17-yr grazed tall fescue	128 ± 41	671 ± 78	1.34 ± 0.12	15.1 ± 0.8	1.20 ± 0.13
13-Fescue	50-yr grazed tall fescue	294 ± 47	542 ± 35	1.38 ± 0.02	14.1 ± 0.8	1.24 ± 0.10
	Contrast 4: Long-term continuous land management systems of forestland, cropland, hayland, and grazingland					
14-Forest	130-yr forest planted to pine	143 ± 40	703 ± 40	1.32 ± 0.05	10.9 ± 2.0	0.40 ± 0.07
1-Cropped	24-yr conservation tillage after conventional tillage	151 ± 30	686 ± 66	1.57 ± 0.04	7.8 ± 1.2	0.56 ± 0.08
10-Bermuda	40-yr hayed Coastal bermuda after cropping	125 ± 17	694 ± 25	1.52 ± 0.02	10.4 ± 1.1	0.71 ± 0.06
13-Fescue	50-yr grazed tall fescue	294 ± 47	542 ± 35	1.38 ± 0.02	14.1 ± 0.8	1.24 ± 0.10

† Mean ± standard deviation among four replicates.

ping until autumn of 1978, when 'Kentucky-31' tall fescue was planted. Conservation-tillage cropping consisted of summer crops of soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.), with winter crops of wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), and crimson clover (*Trifolium incarnatum* L.) and minimum soil disturbance, except for in-row chisel at planting. Fertilization averaged 47, 35, and 108 kg ha^{-1} yr^{-1} of N, P, and K, respectively, during 24 yr of conservation-tillage cropping. Dolomitic limestone was applied six times during this period at a rate of 2.2 Mg ha^{-1}. The tall fescue pasture was grazed seasonally at a moderate stocking density with Angus cattle (*Bos taurus*) and with time was invaded by common bermudagrass because of armyworm (*Pseudaletia unipuncta* Haworth) damage to tall fescue. Fertilization averaged 47, 14, 42 kg ha^{-1} yr^{-1} of N, P, and K, respectively, during the past 7 yr. Dolomitic limestone (2.2 Mg ha^{-1}) was applied once during the past 7 yr.

Contrast 2: Grazed vs. Hayed Hybrid Bermudagrass

Grazed pastures were two 15-yr-old and one 19-yr-old stands of 'Tifton 44'. Hayed fields were two 15-yr-old stands of 'Coastal' and one 19-yr-old stand of Tifton 44. Grazing was seasonal at a moderate stocking density with Angus cattle to utilize forage, and haying was three to four times annually. During the past 7 yr, grazed pastures received an average of 93, 23, 63 kg ha^{-1} yr^{-1} of N, P, and K, respectively, and hayed fields received an average of 162, 45, 134 kg ha^{-1} yr^{-1} of N, P, and K, respectively.

Contrast 3: Stand Age of Hayed Bermudagrass and Grazed Tall Fescue

Ten- and 17-yr-old tall fescue pastures were replicated field experiments receiving 336, 37, 139 ha^{-1} yr^{-1} of N, P, and K, respectively. Two of the replications sampled (one composite sample per replication and stand age) were with high endophyte infection and two were with low endophyte infection. We did not expect endophyte infection to influence our results. A 50-yr-old tall fescue pasture was highly endophyte infected and received fertilizer sporadically with only one application of 45, 20, 37 kg ha^{-1} of N, P, and K, respectively, during the past 7 yr. A 6-yr-old bermudagrass field was fertilized with an average of 149, 35, 105 kg ha^{-1} yr^{-1} of N, P, and K, respectively. Fifteen- and 40-yr-old bermudagrass fields received an average of 162, 45, 134 kg ha^{-1} yr^{-1} of N, P, and K, respectively, during the past 7 yr. Grazing was seasonal at a moderate stocking density with Angus cattle and haying was three to four times annually.

Contrast 4: Long-Term Continuous Land Management Systems of Forestland, Cropland, Hayland, and Grazingland

Forestland was a loblolly pine (*Pinus taeda* L.) plantation established in the 1860s, with pine harvested in the mid 1960s and hardwoods (*Quercus*, *Carya*, and *Pinus* spp.) allowed to regrow. Cropland was the 24-yr-old conservation tillage system described in Contrast 1. Hayland and pastureland were the 40- and 50-yr-old bermudagrass and tall fescue systems, respectively, described in Contrast 3.

Contrast 5: Stand Age and Harvest Strategy of Coastal Bermudagrass

This experiment was located near Farmington, GA (33°20′ N, 83°23′ W) on similar soils (i.e., Typic Kanhapludults). Clay content was 98 ± 25 g kg^{-1} soil at a depth of 0 to 20 mm and 131 ± 30 g kg^{-1} soil at a depth of 20 to 40 mm. Coastal bermudagrass was fertilized with ≈6.6 Mg ha^{-1} yr^{-1} of broiler litter and managed by (i) harvesting monthly from May through October, (ii) not harvesting, (iii) grazing by steers from May through October to maintain ≈1.5 Mg ha^{-1} of available forage, and (iv) grazing by steers from May through October to maintain ≈3.0 Mg ha^{-1} of available forage. Treatments were replicated three times. Soil was sampled during April or May of 1994, 1996, 1997, and 1998 (i.e., 0, 2, 3, and 4 yr after establishment of bermudagrass management) to

depths of 0 to 20 and 20 to 40 mm and treated identically to soil in Contrasts 1 to 4, except that soil in 1994 was ground to <2 mm.

