

Linking leaf and root trait syndromes among 39 grassland and savannah species

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Summary

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- Here, we tested hypothesized relationships among leaf and fine root traits of grass, forb, legume, and woody plant species of a savannah community.
- CO₂ exchange rates, structural traits, chemistry, and longevity were measured in tissues of 39 species grown in long-term monocultures.
- Across species, respiration rates of leaves and fine roots exhibited a common regression relationship with tissue nitrogen (N) concentration, although legumes had lower rates at comparable N concentrations. Respiration rates and N concentration declined with increasing longevity of leaves and roots. Species rankings of leaf and fine-root N and longevity were correlated, but not specific leaf area and specific root length. The C₃ and C₄ grasses had lower N concentrations than forbs and legumes, but higher photosynthesis rates across a similar range of leaf N.
- Despite contrasting photosynthetic pathways and N₂-fixing ability among these species, concordance in above- and below-ground traits was evident in comparable rankings in leaf and root longevity, N and respiration rates, which is evidence of a common leaf and root trait syndrome linking traits to effects on plant and ecosystem processes.

Key words: functional groups, leaf lifespan, nitrogen-use efficiency, photosynthesis, respiration, root turnover, specific leaf area, specific root length.

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Introduction

Despite considerable variation in leaf traits among plant species, common patterns of trait covariation are observed across diverse species and biomes (Diemer *et al.*, 1992; Reich *et al.*, 1997, 1998a, 1999; Niinemets, 1999; Craine & Lee, 2003; Wright *et al.*, 2004). High specific rates of CO₂ exchange are associated with high leaf nitrogen (N) concentrations, high specific leaf area (SLA, leaf area per unit leaf dry mass) and short leaf lifespan. Consistent correlations among leaf traits are thought to reflect fundamental trade-offs in leaf morphology, metabolic rates, and longevity and may be useful in categorizing species based on their ecological attributes and defining the linkages of traits to species effects on ecosystem

functioning (Grime *et al.*, 1997; Lavorel & Garnier, 2002; Eviner & Chapin, 2003; Díaz *et al.*, 2004).

Compared with leaf traits, far less is known about interspecific variation in root traits or their correspondence with above-ground trait syndromes (Eissenstat & Yanai, 1997; Eissenstat *et al.*, 2000; Bouma *et al.*, 2001; Craine & Lee, 2003). Are there consistent correlations of leaf and fine root structure, function and longevity among species? For example, as in leaves, are high specific respiration rates in fine roots correlated with high N, high specific root length (SRL, root length per unit root dry mass) and short lifespan? There is evidence that fine roots of species differ widely in SRL and N concentration (Comas *et al.*, 2002; Pregitzer *et al.*, 2002) and that specific respiration rates of fine roots increase with higher

N concentration and SRL (Pregitzer *et al.*, 1998; Reich *et al.*, 1998b; Comas *et al.*, 2002), likely reflecting metabolic activity associated with nutrient uptake and assimilation, although species may differ in their specific costs of ion uptake (Scheurwater *et al.*, 1998). In some studies, root longevity among species is negatively correlated with N concentration, specific respiration rates, and SRL (Eissenstat *et al.*, 2000) or root tissue density (Ryser, 1996; Craine *et al.*, 2001), a pattern analogous to leaf trait correlations. Nitrogen concentration and tissue density of leaves were correlated with those of fine roots among 24 grass species sampled along an altitudinal transect (Craine & Lee, 2003). The correspondence of leaf and root traits raises the possibility that root traits may, in part, be predicted from more readily observed leaf traits. However, the generality of leaf and root trait syndromes, particularly in relation to physiological function remains largely untested.

The evidence to date suggests that a priori plant functional groups based on taxonomy (e.g. monocot, dicot) or functional categories (N_2 -fixing, photosynthetic pathway) may be useful in categorizing species traits and their effects on ecosystem processes (Aerts & Chapin, 2000; Lavorel & Garnier, 2002). However, species effects on ecosystem function often arise from multiple, often continuously distributed traits and their potentially additive or interactive effects (Eviner & Chapin, 2003). Elucidating structural (tissue morphology and chemistry) and functional trait correlations (e.g. CO_2 exchange) and their correspondence in leaves and roots will aid in identifying underlying mechanisms and scaling relationships that link traits to plant and ecosystem function. Whether or not trait correlations differ among a priori plant functional groups in predictable ways is not well understood. For example, among grass species, high SLA, low tissue density leaves and corresponding low tissue density roots is associated with faster plant relative growth rates (van der Werf *et al.*, 1993; Ryser & Lambers, 1995; Wahl & Ryser, 2000), whereas among tree species, a faster growth rate is associated with higher SRL and smaller root diameters and not root tissue density (Comas *et al.*, 2002; Comas & Eissenstat, 2004). This suggests that grasses and trees may, in part, differ in trait correlations. In addition, woody and herbaceous plant growth forms may differ in traits underpinning leaf and plant-level nutrient-use efficiency (Aerts & Chapin, 2000).

The temperate grassland–savannah ecotone in the northern great plains of North America offers a diverse array of taxa with which to examine hypothesized trait correlations for above and below-ground traits and provide insight into the structure, N dynamics and productivity of communities in this region (Tilman, 1988; Tilman & Wedin, 1991; Reich *et al.*, 2001a; Craine *et al.*, 2002). Moreover, species in these grassland and savannah ecosystems differ in functional attributes in important ways, including photosynthetic pathway (C_4 vs C_3), N_2 fixation, and growth form (grasses, forbs and woody plants). In this study we examined leaf and fine root ecophysiological traits of a large number of sympatric

species, including C_4 and C_3 grasses, nonlegume forbs (hereafter called forbs), herbaceous legumes (hereafter called legumes) and woody plant species. Replicate monoculture plots in a 5-yr-old common garden experiment enabled us to examine both leaf and root traits of 39 species grown individually under common field conditions. A concurrent study of multivariate trait correlations including productivity and N cycling is reported elsewhere (Craine *et al.*, 2002). Here we report an expanded set of bivariate trait relationships of leaves and fine roots, focusing on hypothesized structural–functional relationships.

In this study we sought to address several questions. To what extent do leaf and root traits exhibit structural and functional convergence among sympatric grassland–savannah species? We hypothesized that analogous trait correlations exist for leaves and fine roots in terms of morphology, longevity and rates of CO_2 exchange. Do species with leaves exhibiting high rates of CO_2 exchange and associated high SLA, N contents and short lifespan also exhibit a parallel syndrome of traits in fine roots? Do trait correlations differ among a priori functional groups (i.e. C_3 vs C_4 photosynthetic pathway)? Linking leaf and root trait relationships among species and functional groups may aid in predicting trait combinations and their ecological effects, including composition and productivity at regional scales (Paruelo *et al.*, 1998; Lavorel & Garnier, 2002), as well as species response to global change factors (Reich *et al.*, 2001b; Lee *et al.*, 2001; Poorter & Navas, 2003).

We tested several predictions of correlated leaf and fine root trait relationships among species and functional groups as follows: (1) rates of net photosynthesis and respiration of leaves and fine roots are correlated with tissue N (Ryan, 1991; Reich *et al.*, 1997, 1998a, 1999; Tjoelker *et al.*, 1999); (2) leaf and fine root N concentration increases with increasing SLA and SRL and N concentrations decrease with increasing tissue longevity; and (3) species exhibit similar rankings in leaf and fine root traits, namely, N concentration, SLA and SLR, longevity and specific respiration rates. Given hypothesized functional group contrasts, owing to differing photosynthetic pathways, we tested the predictions that: (4) C_3 vs C_4 groups differed in bivariate leaf trait–N relationships, reflecting expected higher leaf-level water- and photosynthetic N-use efficiencies for C_4 than for C_3 species (Sage & Pearcy, 1987; Ehleringer & Monson, 1993); and (5) that owing to higher N concentrations in legumes, leaf and root traits correlated with increased tissue N concentrations are higher in legumes compared with non- N_2 -fixing forbs and grasses.

Materials and Methods

Site

The study site is at the Cedar Creek Natural History Area, a US National Science Foundation long-term ecological research site near Bethel, in east central Minnesota, USA (<http://www.lter.umn.edu>). The uplands at this site are

dominated by oak savannah, prairie, hardwood forest, pine forests and abandoned agricultural fields. The soils are entisols derived from a glacial outwash sand plain and are sandy and N-poor (Tilman, 1988). The region has a continental climate with cold winters, hot summers (mean January and July temperatures of -10°C and 25°C , respectively), and a mean annual precipitation of 660 mm.

The 39 species we examined in this long-term monoculture study include grasses, forbs, and woody plants common to remnant native oak savannah–prairie grasslands in the Midwestern USA. Species binomials are reported in the Appendices. Names and authorities follow those of Moore (1973) and B. C. Delaney (University of Minnesota, unpublished; <http://www.lter.umn.edu>). In the autumn of 1992, an old field was prepared by removing the topsoil, creating a sandy substrate (93% low in organic matter). Replicated monoculture plots of the species were seeded in a fenced area and maintained by annual weeding. Plots were 2.2×1.5 m for most species, 1.1×1.5 m for the others. Sheet metal barriers that extended 25 cm below the ground separated the plots. We watered the plots weekly during the growing season in 1997 in the 5-yr-old plots as needed to ensure an equivalent of at least 2.5 cm of weekly precipitation to minimize water stress. Further details are provided in Craine *et al.* (2002).

