RESEARCH

Evaluation of Alfalfa–Tall Fescue Mixtures across Multiple Environments

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ABSTRACT

Binary grass–legume mixtures can benefit forage production systems in different ways helping growers cope both with increasing input costs (e.g., N fertilizer, herbicides) and potentially more variable weather. The main objective of this study was to evaluate alfalfa (*Medicago sativa* L.) and tall fescue [*Schedonorus phoenix* (Scop.) Holub] mixtures across a wide range of environments to assess herbage accumulation, weed suppression and fertilizer nitrogen replacement values (FNRV). A common field experiment was established in 2009 and 2010 at six study sites in the United States: Maryland, Pennsylvania, Utah, Virginia, Wisconsin, and Wyoming. Experimental treatments included an alfalfa monoculture, three alfalfa–fescue mixtures with seed ratios of 75:25, 50:50, and 25:75 of alfalfa/tall fescue, and tall fescue monocultures that received nitrogen applications of 0, 50, 100, 150, 200, and 300 kg N ha^{-1}, respectively. Data were collected over a 2-yr period. The responses of tall fescue monocultures to N fertilization differed among sites, and this contrasted with mixture yields, which did not exhibit site × treatment interactions ($P > 0.05$). Herbage accumulation and weed suppression were consistently higher in mixtures compared with alfalfa monocultures and tall fescue monocultures receiving less than 100 kg N ha^{-1}. The FNRVs for alfalfa were within the range reported for other studies and averaged 143 kg N ha^{-1}. The consistent herbage accumulations across these multiple environments suggest binary mixtures of alfalfa–tall fescue may be a good option for many forage–livestock producers although yields could be improved with location specific cultivar selection.

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Abbreviations: FNRV, fertilizer nitrogen replacement value.

RECENT STUDIES have explored the question of whether high plant diversity can improve grassland productivity (Isselstein, 2005; Cardinale et al., 2007; Picasso et al., 2008; Sanderson et al., 2007). Conclusions from these studies have been equivocal, and those involving agricultural grasslands have shown minimal benefit to sowing highly complex mixtures of forage species (Tracy and Sanderson, 2004; Tracy and Faulkner, 2006; Mangan et al., 2011; Sanderson et al., 2012). The mixed results may result from the difficulty in maintaining high species diversity in fertile grasslands because one or two species tend to competitively exclude other species (Grime, 2001). Still, a low level of planned plant diversity (e.g., two to three species) should be beneficial for various aspects of forage production. In particular, some plant diversity may enable grassland communities to resist to environmental stress and produce more stable yield over time (Tilman and Downing, 1994). This issue is timely since environmental stresses may become more pronounced in coming years. With a potentially warmer climate and rising atmospheric CO$_2$ levels,

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hay and pasturelands may face more frequent and intense droughts, greater rainfall variation, and the possibility of expanding weed and pest problems (Hatfield et al., 2011). Since maintaining highly diverse forage communities in agricultural grasslands may be difficult, it may warrant a closer reexamination of simpler grass–legume mixtures to help achieve some of the same beneficial effects in more fertile agricultural soils.

Many experiments have evaluated aspects of grass–legume mixtures, starting in the 1940s (Åberg et al., 1943; Comstock and Law, 1948; Chamblee, 1958). Some evidence suggests grass–legume mixtures may be more adaptable to changing environmental conditions than monocultures. For example, mixtures can exhibit more even seasonal growth distribution due to legumes compensating for slower grass growth in summer (Åberg et al., 1943; Chamblee, 1958; Sleugh et al., 2000). Drought tolerant, deep-rooted perennial legumes such as alfalfa should be particularly useful to help growers cope with more frequent drought. Yield stability also can be generated in the other direction as perennial grasses function to replace declining legume stands over time. Some species like orchardgrass (*Dactylis glomerata* L.) may compete effectively against alfalfa and dominate mixtures (Hamilton et al., 1969; Smith et al., 1973; Weil, 1988). Stress-tolerant grasses, such as tall fescue, may make good companions for alfalfa to improve the ability of mixtures to withstand more extreme environmental variation.