Soil Sampling

Soil samples for Contrasts 1 to 4 were collected from each field (3 ± 2 ha) in four zones, which served as pseudoreplicates for analyses. Fields were separated by a maximum of 4 km. Zones were separated by ≥30 m. Each zone was divided into six sites on a two by three grid. Sites were separated by ≈10 m. At each site, plant material above 40 mm from the soil surface was removed from within a 0.3-m-diam. ring. Surface residue (all organic material at 0–40 mm height above mineral soil) was cut with battery-powered hand shears [data reported in Franzluebbers et al. (2000)]. Soil under forest was moder; therefore, we defined the soil surface as the mineral layer and placed the Oi and Oa horizons into the surface residue component. One soil core (41-mm diam.) within each ring was divided into 0- to 50-, 50- to 125-, and 125- to 200-mm increments. A second core to a depth of 0 to 50 mm within the ring was added to the first core. Samples from the six sites within each zone were composited. Soil was dried at 55°C for 48 h, weighed, and gently crushed to pass a 4.75-mm screen prior to analyses. Stones >4.75 mm were removed and accounted for ≤1% of sample weight.

Soil Characterization

Soil bulk density was calculated from the oven-dried weight (55°C) and volume of the coring device. Particulate organic fraction was collected from a 20- to 65-g sample by shaking in 100 mL of 0.1 *M* $Na_4P_2O_7$ for 16 h, diluting the suspension to 1 L with distilled water, allowing to settle for 5 h, and catching material on a 0.06-mm screen (Franzluebbers et al., 1999, 2000). Sand-sized material retained on the screen was transferred to a drying bottle and weighed after oven drying (55°C, 72 h). Clay content was determined with a hydrometer at the end of the 5-h settling period (Gee and Bauder, 1986).

Soil microbial biomass C was determined with the chloroform fumigation–incubation method without subtraction of a control, and basal soil respiration was determined from the linear rate of C mineralization during 10 to 24 d of incubation at 25°C (Franzluebbers and Arshad, 1996a). Soil and particulate organic C and N, microbial biomass C, basal soil respiration, and bulk density under different management systems were reported previously (Franzluebbers et al., 2000) and are summarized in Table 2.

Subsamples of whole soil and particulate organic fraction (ground in a ball mill for 5 min) were analyzed for total C and N using dry combustion. Organic C was assumed to be equivalent to total C, because soils had pH < 6.5. Organic N was assumed to be equivalent to total N, although total N was composed of 1.3 ± 0.5% inorganic N.

Soil for all aggregate distribution and stability analyses was oven dried (55°C) and gently crushed to pass a 4.75-mm screen. We oven-dried soil to standardize the procedure and avoid confounding effects of antecedent moisture content with management systems (Gollany et al., 1991). Dry aggregate distribution was determined by placing a 100-g portion of soil on top of a nest of sieves (200-mm diam. with openings of 1.0, 0.25, and 0.061 mm), shaking for 1 min at Level 6 on a CSC Scientific Sieve Shaker (Catalogue no. 18480, CSC Scientific Co., Fairfax, VA) and weighing soil retained on the 1.0-, 0.25-, and 0.061-mm screens and that passing the 0.061-mm screen.[1] Water-stable aggregate distribution was determined from the same soil sample used for dry aggregate distribution placed on top of a nest of sieves (175-mm diam. with openings of 1.0 and 0.25 mm), immersed directly in water, and oscillated for 10 min (20-mm stroke length, 31 cycles min^{-1}). Floating organic material retained within the walls of the top sieve was removed by suction, collected on a screen, and dried in a bottle. After removing the two sieves and placing them in an oven to dry, water containing soil passing the 0.25-mm sieve was poured over a 0.053-mm sieve, the soil was washed with a gentle stream of water, and the soil retained transferred into a drying bottle with a small stream of water. The <0.053-mm fraction was calculated as the difference between initial soil weight and summation of the other fractions. All fractions were oven dried at 55°C for ≥24 h following visual dryness.

Mean-weight diameter of both dry- and water-stable aggregates was calculated by summing the products of aggregate fractions and mean diameter of aggregate classes, excluding the floating material. Macroaggregates were defined as soil retained on 1.0- and 0.25-mm sieves. Large macroaggregates

[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

Table 2. Soil properties as affected by depth for all four replications of each of the 14 management systems used in Contrasts 1 to 4.