Leaf gas exchange

We determined light-saturated rates of leaf gas exchange of 36 species in the field sampled across four dates (25 June, and 7, 21 and 28 August, 1997). A portable photosynthesis system (CIRAS-1; PP Systems, Hitchin, UK) measured rates of net CO_2 and water vapor exchange. We conducted measurements on clear sunny days at light-saturating conditions between 10:30 and 14:00 hours Central Daylight Time (CDT). Mean photosynthetic photon flux density (PPFD, 400–700 nm) ranged from 1440 to 1560 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and mean air temperatures ranged from 26.3 to 29.3 $^{\circ}\text{C}$ on the four dates. We measured two to four mature leaves from the top of the canopy in each of two to four replicate plots for a species. Following gas exchange measurement, we removed the sampled leaf and stored it in a cooler before measuring leaf area (one-sided, projected). Samples were oven dried at 65 $^{\circ}\text{C}$ before determining dry mass. We calculated light-saturated photosynthesis rates on the basis of leaf area (A_{area} , $\mu\text{mol m}^{-2} \text{s}^{-1}$) and dry mass (A_{mass} , $\text{nmol g}^{-1} \text{s}^{-1}$).

Leaf respiration

We harvested several intact shoot samples (two or three) from individual plots on the mornings (between 08:30 and 11:00 hours CDT) of 17 and 18 June, placed the samples in plastic bags in a cooler (*c.* 11 $^{\circ}\text{C}$), and transported them to the laboratory. Samples were immediately transferred to a controlled-environment chamber (Conviron E15; Controlled

Environments, Inc., Winnipeg, Manitoba, Canada) to measure dark respiration at a standard temperature ($26.1 \pm 0.6^{\circ}\text{C}$ SD) and CO_2 concentration ($381 \pm 15 \mu\text{mol mol}^{-1} \text{CO}_2$). We determined rates of net CO_2 efflux using infrared gas analysers and cuvettes (LCA-3 and PLC-C; Analytical Development Co. Ltd, Hoddesdon, UK), operated in an open configuration. Columns of magnesium perchlorate removed water vapor from the analyser air stream. Depending on leaf morphology and size, we measured either single leaves or multiple leaves with attached stems to provide adequate differential measurements, one per replicate plot. We dried the samples in an oven (65 $^{\circ}\text{C}$) and determined dry masses for calculation of respiration rates based on leaf mass (R_{mass} , $\text{nmol g}^{-1} \text{s}^{-1}$) or area (R_{area} , $\mu\text{mol m}^{-2} \text{s}^{-1}$).

Fine root respiration

We collected aggregate root samples from soil cores (5 cm diameter, 20 cm deep) for each of up to four plots per species (minimum of two plots for three species) of 36 species on 18, 20, and 21 August. Roots were washed from soil cores with water over a 1.3 mm screen and separated into fine (< 2 mm diameter) and coarse fractions. Based on morphological measures described later, the mean diameter of the fine root sample among species was 0.30 mm with mean species values ranging from 0.13 to 0.44 mm. On average across species, 84% (± 0.08 SD) of the sampled root length was distributed in diameter classes < 0.5 mm and 92% (± 0.03 SD) was < 1.0 mm. An inspection of the diameter distributions and mean values suggested that we sampled only the finest two or three root orders, comparable to those reported for grass (Wahl & Ryser, 2000) and tree species (Pregitzer *et al.*, 2002; Comas & Eissenstat, 2004).

The root samples were kept moist at room temperature (*c.* 26 $^{\circ}\text{C}$) before measurement of respiration, typically within 2.5 h of harvest. We determined the net CO_2 efflux on each fine root sample of each plot at a standard temperature ($25.7 \pm 0.4^{\circ}\text{C}$) and atmospheric CO_2 concentration (366 ± 13 SD $\mu\text{mol mol}^{-1} \text{CO}_2$) using infrared gas analysers and cuvettes, as described above. Checks revealed no direct effect of measurement CO_2 concentration on rates of root respiration in agreement with recent findings (Amthor *et al.*, 2001; Tjoelker *et al.*, 2001; Burton & Pregitzer, 2002). Use of detached roots for measures of respiration followed standard protocols (Burton & Pregitzer, 2002; Comas *et al.*, 2002) and no correlation was observed between respiration rate and time of measurement for each of three sampling dates. Root length (see next section) and oven-dry mass measures were used to calculate respiration rates on the basis of root mass (R_{mass} , $\text{nmol g}^{-1} \text{s}^{-1}$) and root length (R_{length} , $\text{nmol m}^{-1} \text{s}^{-1}$).

Tissue morphology, chemistry, and longevity

We measured leaf area (one-sided projected) using a video image analysis system (AgVision; Decagon Devices, Inc.,

Pullman, WA, USA). Root lengths and diameters were determined using a scanner-based, digital image analysis system (WinRhizo; Régent Instruments, Inc. Quebec City, Quebec, Canada). Following area or length determinations, the tissues were oven dried (65°C) and masses determined to calculate specific leaf areas (SLA, cm² leaf g⁻¹ leaf) and specific root lengths (SRL, m root g⁻¹ root). Nitrogen and carbon (C) concentrations of dried and ground leaf and root samples were measured using a CHN analyser (NA1500; Carlo Erba Instruments, Milan, Italy). Leaves sampled for the photosynthesis measures were pooled by plot before C and N analysis. Leaf N concentrations were used to calculate instantaneous photosynthetic nitrogen-use efficiency (PNUE, μmol CO₂ g N⁻¹ s⁻¹).

We obtained leaf longevity data of 14 species determined the same year in the same study (Craine *et al.*, 1999). Root longevity was estimated based on measured root turnover determined by in-growth and *in situ* root sampling in the plots. The standing crop of root biomass was determined in mid-August and root production estimated from ingrowth cores collected in July, August and October (Craine *et al.*, 2002). Root longevity was calculated as standing crop divided by total ingrowth, the inverse of root turnover. We assumed that annual root production and turnover approximated steady-state levels in these long-term (5-yr-old) monoculture plots, based on observed plant density and dry matter production values. With the exception of one annual and two biennial species, all species are perennial. Poorly stocked plots were excluded from the analysis of root turnover. Our estimates of root turnover were comparable to values in nearby grassy savannah openings (Reich *et al.*, 2001a) and other grasslands (Gill & Jackson, 2000).

Data analysis

The experimental design was completely random with individual monoculture plots serving as replicates for each species ($n = 2-4$). We calculated mean values for each species (see Appendices 1 and 2), since our objective was to examine variation in traits among species and species groups. Species means were log-transformed to satisfy assumptions of normality and homogeneity of variance. A priori, functional groups were C₃ grasses, C₄ grasses, forbs, legumes and woody plants. The woody plant group was comprised of only two species and consequently was excluded from functional group comparisons, but included in the rank correlation analysis of leaf vs root traits across all species. We tested hypothesized functional group effects using *F*-tests in analysis of variance in which fixed functional group effects (3 df) were tested against the effect of species nested within functional groups (experimental error). Preplanned comparisons among the four a priori groups included contrasts of C₃ vs C₄ photosynthetic pathways, grasses vs nongrasses, and N₂-fixing legumes vs nonlegumes. These comparisons were made using single-

degree-of-freedom contrasts in the analysis of variance. Least squares means of log-transformed variables were back-transformed for reporting functional group means.

Bivariate trait relationships of log-transformed species means among the four a priori functional groups (excluding the woody plants) were examined using Type II linear regression. Unlike Type I regression, error is quantified in both variables and the linear regression fits are equivalent to the standard major axis or first principal component of the bivariate trait correlation. The slope of the Type II regression line between two log-transformed traits represents a proportional (scaling) relationship between the two variables. The intercept (or elevation) denotes the position of the regression line (scaling relationship) in bivariate trait space. The slopes and intercepts of the Type II major axes were compared among the four a priori groups using an approach analogous to testing the homogeneity of slopes and equality of intercepts in analysis of covariance (Wright *et al.*, 2001; Warton & Weber, 2002). Regression intercepts among the four functional groups were compared using *t*-tests (*post hoc* Tukey's HSD) after fitting same-slopes models (where appropriate) to variables transformed as $y - m(x)$, where m is the common slope. We first tested for differences in slopes and intercepts among the four a priori functional groups (C₃ grasses, C₄ grasses, forbs and legumes) and those that did not differ statistically were subsequently grouped and separate Type II linear regressions fitted to illustrate the a posteriori group relationships. Incomplete sampling resulted in differing numbers of species in the various trait comparisons ($n = 31-36$). Spearman's nonparametric rank correlation analysis was used to compare leaf vs root traits among species. All analyses were conducted using statistical analysis software (JMP 4.0; SAS Institute, Cary, NC, USA). Unless otherwise stated, $\alpha = 0.05$.

Results

Comparison of leaf traits among functional groups

The a priori functional groups differed in mean rates of leaf net photosynthesis whether expressed on the basis of leaf area (A_{area} , μmol m⁻² s⁻¹) or leaf dry mass (A_{mass} , nmol g⁻¹ s⁻¹). Overall, the C₃ and C₄ grasses had the highest mean rates of A_{area} or A_{mass} followed by the legumes and forbs (Table 1). Since specific leaf area (SLA, cm² g⁻¹) did not differ significantly among the functional groups (Table 1), group rankings of mean A_{area} and A_{mass} were comparable. Mean leaf longevity of a subset of the species ($n = 14$) ranged from 29 to 94 d (Appendix 1; see also Craine *et al.*, 1999).