In addition to potentially greater yield stability, mixtures can provide other benefits compared with pure legume or grass monocultures. One benefit includes better forage nutritive value for cattle compared with grass monoculture (Barnett and Posler, 1983; Sleugh et al., 2000). Mixtures also provide effective bloat protection for animals grazing legumes. Majak et al. (2003) found that cattle fed a diet of 100% alfalfa became bloated 105 times over a 2-yr study period while those fed a 50% orchardgrass–alfalfa mix bloated only twice. Mixtures can help protect soil and water quality by increasing water infiltration and reducing runoff and erosion (Casler and Walgenbach, 1990). Grasses mixed with alfalfa also have been shown to reduce insect pests like alfalfa weevil *Hypera postica* (Coleoptera: Curculionidae), as well as potato leafhopper *Empoasca fabae* (Hemiptera: Cicadellidae) infestations in young stands (Lamp, 1991; Roda et al., 1996). Weed suppression may be another important benefit of mixtures over monoculture stands (Cummings et al., 2004). From an energy balance perspective, legume-based pastures can supply sufficient N through fixation to supply grazing animals with enough protein and energy to sustain weight gains with much less external energy expenditure and greenhouse gas emission than fertilized grass pasture (Chen et al., 2004). This fertilizer-replacement effect of legumes in grass stands can be significant, sometimes exceeding 200 kg N ha^{-1} (Zemenchik et al., 2001). This effect is usually termed the fertilizer nitrogen replacement value (FNRV) as it refers to the amount of N fertilizer required for a grass monoculture to yield as much dry matter as the same grass in mixture with a legume (Ta and Faris, 1987).

Although much research has evaluated aspects of grass–legume mixtures, we were interested in determining whether mixture yields, potential weed suppression and FNRVs would show consistent patterns across a range of environments. This issue is timely as input costs continue to rise, and forage producers may be facing increasingly variable weather patterns. To address this overarching question, a common field experiment was established across six sites including a range of cool to warm humid environments and semiarid, irrigated conditions. The specific objectives of this study were to (i) compare herbage accumulation and weed suppression of alfalfa–tall fescue mixtures with grass monocultures across a wide range of environments, and (ii) estimate the range of FNRVs supplied by alfalfa in tall fescue swards in these environments.

MATERIALS AND METHODS

Study Sites

Characteristics of the six sites used in this study are described in Table 1. A goal was to plant all sites in fall 2009, but this was not feasible so several sites were established in 2010 (Table 1). Experimental treatments included three grass–legume mixtures, one legume monoculture, and five N fertilizer rates applied to grass monocultures plus an unfertilized control for a total of ten treatments. For the legume component, 'Ameristand 403T' alfalfa (fall dormancy = 4, winter hardiness = 2) was sown at all sites due to its adaptation across a wide range of environments. Alfalfa seed was coated and pre inoculated. MaxQ forage type tall fescue ('Jesup' with MaxQ endophyte) was sown at all sites except Wisconsin and Utah, which used 'Select', a low endophyte tall fescue cultivar. Alfalfa and fescue monoculture treatments were planted at a rate of 25 kg ha^{-1}. Three mixtures were sown at the same rate but with alfalfa/fescue seed ratios of 75:25, 50:50, and 25:75 (seed number per kg is approximately equivalent for these species). The ten treatments were randomly assigned to 30 plots at each site yielding three replications per treatment. An exception was the Virginia site that had four replications. Plot size varied slightly across sites and averaged 3.1 × 5.8 m. Seed was drilled into a conventionally tilled seedbed with 15-cm rows to an average depth of 1.2 cm. Alfalfa and fescue seed in mixtures was sown simultaneously with no attempt to spatially separate species.

Prior to planting, three or four soil cores (15 cm depth) were taken from each site and analyzed at the Virginia Tech Soil Testing Lab for pH, P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B by standard methods. Soil fertility was adjusted based on soil test recommendations if necessary (Table 1). After the seeding year, five nitrogen application rates were applied to tall fescue monoculture plots using rates of 50, 100, 150, 200, and 300 kg N ha^{-1}. Nitrogen fertilizer, as urea, was split applied after the

Table 1. Site information for the six study locations.

Site	Lat. Long.	Elevation	Soil description	Annual precipitation†	Mean air temperature	Fertilizer applied	Planting date
		m		cm	°C	kg ha^{-1}	
Keedysville, MD	39°30′ N 77°43′ W	156	Swanpond-Funkstown silt loam (very-fine, mixed, mesic Oxyaquic Paleudalfs)	90	11.5	None	August 2010
State College, PA	40°48′ N 77°52′ W	111	Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf)	100	10.4	P, 317 K, 216 Lime, 4400	August 2010
Logan, UT	41°54′ N 111°48′ W	1400	Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll)	50	8.8	None	August 2009
Blackstone, VA	37°29′ N 77°23′ W	134	Appling sandy loam (fine, kaolinitic, thermic Typic Kanhapludults)- Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult)	111	14.2	P, 66 K, 275 B, 2.2	October 2009
Arlington, WI	43°18′ N 89°21′ W	100	Plano silt loam (well-drained, fine-silty, mixed, superactive, mesic Typic Hapludalf)	83	7.7	P 77 K, 440	August 2010
Lingle, WY	42°14′ N 104°30′ W	1272	Haverson loam soil (fine-loamy, mixed, superactive, calcareous, mesic Aridic Ustifluvent)	35	8.7	P, 66	Septmber 2009

† 30-year mean.

first cut in spring and again in late summer. Alfalfa pure stands and alfalfa–tall fescue mixtures were not fertilized.

