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Nutritive value of bamboo as browse for livestock

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Abstract

Small farms in Appalachia need management options that diversify income opportunities, are adaptable to new livestock management strategies, and help maintain environmental integrity. Plantings of temperate bamboo (*Poaceae*), including species native to West Virginia, were established to determine the potential nutritive value for small ruminants, such as goats (*Capra hircus*), at different times of the year. The bamboo species we evaluated, included several *Phyllostachys* spp., *Semiarundiaria fastuosa* and *Arundinaria gigantea*, were able to withstand Appalachian winter temperatures and retain some green leaves even in late winter. Although small differences were evident, the nutritive value was generally comparable among species and exhibited similar trends over the season. Total non-structural carbohydrates in bamboo leaves decreased throughout the growing season, and then remained stable or increased during winter. Conversely, crude protein was relatively low in young leaves compared to late season or over-wintered leaves. Concentrations of fiber and protein were sufficient to meet the maintenance needs of adult goats. The ability of bamboo to remain green and maintain the nutritive value throughout winter suggested that it has potential as winter forage for goats in central Appalachia. As an upright browse, bamboo may reduce the exposure of goats to gastrointestinal parasites. Perennial stands of temperate bamboo could prove to be a valuable, multiple-use crop suitable for Appalachian farm operations and easily adaptable to goat production systems.

Key words: nutritive value, bamboo, forage, goats, *Phyllostachys*, *Arundinaria*

Introduction

Bamboo (*Poaceae*, subfamily *Bambusoideae*) is a group of broadly distributed large grasses, including more than 100 genera and at least 1400 species. They contribute to both traditional and developing technologies needed to provide important resources throughout the world. Bamboo are used for human and animal food, fuel, pharmaceuticals, building materials, chemicals and also provide wildlife habitat, stream bank stabilization and erosion control[1–5]. In addition, the potential importance of bamboo as a biofuel and means for carbon sequestration has received recent attention[6,7].

The collection of temperate bamboo germplasm was initiated in the USA during the late 19th and early 20th century by the USDA with most of the research directed toward wood, pulp and forage production[8–10]. When funding for bamboo research dwindled in the 1960s and 1970s, research waned and existing stands were either lost or moved into custodial collections. Subsequent research and development of commercial bamboo-based enterprises in the USA have been mainly directed toward smaller-scale operations such as ornamental and zoological horticulture, and niche markets such as poles and shoots.

Bamboo, a well-known source of food for pandas (*Ailuropoda melanoleuca* and *Ailurus fulgens*), is also consumed by a wide variety of wild animals including ungulates, primates, rodents and insects[11–17]. Many species of bamboo are also employed as pasture or fodder throughout the world. For example, bamboo has been offered to cattle (*Bos* spp.) and sheep (*Ovis* spp.) in Japan[18–20], cattle and yaks (*Bos grunniens*) in Bhutan[18], gayals (*Bos frontalis*) in Pakistan[19], dairy cattle and buffalo (*Bubalus* spp.) in Nepal[20,21], goats (*Capra* spp.) and cattle in Africa[22–24].

However, bamboo has received only modest attention in the USA as forage for livestock, despite historical

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Table 1. Bamboo species information.

Species	Height (m)	Maximum diameter (cm)	Minimum temperature (°C)	Light preference
P. aureosulcata	14	5.6	−23	Full sun
P. bambusoides	22	15.2	−15	Full sun
P. bissetii	12	5.1	−26	Full sun
P. dulcis	12	7.1	−18	Full sun
P. flexuosa	10	7.1	−18	Full sun
P. mannii	8	5.1	−18	Full sun
P. nuda	10	4.6	−29	Full sun
P. rubromarginata	18	7.6	−21	Full sun
Semiarundinaria fastuosa	9	3.8	−21	Full sun
Arundinaria gigantea	6	2.5	−23	Full sun

precedents. The vast acreages of native bamboo (*Arundinarea* spp.), encountered by European settlers, served as habitat for native birds and animals and were indicative of rich alluvial soils[25,26]. These canebrakes were valued as pasture but easily destroyed by overgrazing and now exist only as remnant populations[27]. Research conducted during the mid 20th century, on rangelands of the southeastern USA, confirmed native cane to be of acceptable quality for livestock, but best grazed conservatively together with other forages[9,28–30]. Limited information is available about the nutritive value and potential use as forage of other temperate, non-native bamboos such as those in the genus *Phyllostachys*[31,32]. This may be due in part to the preconception that bamboo grows only in tropical regions, availability of alternative forages and ecological concerns about the risks associated with introduction of non-native plant species.