As predicted, light-saturated rates of net photosynthesis on mass and area bases were positively correlated with leaf N_{mass} (%) and N_{area} (g N m⁻² leaf area), respectively (Fig. 1a,b). A_{area} was positively correlated with SLA ($r = 0.52$, $P = 0.002$, $n = 32$, not shown). Mean leaf N_{mass} ranged from 1.0 to 4.1% among species and differed among functional groups (Table 1),

Table 1 Least squares mean (lower and upper 95% confidence intervals) leaf and fine root traits for functional groups of 39 grassland and savannah species grown in a common garden

	C ₃ grasses			C ₄ grasses			Forbs			Legumes			ANOVA <i>P</i> > <i>F</i>		Contrast <i>P</i> > <i>t</i>		
	Mean	95% CI	<i>n</i>	Mean	95% CI	<i>n</i>	Mean	95% CI	<i>n</i>	Mean	95% CI	<i>n</i>	Functional group	C ₃ vs C ₄	Grass vs rest	Legume vs rest	
Leaf traits																	
A _{area} ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	29.2	23.0–37.1	5	27.4	22.0–34.1	7	16.9	14.6–19.5	16	19.7	15.5–25.1	6	< 0.001	0.05	< 0.001	0.16	
A _{mass} ($\text{nmol g}^{-1} \text{s}^{-1}$)	283	207–386	5	263	202–342	7	177	148–210	16	232	174–308	6	0.02	0.32	0.03	0.91	
gs ($\text{mmol m}^{-2} \text{s}^{-1}$)	588	407–849	5	273	195–382	7	454	365–566	16	539	373–778	6	0.02	0.002	0.20	0.21	
SLA ($\text{cm}^2 \text{g}^{-1}$)	99	78–127	5	102	82–128	7	103	89–119	16	118	92–151	6	0.74	0.75	0.42	0.27	
N _{mass} (%)	1.79	1.43–2.23	5	1.34	1.09–1.64	7	1.86	1.63–2.12	16	2.87	2.29–3.58	6	< 0.001	< 0.001	< 0.001	< 0.001	
N _{area} (g m^{-2})	1.90	1.47–2.45	5	1.38	1.09–1.74	7	1.83	1.57–2.13	16	2.47	1.91–3.18	6	0.02	0.005	0.02	0.01	
C:N	25.1	19.9–31.6	5	33.3	26.9–41.1	7	23.2	20.2–26.6	16	15.7	12.5–19.8	6	< 0.001	< 0.001	< 0.001	< 0.001	
WUE ($\text{mmol CO}_2 \text{mol}^{-1} \text{H}_2\text{O}$)	3.52	3.05–4.06	5	5.83	5.11–6.65	7	3.40	3.12–3.71	16	3.36	2.91–3.88	6	< 0.001	< 0.001	< 0.001	0.01	
PNUE ($\mu\text{mol CO}_2 \text{g}^{-1} \text{N s}^{-1}$)	16.3	13.0–20.4	5	20.3	16.5–24.9	7	9.4	8.2–10.7	16	8.0	6.4–10.0	6	< 0.001	< 0.001	< 0.001	< 0.001	
R _{mass} ($\text{nmol g}^{-1} \text{s}^{-1}$)	17.5	13.7–22.3	5	13.0	10.4–16.2	6	16.2	14.0–18.7	14	18.0	14.1–22.9	5	0.18	0.03	0.26	0.26	
R _{area} ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	2.1	1.5–3.0	5	1.0	0.7–1.4	6	1.4	1.1–1.7	14	1.4	1.0–1.9	5	0.02	0.01	0.64	0.78	
A : R	13.3	9.7–18.3	5	28.1	21.1–37.6	6	12.8	10.6–15.5	14	15.0	10.9–20.6	5	< 0.001	< 0.001	0.02	0.49	
Longevity (d)	77	50–118	3	68	44–104	3	56	40–77	5	47	30–72	3	0.31	0.50	0.08	0.14	
Fine root traits																	
R _{mass} ($\text{nmol g}^{-1} \text{s}^{-1}$)	11.4	7.7–16.6	5	5.7	4.0–8.1	6	12.4	9.8–15.7	17	13.2	9.0–19.3	6	0.005	< 0.001	0.01	0.10	
N _{mass} (%)	1.08	0.81–1.44	5	0.52	0.40–0.67	6	1.13	0.95–1.35	15	1.99	1.49–2.64	6	< 0.001	< 0.001	< 0.001	< 0.001	
N _{length} (mg m^{-1})	0.32	0.10–1.03	5	0.18	0.06–0.52	6	0.41	0.20–0.83	15	0.76	0.24–2.43	6	0.32	0.12	0.11	0.13	
SRL (m g^{-1})	76.5	50.6–115.6	5	56.2	38.5–81.9	6	60.6	46.9–78.3	17	41.0	27.1–61.9	6	0.20	0.91	0.14	0.06	
C : N	37.8	28.4–50.2	5	79.5	61.3–103.1	6	38.9	32.6–46.4	15	23.5	17.7–31.2	6	< 0.001	< 0.001	< 0.001	< 0.001	
Longevity (d)	504	243–1044	5	791	407–1540	6	182	118–281	15	136	65–281	5	0.001	0.003	< 0.001	0.009	

Means and 95% confidence intervals were back-transformed from \log_{10} ; *n* is the number of species (see Appendices). A_{area}, area-based photosynthesis; A_{mass}, mass-based photosynthesis; gs, stomatal conductance; SLA, specific leaf area; N_{mass}, nitrogen concentration; N_{area}, area-based nitrogen concentration; C : N, carbon–nitrogen ratio; WUE, water use efficiency; PNUE, photosynthetic N-use efficiency; R_{mass}, mass-based respiration; R_{area}, area-based respiration; A : R, ratio of net photosynthesis to respiration; N_{length}, root length-based nitrogen concentration; SRL, specific root length.

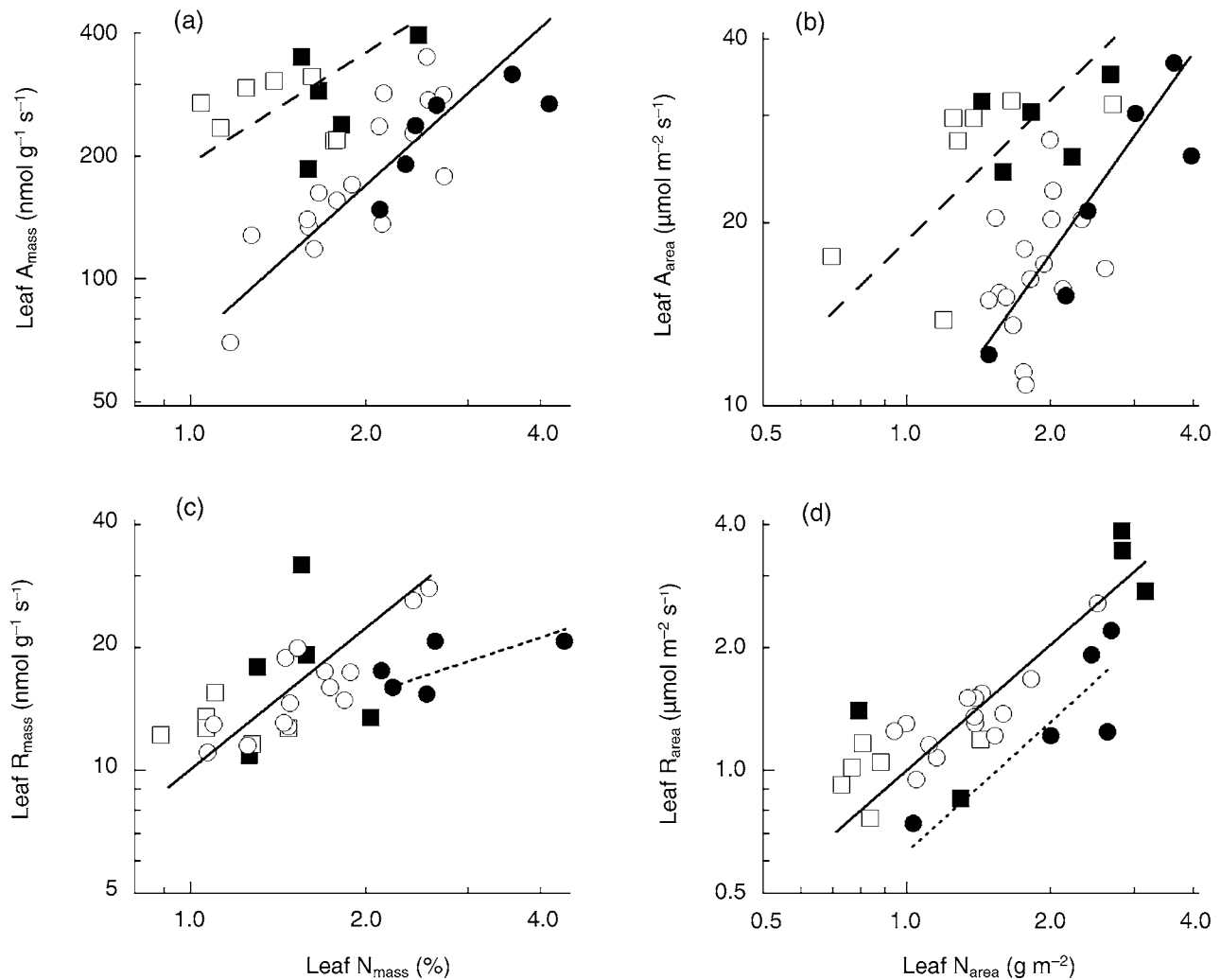


Fig. 1 Leaf trait relationships among 39 savannah species. Species means are shown identified as forbs (○), legumes (●), C_3 grasses (■), and C_4 grasses (□). Note the \log_{10} scale. Type II regression lines illustrate a posteriori group contrasts among species. (a) $A_{\text{mass}} - N_{\text{mass}}$ correlations for the combined C_3 and C_4 grass groups ($r = 0.20$, $P = 0.52$, $n = 12$) and combined forb and legume groups ($r = 0.82$, $P < 0.001$, $n = 22$). (b) $A_{\text{area}} - N_{\text{area}}$ correlations for the combined C_3 and C_4 grass groups ($r = 0.62$, $P = 0.03$, $n = 12$) and combined forb and legume groups ($r = 0.72$, $P < 0.001$, $n = 22$). (c) $R_{\text{mass}} - N_{\text{mass}}$ correlations for the legume group ($r = 0.63$, $P = 0.26$, $n = 5$) and for the combined C_3 and C_4 grass and forb groups ($r = 0.64$, $P < 0.001$, $n = 25$). (d) $R_{\text{area}} - N_{\text{area}}$ correlations for the legume group ($r = 0.85$, $P = 0.07$, $n = 5$) and for the combined C_3 and C_4 grass and forb groups ($r = 0.86$, $P < 0.001$, $n = 25$).

being greatest in legumes, followed in decreasing order by forbs, C_3 grasses, and C_4 grasses. However, for a given leaf N_{mass} or N_{area} the two grass groups (regardless of photosynthetic pathway) had higher A_{mass} and A_{area} compared with the forbs and legumes. Among the four a priori groups, the C_3 and C_4 grasses differed from forbs and legumes in terms of intercept ($P < 0.001$) but not slopes ($P \geq 0.32$) of the Type II regression between A_{mass} and N_{mass} as well as A_{area} and N_{area} , providing evidence of separate trait correlations for the combined grass and combined forb and legume species (Fig. 1a,b).