Plots were mechanically harvested with a sickle bar mower when alfalfa plots had reached ~10% bloom. This strategy resulted in three or four harvests per site. One exception was the Virginia site where a fifth harvest was taken after vigorous fall growth in 2011. Once established, plots received no herbicides or other pesticides. Irrigation was used at the Utah and Wyoming sites as this is common practice for hay production at these locations. At the Utah and Wyoming sites, plots received approximately 5.5 and 4 cm of water each week during the growing season, respectively.

Samples were collected during the first and second growing seasons following the seeding year at all sites and are hereafter termed Year 1 and 2. Complete Year 1 and 2 data could not be collected at the Virginia and Wisconsin sites and thus these sites were excluded from Year 1 and 2 analyses, respectively. Herbage mass was quantified at each harvest by cutting a strip from the center of each plot to an 8-cm stubble height. The minimum strip length was 3 m, and widths ranged between 0.72 and 1 m. Wet herbage mass was weighed and a subsample (500–1000 g) was dried for at least 48 h at 60°C to estimate percent dry matter. Herbage accumulation was calculated by summing dry matter herbage mass from each harvest over the growing season. Another subsample of the same size was taken and sorted by hand to tall fescue, alfalfa and weed components to estimate their proportion of total yield. Weeds were considered all species that were not sown in plots. Sample components were dried and weighed as described above. After harvest, the remaining plot was cut to the same stubble height and herbage mass discarded. Weed biomass was calculated by summing weed herbage mass from each harvest. To estimate the N content in tall fescue swards, the tall fescue fraction from each sample was ground to pass through a 1-mm screen and then analyzed for %N concentration by combustion with a VarioEL Cube carbon and nitrogen analyzer (Elementar Americas, Inc.) at the Virginia Tech Ruminant Nutrition Lab. Nitrogen content was estimated only from Year 2 samples. Seasonal grass N content was determined by summing the products of grass dry matter yield and tissue N concentration calculated for each harvest.

Data Analysis

The main response variables evaluated in this experiment were total herbage accumulation, grass N content, weed biomass, and FNRV. Herbage data were analyzed in two ways. First, a global ANOVA was used to include site, treatment and their interaction. We treated years separately because not all sites included data from Year 1 and Year 2. If both years showed significant site × treatment interactions ($P < 0.05$), we then conducted ANOVAs on the tall fescue monocultures and alfalfa mixtures separately following the same model structure. Relationships between tall fescue monoculture yield and N application rate were evaluated by regression. Regression also was used to evaluate how well mixture component yields (tall fescue and alfalfa) explained total yield. Prior to all analyses, data were checked to meet ANOVA assumptions and not transformed.

The FNRV of alfalfa in mixture was estimated by methods similar to Zemenchik et al. (2001). First, tall fescue yield in monoculture was regressed against N fertilization application rate at each respective site and year. Data were fitted with linear and quadratic models for each site per year as other models did not yield substantially better relationships (Cerrato and Blackmer, 1990). If both terms of the quadratic model were significant ($P < 0.05$) it was chosen. If the linear term was significant, it was chosen. Following model selection, the equation was solved for N application rate (x) by substituting tall fescue yield (y) of each mixture of fescue and alfalfa. Statistical analyses were conducted in the R statistical package (R Core Team, 2015).

RESULTS

Herbage Accumulation

Total herbage accumulation averaged 7270 kg ha^{-1} in Year 1 and was strongly affected by site ($P < 0.001$) and treatment effects ($P < 0.001$) and a site × treatment interaction ($P = 0.05$). Herbage accumulation ranged from 8401 kg ha^{-1} at the Pennsylvania site to 5529 kg ha^{-1} at the Wisconsin site. The site × treatment interaction was due to variation within the tall fescue monocultures in response to N fertilization. At most sites in Year 1, herbage accumulation of tall fescue monocultures leveled off above 100 kg N ha^{-1}. The exception was the Pennsylvania site that appeared to level off then showed a large N response from 200 to 300 kg N ha^{-1} (Fig. 1a). Year 2 herbage accumulations were lower than Year 1, averaging 6403 kg ha^{-1} and showing a site × treatment interaction ($P < 0.001$). The Virginia and Pennsylvania sites had the highest yields in Year 2 (6842 kg ha^{-1}) while the Utah and Wyoming sites yielded about 17% less (5684 kg ha^{-1}). The interaction was due again to responses of tall fescue monocultures to N fertilization. At the Virginia and Pennsylvania sites, tall fescue yield continued to increase beyond the 150 kg N rate, while yields were largely unresponsive at other sites to the highest N rates (Fig. 1b). When mixtures were analyzed separately from monoculture treatments, site and treatment effects were significant in both years ($P < 0.05$), and no site × treatment interaction was observed. Plots seeded to 75:25 and 50:50 mixtures produced the greatest biomass in both years (Fig. 2)

