

Title: Belowground biomass response to nutrient enrichment depends on light-limitation across globally distributed grasslands

Running title: Root response to nutrients depends on light

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Abstract:

Anthropogenic activities are increasing nutrient inputs to ecosystems worldwide, with consequences for global carbon and nutrient cycles. Recent meta-analyses show that aboveground primary production is often co-limited by multiple nutrients, however little is known about how root production responds to changes in nutrient availability. At twenty-nine grassland sites on four continents, we quantified shallow root biomass responses to nitrogen (N), phosphorus (P) and potassium plus micronutrient enrichment and compared below- and aboveground responses. We hypothesized that optimal allocation theory would predict context dependence in root biomass responses to nutrient enrichment, given variation among sites in the resources limiting to plant growth (specifically light versus nutrients). Consistent with the predictions of optimal allocation theory, the *proportion* of total biomass belowground declined with N or P addition, due to increased biomass aboveground (for N and P) and decreased biomass belowground (N, particularly in sites with low canopy light penetration). *Absolute* root biomass increased with N addition where light was abundant at the soil surface, but declined in sites where the grassland canopy intercepted a large proportion of incoming light. These results demonstrate that belowground responses to changes in resource supply can differ strongly from aboveground responses, which could significantly modify predictions of future rates of nutrient cycling and carbon sequestration. Our results also highlight how optimal allocation theory developed for individual plants may help predict belowground biomass responses to nutrient enrichment at the ecosystem scale across wide climatic and environmental gradients.

Keywords: belowground biomass, fertilization, nitrogen, Nutrient Network, optimal allocation, phosphorus, roots

Manuscript highlights

- Both N and P addition reduced the proportion of total biomass in shallow roots
- N addition decreased roots most where there was low light beneath the canopy
- These results show plant allocation to roots vs shoots depends on limiting resources

Introduction

Grasslands and other herbaceous plant communities cover 20 - 40% of the terrestrial land surface (Leith, 1978), provide critical ecosystem services such as rangeland forage, and play an important role in the global carbon (C) cycle, with grassland soils containing up to 30% of the world's soil C (Anderson, 1991). Across the world's biomes, grasslands have some of the highest fractions of total biomass as roots (Poorter and others, 2012). There is large variation in partitioning of biomass and productivity across sites, however; for instance, Sims and Singh (1978) estimated between 24% and 87% of net primary production was belowground across ten North American grassland sites, and Hui and Jackson (2006) found similar levels of variation across grasslands worldwide (40-86%). This variation in the proportion of growth allocated belowground is important not only for regional estimates of primary production and C sequestration (Scurlock & Hall, 1998, Mokany and others, 2006) but also for understanding ecosystem responses to global change (Friedlingstein and others, 1999, Jackson and others, 2000).

Anthropogenic activities are increasing global nutrient availability, with effects on net primary production (Elser and others, 2007), plant allocation above- and belowground (Poorter

and others, 2012), and net ecosystem C balance (Mack and others, 2004). Fossil fuel combustion and agricultural intensification have doubled annual nitrogen (N) inputs into terrestrial ecosystems and have increased phosphorous (P) inputs more than fourfold (Falkowski and others, 2000). Shifts in C balance resulting from nutrient enrichment could depend on allocation above- versus belowground (Friedlingstein and others, 1999, Smithwick and others, 2014). High proportional allocation to root biomass increases the potential for ecosystem C sequestration because root-derived C is more likely to enter long-lasting soil organic C pools than C from aboveground tissues (Rasse and others, 2005), and roots can promote physical stabilization of soil organic matter via soil aggregate formation (Jastrow, 1996).