Expressing rates of photosynthesis on a leaf nitrogen basis provided an estimate of leaf photosynthetic N-use efficiency (PNUE, $\mu\text{mol CO}_2 \text{ g}^{-1} \text{ N s}^{-1}$). The two grass groups, regardless of photosynthetic pathway, had roughly double the

PNUE of the legume and forb dicot groups (Table 1). The C_4 grasses also had higher PNUE than the C_3 grasses (Table 1), but this difference was modest compared with the monocot–dicot distinction. In addition, mean leaf conductance to water vapor (g_s) was lower in the C_4 grasses than the remaining C_3 groups. Consequently, measures of instantaneous leaf WUE were about 60% higher among the C_4 grasses than in the other functional groups (Table 1).

Rates of leaf dark respiration differed three- to four-fold among species and increased with increasing leaf N_{mass} and N_{area} (Fig. 1c,d). Slopes of leaf respiration–N regression relationships did not differ from a common slope among the four functional groups on either a leaf mass ($P = 0.22$) or area basis ($P = 0.85$). However, legumes differed from the forb and two

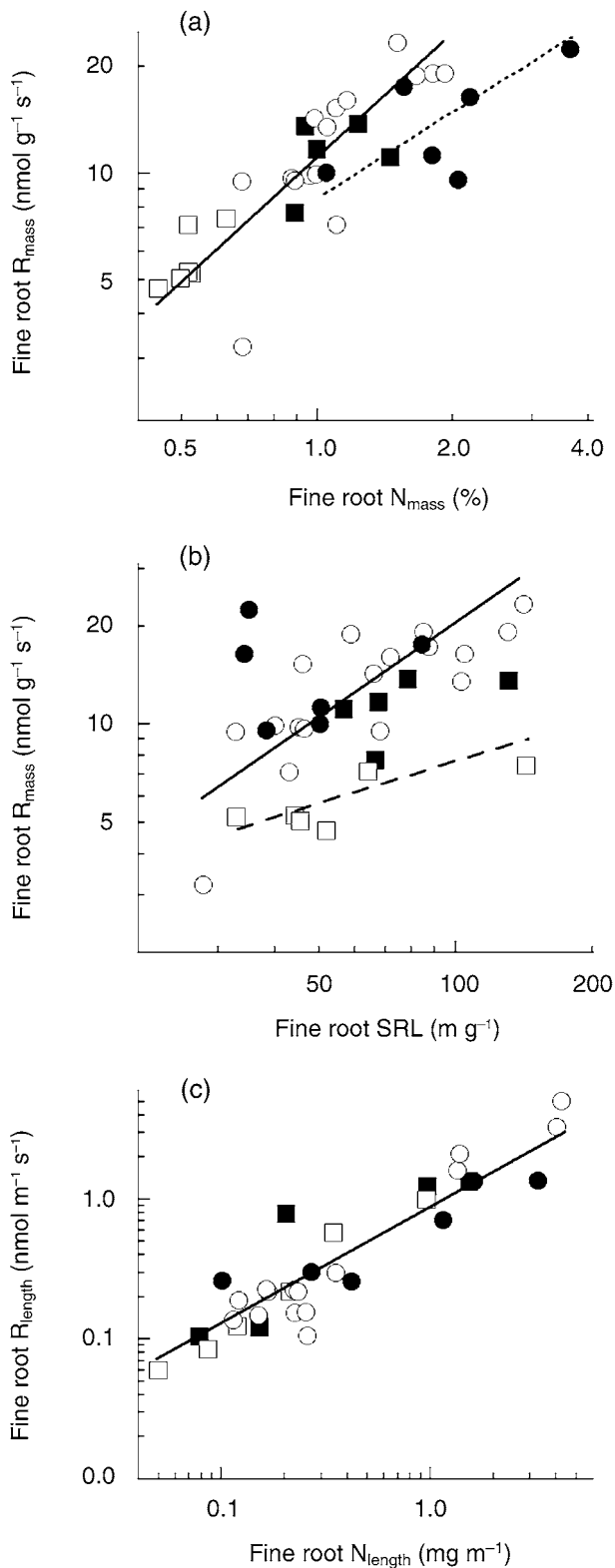


Fig. 2 Rates of fine root respiration in relationship to root traits among functional groups of 39 savannah species (○, forbs; ●, legumes; ■, C₃ grasses; □, C₄ grasses). Type II regression lines illustrate a posteriori group contrasts among species. (a) R_{mass}–N_{mass} correlations for the legume ($r = 0.65$, $P = 0.16$, $n = 6$) and the combined C₃ and C₄ grass and forb groups ($r = 0.85$, $P < 0.001$,

grass groups by exhibiting lower elevations of the leaf R_{mass}–N_{mass} ($P = 0.002$) and R_{area}–N_{area} ($P = 0.003$) relationships, suggesting an a posteriori contrast between the legumes and the nonlegume species (Fig. 1c,d). As a group, the C₄ grasses had lower mean leaf N_{area} and lower rates of leaf respiration than the C₃ grass, forb, and legume groups on a leaf area basis (Table 1). As a result of comparatively lower respiration and higher rates of net photosynthesis, C₄ grasses had roughly doubled ratios of net photosynthesis to respiration (A : R, C-use efficiency) compared with the C₃ grass, forb, and legume groups, which were similar in this regard (Table 1). Unlike the photosynthesis–leaf trait correlations in which C₃ and C₄ grasses differed from forbs and legumes, respiration–leaf trait correlations differed between legumes and the three nonlegume groups.

Comparison of fine root traits among functional groups

Overall, fine root R_{mass} was highest for the legume group and lowest for C₄ grasses compared with the other functional groups, largely paralleling functional group differences in fine root N_{mass} (Table 1). Specific rates of fine root respiration (R_{mass}) increased with increasing fine root N_{mass} (%) among the species (Fig. 2a). The regression slopes did not differ among the four functional groups ($P = 0.53$), but legumes differed from the remaining three groups in terms of the intercept ($P < 0.001$) of the relationships, providing evidence of differing correlations for legumes and nonlegume species (Fig. 2a). Legumes had a lower fine root R_{mass} at a given N_{mass} than the forb and two grass groups, similar to the leaf respiration–N relationships (Fig. 1c,d).

Specific root length (SRL, m root length g⁻¹ root dry mass) and N_{length} (mg N m⁻¹ root length) of fine roots did not differ among the functional groups, although legumes had a lower SRL than the other groups (Table 1). Yet, fine root R_{mass} was positively correlated with SRL among species, which were differentiated by Type II regression relationships of common slope ($P = 0.16$) but lower elevation ($P < 0.001$) for C₄ grasses compared with the C₃ grasses, forbs and legumes. For a given SRL, the C₄ grasses had lower fine root R_{mass} (Fig. 2b). However, across species, fine root respiration rates expressed on the basis of root length (R_{length}, nmol m⁻¹ s⁻¹) were positively correlated with N_{length}. Neither regression slopes ($P = 0.32$) nor intercepts ($P = 0.40$) differed among the four a priori functional groups, providing evidence that all species groups exhibited the same regression relationship (Fig. 2c).

Estimated mean root longevity, based on root turnover calculations, ranged from 32 to 1409 d among the species and differed among species groups (Table 1). Mean root longevity ranged from 136 d in legumes to 791 d in C₄ grasses.

$n = 26$). (b) R_{mass}–specific root length (SRL) correlations for the C₄ grasses ($r = 0.79$, $P = 0.06$, $n = 6$) and the combined C₃ grass, legume and forb groups ($r = 0.53$, $P = 0.003$, $n = 29$). (c) R_{mass}–N_{length} correlation across all species ($r = 0.93$, $P < 0.001$, $n = 32$).

Leaf and fine root longevity relationships

When comparing trait correlations with leaf and root longevity, R_{mass} and N_{mass} of leaves and fine roots declined with increased tissue longevity (Fig. 3a–d). Although Leaf R_{mass} and longevity were weakly correlated for a subset of 14 species for which leaf longevity data were available (Fig. 3a), the trend follows well-established relationships. Neither the regression slopes of the fine root R_{mass} –root longevity relationship ($P = 0.21$) nor the intercepts ($P = 0.39$) differed among functional groups, suggesting a common relationship among species (Fig. 3b). Similarly, slopes of the fine root N_{mass} –root longevity relationship did not differ among the a priori functional groups ($P = 0.66$). The slope of the major axis for the C_4 grasses had a lower intercept compared with the legumes ($P = 0.009$); however, the individual group correlations were not statistically significant and thus the overall linear relationship is shown (Fig. 3d). Although SLA declined with increasing leaf longevity (Fig. 3e), root longevity was unrelated to SRL (Fig. 3f), N_{length} or R_{length} among species ($P \geq 0.28$, not shown). Leaf N_{mass} and SLA were positively correlated among the species ($r = 0.38$, $P = 0.02$, $n = 36$, not shown). By contrast, fine root N_{mass} was unrelated to SRL (not shown). Therefore, for leaves, and not for roots, an increased ratio of area or length per unit dry mass was associated with higher tissue N_{mass} .