Regression was used to determine whether the amount of alfalfa seed sown in mixtures predicted its proportion of the total herbage accumulation. Although alfalfa herbage accumulation was variable at the 25:75 treatment, the proportion of alfalfa seed sown in mixtures still predicted its accumulation proportion ($P < 0.001$, df = 1, 38), and explained 52% of the variation (data not shown). Alfalfa sown at 100, 75, 50, and 25% of mixture accounted for 80, 48, 45, and 35% of total yields, respectively. Exploring these relationships more closely, we found that the alfalfa component of mixtures explained more of the variation in total herbage accumulation in Year 1 ($r^2 = 0.38$. $P < 0.001$, df = 1, 43) (Fig. 3a). This trend continued in Year 2 as the alfalfa component explained an even higher proportion of the variation in yield ($r^2 = 0.48$, $P < 0.001$) (Fig. 3b). The r^2 values for tall fescue were 0.26 and 0.29 for Years 1 and 2, respectively.

Significant site × treatment interactions were found for grass N content in Year 2 ($P < 0.001$) mostly due to low and variable N content at the Wyoming site. Despite the interaction, N content in tall fescue monocultures increased with N application rates as expected (Table 2). Nitrogen content of mixtures differed by site ($P < 0.001$) and treatment ($P = 0.001$) but the interaction was nonsignificant ($P = 0.15$). The N content of mixtures was related to the proportion of alfalfa sown, being highest in 75% sown alfalfa and lowest in 25% alfalfa (Table 2).

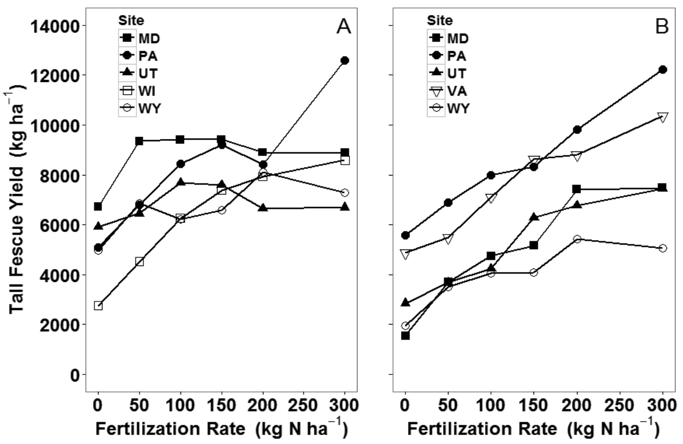

Fig. 1. Tall fescue monoculture yields in response to N fertilization in Year 1 (A) and Year 2 (B) separated by site.

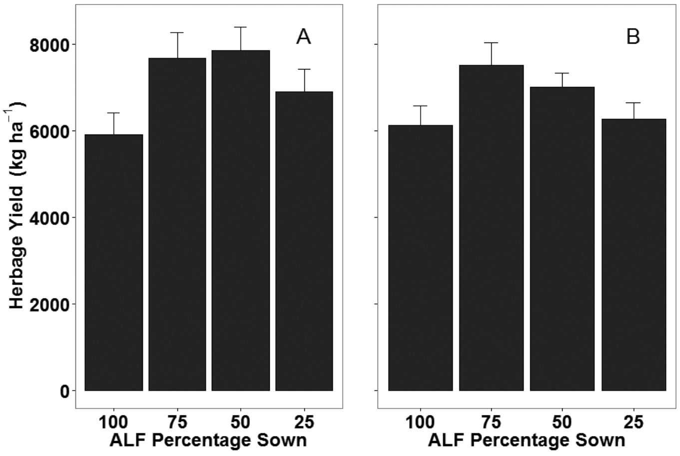

Fig. 2. Herbage accumulation for alfalfa–tall fescue mixtures in Year 1 (A) and Year 2 (B). Means include weed herbage mass in mixtures.