Soil property	Soil depth, mm		
	0–50	50–125	125–200
Bulk density, Mg m^{-3}	1.10 ± 0.14	1.57 ± 0.11	1.62 ± 0.11
Clay content, g kg^{-1}	220 ± 55	174 ± 70	213 ± 96
Sand content, g kg^{-1}	636 ± 102	651 ± 87	599 ± 96
Soil organic C, g kg^{-1}	28.5 ± 9.1	9.1 ± 2.7	5.9 ± 2.3
Total N, g kg^{-1}	2.06 ± 0.94	0.69 ± 0.28	0.39 ± 0.18
Particulate organic C, g kg^{-1}	11.6 ± 4.6	1.9 ± 0.7	1.1 ± 0.6
Microbial biomass C, mg kg^{-1}	918 ± 241	371 ± 114	279 ± 94
Basal respiration, mg kg^{-1} d^{-1}	17.3 ± 19.3	2.1 ± 1.2	1.5 ± 1.6
Total glomalin (1.0–4.75 mm dry), g kg^{-1}	2.83 ± 0.95	1.01 ± 0.39	0.55 ± 0.39
Immunoreactive glomalin (1.0–4.75 mm dry), g kg^{-1}	0.61 ± 0.11	0.51 ± 0.19	0.27 ± 0.11
Dry-stable fraction (1.0–4.75 mm), kg kg^{-1}	0.39 ± 0.09	0.44 ± 0.12	0.47 ± 0.09
Dry-stable fraction (0.25–1.0 mm), kg kg^{-1}	0.42 ± 0.06	0.39 ± 0.07	0.38 ± 0.06
Dry-stable fraction (0.06–0.25 mm), kg kg^{-1}	0.15 ± 0.03	0.13 ± 0.04	0.12 ± 0.03
Dry-stable fraction (<0.061 mm), kg kg^{-1}	0.04 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
Dry-stable mean-weight diameter, mm	1.41 ± 0.21	1.54 ± 0.28	1.62 ± 0.22
Wet-stable fraction (1.0–4.75 mm), kg kg^{-1}	0.30 ± 0.07	0.32 ± 0.09	0.26 ± 0.07
Wet-stable fraction (0.25–1.0 mm), kg kg^{-1}	0.46 ± 0.07	0.44 ± 0.09	0.45 ± 0.08
Wet-stable fraction (0.05–0.25 mm), kg kg^{-1}	0.15 ± 0.02	0.17 ± 0.03	0.20 ± 0.04
Wet-stable fraction (<0.053 mm), kg kg^{-1}	0.07 ± 0.01	0.07 ± 0.03	0.10 ± 0.03
Wet-stable mean-weight diameter, mm	1.21 ± 0.17	1.23 ± 0.22	1.05 ± 0.16
Stability of macroaggregates, kg kg^{-1}	0.94 ± 0.04	0.92 ± 0.06	0.83 ± 0.08
Stability of mean-weight diameter, mm mm^{-1}	0.86 ± 0.05	0.80 ± 0.06	0.65 ± 0.08

† Mean ± standard deviation, $n = 56$.

were defined as soil retained on the 1.0-mm sieve. Stability of macroaggregates was calculated as the weight of water-stable macroaggregates divided by the weight of dry-stable macroaggregates. Stability of mean-weight diameter was calculated as water-stable mean-weight diameter divided by dry-stable mean-weight diameter.

Glomalin was extracted from duplicate 1-g portions of dry-stable aggregates retained on the 1.0-mm sieve following the procedures outlined in Wright and Upadhyaya (1996, 1998). Briefly, samples were autoclaved (121°C) for 60 min in 8 mL of 50 m*M* citrate buffer (pH = 8.0), centrifuged at 10 000 *g* for 10 min, and the supernatant containing glomalin was collected. The extraction process was repeated two more times on the same sample. Material remaining after the three centrifugations was passed over a 0.25-mm screen and coarse material retained on the screen washed with water, dried at 103°C, and weighed. Total glomalin was determined with the Bradford assay using bovine serum albumin standards. Immunoreactive glomalin, an indicator of more recently deposited glomalin, was determined with an enzyme-linked immunosorbent assay using monoclonal antibody 32B11 (Wright et al., 1996). Percentage of immunoreactivity was determined by comparing with an active culture of arbuscular mycorrhizae.

Statistical Analyses

Soil properties from each depth and from the weighted mean of the 0- to 200-mm depth were analyzed for variance using the general linear models procedure of SAS (SAS Institute, 1990). Differences among treatments were considered significant at $P \leq 0.1$. Regression was used to test relationships among variables.

RESULTS

Contrast 1: Pasture vs. Conservation-Tillage Cropland

Mean-weight diameter of water-stable aggregation under tall fescue–bermudagrass pasture was not different than under conservation-tillage cropland at a depth of 0 to 50 mm and was 26% greater at depths of 50 to 125 mm ($P = 0.06$) and 125 to 200 mm ($P = 0.002$) (data not shown). To a depth of 200 mm, mean-weight diameter under tall fescue–bermudagrass pasture was 20% greater than under conservation-tillage cropland (Table 3). However, fraction of soil as water-stable macroaggregates (>0.25 mm) was statistically lower under tall fescue–bermudagrass pasture than under conservation-tillage cropland (Table 3). This difference occurred primarily at the soil surface (0–50 mm), where the fraction of soil as water-stable macroaggregates was 0.75 kg kg^{-1} under tall fescue–bermudagrass pasture and 0.80 kg kg^{-1} under conservation-tillage cropland ($P = 0.03$). Macroaggregation and mean-weight diameter differed between management systems because a greater fraction of soil was in large macroaggregates (1.0–4.75 mm) under tall fescue–bermudagrass pasture (0.32 kg kg^{-1}) than under conservation-tillage cropland (0.23 kg kg^{-1}), but a lower fraction of soil (0.39 vs. 0.52 kg kg^{-1}) was in small macroaggregates (0.25–1.0 mm).

Stability of large macroaggregates and stability of mean-weight diameter were 22 and 10% greater, respectively, under tall fescue–bermudagrass pasture than under conservation-tillage cropland (Table 3). However, stability of all macroaggregates was not affected by land use. In general, long-term pasture had soil aggregate distribution and stability properties that were relatively similar to long-term conservation-tillage cropping.