The bamboo genus *Phyllostachys* contains a number of commercially important species including some that can remain winter green and survive temperatures as low as −28°C. *Phyllostachys* are a running- or spreading-type of bamboo, characterized by a monopodial rhizome system that runs horizontally under the ground, and form groves of evenly spaced culms[25]. Mean total biomass in stands of monopodial bamboo was reported to be near 145 t ha^{-1} with about 57% allocated above ground[6,26]. Above ground production was most rapid in young (<3 years) stands reaching an estimated 6–9 t ha^{-1} yr^{-1} with about 5–15% in leaf mass and a leaf area index (LAI) approaching 12[10,21–23]. Bamboo leaves are likely to contain much higher concentrations of nutritionally important components such as non-structural carbohydrates and protein, as well as minerals such as phosphorus and potassium, compared to other plant parts[33].

Upright, cold-hardy bamboo capable of remaining green throughout Appalachian winter conditions could be a useful source of forage for small ruminants such as goats, while providing materials for other products that could increase or diversify small-farm income opportunities and improve ecosystem integrity. Production of meat goats is one of the fastest-growing livestock enterprises in the USA because of rising product demand from ethnic populations[28]. In contrast to cattle and sheep, goats are opportunistic browsers often preferring herbage near the top of forage plants[29,30]. However, we know little about bamboo survival, growth requirements, productivity or nutritive value for livestock under Appalachian hill-land conditions. Therefore, we established plantings of several species of cold-hardy temperate bamboo, including one species native to West Virginia, with the objective of determining the potential nutritive value for goats at different times of the year.

Materials and Methods

Bamboo and sites

Plantings of non-native, cold-hardy bamboo including *Phyllostachys aureosulcata, Phyllostachys bambusoides, Phyllostachys bissetii, Phyllostachys dulcis, Phyllostachys flexuosa, Phyllostachys mannii, Phyllostachys nuda, Phyllostachys rubromarginata* and *Semiarundinaria fastuosa* were acquired from the USDA-ARS temperate bamboo germplasm center at Byron, GA in April of 2001 or purchased from commercial nurseries in 2002. We also collected specimens of native bamboo, *Arundinaria gigantea* from several locations in West Virginia in 2002 (Table 1). All species were chosen for their potential to survive winter temperatures characteristic of most of West Virginia that include USDA hardiness zones five (−10 to −20°F or −23 to −28°C) and six (0 to 10°F or −18 to −23°C). Clones were acclimated in a greenhouse, planted at two field locations and maintained with periodic applications of balanced fertilizer (14-14-14). The bamboo were not grazed during this study. Soils at the first location, near Bragg, West Virginia (37.80 N, 80.97 W, elevation 850 m), are a mixture of fine loamy, mixed, mesic Typic Hapludults and loamy-skeletal, siliceous, active, mesic Typic Dystrudepts. Soils at the second location, near Alderson WV (37.70 N, 80.66 W, elevation 550 m) are a mixture of fine-loamy, mixed, active, acid, mesic Fluvaquentic Endoaquepts and fine-loamy, mixed, superactive,

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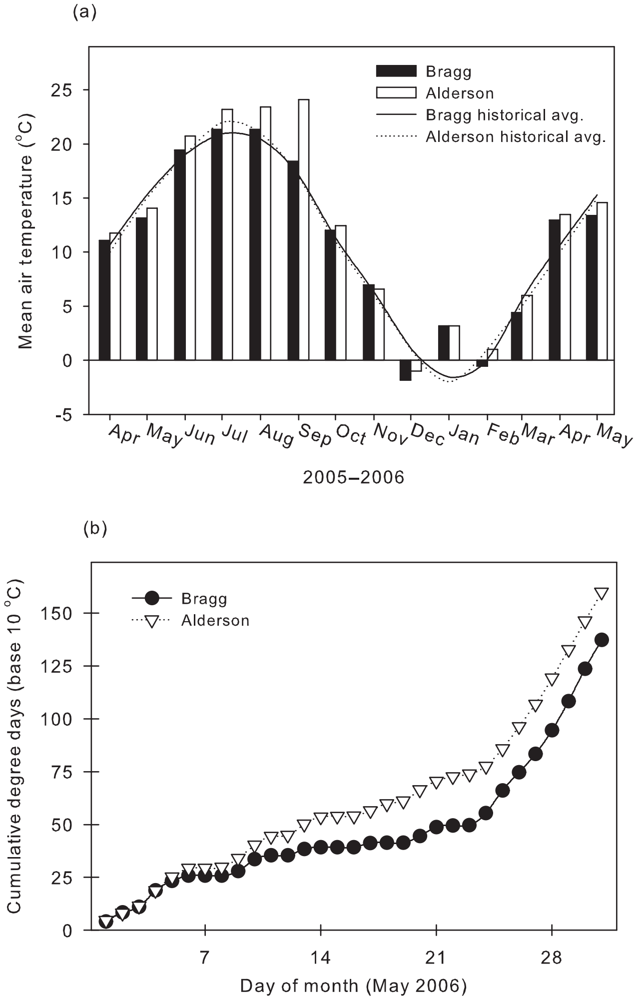