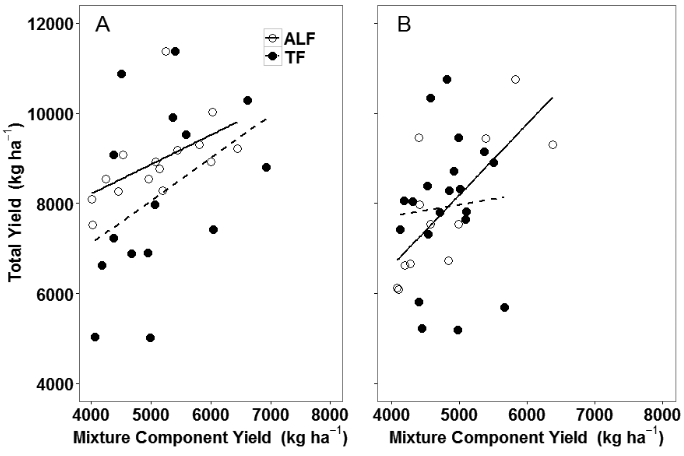

Fig. 3. Mixture component yields (tall fescue and alfalfa) regressed against total yield in Year 1 (A) and Year 2 (B). Alfalfa, solid line; Tall fescue, dashed line.

Weed Herbage Mass

In Year 1, weed herbage mass averaged 608 kg ha^{-1} and differed only by site ($P < 0.001$) mainly due to high weed pressure at the Utah site (1143 kg ha^{-1}). Despite the high weed pressure, this still only accounted for about 16% of the total herbage accumulation at this site. Weed herbage mass in Year 2 was affected by site ($P > 0.001$) and treatment ($P < 0.001$) but the interaction was not significant ($P = 0.11$). The site differences were mainly due to high weed pressure at the Pennsylvania site (793 kg ha^{-1}) while the other sites averaged less than 270 kg ha^{-1}. High weed biomass in the alfalfa monocultures and tall fescue monocultures that received no N explained the significant treatment differences (Fig. 4).

Fertilizer Nitrogen Replacement Value

For estimation of FNRV, linear and quadratic models were used to evaluate the relationships between N fertilization rate and tall fescue yield at each site. In Year 1, relationships between N rate and tall fescue yield were not significant for the Utah site (Table 3). The Wyoming site in Year 1 produced high FNRV values in part because the 0-fertilizer yields were very high (5999 kg ha^{-1}) possibly due to residual N in the soil (Table 3). Although significant, the R^2 value for the equation at the Wyoming site was 0.19 thus these FNRVs should be taken with caution. In one case (Maryland) and all cases at the Wyoming site in Year 2, mixture yields were outside of the range that could be predicted by the fertilizer response trials (Table 3). In the remaining sites with statistically significant relationships, FNRV averaged 143 kg ha^{-1}. Values were highest at the Virginia, Pennsylvania, and Maryland sites especially in Year 2 and greater in plots with 75% sown alfalfa (Table 3).

DISCUSSION

Herbage Accumulation

An overarching goal of this study was to evaluate alfalfa–fescue mixture yield, weed suppression and FNRV across a wide range of environments. Herbage accumulation was highest in the eastern sites (Pennsylvania, Maryland, and Virginia) averaging approximately 7600 kg ha^{-1} while the western sites (Utah, Wyoming) averaged close to 6000 kg ha^{-1}. This result was not unexpected as the eastern region is probably better suited to tall fescue production in particular (Sleper and West, 1996). Rainfall amounts also were generally adequate at the eastern sites (data not shown). The Wisconsin site did not yield as well as expected, but only Year 1 data could be collected. The limited results at the Wisconsin site, then, may not be reflective of potential productivity. Even though irrigation was used at Utah and Wyoming sites, yields were still about 20% lower than at more productive eastern sites. This result suggests that alfalfa and fescue

Table 2. Nitrogen content in tall fescue samples collected from Year 2 sites. Values are means ± 1 SE.

Monoculture		Mixture	
N fertilization rate	Tall fescue N content	Mixture treatment	Tall fescue N content
kg N ha^{-1}	kg N ha^{-1}	Alfalfa/tall fescue	kg N ha^{-1}
0	63 ± 8.7	25:75	123 ± 12.9
50	89 ± 9.2	50:50	150 ± 13.2
100	110 ± 11.2	75:25	160 ± 17.6
150	145 ± 14.5		
200	178 ± 13.6		
300	236 ± 22.0		