Total and immunoreactive glomalin in 1.0- to 4.75-mm aggregates were not different between tall fescue–bermudagrass pasture and conservation-tillage cropland averaged to a depth of 200 mm (Table 3), nor at any of the depth increments (data not shown). Total glomalin averaged 1.9, 0.9, and 0.5 g kg^{-1} of 1.0- to 4.75-mm aggregates at depths of 0 to 50, 50 to 125, and 125 to 200 mm, respectively. Immunoreactive glomalin averaged 33, 43, and 52% of total glomalin at depths of 0 to 50, 50 to 125, and 125 to 200 mm, respectively.

Table 3. Soil aggregate distribution and stability and glomalin properties (0–200 mm depth) at the end of 24 yr following conversion of conventional-tillage to conservation-tillage cropland and at the end of 20 yr following conversation of a portion of this conventional-tillage cropland to pasture (Contrast 1).

Soil property	Conservation-tillage cropland	Tall fescue–bermudagrass pasture	LSD$_{(P \leq 0.1)}$
Water-stable aggregate distribution			
Macroaggregates (>0.25 mm), kg kg^{-1}	0.75	0.71	0.03†
Mean-weight diameter, mm	1.01	1.22	0.14†
Aggregate stability in water (wet dry^{-1})			
Large macroaggregate stability, kg kg^{-1}	0.58	0.71	0.08†
Macroaggregate stability, kg kg^{-1}	0.89	0.84	0.05NS
Mean-weight diameter stability, mm mm^{-1}	0.67	0.74	0.06†
Glomalin (1.0–4.75 mm dry-stable aggregate fraction)			
Total protein, mg g^{-1}	0.91	0.92	0.28NS
Immunoreactive protein, mg g^{-1}	0.36	0.38	0.09NS

† Significant at the 0.1 level of probability; NS is nonsignificant.

Contrast 2: Grazed vs. Hayed Hybrid Bermudagrass

Grazing compared with haying management of hybrid bermudagrass for 15 to 19 yr had little effect on water-stable aggregate distribution or stability averaged to a depth of 200 mm (Table 4) or at any of the depth increments (data not shown). Macroaggregate stability declined with depth under both systems from 0.93 kg kg^{-1}

Table 4. Soil aggregate distribution and stability and glomalin properties (0–200 mm depth) under 15- to 19-yr-old grazed and hayed bermudagrass management (Contrast 2).

Soil property	Grazed	Hayed	LSD$_{(P \leq 0.1)}$
Water-stable aggregate distribution			
Macroaggregates (>0.25 mm), kg kg^{-1}	0.74	0.72	0.03NS
Mean-weight diameter, mm	1.13	1.21	0.12NS
Aggregate stability in water (wet dry^{-1})			
Large macroaggregate stability, kg kg^{-1}	0.68	0.68	0.04NS
Macroaggregate stability, kg kg^{-1}	0.89	0.85	0.03†
Mean-weight diameter stability, mm mm^{-1}	0.74	0.72	0.03NS
Glomalin (1.0–4.75 mm dry-stable aggregate fraction)			
Total protein, mg g^{-1}	1.30	1.07	0.27NS
Immunoreactive protein, mg g^{-1}	0.41	0.44	0.05NS

† Significant at the 0.1 level of probability; NS is nonsignificant.

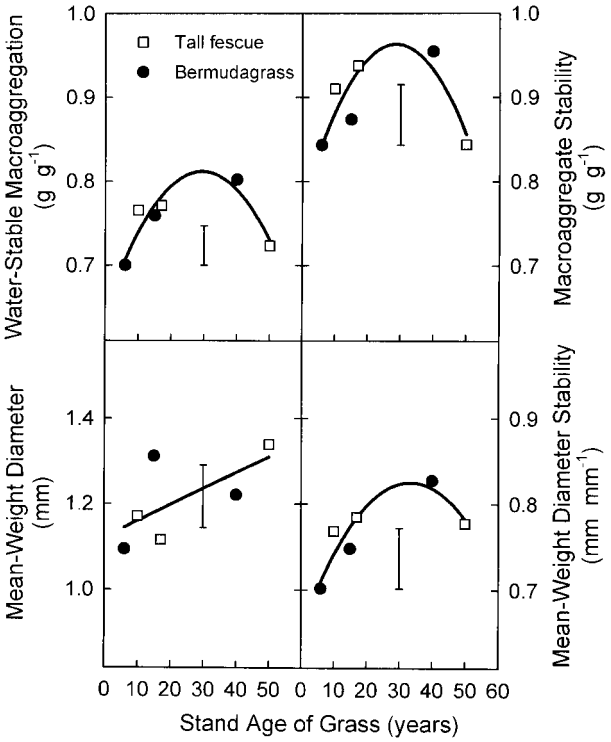

Fig. 1. Water-stable macroaggregation (>0.25 mm) and its stability (wet/dry) and mean-weight diameter of water-stable aggregates and its stability (wet/dry) as affected by stand age of grazed Kentucky-31 tall fescue and hayed Coastal bermudagrass in soil at a depth of 0 to 200 mm (Contrast 3). Error bars are LSD (P = 0.05) among all combinations of stand age and grass species.

at 0 to 50 mm to 0.90 g g^{-1} at 50 to 125 mm to 0.81 kg kg^{-1} at 125 to 200 mm. Long-term animal traffic from grazing, therefore, had no negative effect on soil aggregation compared with machine traffic from haying.