Figure 1. (a) Mean air temperature and (b) cumulative degree-days for Bragg and Alderson sites.

mesic Oxyaquic Fragiudalfs. The lower-elevation Alderson site has a slightly warmer average growing season than the Bragg site (Fig. 1a).

Average composition of temperate bamboo foliage (green leaves and attached petioles) was determined from grab samples collected from all species in late July (mid-summer) and mid-September (late summer) 2003 and 2005 and winter (February and January) 2004 and 2006 (Table 2). Additional samples of *Phyllostachys* foliage were collected, on August 29, and October 13, 2005, to provide more details about intraseasonal patterns of forage composition and possible site effects. Emerging shoots (elongating culms + leaves and petioles) were collected from *Phyllostachys* species on May 11 and June 15–16, 2005 and on May 9 and May 25, 2006 to compare the composition of young shoots to more mature foliage. Bamboo plots were mowed to a height of about 7.5 cm on April 10–11, 2006, about 4 weeks before sampling. All samples were dried (55°C) in a forced-air oven, ground (Wiley mill, 1 mm sieve) and stored in a freezer (−21°C) until analysis.

Chemical analyses

Total carbon (C) and nitrogen (N) concentration were determined by dry combustion[34] with a FlashEA 1112 NC Analyzer (CE Elantech, Lakewood, NJ). Total N data were multiplied by a factor of 6.25 to estimate the crude protein (CP). Total non-structural carbohydrates (TNC) were determined by an automated hydrolysis method[35]. Acid detergent fiber (ADF) was determined by the procedures of Van Soest et al.[36] using an ANKOM 200 Fiber Analyzer (Ankom Technology Corp., Fairport, NY). Acid detergent lignin (ADL) was determined by subjecting ADF residue to 72% sulfuric acid. Cellulose was calculated by subtracting ADL from ADF. Ash content was determined on 0.5 g samples and reported as the percentage of total plant dry matter remaining after combustion in a muffle furnace at 525°C for 3 h. We used the values from total C, N, TNC and the ADL to calculate C : N, TNC : CP and lignin : N ratios.

Statistical analyses

The influence of species and season on the composition of bamboo leaves was determined with SAS 9.2 and PROC MIXED (SAS Institute, Cary, NC) using a model that contained both fixed (species) and random (side) effects and treated sample dates as repeated measures[37,38]. In other analyses, intraseasonal trends and intersite differences, within the genus *Phyllostachys*, were analyzed for leaf samples, collected monthly from June to October 2005 and in January 2006, by considering individual species as independent replicates ($n = 8$) and sample dates as repeated measures. Finally, we compared *Phyllostachys* shoot composition in early May 2005 to that in early May 2006 and composition in early May 2006 to that in late May 2006.

For all analyses, assumptions of data normality were evaluated and appropriate data transformations identified with SAS/ASSIST. Covariance structures were selected to minimize Akaike's Information Criterion. Pairwise comparisons of means were adjusted by the Tukey–Kramer method assuming a value of 5% as the minimum criterion for significance. Values indicated in text and graphs are the arithmetic mean, ± standard error of the mean, expressed on a dry matter basis.

Results

All species of bamboo were able to withstand Appalachian winter temperatures during the period 2001–2006 and retain some green leaves even in late winter. The experiment was terminated and all bamboo killed with the application of Roundup Ultra® [*N*-(phosphonomethyl) glycine; Monsanto, St. Louis, MO] applied at 26.4 ml l^{-1} in June 2006.