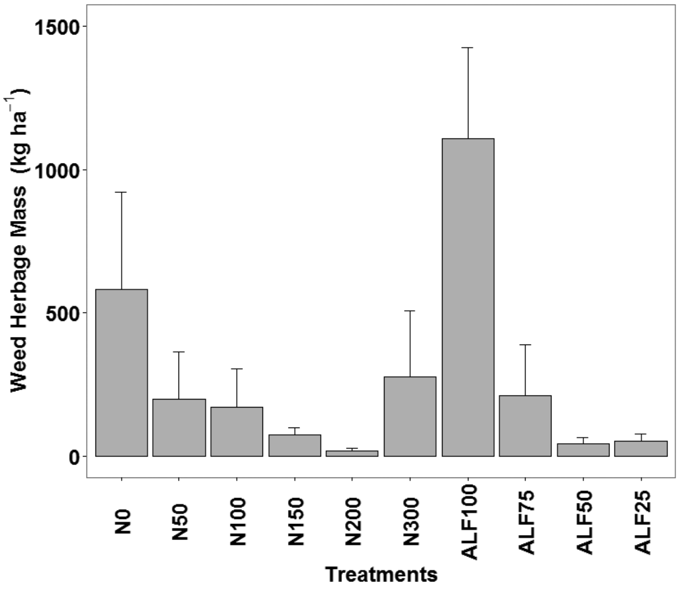

Fig. 4. Mean weed herbage mass collected from treatments in Year 2. N0, N50, N100, N150, N200, and N300 are tall fescue monocultures fertilized with 0, 50, 100, 150, 200, and 300 kg N ha^{-1}, respectively. ALF100, ALF75, ALF50, and ALF25 are alfalfa–tall fescue mixtures sown with 100, 75, 50, and 25% alfalfa, respectively.

Table 3. Forage nitrogen replacement values (FNRV, kg N ha^{-1}) calculated for each site in Years 1 and 2 with supporting statistics. Mixtures were sown with alfalfa/tall fescue seed ratios of 75:25, 50:50, and 25:75. Values are means ± 1 SE.

Site	Year	Model	*y*-intercept	Linear term	Quadratic term	Adj. R^2	FNRV		
							75:25	50:50	25:75
MD	1	Quadratic	7569	22.4	−0.063	0.27	36.1 ± 31	15.4 ± 27	−4.6 ± 18
MD	2	Quadratic	1694	36.	−0.056	0.85	173 ± 19	155 ± 25	178 ± 58
PA	1	Linear	5518	24.6	–	0.88	141 ± 3.6	145 ± 6.8	92.9 ± 21
PA	2	Linear	5610	21.3	–	0.88	172 ± 26	119 ± 29	82.6 ± 11
UT	1	NS					NS†	NS	NS
UT	2	Linear	2995	16.5	–	0.71	88.5 ± 33	147 ± 23	91.5 ± 39
VA	2	Quadratic	4625	27.7	−0.029	0.92	212 ± 48	148 ± 15	104 ± 41
WI	1	Quadratic	2738	41.3	−0.073	0.93	54.0 ± 16	48.5 ± 9.9	39.2 ± 8.2
WY	1	Linear	5699	7.2	–	0.19	338 ± 133	632 ± 78	81.4 ± 86
WY	2	Quadratic	2097	24.0	−0.047	0.78	NS	NS	NS

† NS, not significant.

cultivars used in this study may not have been well suited to these western environments. Grasses have been shown to exhibit wide variation in cultivar performance when planted with alfalfa so other cultivar combinations may show better forage production for these regions (Casler and Walgenbach, 1990). Lower relative humidity in the western sites also could have resulted in elevated evapotranspiration rates and moisture stress between irrigations.

The responses of tall fescue monocultures to N fertilization differed among sites, and this contrasted with mixture yields, which did not exhibit site × treatment interactions. The lack of significant site × treatment effects for mixtures was surprising given the wide range of environments covered and might reflect an environmental buffering effect present in grass–legume mixtures that was not present in monocultures. Alfalfa and tall fescue differ in various growth characteristics (e.g., tap vs. fibrous roots, N fixation vs. no N fixation), and these differences can permit complementary growth under different environmental conditions (Sleugh et al., 2000). For example, alfalfa growth may be favored under dry conditions due to its deep tap root, while the more fibrous root system of tall fescue might help it thrive under wetter conditions. In terms of aboveground effects, more rapid growth of alfalfa could shade neighboring tall fescue plants and possibly aid their growth during hot conditions (Chamblee, 1958). More commonly, growth compensation between species in mixture usually occurs from alfalfa compensating for slower grass growth in summer (Åberg et al., 1943; Sleugh et al., 2000). This complementary effect can be seen in the seasonal yield distribution at the Virginia site in 2011 (Fig. 5). Given these complementary growth characteristics, mixtures may be better able to compensate, or buffer, variable environmental conditions compared with monocultures even if monocultures were not fertilized with high N rates. The resultant effect may have been more uniform yield responses across environments used in this study.