Comparing leaf and fine root trait syndromes

Rankings of leaf and fine root N_{mass} were correlated among the species (Spearman rank correlation, Table 2), as was the bivariate trait correlation ($r = 0.77$, $P < 0.001$). Similarly, species rankings of leaf R_{mass} and fine root R_{mass} were positively correlated. Overall, specific rates of respiration of leaves and fine roots were positively correlated with tissue N_{mass} and the regression slopes did not differ among the four a priori functional groups ($P = 0.21$, Fig. 4). However, the intercept was lower in the legumes compared with the other species groups ($P < 0.001$), suggesting differing correlations between legumes and nonlegume species (Fig. 4). By contrast, neither the rankings of SLA and SRL nor leaf N_{area} and fine root N_{length} were related among species (Table 2). Root and leaf longevity were positively correlated ($r = 0.67$, $P = 0.009$), as was the rank correlation (Table 2).

Discussion

Are there parallel leaf and root trait syndromes?

We tested several specific predictions of parallel leaf and fine root trait relationships among species and functional groups of the grassland savannah taxa. First, rates of CO_2 exchange of leaves and fine roots were positively correlated with tissue N, as expected (prediction 1) based on well-documented leaf trait

relationships (Evans, 1989; Ryan, 1991; Reich *et al.*, 1997, 1998a). However, our findings suggest that these relationships also hold among sympatric taxa within a regional flora. A striking pattern was that specific respiration rates of both leaves and fine roots shared a common regression relationship with N, with the exception of the legumes which exhibited somewhat lower respiration rates for a given N concentration. Thus, species not only exhibited concordant rankings in leaf and fine root N concentrations and leaf and fine root specific respiration rates, but also exhibited a common respiration–N regression relationship across combined roots and leaves of C_3 and C_4 grasses and forbs. By contrast, for young seedlings of nine woody plant species during a rapid growth phase, both leaf and fine root specific respiration rates were linearly related to leaf and fine root N_{mass} , respectively, but fine roots had much higher respiration rates than leaves at any given tissue N concentration (Reich *et al.*, 1998b). The relative contribution of growth vs maintenance respiration was likely much higher in the study of young woody plant seedlings than in our current study of older field-grown plants late in the growing season. We are unaware of other direct comparisons of leaf and root respiration–N relationships. Our findings suggest that the respiration–N relationship may be robust across species and tissue type and thus a useful predictor in linking species traits to their effects on ecosystem function (Lavorel & Garnier, 2002; Eviner & Chapin, 2003). In this regard, tissue N contents may be used to model autotrophic respiration (Ryan, 1991), a critical component of net ecosystem exchange and production.

Second, we tested predicted leaf and root trait correlations linking structural traits to tissue longevity (prediction 2). Although root longevity (estimated as the inverse of root turnover) was much greater than that of leaves, species rankings in leaf and root longevity were correlated, suggesting that tissue longevity constitutes a consistent leaf and root trait syndrome among these species. In leaves, respiration rates, N concentration, and SLA decreased with increasing longevity in agreement with well-documented leaf trait syndromes in plants (Reich *et al.*, 1997, 1998a,b, 1999; Garnier *et al.*, 1999; Wright *et al.*, 2001, 2004). Similarly in roots, N concentration and respiration rates declined with increasing longevity, as noted in other studies (Eissenstat *et al.*, 2000), but demonstrated here among a large set of species. We are unaware of other studies that directly compare leaf and root longevity among species grown in a common environment as there are few datasets available to compare leaf and root traits on the same sets of plants. Nitrogen concentration and tissue density of leaves are correlated with those of fine roots among 24 grass species along an altitudinal transect (Craine & Lee, 2003). Our findings suggest that tissue longevity, N concentration and metabolic activity (respiration) traits are linked above and below ground, constituting a consistent leaf–root trait syndrome among this set of sympatric grassland and savannah species, and potentially linking above- and below-ground processes.

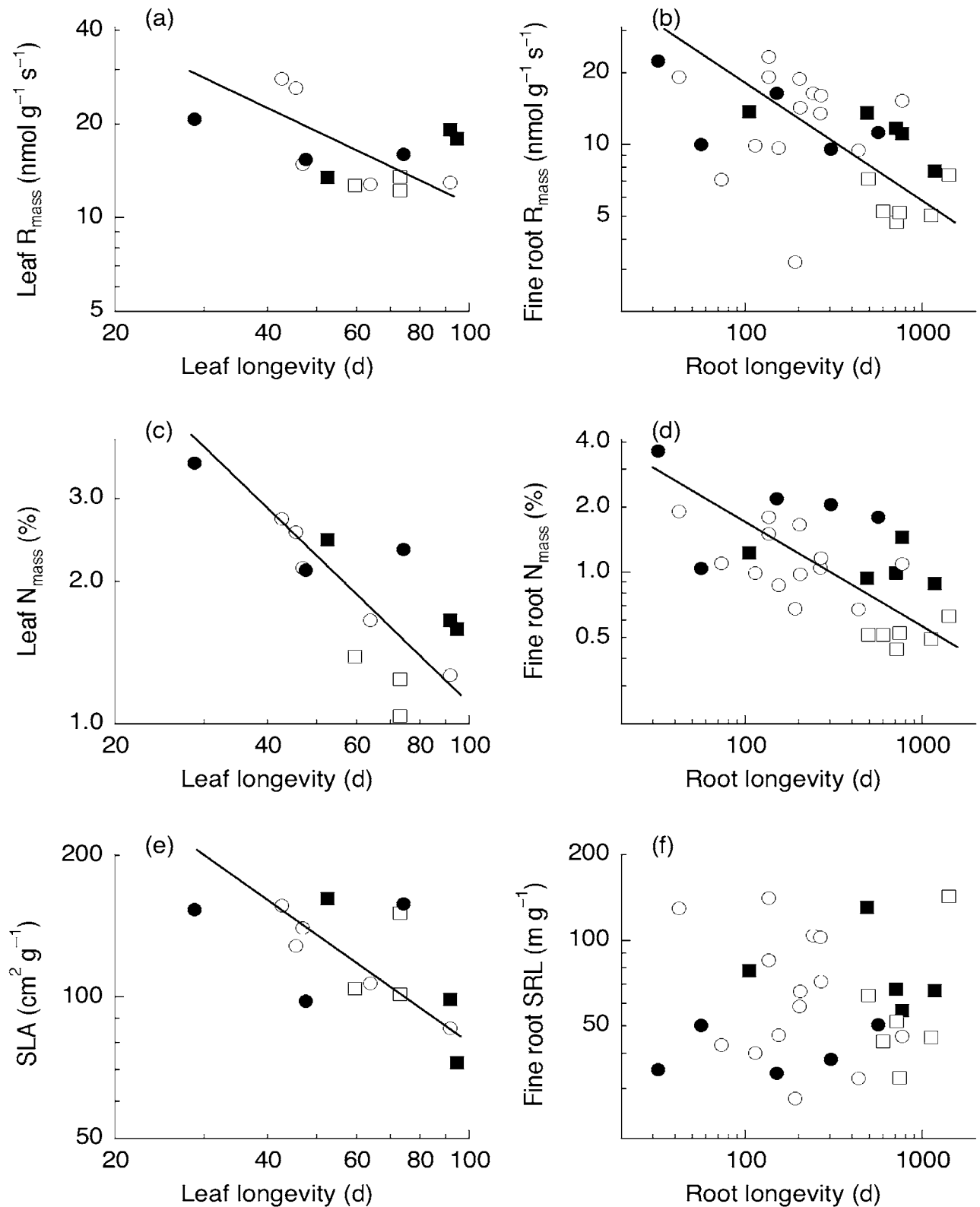


Fig. 3 Comparison of leaf and fine root traits of savannah species in relation to tissue longevity (○, forbs; ●, legumes; ■, C_3 grasses; □, C_4 grasses). Type II regression lines illustrate a posteriori group contrasts among species. Leaf longevity was determined on a subset of the species (Appendix 1; see also Craine *et al.*, 1999). (a) Leaf R_{mass} –leaf longevity ($r = -0.43$, $P = 0.12$, $n = 14$); (b) fine root R_{mass} –root longevity ($r = -0.48$, $P = 0.0076$, $n = 30$); (c) leaf N_{mass} –leaf longevity ($r = -0.77$, $P = 0.0012$, $n = 14$); (d) fine root N_{mass} –root longevity ($r = -0.60$, $P < 0.001$, $n = 29$); (e) specific leaf area (SLA)–leaf longevity ($r = -0.61$, $P = 0.02$, $n = 14$); (f) fine root SRL–root longevity ($r = 0.03$, $P = 0.89$, $n = 30$).

Table 2 Nonparametric rank correlation coefficients for leaf and fine root traits among grassland and savannah species

Leaf–root trait	<i>n</i>	Spearman's ρ	$P > \rho $
Leaf N_{area} –fine root N_{length}	31	–0.13	0.48
Leaf N_{mass} –fine root N_{mass}	31	0.69	< 0.001
Leaf C : N–fine root C : N	31	0.70	< 0.001
Leaf SLA–fine root SRL	33	0.12	0.50
Leaf R_{mass} –fine root R_{mass}	31	0.53	0.002
Leaf R_{area} –fine root R_{length}	31	–0.02	0.90
Leaf longevity–root longevity	14	0.50	0.067

n is number of species; SLA, specific leaf area; SRL, specific root length.