Composition of cold-hardy bamboo

Total leaf C, averaging 48.1 ± 0.1%, did not vary among bamboo species or with season. However, there was a

Table 2. Sample dates for temperate bamboo foliage and shoots.

Sample	Sample description	Sample dates	Additional comments
Foliage from all species	Green leaves and attached petioles	July 21–22, 2003 and July 25, 2005	Mid-summer
		September 9–10, 2003 and September 20, 2005	Late summer
		February 19, 2004 and January 27, 2006	Winter
Phyllostachys foliage		August 29 and October 13, 2005	Additional sample dates
Phyllostachys shoots	Emerging shoots (elongating culms, leaves and petioles)	May 11 and June 15–16, 2005 May 9 and May 25, 2006	Plots were mowed to a height of 7.5 cm on April 10–11, 2006

Table 3. Nutritive value of foliage from cold-hardy bamboo species[1].

	% of dry mass						Ratios		
Species	**TNC**	**Crude protein**	**ADF**	**Cellulose**	**ADL**	**Ash**	**C:N**	**ADL:N**	**TNC:CP**
P. aureosulcata	9.4	15.5^{AB}	34.8^{ABC}	24.4^{AB}	10.4	7.4	19.7^{AB}	4.2^{AB}	0.62
P. bambusoides	8.3	15.7^{AB}	34.0^{ABC}	24.6^{AB}	9.4	7.6	19.3^{AB}	3.9^{AB}	0.54
P. bissetii	9.4	16.5^{AB}	34.2^{ABC}	23.7^{AB}	10.5	8.7	18.4^{AB}	4.0^{AB}	0.59
P. dulcis	10.7	16.1^{AB}	31.5^{C}	22.6^{B}	8.9	6.6	19.1^{AB}	3.5^{AB}	0.67
P. flexuosa	9.2	16.3^{AB}	34.8^{ABC}	25.8^{A}	9.0	7.7	18.5^{AB}	3.5^{AB}	0.57
P. mannii	7.8	15.2^{B}	36.2^{A}	26.1^{A}	10.1	7.2	20.2^{A}	4.2^{A}	0.52
P. nuda	9.6	15.3^{B}	34.7^{ABC}	25.1^{AB}	9.5	6.9	19.8^{A}	3.9^{AB}	0.63
P. rubromarginata	7.5	15.6^{AB}	36.2^{AB}	25.3^{AB}	10.8	7.8	19.6^{AB}	4.4^{AB}	0.49
Semiarundinaria fastuosa	10.2	17.9^{A}	32.9^{BC}	24.4^{AB}	8.5	7.3	17.0^{B}	3.0^{B}	0.58
Arundinaria gigantea	8.9	14.8^{B}	35.0^{ABC}	26.2^{A}	8.8	6.7	20.6^{A}	3.7^{AB}	0.61
Season									
Mid-summer ($n = 38$)	10.5^{X}	15.2^{Y}	33.1^{Y}	25.1	8.0^{Z}	6.9^{Y}	20.2^{X}	3.4^{Y}	0.69^{X}
Late summer ($n = 37$)	8.9^{XY}	15.6^{Y}	35.2^{X}	25.2	9.9^{Y}	7.4^{XY}	19.5^{X}	4.0^{X}	0.57^{Y}
Winter ($n = 36$)	8.0^{Y}	16.9^{X}	35.2^{X}	24.2	11.0^{X}	7.9^{X}	18.0^{Y}	4.1^{X}	0.48^{Y}
Overall									
Mean (SEM) ($n = 111$)	9.1 (0.3)	15.9 (0.2)	34.5 (0.3)	24.8 (0.2)	9.6 (0.2)	7.4 (0.2)	19.2 (0.2)	3.8 (0.1)	0.58 (0.02)

[1] Samples of green leaves and petioles were collected during mid-summer (July 21–22, 2003 and July 25, 2005), late summer (September 9–10, 2003 and September 20, 2005) and winter (February 19, 2004 and January 27, 2006) from two locations. Data are for total non-structural carbohydrate (TNC), crude protein (CP) (calculated as $N\% \times 6.25$), acid detergent fiber (ADF), cellulose, acid detergent lignin (ADL), ash, total carbon (C) and nitrogen (N). Within each column, superscript letters denote significant Tukey–Kramer adjusted differences among species or seasons ($P \leqslant 0.05$).

significant ($P \leqslant 0.05$) main effect of species or season on the other foliage characteristics (Table 3).