Total and immunoreactive glomalin were unaffected by bermudagrass management averaged to a depth of 200 mm (Table 4), but total glomalin was 44% greater with grazing than haying at a depth of 0 to 50 mm (data not shown). No other differences in total or immunoreactive glomalin were observed at other depths. Immunoreactive glomalin averaged 0.6, 0.5, and 0.3 kg kg^{-1} of 1.0- to 4.75-mm aggregates at depths of 0 to 50, 50 to 125, and 125 to 200 mm, respectively; however, as a percentage of total glomalin, immunoreactive glomalin averaged 22, 49, and 52% at depths of 0 to 50, 50 to 125, and 125 to 200 mm, respectively.

Contrast 3: Stand Age of Hayed Bermudagrass and Grazed Tall Fescue

Water-stable macroaggregates and stability of macroaggregates increased with increasing stand age of grass up to a maximum at ≈30 yr and then declined thereafter (Fig. 1). Mean-weight diameter of water-stable aggregates increased with stand age of grass, with no indication of decline, whereas its stability function reached an optimum at ≈30 yr and then declined. There were no differences in aggregate distribution and stability properties between grazed Kentucky-31 tall fescue and hayed Coastal bermudagrass when averaged across

Table 5. Soil glomalin properties (0–200 mm depth) of the 1.0- to 4.75-m dry-stable aggregate fraction as affected by stand age of grazed Kentucky-31 tall fescue and hayed Coastal bermudagrass (Contrast 3).

Soil property	Management			
	Grazed tall fescue			
	10 yr	17 yr	50 yr	$LSD_{(P\leq0.1)}$
Total protein, mg g^{-1}	1.05	1.82	1.07	0.18†
Immunoreactive protein, mg g^{-1}	0.50	0.56	0.41	0.11†
	Hayed bermudagrass			
	6 yr	15 yr	40 yr	$LSD_{(P\leq0.1)}$
Total protein, mg g^{-1}	0.94	0.97	1.01	0.17NS
Immunoreactive protein, mg g^{-1}	0.45	0.44	0.39	0.06NS

† Significant at the 0.1 level of probability; NS is nonsignificant.

years. Although an interaction between plant species and time might be deduced from aggregation data (Fig. 1), we believe this not to be the case, but rather that aggregation properties should increase with stand age until pastures decline in vigor and are invaded with less desirable plant species. Limited fertilization of the 50-yr-old tall fescue pasture and diversification of the pasture through invasion with white clover (*Trifolium repens* L.), ryegrass (*Lolium perenne* L.), and common bermudagrass may have reduced soil aggregate properties relative to younger, purer, and more heavily fertilized stands of tall fescue. These management differences between younger and older tall fescue stands may have confounded soil aggregation properties, especially since aggregation properties tended to be linearly related with stand age under bermudagrass. However, soil organic C and N were not significantly reduced in 50-yr-old compared with 17-yr-old tall fescue stands (Franzluebbers et al., 2000). It appears that soil aggregation properties increase with stand age until at least 30 yr. Further research is required to estimate these properties in older stand ages.

Total glomalin was higher in 17-yr-old tall fescue than in 10- and 50-yr-old grazed Kentucky-31 tall fescue, but was unaffected by stand age in hayed Coastal bermudagrass (Table 5). Immunoreactive glomalin generally declined with stand age in both tall fescue and bermudagrass pastures. Glomalin may be an important binding agent in disturbed agroecosystems (Wright et al., 1999), but our results suggest that, independent of glomalin, accumulation of soil organic matter may be more important in keeping aggregates stable under long-term grassland systems.

Contrast 4: Long-Term Land Management Systems

Water-stable macroaggregation of long-term grazingland and hayland was equal to or higher than long-term conservation-tillage cropland and forestland (Table 6). Mean-weight diameter of water-stable aggregates was greater under grazingland and hayland than under conservation-tillage cropland and forestland.

Stability of macroaggregates was lower under grazingland than under hayland and forestland, but not different from that under conservation-tillage cropland.

Table 6. Soil aggregate distribution and stability and glomalin properties (0–200 mm depth) under four long-term land management systems (Contrast 4).

Soil property	Crop	Forest	Grazing	Hay	$LSD_{(P\leq 0.1)}$
		Water-stable aggregate distribution			
Macroaggregates (>0.25 mm), kg kg^{-1}	0.75	0.73	0.72	0.80	0.03†
Mean-weight diameter, mm	1.01	0.92	1.34	1.22	0.10†
		Aggregate stability in water (wet dry^{-1})			
Large macroaggregate stability, kg kg^{-1}	0.58	0.78	0.77	0.81	0.06†
Macroaggregate stability, kg kg^{-1}	0.89	0.96	0.84	0.95	0.05†
Mean-weight diameter stability, mm mm^{-1}	0.67	0.80	0.78	0.83	0.05†
		Glomalin (1.0–4.75 mm dry-stable aggregate fraction)			
Total protein, mg g^{-1}	0.91	1.33	1.07	1.01	0.45NS
Immunoreactive protein, mg g^{-1}	0.36	0.39	0.41	0.39	0.10NS

† Significant at the 0.1 level of probability; NS is nonsignificant.

Mean-weight diameter stability and large macroaggregate stability were similar among grazingland, hayland, and forestland, which were all greater than under conservation-tillage cropland. Total and immunoreactive glomalin were unaffected by long-term land management systems (Table 6).

Contrast 5: Stand Age and Harvest Strategy of Coastal Bermudagrass

Averaged across years, water-stable macroaggregation and its stability and mean-weight diameter and its stability were 5 to 11% lower under both grazing pressures than under haying or unharvested bermudagrass (Fig. 2). Stand age had relatively little effect on water-stable macroaggregation and mean-weight diameter. Macroaggregate stability increased with increasing stand age only under high grazing pressure. However, stability of mean-weight diameter increased with stand age under all management systems.