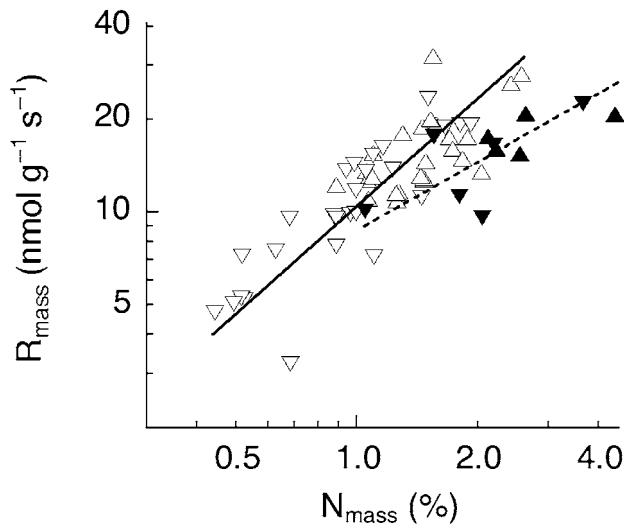


Fig. 4 Specific respiration rates (R_{mass} , $\text{nmol g}^{-1} \text{s}^{-1}$) of leaves (Δ , \blacktriangle) and fine roots (∇ , \blacktriangledown) in relation to nitrogen concentration (N_{mass}) for legumes (closed symbols) and the combined C_3 and C_4 grass and forb groups (open symbols). Type II regression lines are shown for pooled leaf and fine root data for legumes ($r = 0.71$, $P = 0.01$, $n = 11$) and nonlegume species ($r = 0.85$, $P < 0.001$, $n = 51$).

Although our root samples reflect the architecture of the finest root orders of all species, potentially important variation in longevity within root systems (Wells & Eissenstat, 2001; Anderson *et al.*, 2003) may be averaged across when using sequential soil coring to estimate root turnover, and longevity estimates may differ among methods (Matamala *et al.*, 2003). Within a species, the finest roots and lowest root orders tend to have higher N concentrations, higher specific respiration rates, higher SRL and shorter lifespans than higher-order roots (Pregitzer *et al.*, 1997, 1998; Eissenstat *et al.*, 2000; Wells & Eissenstat, 2001; Anderson *et al.*, 2003) and exhibit declining metabolic activity with age (Volder *et al.*, 2005). These within species patterns largely parallel the broad interspecific patterns described in the present study.

Unlike the concordant rankings observed in leaf and root N, rates of respiration, and longevity among species, SLA and

SRL were unrelated, representing a contrast between leaf and root trait syndromes among these grassland and savannah species. In addition, both SRL and SLA failed to differ among the a priori functional groups in agreement with Craine *et al.* (2001) and Díaz *et al.* (2004). Moreover, unlike leaves, SRL was unrelated to root longevity or N concentration. Among grasses, leaf and root tissue density (dry mass to volume ratio) is positively correlated with tissue longevity (Ryser, 1996); however, leaf thickness and not leaf density is related to A_{area} in 14 grass species (Garnier *et al.*, 1999) and among woody plants (Niinemets, 1999). Among species in the present study, SRL and mean fine root diameter were uncorrelated ($r = -0.19$, $P = 0.25$, $n = 36$, not shown), suggesting that differences in SRL among these savannah and grassland species may be related more to differences in tissue density than diameter (Wahl & Ryser, 2000; Craine *et al.*, 2001).

Overall, our findings demonstrate a common leaf and root trait syndrome of N concentration, respiration rate and longevity among a diverse array of sympatric grassland taxa when grown in a common garden. These findings support the concept of key trait syndromes that arise from trade-offs in plant traits and function (Lambers & Poorter, 1992; Aerts & Chapin, 2000; Lavorel & Garnier, 2002; Westoby *et al.*, 2002; Eviner & Chapin, 2003; Díaz *et al.*, 2004). In both leaves and roots, increasing tissue N concentrations were associated with increased rates of metabolic activity and declining tissue longevity, reflecting a tradeoff between rapid acquisition of resources and conservation of resources within protected tissues (Díaz *et al.*, 2004). The strong leaf and root trait relationship with tissue N shown in the present study perhaps reflects the low N availability in this grassland ecosystem (Tilman, 1988; Craine *et al.*, 2002). Low tissue nutrient concentrations and turnover rates are key determinants of high nutrient retention in nutrient-poor environments (Aerts & Chapin, 2000). Finding consistent trait differences among species is one objective in assembling comparative datasets of plant functional types across wide-ranging sites and timescales (Wilson *et al.*, 1999; Garnier *et al.*, 2001). Although mean values of many of the traits differed among the a priori functional groups in this study, the trait values were largely continuously distributed among the species. Thus, our findings demonstrate that trait differences among species may be represented in terms of their bivariate trait relationships that link structural traits to function and, in turn, provide insight into the mechanisms governing species effects on ecosystem processes.

Do a priori functional groups differ in trait scaling relationships?

The regression analysis of trait relationships permitted examination of functional group effects in terms of the slope (scaling relationship) and its elevation. The C_3 and C_4 grass species groups together differed from forbs and legumes in the elevation of the slopes of the leaf photosynthesis–N

relationships but not respiration. As expected (prediction 4) based on well-documented differences between photosynthetic pathways (Sage & Pearcy, 1987; Ehleringer & Monson, 1993), C_4 grasses exhibited higher instantaneous efficiencies of N use (PNUE), water use (WUE) and carbon use ($A : R$) compared with the C_3 grasses, forbs and legumes. Somewhat unexpected was the increased PNUE of the C_3 grasses relative to the forbs and legumes, the similarity of PNUE of C_3 and C_4 grasses and the comparable slope of the leaf photosynthesis–N relationship for C_3 and C_4 grasses despite their different photosynthetic pathways. Thus, for C_3 and C_4 grass species together, the increased efficiencies were manifested in shifts in elevation but not slopes of the regression relationships that, in effect, resulted in greater A_{mass} or A_{area} for a given N_{mass} or N_{area} . In addition, the grasses and C_4 grasses in particular had the lowest leaf N concentrations compared with the other functional groups. These findings suggest that compared with forbs and legumes, the C_3 and C_4 grasses exhibit increased leaf-level resource-use efficiencies, which are reflected in a shift in elevation of the leaf-trait regression slopes.

In a greenhouse study of seedlings of many of the same species, C_4 grasses did have a different elevation of the photosynthesis–N relationship than the C_3 grasses, which followed the same relationship as all other C_3 plants (Reich *et al.*, 2003). Moreover, the young seedlings of the C_3 grasses had similar tissue N_{mass} (%) and lower photosynthetic rates than the C_4 grasses. Perhaps plant maturation under field conditions leads these species in different ontogenetic pathways, with the C_4 grasses exhibiting progressively lower N concentrations and concomitantly, having slightly lowered photosynthetic rates relative to the C_3 grasses. Among woody plant species, trait correlations may differ between juvenile and mature plants (Cornelissen *et al.*, 2003).

The photosynthesis–N relationships for legumes were shifted upward along a common slope that included the forb species (supporting prediction 5). Consequently, legumes had higher leaf and fine root N concentrations, increased CO_2 exchange rates and reduced tissue longevity than forbs. These structural and functional traits in large part contributed to the more rapid N cycling in legumes in monoculture compared with the other functional groups among these grassland species (Craine *et al.*, 2002). By contrast to the common photosynthesis–N relationship among legumes and forbs, both leaf and fine root respiration–tissue N relationships exhibited a lower elevation in legumes compared with the forb or grass species groups. The legumes had lower rates of respiration for a given tissue N concentration compared with the other functional groups. This was somewhat surprising, especially in roots, given the expectation that respiratory carbon costs are higher for roots that support N_2 fixation compared with nitrate assimilation. Maintenance respiration is thought to scale generally with the adenylate demand associated with turnover of protein, maintenance of ion gradients and nutrient assimilation (Amthor, 2000). The respiration–N relationship in legumes

may, in effect, be altered through increased concentrations of organic nitrogen in roots and leaves, reflected in the substantially lower root C : N ratio in legumes compared with the other functional groups ($24 \text{ vs } \geq 38$). Production, storage and transport of organic forms of N in legumes would also presumably differ in underlying respiratory carbon costs on a per unit N basis compared with non- N_2 -fixing forbs. For a given root N concentration, a comparatively lower net CO_2 efflux from roots of legumes may, in part, result from re-fixation of respired CO_2 in roots and root nodules (Atkins *et al.*, 2001).

Conclusions

Concordance in above- and below-ground traits was evident in similar rankings in leaf and root tissue N, respiration rate and longevity among this set of sympatric grassland species. Moreover, the relationships between tissue N and respiration rate exhibited a common regression relationship for leaves and fine roots. Although trait values were continuously distributed among species, a priori functional group differences were manifested in differing elevations of regression slopes of certain gas exchange and structural trait relationships. In this regard, C_3 and C_4 grasses had lower leaf N concentrations but higher photosynthesis rates across a similar range of leaf N compared with forbs and legumes. Similarly, legumes had lower respiration rates for a given tissue N concentration compared with grasses and forbs. Functional shifts in ecophysiological traits reflect key trade-offs in tissue structure and function that resulted in greater tissue level resource-use efficiency among C_3 and C_4 grasses compared with forbs and legumes. Tissue-level traits are associated with competitive abilities and species effects on ecosystem-scale processes in grasslands (Tilman & Wedin, 1991; Craine *et al.*, 2001) and other ecosystems (Grime *et al.*, 1997; Aerts & Chapin, 2000; Lavorel & Garnier, 2002; Westoby *et al.*, 2002; Eviner & Chapin, 2003; Díaz *et al.*, 2004). Understanding leaf and root function in the context of integrated above- and below-ground trait syndromes will aid in predicting plant and ecosystem response to global change factors (Reich *et al.*, 2001b).