TNC of leaves, with an overall mean of more than 9%, varied with season, decreasing from 10.5% in late July to 8% in the winter. CP averaged nearly 16% across all species and seasons with the highest content observed for *S. fatuosa* and the lowest content observed for *P. nuda*, *P. mannii* and *A. gigantea* (Table 3). CP varied little during the summer growing season but increased during winter.

ADF (mean 34.5%) varied among species and with season. Among species, *P. dulcis* contained the lowest concentration of ADF, whereas *P. mannii* and *P. rubromarginata* contained the highest. Mean ADF increased from late July to late September but remained unchanged in mid-winter. Cellulose varied among species, being least in *P. dulcis* and greatest in *P. mannii*, *P. flexuosa* and *A. gigantea*, and was the only variable that did not vary with time, remaining at nearly 25% throughout the year. Average ADL, approaching 10%, did not vary among species, but increased with each successive sampling. Similarly, the ash content (mean 7.4%) did not vary among species, but increased from late July to mid-winter.

The ratios of total C : N (mean 19) and ADL : N (mean 4) varied with species and season. In both instances, lowest average values were observed for *S. fastuosa*, but the range among species was narrow. Average C : N ratios decreased from July to winter, whereas ADL : N ratios increased from July to September. The ratio, TNC : CP, is thought to link nutritionally important indicators of energy and protein in herbage[39]. Clear differences among the various bamboo species were not apparent but ratios decreased from early to late season reflecting the increased N content of herbage.

Intra-seasonal and site patterns in Phyllostachys *foliage*

Seasonal and site variations for some *Phyllostachys* leaf characteristics were observed during the 2005–2006 season.

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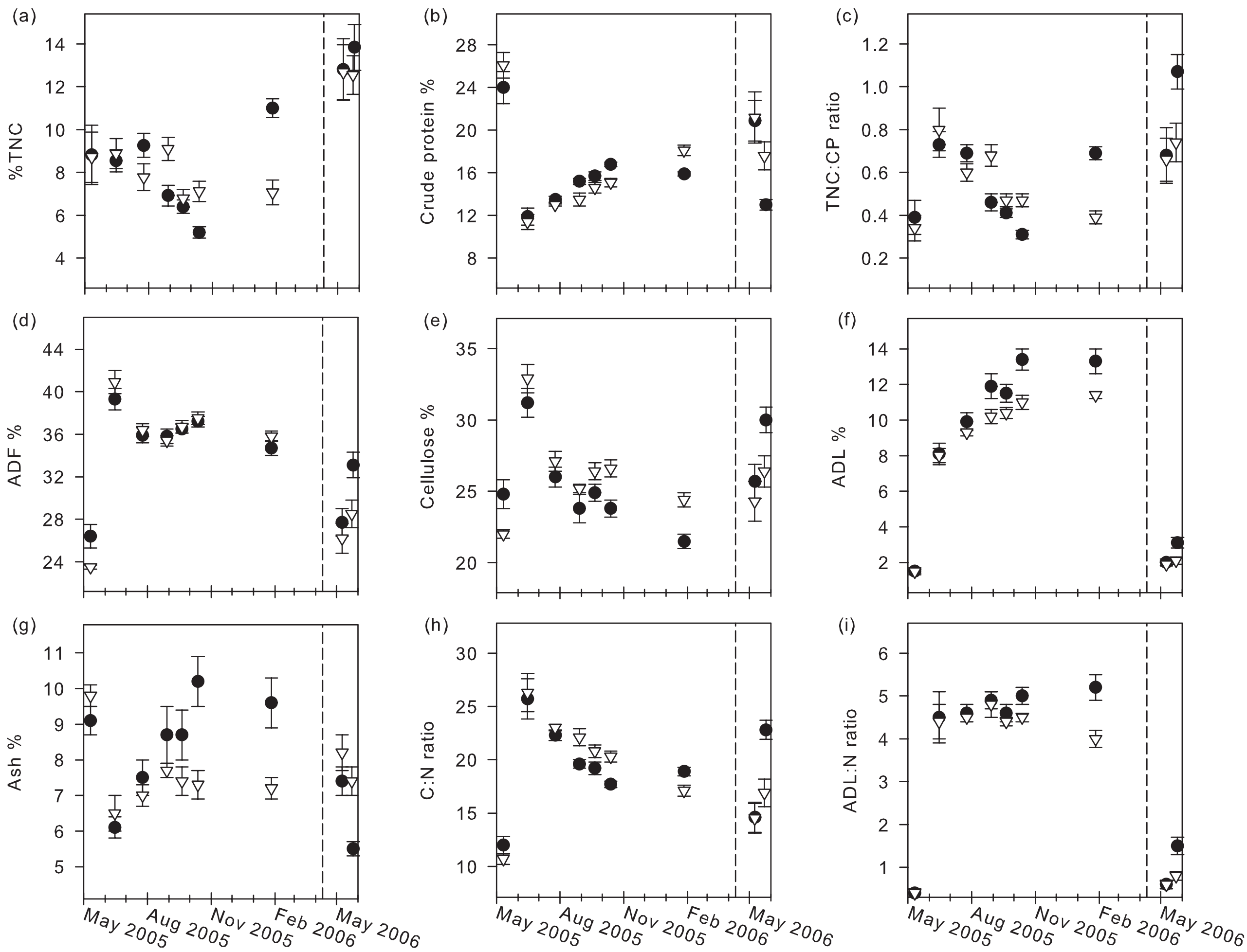