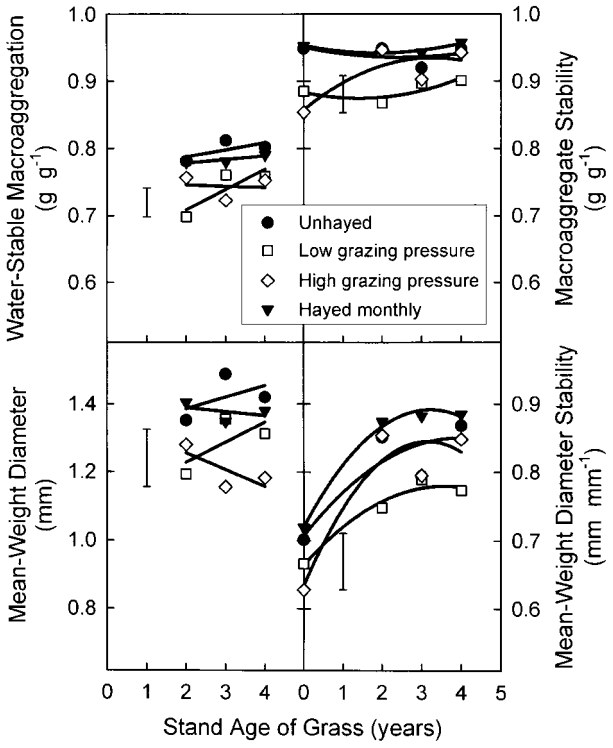

Fig. 2. Water-stable macroaggregation (>0.25 mm) and its stability (wet/dry) and mean-weight diameter of water-stable aggregates and its stability (wet/dry) as affected by stand age and harvest management of Coastal bermudagrass in soil at a depth of 0 to 20 mm (Contrast 5). Error bars are LSD (P = 0.05) among all combinations of stand age and grass management.

Total glomalin increased with stand age under all harvest management systems at both depths of 0 to 20 and 20 to 40 mm, except under monthly haying at a depth of 0 to 20 mm (Fig. 3). Although total glomalin increased with stand age of bermudagrass pastures from 0 to 4 yr at both soil depths, immunoreactive glomalin only increased with stand age at a depth of 20 to 40 mm and not at 0 to 20 mm (Fig. 4). More recently deposited glomalin expressed in the immunoreactive fraction, therefore, occurred at a depth of 20 to 40 mm rather than at a depth of 0 to 20 mm. The 20- to 40-mm depth may have been a more favorable environment for arbuscular mycorrhizal hyphal exploration compared with the soil surface because of less extreme drying–wetting cycles.

Relationships among Soil Aggregation Properties

Distribution of soil from the 0- to 50-mm depth into water-stable aggregate classes was dependent on soil clay content (Fig. 5). This was particularly true for the distribution between the large (1.0–4.75 mm) and small (0.25–1.0 mm) macroaggregate classes, where soils low

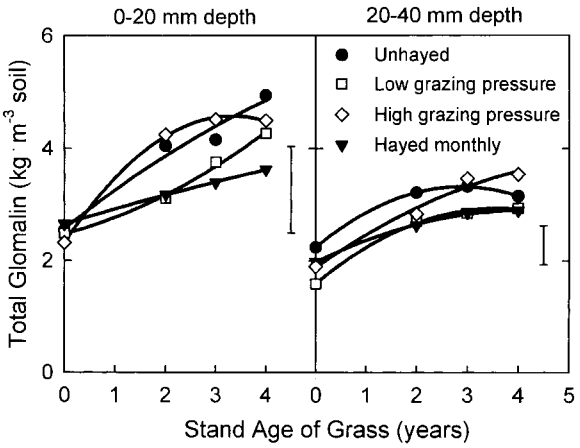

Fig. 3. Total glomalin in 1.0- to 4.75-mm dry-stable aggregates as affected by soil depth, stand age, and harvest management of Coastal bermudagrass (Contrast 5). Error bars are LSD (P = 0.05) among all combinations of stand age and grass management.

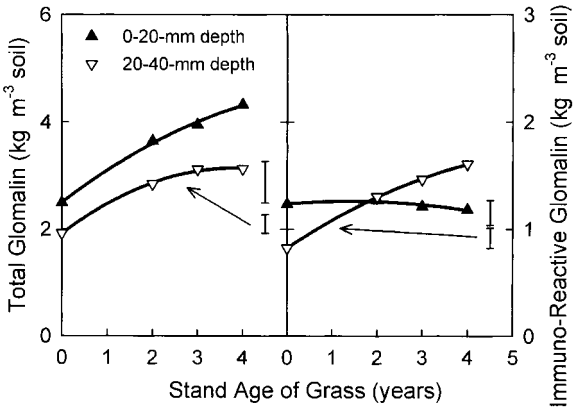

Fig. 4. Total and immunoreactive glomalin in 1.0- to 4.75-mm dry-stable aggregates as affected by soil depth and stand age of Coastal bermudagrass (Contrast 5). Error bars are LSD (P = 0.05) among stand ages within a soil depth.