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Appendix 1

Mean leaf traits (± 1 SE) of North American grassland savannah species

Species	<i>n</i>	<i>A</i> _{area}	SE	<i>A</i> _{mass}	SE	<i>gs</i>	SE	WUE	SE	PNUE	SE	SLA	SE	<i>N</i> _{mass}	SE	C : N	SE	<i>N</i> _{area}	SE
C₃ grasses																			
<i>Agropyron repens</i>	4	24.3	2.5	396	65	455	98	3.97	0.58	16.3	3.1	162	20	2.46	0.16	18.9	1.3	1.59	0.21
<i>Agrostis scabra</i>	2	31.7	2.5	351	66	513	43	4.49	0.71	25.3	10.5	118	4	1.55	0.38	29.4	5.5	1.43	0.48
<i>Koeleria cristata</i>	4	25.7	3.1	186	23	536	99	3.42	0.35	11.8	1.3	73	2	1.59	0.10	27.6	1.5	2.22	0.15
<i>Poa pratensis</i>	3	30.4	4.2	289	66	747	127	2.52	0.54	17.9	4.9	99	16	1.66	0.07	25.9	1.3	1.82	0.29
<i>Stipa spartea</i>	4	35.1	3.0	240	10	753	129	3.49	0.36	13.3	0.3	71	7	1.81	0.10	25.0	1.2	2.67	0.30
C₄ grasses																			
<i>Andropogon gerardii</i>	4	29.7	3.5	295	32	271	33	6.71	0.56	23.6	0.5	102	8	1.24	0.12	36.3	3.1	1.25	0.13
<i>Bouteloua curtipendula</i>	4	27.3	3.2	235	12	312	46	5.22	0.45	21.0	0.7	95	7	1.12	0.06	38.6	1.4	1.28	0.10
<i>Calamovilfa longifolia</i>	4	31.3	4.3	218	34	387	136	5.68	0.25	12.7	2.4	73	9	1.76	0.11	25.8	1.6	2.71	0.52
<i>Panicum capillare</i>	2	13.9	4.1	220	99	308	165	3.07	0.16	11.7	3.7	151	27	1.78	0.28	24.9	3.4	1.19	0.03
<i>Panicum virgatum</i>	3	31.7	3.1	314	20	304	31	5.75	0.49	19.5	1.8	103	8	1.61	0.04	27.8	0.0	1.65	0.21
<i>Schizachyrium scoparium</i>	4	17.6	2.1	270	45	165	20	5.07	0.30	25.8	3.0	151	6	1.04	0.07	42.1	2.6	0.69	0.04
<i>Sorghastrum nutans</i>	4	29.8	1.5	307	20	251	28	6.75	0.57	22.1	1.2	104	6	1.39	0.08	32.1	1.7	1.38	0.11
Forbs																			
<i>Achillea millefolium</i>	2	20.3	3.2	276	50	542	52	3.76	0.36	10.7	0.4	130	10	2.56	0.36	17.2	2.7	2.01	0.11
<i>Agastache foeniculum</i>	2	16.8	2.5	179	8	449	53	3.42	0.62	6.6	0.6	108	12	2.73	0.37	18.0	2.8	2.61	0.64
<i>Ambrosia artemisiifolia</i>	4	27.4	4.3	351	54	1035	326	3.63	0.42	13.9	0.8	129	2	2.55	0.44	18.2	3.0	1.99	0.35
<i>Anemone cylindrica</i>	4	15.4	0.8	163	7	390	27	3.30	0.10	9.9	0.4	107	4	1.66	0.06	27.1	0.7	1.56	0.05
<i>Asclepias syriaca</i>	3	18.1	2.0	284	35	455	115	4.39	0.54	10.5	1.5	157	2	2.72	0.09	14.8	0.9	1.76	0.08
<i>Asclepias tuberosa</i>	3	11.3	1.4	137	12	188	29	3.32	0.24	6.6	0.9	121	4	2.13	0.25	21.9	2.3	1.76	0.19
<i>Asclepias verticillata</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Aster azureus</i>	4	13.6	1.5	135	21	460	69	3.16	0.14	8.4	1.1	98	6	1.60	0.11	25.1	1.3	1.67	0.12
<i>Aster ericoides</i>	3	20.3	1.3	156	10	355	87	4.16	0.31	8.7	0.4	78	8	1.78	0.06	23.5	0.9	2.33	0.15
<i>Aster novae-angliae</i>	3	15.1	1.4	228	12	314	27	3.19	0.18	9.5	0.4	152	6	2.41	0.21	17.7	1.5	1.61	0.20
<i>Coreopsis palmata</i>	4	10.8	2.3	70	13	255	27	2.32	0.33	6.0	1.0	66	3	1.17	0.07	37.2	2.3	1.77	0.14
<i>Liatris aspera</i>	4	15.6	1.9	119	13	460	97	2.81	0.11	7.5	0.4	78	3	1.63	0.25	28.1	4.2	2.12	0.35
<i>Penstemon grandiflorus</i>	4	22.6	1.0	237	15	720	71	3.87	0.15	11.3	0.7	105	5	2.11	0.11	22.2	1.2	2.03	0.09
<i>Potentilla arguta</i>	4	16.2	1.1	170	17	409	34	3.42	0.17	9.0	0.4	105	11	1.89	0.18	22.3	1.2	1.82	0.08
<i>Rudbeckia serotina</i>	3	20.4	0.4	287	5	619	43	3.54	0.11	13.5	1.0	140	5	2.14	0.16	17.0	1.4	1.53	0.12
<i>Solidago nemoralis</i>	4	17.1	1.2	141	12	480	78	3.37	0.19	8.9	0.5	82	2	1.58	0.11	26.2	2.4	1.94	0.13
<i>Solidago rigida</i>	3	14.9	0.9	128	12	511	66	3.12	0.31	10.1	0.7	86	3	1.27	0.05	34.8	1.4	1.49	0.03
<i>Solidago speciosa</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Legumes																			
<i>Astragalus canadensis</i>	3	25.8	5.1	269	49	734	191	3.68	0.27	6.4	0.9	106	7	4.13	0.25	10.5	0.6	3.95	0.40
<i>Desmodium canadense</i>	4	12.1	1.2	191	21	257	40	2.82	0.15	8.1	0.7	158	2	2.34	0.07	20.7	0.8	1.49	0.04
<i>Lespedeza capitata</i>	4	15.2	1.5	149	15	333	27	3.41	0.36	7.0	0.5	98	1	2.11	0.10	21.8	1.0	2.16	0.09
<i>Lupinus perennis</i>	4	20.9	1.7	318	28	834	146	3.51	0.17	8.9	0.7	154	10	3.57	0.14	12.0	0.4	2.39	0.22
<i>Petalostemon candidum</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Petalostemon purpureum</i>	4	36.6	7.8	238	23	1209	364	3.30	0.17	9.8	0.8	75	16	2.43	0.03	18.2	0.2	3.63	0.58
<i>Petalostemon villosum</i>	4	30.3	3.5	267	20	866	118	3.44	0.05	10.2	0.9	90	6	2.64	0.08	16.8	0.6	3.02	0.25
Woody plants																			
<i>Corylus americana</i>	4	15.6	0.6	149	12	458	37	3.22	0.17	7.5	0.8	95	6	2.01	0.09	23.3	1.0	2.17	0.16
<i>Quercus macrocarpa</i>	3	15.9	0.9	167	8	286	6	3.66	0.33	7.1	0.4	106	6	2.36	0.08	20.3	0.8	2.26	0.20

Appendix 1 continued

Species	<i>n</i>	R_{area}	SE	N_{area}	SE	R_{mass}	SE	N_{mass}	SE	<i>n</i>	Longevity	SE
C₃ grasses												
<i>Agropyron repens</i>	3	0.86	0.05	1.29	0.12	13.5	0.6	2.04	0.12	4	52	1
<i>Agrostis scabra</i>	3	1.40	0.11	0.79*	0.08	32.0	7.7	1.55*	0.38	–	–	–
<i>Koeleria cristata</i>	4	3.87	0.22	2.83	0.22	18.0	0.9	1.30	0.02	4	94	6
<i>Poa pratensis</i>	3	3.47	0.44	2.84	0.28	19.2	0.7	1.58	0.05	4	92	3
<i>Stipa spartea</i>	4	2.75	0.45	3.16	0.49	10.9	0.6	1.26	0.07	–	–	–
C₄ grasses												
<i>Andropogon gerardii</i>	4	0.92	0.05	0.73	0.07	13.6	0.8	1.06	0.07	4	73	1
<i>Bouteloua curtipendula</i>	4	1.17	0.15	0.81	0.02	15.5	1.1	1.10	0.07	–	–	–
<i>Calamovilfa longifolia</i>	4	1.19	0.11	1.43	0.18	12.7	2.1	1.47	0.13	–	–	–
<i>Panicum capillare</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Panicum virgatum</i>	4	0.76	0.02	0.84	0.03	11.6	0.3	1.27	0.05	–	–	–
<i>Schizachyrium scoparium</i>	4	1.02	0.16	0.77	0.19	12.2	0.9	0.89	0.08	4	73	8
<i>Sorghastrum nutans</i>	4	1.05	0.05	0.88	0.07	12.7	0.3	1.06	0.05	4	60	4
Forbs												
<i>Achillea millefolium</i>	4	2.57	0.29	2.51	0.09	17.5	2.2	1.70	0.01	–	–	–
<i>Agastache foeniculum</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Ambrosia artemisiifolia</i>	4	1.55	0.10	1.44	0.15	26.1	2.9	2.41	0.24	4	46	2
<i>Anemone cylindrica</i>	4	1.38	0.15	1.59	0.06	12.8	1.6	1.47	0.03	4	64	4
<i>Asclepias syriaca</i>	4	1.51	0.15	1.39	0.18	28.1	3.2	2.57	0.33	4	43	2
<i>Asclepias tuberosa</i>	4	1.31	0.09	1.00	0.11	18.9	2.0	1.45	0.20	–	–	–
<i>Asclepias verticillata</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Aster azureus</i>	4	1.31	0.22	1.39	0.14	17.4	2.1	1.88	0.14	–	–	–
<i>Aster ericoides</i>	4	1.25	0.25	0.94	0.07	20.0	3.3	1.52	0.05	–	–	–
<i>Aster novae-angliae</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Coreopsis palmata</i>	4	1.08	0.15	1.15	0.22	11.5	1.4	1.25	0.25	–	–	–
<i>Liatris aspera</i>	4	1.16	0.17	1.11	0.21	11.1	1.7	1.07	0.20	–	–	–
<i>Penstemon grandiflorus</i>	4	1.68	0.14	1.82	0.16	16.0	0.9	1.73	0.07	–	–	–
<i>Potentilla arguta</i>	4	0.95	0.04	1.05	0.05	13.1	0.5	1.44	0.06	–	–	–
<i>Rudbeckia serotina</i>	3	1.22	0.12	1.53	0.16	14.9	2.0	1.83	0.13	3	47	3
<i>Solidago nemoralis</i>	4	1.35	0.11	1.39	0.14	14.6	1.1	1.48	0.04	–	–	–
<i>Solidago rigida</i>	4	1.51	0.21	1.34	0.33	13.0	1.1	1.09	0.07	4	92	2
<i>Solidago speciosa</i>	–	–	–	–	–	–	–	–	–	–	–	–
Legumes												
<i>Astragalus canadensis</i>	4	1.24	0.19	2.64	0.41	20.8	2.1	4.39	0.38	–	–	–
<i>Desmodium canadense</i>	4	0.74	0.11	1.03	0.17	16.0	1.2	2.22	0.19	4	74	4
<i>Lespedeza capitata</i>	4	1.22	0.11	2.00	0.12	15.4	1.2	2.55	0.13	4	48	1
<i>Lupinus perennis</i>	4	1.92	0.20	2.44	0.23	20.8	1.8	2.63	0.11	3	29	6
<i>Petalostemon candidum</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Petalostemon purpureum</i>	–	–	–	–	–	–	–	–	–	–	–	–
<i>Petalostemon villosus</i>	4	2.20	0.16	2.68	0.30	17.6	1.8	2.12	0.22	–	–	–
Woody plants												
<i>Corylus americana</i>	4	0.81	0.07	1.12	0.14	10.1	0.8	1.36	0.05	–	–	–
<i>Quercus macrocarpa</i>	3	1.68	0.09	2.24	0.20	17.7	1.1	2.36	0.08	–	–	–