Figure 2. Seasonal trends of (a) TNC, (b) CP, (c) ratios of TNC:CP, (d) ADF, (e) cellulose, (f) ADL, (g) ash, (h) total C:N and (i) ADL:N in shoots and leaves of *Phyllostachys* spp. growing at two sites (Alderson ● and Bragg ▽). Values (combined species, means ± SEM) are from entire shoots collected on May 11 ($n = 3$–7) and June 15–16 ($n = 6$–8) 2005 and on May 9 ($n = 7$) and May 25 ($n = 7$–8) 2006. Leaves (including petiole) were sampled in 2005 on July 25 ($n = 8$), August 29 ($n = 7$–8), September 20 ($n = 8$) and October 13 ($n = 8$) and in 2006 on January 27 ($n = 6$–8). Bamboo plots were mowed to a height of about 7.5 cm on April 10–11, 2006 (dashed line).

TNC decreased at both sites during the 2005 growing season, most clearly at the Alderson site, declining from 8.6% in June to 5.2% in October, compared to 8.9 and 7.1% at the Bragg site (Fig. 2a). Concentrations of TNC remained constant at the Bragg site through late January but TNC increased at the Alderson site, reaching levels comparable to the previous June.

Crude protein in bamboo leaves increased during the growing season, from about 11.5% at both sites in June 2005 to between 15 and 17%, by mid-October (Fig. 2b). CP was slightly higher at Alderson during most part of the year, but meaningful differences between the sites were evident only in October and January. Highest values of foliage CP were observed at the Bragg site during winter 2005, whereas CP remained relatively constant at Alderson, from fall through January 2006.

Seasonal patterns of TNC : CP ratios resembled those observed for TNC, declining from mean values in June, at the Alderson and Bragg sites, of 0.73 and 0.81, respectively, to 0.31 and 0.47, in October (Fig. 2c). Ratios declined slightly at the Bragg site, from October through January, but increased at the Alderson site to 0.69, close to June values. Differences between sites were observed in August and October (Bragg > Alderson) and January (Alderson > Bragg).

Concentrations of ADF in bamboo leaves decreased at both sites, from about 40% in June to 35% in January 2006 (Fig. 2d). Although about 2% higher at the Bragg site, cellulose content in bamboo leaves decreased at both sites from 32% in June to 22.7% by January (Fig. 2e). Unlike ADF and cellulose, ADL, increased from 8% in June at both sites, to about 11 and 13% for Bragg and Alderson sites, respectively, in October and January (Fig. 2f).

Ash content of leaves increased at the Alderson site from about 6% in June to about 10% in October and January (Fig. 2g), but did not vary at the Bragg site, and remained nearly 7% throughout the season. Differences between the

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two sites became greater as the season progressed, peaking in October.

The C : N ratios of bamboo leaves decreased from 25 in June to 18–19 in January (Fig. 2h) with differences between the sites evident in October samples. In contrast, ADL : N ratios changed a little during the year (mean 4.6), with site distinctions detected only in January (Fig. 2i).