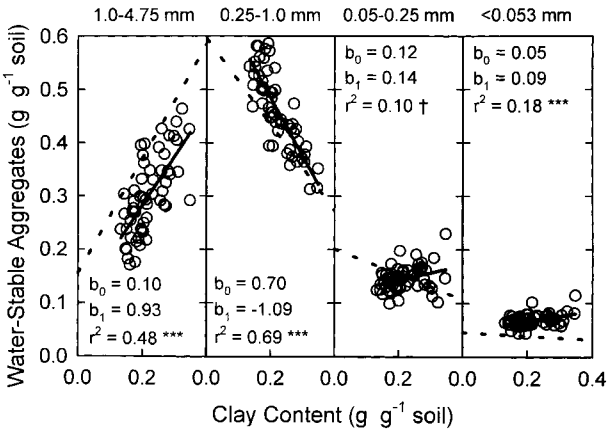

Fig. 5. Water-stable aggregate distribution among four size classes as affected by clay content of soil at a depth of 0 to 50 mm for each of the four replications of each of the 14 management systems in Contrasts 1 to 4 (n = 56). Dashed line is regression of dry-stable aggregate distribution within each size class (data points not shown). † and * indicate significance at the 0.1 and 0.001 levels of probability, respectively.**

in clay content had fewer large macroaggregates and more small macroaggregates, but soils high in clay content had similar distribution of large and small macroaggregates. Total water-stable macroaggregation was lower (P = 0.03) in soils with higher clay content, but clay content explained only 8% of the variation in water-stable macroaggregation. Macroaggregate stability, however, was lower ($P < 0.001$) in soils with higher clay content, with clay content explaining 48% of the variability in macroaggregate stability.

Water-stable macroaggregation was not very strongly related with mean-weight diameter (r = 0.48, Table 7). Soils under different management and at different depths had relatively similar macroaggregation (0.74 ± 0.05 kg kg^{-1}), but since we separated macroaggregates into small and large components, soils higher in clay content tended to have a higher mean-weight diameter because of a greater fraction of soil in the larger macroaggregate class (Fig. 5). Soils lower in clay content have less cohesive affinity to make larger aggregates (Kemper et al., 1987), but this did not make these smaller aggregates less stable. Stability of macroaggregates and stability of mean-weight diameter were highly related (r = 0.82, Table 7). Either of the stability functions was more related with water-stable macroaggregation than it was with mean-weight diameter.

Total and immunoreactive glomalin were both related to soil organic C content, although the relationship between total glomalin and soil organic C was much stronger (Fig. 6, Table 7). Total glomalin was also highly related with total soil N, particulate organic C and N, potentially mineralizable C, and soil microbial biomass C (data not shown). With these properties, immunoreactive glomalin was always less related (r = 0.51 ± 0.03) than total glomalin (r = 0.85 ± 0.04). Immunoreactive glomalin was 23 ± 8% of total glomalin at a depth of 0 to 50 mm, was 55 ± 22% of total glomalin at a depth of 50 to 125 mm, and was 57 ± 21% of total glomalin at a depth of 125 to 200 mm.

DISCUSSION

Soils under pastures and other conservation management systems of the Southern Piedmont USA were well aggregated and stable in water. Water-stable aggregate distribution and stability under various pasture management systems were similar to those under long-term forestland and conservation-tillage cropping at the same location. In Typic Kanhapludults using the same techniques, water-stable macroaggregation at a depth of 0 to 25 mm under conventional-tillage cropping was 0.69 kg kg^{-1} soil and under various conservation-tillage systems was 0.79 ± 0.02 kg kg^{-1} soil (Franzluebbers et al., 1999) compared with 0.76 ± 0.03 kg kg^{-1} at a depth of 0 to 50 mm in this study. Mean-weight diameter under these same comparisons was 0.96, 1.21 ± 0.06, and 1.21 ± 0.17 mm, respectively. It is clear that lack of soil

Table 7. Correlation coefficients and significance levels among soil aggregate distribution and stability characteristics, total and immunoreactive glomalin, and soil and particulate organic C represented by each of the four replications of the 14 management systems in Contrasts 1 to 4 at depths of 0 to 50, 50 to 125, and 125 to 200 mm (n = 168).

Property	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Water-stable macroaggregates	–	***	***	***	***	***	***	***
(2) Water-stable mean-weight diameter	0.48	–	NS	***	**	***	***	**
(3) Stability of macroaggregates	0.80	0.03	–	***	***	***	***	***
(4) Stability of MWD	0.71	0.41	0.82	–	***	***	***	***
(5) Total glomalin	0.31	0.20	0.44	0.60	–	***	***	***
(6) Immuno-reactive glomalin	0.43	0.36	0.47	0.61	0.62	–	***	***
(7) Soil organic C	0.28	0.29	0.37	0.60	0.90	0.57	–	***
(8) Particulate organic C	0.25	0.19	0.39	0.58	0.88	0.51	0.91	–

** and *** Significant at the 0.01 and 0.001 levels of probability, respectively; NS is not significant ($P > 0.1$).

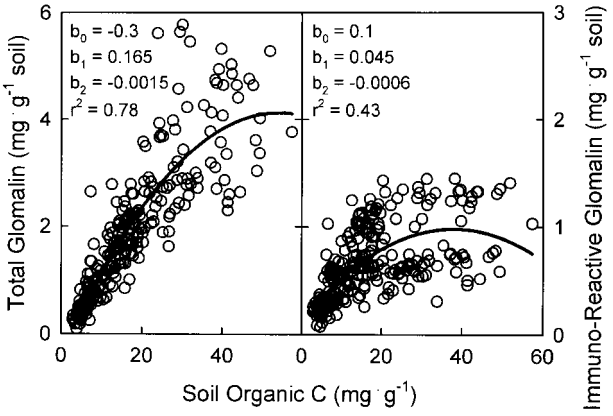

Fig. 6. Total and immunoreactive glomalin of 1.0- to 4.75-mm dry-stable aggregates in relationship with organic C of whole soil for all data in Contrasts 1 to 5 (n = 264).

disturbance in either pasture or cropping management systems is critical to promote water-stable aggregation.