Studies that have compared grass–legume mixtures and N fertilized monocultures have reported mixed results. Hamilton et al. (1969) found that alfalfa–grass mixtures yielded more than grass monocultures fertilized with 112 to 168 kg N ha^{-1}. Barnett and Posler (1983) and Berdahl et al. (2001) found that alfalfa–grass mixtures were more productive than N fertilized grasses that were fertilized at low N rates (50–90 kg ha^{-1}). Several studies also have shown that grass–legume mixtures are not more productive than N fertilized monocultures (Comstock and Law, 1948; Jones et al., 1988; Mooso and Wedin, 1990). Mixture herbage accumulation in this study was consistently higher compared with alfalfa monocultures and tall fescue monocultures that received low N fertilization rates. Interestingly, a recent study showed that grass–legume mixtures fertilized with moderate N rates (50 kg ha^{-1}) could yield more than the highest yielding grass or legume monocultures (Nyfeler et al., 2009). Possibly, moderate N fertilization of alfalfa–tall fescue mixtures could stimulate even greater productivity. Overall mixture herbage accumulation averaged 7480 and 6927 kg ha^{-1} in Years 1 and 2, respectively, while alfalfa monocultures averaged 5903 and 6122 kg ha^{-1}. Herbage accumulation was highest for mixtures sown with more than 50% alfalfa, supporting the idea that maximizing mixture yield may require alfalfa-dominated mixtures probably because it helps maximize N transfer to grasses (Brophy et al., 1987). Supporting this result were the tall fescue N contents, which tended to be highest at the 50 and 75% alfalfa treatments. The actual alfalfa herbage components in mixture were similar in these treatments accounting for about 45% of total herbage accumulation. This result suggests planting alfalfa–tall fescue mixtures at greater than 1:1 ratios may be unnecessary to maximize yield under these environmental conditions.

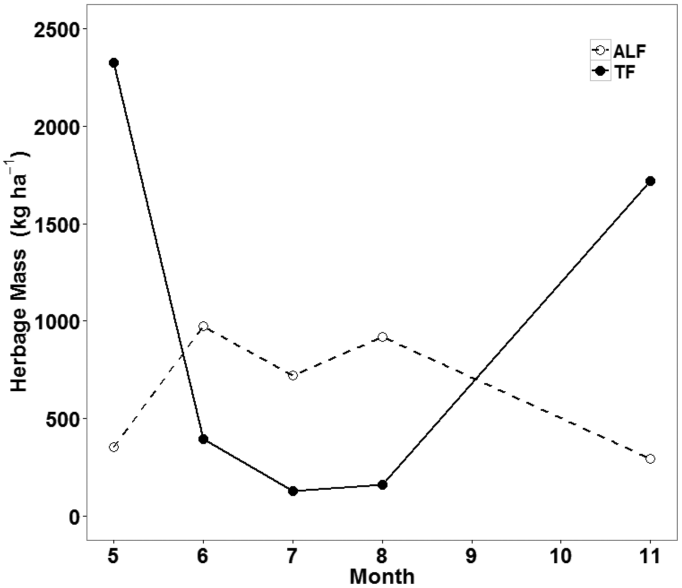

Fig. 5. Alfalfa and tall fescue herbage mass in mixture over the 2011 growing season at the VA site. Low alfalfa herbage mass in Month 5 (May) was in part due to alfalfa weevil damage.

The alfalfa component of mixtures explained more of the variation in total yield than tall fescue, especially in Year 2 when swards had developed more fully. This result is in agreement with other studies (Carter and Scholl, 1962; Barnett and Posler, 1983; Jones et al., 1988). The higher yield of mixtures over alfalfa monocultures may have been related to the association of tall fescue with alfalfa as the presence of grasses in mixture may benefit legume growth in different ways. For example, nitrogen uptake from soil by grasses and possible N immobilization by the microbial community could help stimulate N fixation and associated legume growth (Craig et al., 1981; Brophy et al., 1987; Nyfeler et al., 2011). Another example of this possible effect were findings from a systematic planting study that found alfalfa produced considerably more biomass when grown between orchardgrass rows than in monoculture (Chamblee 1958). Harvest interval also can affect grass–legume balance. Generally, grasses may compete better with alfalfa if harvested two to three times per year compared to one harvest (Comstock and Law, 1948). Smith et al. (1973) found that if tall fescue was cut at a short stubble height (4 cm) and only harvested twice a year, it was almost eliminated from alfalfa mixtures likely due to shading. Under more frequent harvests, fescue persisted well regardless of cutting height. Harvest intervals used in this study were probably frequent enough to favor fescue and indirectly help stimulate alfalfa growth.