Phyllostachys shoots

The composition of young *Phyllostachys* shoots (culms and leaves) was distinct from more mature leaves, and could vary quickly with time as they elongated and segregated more distinctly into component elements such as culms, petioles and leaves.

The concentrations of TNC, measured in early May, were higher in 2006 than in 2005, but did not differ between the two sites (Fig. 2a). A similar pattern, observed for TNC : CP ratios, was attributable to these increased values of TNC (Fig. 2c). Mean shoot TNC ($12.7 \pm 0.9\%$) and TNC : CP ratios ($0.67 \pm 0.08\%$) in early May 2006 were comparable to winter foliage values at the Alderson site but higher than those at the Bragg site.

With these exceptions, the composition of bamboo shoots, measured in early May 2005 and 2006 did not vary between years or sites. CP in shoots ($22.5 \pm 1\%$), was about twice that of leaves (Fig. 2b). Mean ADF ($26.4 \pm 0.7\%$), cellulose ($24.6 \pm 0.6\%$), ADL ($1.8 \pm 0.1\%$), C : N ($13.4 \pm 0.7\%$) and ADL : N ratios ($0.53 \pm 0.04\%$) in shoots were lower than leaves (Figs. 2d–f,h,i). The ash content of shoots was comparable to bamboo leaves ($8.4 \pm 3\%$, Fig. 2g). By late May 2006, only 2 weeks after initial measurements, CP and ash content in shoots decreased, while TNC, ADF, cellulose and ADL in young shoots increased. Greatest changes in nutritive value were observed in plants growing at Alderson, a relatively warm site that accumulated 40–50% more growing degree-days than the Bragg site between the two sampling dates (Fig. 1b).

Discussion

The values of TNC observed for bamboo leaves in this study are only about 50% of the more than 200 mg g^{-1} reported for *Phyllostachys pubescens*[33], but they compare reasonably to other Appalachian silvopasture forage species[40,41]. Concentrations of TNC in bamboos have been reported to be highest in leaves > branches ⩾ rhizomes ⩾ stems ⩾ roots with rapid spring growth of new shoots corresponding to reduced concentration of TNC in the rhizomes[33]. Although TNC generally declined during the growing season (Table 3), high amounts of TNC and CP were observed at the Alderson site during winter and at both sites in *Phyllostachys* shoots in spring (Fig. 2a,b).

Mean concentrations of CP in bamboo leaves (Table 3) compare well with those from recent studies of *Phyllostachys*[31,32,42], and with values for *Arundinarea*[9]. Although lower than the range reported for some leguminous browse species[43] and *Paulownia*[44], bamboo leaf CP was comparable to other temperate browse species consumed by goats[45–47]. Concentrations of CP in *Phyllostachys* leaves were an order of magnitude greater than expected in mature culms[13,42]. High CP in *Phyllostachys* shoots, in excess of 20% dry weight, were consistent with values commonly reported for edible bamboo shoots[48,49].

The balance of TNC : CP suggests that bamboo foliage can meet the maintenance or growth needs of goats[50,51]. The TNC : CP quotients of bamboo ranged from about 0.35 to 0.8 and were slightly greater than cool-temperate grasses managed for forage productivity and nutritive value in silvopasture[30,47].

Although the levels of TNC and CP observed in young culms (shoots) infer a high forage nutritive value, significant grazing of elongating shoots would likely have adverse impacts on stand productivity and sustainability by consuming new growth and thus preventing the formation of new leaves, and also because young bamboo culms (shoots) can break easily[52]. Shoots also have considerable economic value as a fresh crop to supply food-grade produce to various niche markets. The differences between early and late May 2006 indicated that shoot composition changes rapidly as culms mature. Similar short-term (<14 days) decreases in protein content and increases in fiber content were reported in edible bamboo shoots[53] and are associated with the mobilization of stored carbohydrates from rhizomes and translocation of nutrients from senescing to developing leaves and roots[33,54,55].

Concentrations of ADF, cellulose and lignin were higher in these bamboo species than in leaves of other potential browse species including *Paulownia*[44], locust (*Robinia* spp.), mimosa (*Albizia julibrissin*)[43], autumn olive (*Elaeagnus umbellata*), multiflora rose (*Rosa multiflora*) or honeysuckle (*Lonicera japonica*)[47]. Ash content in bamboo leaves and shoots (Table 3, Fig. 2g) was similar to published values[13,48] and was expected to be about 3–4 times higher than in mature culms or rhizomes. The ash content of bamboo is composed of silica together with metals such as calcium and potassium[56].