Water-stable macroaggregation and mean-weight diameter of water-stable aggregates in soils from this study were high compared with soils in other studies from western USA and Canada using similar slaking techniques (i.e., direct immersion of dried soil in water). Water-stable macroaggregation was 0.54 ± 0.13 kg kg^{-1} soil in four soils under conservation-tillage cropping in Alberta and British Columbia (Franzluebbers and Arshad, 1996b), was 0.47 kg kg^{-1} soil under native grassland in Nebraska (Elliott, 1986), and was 0.41 ± 0.08 kg kg^{-1} soil in two soils in Quebec (Angers, 1998). Mean-weight diameter of water-stable aggregates in these same soils was 1.08 ± 0.33 mm in Alberta and British Columbia and 1.15 mm in Nebraska. Initial sieve size was smaller in our study (4.75 mm) than in the studies of Franzluebbers and Arshad (1996b) (5.6 mm) and Elliott (1986) (8.0 mm), which would have tended to reduce mean-weight diameter in our study.

Stability of macroaggregates (0.90 ± 0.08 g water-stable g^{-1} dry-stable) and stability of mean-weight diameter (0.77 ± 0.11 mm water-stable mm^{-1} dry-stable) in soils of this study were also high in comparison with soils from other studies. A Duroc loam (fine-silty, mixed, mesic Pachic Haplustoll) in western Nebraska under native grassland had 67% of macroaggregates (>0.3 mm) stable when slaked compared with premisting and only 27% stable macroaggregates when soil was under 14 yr of conventional cultivation (Elliott, 1986). Stability of mean-weight diameter in the Duroc loam was 54% under native grassland and 13% under cultivation. Differences in stability among soils in these two studies may have been even greater if similar control systems were used (i.e., dry-stable aggregation in our study vs. water-stable aggregation under misting in the study of Elliott, 1986).

We oven-dried (55°C) soils prior to sieving and aggregate analyses. It is unlikely that oven drying affected our results when compared with other studies, which were otherwise similar in direct water immersion and sieve sizes, but used air-dried soil (Elliott, 1986; Franzluebbers and Arshad, 1996b). With similar Piedmont soils, air drying and slaking yielded water-stable macroaggregates of 0.85 ± 0.07 kg kg^{-1} soil (Beare and Bruce, 1993) compared with 0.70 to 0.76 kg kg^{-1} soil in our study. However, Beare and Bruce (1993) observed that air drying and capillary wetting tended to increase macroaggregation compared with keeping soil at field moisture and capillary wetting, but that this effect was not consistent among soils and sampling events.

Aggregate distribution and stability from field-moist soils can be a function of antecedent water content (Gollany et al., 1991; Yang and Wander, 1998). However, the effects of water content on aggregate distribution and stability may depend also on organic matter and clay content, clay mineralogy, and porosity (Kemper et al., 1987; Perfect et al., 1990). Uniformly drying soils prior to dry or wet sieving provides a standard protocol that avoids interactions of treatments with environmental conditions at the time of sampling. However, standardizing aggregation analyses with oven drying may possibly overlook subtle changes in aggregation due to biologically mediated binding agents.

Although soil organic C and total glomalin were highly related in our study (Fig. 6), neither of these soil properties could explain more than 36% of the variation in aggregate distribution and stability. At least some soils would have to be severely degraded before strong relationships would form among these soil properties. Water-stable macroaggregation and its stability were high (≈70–90%) in all management systems we investigated, despite notable differences in soil organic matter. It should be noted that all management systems we sampled were undisturbed for relatively long periods of time. In a no-tillage chronosequence following conversion from conventional tillage, total glomalin was highly related with aggregate stability, which varied from 10 to 60% (Wright et al., 1999). Although soil biological activity and deposition of glomalin by arbuscular mycorrhizal fungi (Wright et al., 1996), of carbohydrates by various microorganisms (Tisdall and Oades, 1982), of muramic acid by bacteria, and of glucosamine by fungi (Chantigny et al., 1997) may be essential in binding soil aggregates, other physical and chemical factors appear to be equally important in the development of strong aggregate distribution and stability properties of soils in this study. These factors may be the extent of physical weathering of soils, high Al and Fe contents, and intense drying–wetting cycles that occur in the summer.

SUMMARY AND CONCLUSIONS

Soils under long-term pasture management systems in the Southern Piedmont USA had aggregate distribution and stability properties greater than or equal to those under conservation-tillage cropping and forestland. Long-term grazing of pastures with cattle did not adversely affect aggregate distribution and stability compared with haying. Aggregate distribution and stability properties increased with increasing stand age up to ≈30 yr and then declined. Linkage between glomalin, a protein produced by arbuscular mycorrhizal fungi and implicated in cementing aggregates, and aggregate dis-

tribution or stability properties was not particularly strong, perhaps because we investigated soils that were not disturbed and had relatively high organic matter for the region. We conclude that typically grazed pasture management systems have few discernable negative impacts on macroaggregation and aggregate stability of soils in the Southern Piedmont USA.

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