The number of samples (*n*) indicated for each species applies to all photosynthesis and respiration traits, except where indicated (**n* = 2). No data are indicated as dashes. Units for traits are: A_{area} , area-based photosynthesis, $\mu\text{mol m}^{-2} \text{s}^{-1}$; A_{mass} , mass-based photosynthesis, $\text{nmol g}^{-1} \text{s}^{-1}$; *gs*, stomatal conductance, $\text{mmol m}^{-2} \text{s}^{-1}$; WUE, water-use efficiency, $\text{mmol CO}_2 \text{ mol}^{-1} \text{H}_2\text{O}$; PNUE, photosynthetic N-use efficiency, $\mu\text{mol CO}_2 \text{ g}^{-1} \text{N s}^{-1}$; SLA, specific leaf area, $\text{cm}^2 \text{g}^{-1}$; N_{mass} , %; C : N, carbon–nitrogen ratio; N_{area} , g m^{-2} ; R_{area} , area-based respiration, $\mu\text{mol m}^{-2} \text{s}^{-1}$; R_{mass} , mass-based respiration, $\text{nmol g}^{-1} \text{s}^{-1}$; leaf longevity, d. Note that leaf N-values are shown separately for both photosynthesis and respiration samples. Leaf longevity data are from Craine *et al.* (1999).

Appendix 2

Mean root traits (± 1 SE) of North American grassland savannah species

Species	<i>n</i>	<i>R</i> _{mass}	SE	<i>N</i> _{mass}	SE	<i>R</i> _{length}	SE	<i>N</i> _{length}	SE	SRL	SE	C:N	SE	<i>n</i>	Longevity	SE
C₃ grasses																
<i>Agropyron repens</i>	4	11.1	1.1	1.45	0.18	0.79	0.63	0.20	0.05	57	19	31.4	4.4	4	761	538
<i>Agrostis scabra</i>	4	13.7	2.0	1.23	0.16	1.35	1.23	1.53	1.43	78	37	36.0	4.7	2	105	20
<i>Koeleria cristata</i>	4	13.6	2.3	0.94	0.01	0.10	0.01	0.08	0.01	131	22	46.6	2.7	4	484	83
<i>Poa pratensis</i>	3	11.7	1.1	1.00	0.15	1.24	0.84	0.97	0.59	68	57	35.0	2.8	3	709	148
<i>Stipa spartea</i>	4	7.7	0.8	0.89	0.05	0.12	0.01	0.15	0.04	67	11	44.7	1.0	4	1173	696
C₄ grasses																
<i>Andropogon gerardii</i>	4	4.7	0.6	0.44	0.02	0.08	0.02	0.09	0.02	52	5	85.1	11.1	4	710	107
<i>Bouteloua curtipendula</i>	4	7.2	1.2	0.52	0.05	0.58	0.51	0.34	0.29	64	21	85.4	9.3	4	494	108
<i>Calamovilfa longifolia</i>	4	5.2	0.7	0.52	0.03	0.22	0.10	0.21	0.07	33	9	89.8	7.4	4	740	584
<i>Panicum capillare</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Panicum virgatum</i>	3	5.3	0.8	0.52	0.06	0.12	0.03	0.12	0.01	44	5	85.3	17.4	4	600	140
<i>Schizachyrium scoparium</i>	4	5.0	0.6	0.49	0.05	1.00	0.55	0.95	0.52	45	25	83.0	10.1	4	1118	518
<i>Sorghastrum nutans</i>	3	7.4	0.4	0.63	0.02	0.06	0.02	0.05	0.01	143	33	61.0	7.6	4	1409	492
Forbs																
<i>Achillea millefolium</i>	4	16.5	1.3	–	–	0.19	0.05	–	–	104	23	–	–	2	241	45
<i>Agastache foeniculum</i>	3	17.2	0.4	–	–	0.20	0.01	–	–	87	5	–	–	–	–	–
<i>Ambrosia artemisiifolia</i>	4	23.3	3.1	1.51	0.15	0.19	0.06	0.12	0.03	141	26	30.9	2.9	4	135	80
<i>Anemone cylindrica</i>	4	15.3	1.1	1.10	0.14	1.60	1.34	1.34	1.17	46	15	39.3	6.7	4	768	481
<i>Asclepias syriaca</i>	3	19.2	1.1	1.80	0.11	0.30	0.10	0.35	0.05	85	33	25.3	2.0	4	135	61
<i>Asclepias tuberosa</i>	4	18.9	1.1	1.66	0.11	5.03	4.79	4.25	4.03	59	20	28.2	1.8	4	201	39
<i>Asclepias verticillata</i>	2	9.8	2.1	0.96	0.18	0.22	0.02	0.22	0.03	45	14	47.1	7.6	–	–	–
<i>Aster azureus</i>	4	14.3	2.1	0.98	0.07	0.22	0.03	0.17	0.01	66	5	43.1	3.4	3	203	41
<i>Aster ericoides</i>	2	7.1	4.5	1.10	*	0.15	0.08	0.22	*	43	6	40.0	*	2	73	8
<i>Aster novae-angliae</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Coreopsis palmata</i>	4	9.9	1.9	0.99	0.14	3.27	3.10	4.01	3.82	40	20	47.1	7.4	4	113	28
<i>Liatris aspera</i>	4	13.5	0.9	1.05	*	0.14	0.02	0.11	*	103	10	40.1	*	2	265	126
<i>Penstemon grandiflorus</i>	4	9.7	2.3	0.88	0.11	0.22	0.03	0.23	0.06	46	12	51.6	8.1	4	153	66
<i>Potentilla arguta</i>	2	3.2	2.1	0.68	0.02	0.11	0.05	0.26	0.06	28	5	69.6	2.5	2	191	72
<i>Rudbeckia serotina</i>	3	19.2	6.1	1.92	0.24	0.15	0.05	0.15	0.03	130	7	23.3	2.6	3	42	9
<i>Solidago nemoralis</i>	4	16.1	0.4	1.16	0.08	0.23	0.01	0.16	0.01	72	5	40.3	2.9	4	267	69
<i>Solidago rigida</i>	4	9.5	1.1	0.68	0.09	2.11	1.13	1.38	0.77	33	18	66.4	5.9	4	433	74
<i>Solidago speciosa</i>	3	9.5	1.7	0.89	*	0.16	0.04	0.25	*	68	17	53.0	*	–	–	–
Legumes																
<i>Astragalus canadensis</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Desmodium canadense</i>	4	16.4	1.8	2.19	0.08	1.34	0.75	1.61	0.82	34	15	20.7	0.5	4	150	37
<i>Lepedeza capitata</i>	4	9.6	1.4	2.05	0.19	1.36	1.08	3.28	2.66	38	21	24.1	2.2	4	302	111
<i>Lupinus perennis</i>	3	22.4	3.5	3.65	0.74	0.72	0.23	1.15	0.38	35	6	14.1	3.8	3	32	14
<i>Petalostemon candidum</i>	3	17.6	3.8	1.55	0.02	0.30	0.11	0.27	0.15	84	48	31.7	2.3	–	–	–
<i>Petalostemon purpureum</i>	4	11.3	2.6	1.80	0.14	0.26	0.05	0.42	0.12	51	20	27.1	2.1	4	562	133
<i>Petalostemon villosum</i>	3	10.0	3.2	1.05	*	0.26	0.07	0.10	*	50	27	44.0	*	2	56	0
Woody plants																
<i>Corylus americana</i>	4	6.8	0.8	1.12	0.13	0.61	0.49	0.88	0.67	40	12	39.1	6.9	4	430	179
<i>Quercus macrocarpa</i>	4	6.7	0.2	0.99	0.04	0.13	0.02	0.20	0.02	52	7	43.7	3.2	4	360	153

The number of individual plots (*n*) applies to all traits of each species, except where indicated (**n* = 1). No data are indicated by dashes. Units for traits are: *R*_{mass}, mass-based respiration, nmol g⁻¹ s⁻¹; *N*_{mass}, %; *R*_{length}, length-based respiration, nmol m⁻¹ s⁻¹; *N*_{length}, mg m⁻¹; SRL, specific root length, m g⁻¹; C : N, carbon–nitrogen ratio; longevity, d.