Bamboo leaves contain a number of biologically active components with potential health benefits[57,58]. However, some parts of the bamboo, notably the shoots may also contain toxic compounds, such as oxalic acid and cyanogenic glycosides[49,59,60]. Some bamboo species (e.g. *Bambusa vulgaris* from Brazil) have been reported to contain unidentified compounds toxic to horses[61]. Unlike other browse species or plants that have been considered as candidates for biofuel production, such as hybrid poplars (*Populus* spp.), bamboo is unlikely to contain significant amounts of polyphenolic plant secondary compounds such as tannins that can affect the forage nutritive value[46,62,63].

Bamboo may help mitigate the effects of gastrointestinal nematodes (GIN), such as the barberpole worm (*Haemonchus contortus*), a major parasite of small ruminants in the southern USA. In contrast to cattle and sheep, goats are browsers that prefer to graze plants from the top down[29]. However, when browse is scarce, goats will graze traditional grasses and legumes in pastures contributing to problems with GIN control. In infected animals, adult female GIN shed eggs, which pass onto pastures with livestock feces. Under favorable conditions, larvae hatch, crawl up forage into the grazed horizon, and are consumed as livestock graze. Larvae are more concentrated in lower levels of the plant canopy[64]. Goats have very poor tolerance of GIN loads, having evolved to avoid larvae by browsing above the infested layers. The detrimental effects of GIN are exacerbated because of increased resistance of GIN to chemical anthelmintics[65]. By providing a source of browse with a higher grazed horizon at critical times, bamboo may help reduce infection with GIN, especially *Haemonchus*[66,67].

Temperate bamboo seem particularly well adapted to the heterogeneous mosaic of light and soil conditions that characterize Appalachian silvopastures because they can adapt morphologically to low-light conditions. More importantly, some genera are able to physiologically integrate environmental heterogeneity by translocation of photosynthetic assimilates and nutrients, such as N, from zones of relatively high availability to biomass located in zones of relative paucity, primarily via translocation through rhizomes, thus stabilizing productivity[62–64]. In the present study, decreasing C : N ratios in foliage during the winter season were associated with increasing concentrations of leaf-N, indicative of acclimation to retain photosynthetic capacity accompanied by reallocation of non-structural carbohydrate from leaves to culms.

Adaptation of temperate bamboo will require further research to develop management strategies that effectively incorporate controlled grazing to maintain the productivity and sustainability of temperate silvopastoral grazing systems[68]. Too little grazing may result in competition between bamboo and overstory trees for resources, such as light or water[69,70]. In addition, some species of *Phyllostachys* are thought to contain allelopathic substances, such as phenolic acids, that could interfere with the growth of other forage species[71]. Conversely, overgrazing can damage bamboo by reducing culm density or size, and damage or hamper regeneration of tree species[18,27,72]. However, controlled grazing, especially with browsers such as goats, alone or together with cattle, may contribute to sustained pasture productivity by maintaining desirable botanical composition of forage species, controlling undesirable invaders and promoting regeneration of tree species[18,29,73,74].

Cold-hardy bamboo species seem capable of retaining green foliage and nutritive value throughout winter months, a time when few other green fodder options are available. The upright growth habit of bamboo makes this fodder accessible to livestock even under snow conditions and could help reduce initial GIN loadings in goats in the spring. High potential for biomass production, coupled with the possibility of photosynthesis early and late in the growing season, suggest that in addition to serving as a source of forage for livestock, bamboo could be managed as an effective carbon sink[6,75]; or a source of raw material for biofuel, pulp wood or fresh shoot production[76].

More research is needed to expand the nutritional database beyond the few bamboo examined in this study and to establish criteria for selecting from among species with comparable nutritive qualities. In addition to selecting a suitable species, successful integration of bamboo into small ruminant production systems will also require cultural recommendations, tailored to local conditions, needed to establish forage bamboo, maintain its productivity and quality, and manage its growth. Potential concerns about invasiveness of monopodial bamboo, such as *Phyllostachys*, may be allayed by known control strategies including barriers, cultivation, spraying or intentional overgrazing[77], but these may be costly and result in unwanted environmental consequences. Thus, decision support tools are needed to help identify and compare economic and environmental consequences of bamboo-based enterprises, in order to adopt prudent measures that protect the environment[78].

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