Weed Suppression

As swards developed in Year 2, mixtures had fewer weeds than alfalfa monocultures. This result was not unexpected as added plant diversity can sometimes help suppress invasive weeds in pastures (Tracy et al., 2004; Sanderson et al., 2012). Cummings et al. (2004) found that interseeding ryegrass (*Lolium multiflorum* L.) or wheat (*Triticum* L.) into thin alfalfa stands effectively suppressed weeds and increased forage yield although interseeding had little effect on a fuller stand of alfalfa. Spandl et al. (1997) also found fewer weeds in alfalfa–grass swards compared with alfalfa monoculture. Many alfalfa monoculture plots in this study experienced heavy weed pressure as has been found in other studies (Barnett and Posler, 1983). The highest weed pressure occurred in the early spring most likely from winter annuals (data not shown). In some alfalfa plots, weed invasion was related to alfalfa weevil infestations, which were heavier in some monoculture stands than mixtures (B. Tracy, person observation, 2010) As winter annuals faded in late spring, however, enough alfalfa still remained to recover and sustain high growth during summer to help stabilize seasonal yield. It should be noted that although mixtures suppressed weeds better than alfalfa monocultures, high N fertilization of tall fescue monoculture fescue plots suppressed weeds equally well. Overall, grass inclusion in mixtures and N fertilization probably made stands more competitive. In mixtures, grasses likely took up space that weeds could potentially occupy in the alfalfa stands while the high productivity of tall fescue in response to N fertilization probably made it harder for weeds to invade stands.

Forage Nitrogen Replacement Value

The average FNRV reported across our sites (143 kg N ha^{-1}) was close to the range reported in other studies. For example, Chen et al. (2004) found that 40 to 50% alfalfa in pasture could provide enough N to replace fertilizer application to grass monoculture ranging between 52 and 153 kg N ha^{-1}. Other alfalfa–grass mixtures studies have reported similar values (Carter and Scholl, 1962; Jones et al., 1988). Some studies have reported higher values. Zemenchik et al. (2001) found that kura clover and birdsfoot trefoil could replace over 250 kg N ha^{-1} in orchardgrass mixtures while Sollenberger et al. (1984) reported that high seeding rates of alfalfa (18 kg ha^{-1}) sown with orchardgrass could replace 200 kg N ha^{-1}. Among our sites, FNRVs were higher and more consistent in Year 2 than in Year 1. This result could have been related to several factors. First, most N provided by legumes to grasses in mixture likely comes from nodule decomposition and subsequent mineralization. Although some N could have been provided to tall fescue in Year 1, it was probably small due to slow decomposition of root nodules that has been reported to occur with alfalfa (Louarn et al., 2015). Additionally, nitrogen released by legumes also can be immobilized by microbial biomass and be unavailable to companion grasses at least temporarily (Walker et al., 1954). In a study that evaluated orchardgrass–alfalfa mixtures planted with and without belowground partitions, significant potential belowground N transfer to orchardgrass occurred only after two years (Chamblee, 1958). Some of our sites also appeared to have high residual soil N in Year 1 possibly resulting from tillage effects during plot conversion. High N availability could have caused tall fescue monocultures to be less responsive to N fertilization and reduced FNRVs in Year 1. In addition to FNRV differences between years, a clear distinction was found between eastern and western sites. Most FNRVs at the western sites either were nonsignificant or highly variable. We can only speculate on the reasons for these differences, however, high residual soil N, weed pressure and possibly low N transfer from alfalfa to tall fescue could have played a role. This result also may suggest that the alfalfa and tall fescue cultivars used in this study were not well suited for irrigated, semiarid conditions.

SUMMARY AND CONCLUSIONS

Across a diverse set of study sites, we found that alfalfa mixtures provided similar yields to fertilized grass monocultures. On average, alfalfa ‘replaced’ approximately 143 kg N ha^{-1} in grass mixtures. Mixtures sown with 50 to 75% alfalfa also consistently outperformed alfalfa monocultures and provided higher FNRVs. This finding was encouraging as it suggests that alfalfa–tall fescue mixtures should be competitive with monocultures across a wide range of environments. Careful selection of cultivars may be warranted under semiarid, irrigated conditions, however, as these sites often exhibited lower herbage accumulation and FNRVs compared with eastern sites. Alfalfa–fescue mixtures also suppressed weeds better than alfalfa monocultures probably due to the inclusion of tall fescue that helped to increase the competitiveness of swards against weed invasion. High N fertilization rates also increased herbage accumulation of grass monocultures, and this helped to suppress weeds as well. While alfalfa–tall fescue mixtures could clearly offer some advantages in forage production systems, grass–legume interactions are dynamic and may change in response to many environmental variables. In light of climate change, more studies should be directed towards better understanding these interactions across variable environmental conditions.

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