Optimal allocation theory, developed for individual plants, predicts that plant allocation belowground should depend on the identity of the most growth-limiting resource (Thornley, 1972, Bloom and others, 1985, Wilson, 1988). Specifically, proportional root allocation should decline when plant growth is limited by aboveground resources (e.g. light) and increase when plant growth is limited by belowground resources such as water and nutrients (Gleeson & Tilman, 1992). A recent meta-analysis summarizing the results of nearly 800 experimental manipulations of resource availability found strong support for optimal allocation theory; the proportion of biomass allocated to roots was higher under water or nutrient limitation, and lower under light limitation (Poorter and others, 2012). Most of these studies were focused at the species level, and if there is significant interspecific variation in allocation responses to environmental change (Craine and others, 2003), then the predictions of optimal allocation theory might not explain community-level variation in root allocation. However, patterns observed across environmental gradients also support the hypothesis that community-level allocation to roots declines as belowground resources increase. For instance, proportional root

allocation in grasslands is inversely correlated with mean annual precipitation and is highest in xeric regions where water is the predominant factor limiting plant growth (Hui & Jackson, 2006, Mokany and others, 2006).

While many studies have evaluated how allocation responds to variation in individual environmental factors, few have evaluated how allocation responds when multiple factors change simultaneously. This is a critical knowledge gap because primary production is frequently co-limited by multiple resources as opposed to single resources (Hooper & Johnson, 1999, Elser and others, 2007, Harpole and others, 2011, Fay and others, 2015) and ecosystem responses to multiple aspects of global change often deviate from predictions based on single factor experiments (Norby & Luo, 2004). The importance of community-scale biomass partitioning for understanding regional and global C budgets (Scurlock & Hall, 1998, Jackson and others, 2000, Smithwick and others, 2014) underscores the need for a framework that effectively predicts both the absolute quantities as well as proportion of biomass above- versus belowground, in response to global changes such as eutrophication. Further, while regional and global estimates of total net primary production generally rely on modeled estimates of root allocation (Friedlingstein and others, 1999, Woodward & Osborne, 2000, Gill and others, 2002, Michaletz and others, 2014), these estimates are rarely validated because continental and global relationships between biomass allocation and climate and soil variables remain poorly characterized (Smithwick and others, 2014).

To evaluate how community-scale root biomass production and allocation respond to local experimental nutrient enrichment across environmental gradients, we leveraged a global network of grassland sites where nutrient availability was manipulated using common protocols, the Nutrient Network (Borer and others, 2014a). By using this experimental network that spans a

broad range of climates and grassland soils, we characterized both global trends in allocation patterns in response to eutrophication as well as regional contingencies in this response. Prior efforts from this network have demonstrated that aboveground primary production across these sites is frequently co-limited by multiple nutrients (Fay and others, 2015), and that the impact of soil nutrients on species richness depends on light limitation (Borer and others, 2014b); however belowground biomass responses to multiple nutrient enrichment have not yet been evaluated.

Here we refer to “biomass allocation” as reflecting static pools of biomass, distinct from efforts aimed at identifying the dynamic partitioning of new photosynthates (*sensu* Poorter and others, 2012, also discussed in Reich 2002, and alternatively referred to as "biomass distribution in Reich and others, 2014). We focus on root responses near the soil surface (top 10 cm), because 80-90% of root biomass in grasslands is concentrated near the surface, in the top 30 cm (Jackson and others, 1996). Surface roots play a disproportionate role in nutrient acquisition because the greatest concentrations of N, P, and K are found high in soil profiles (Sposito, 1989, Jobbagy & Jackson, 2001), and both experimental and anthropogenic nutrient inputs occur at the soil surface. Furthermore, grasslands store the greatest proportion of soil C near the soil surface (Jobbagy & Jackson, 2000), contributing to greater microbial biomass (Blume and others, 2002, Eilers and others, 2012) and fueling greater microbial activity in surface versus subsurface soils. Hence, C pools with potential for high turnover and release to the atmosphere are likely most sensitive to fertilization at shallow depths. Accordingly, a meta-analysis of 257 studies across a variety of ecosystems found that N addition tended to reduce carbon stocks in shallow but not deep soil layers, correlated with a decline in root allocation in shallow soil layers (Lu and others 2011).

Across the Nutrient Network sites, we hypothesized that 1) *absolute* belowground biomass would respond positively and synergistically to the addition of multiple nutrients, consistent with patterns of multiple nutrient limitation of aboveground plant biomass observed across these sites (Fay and others, 2015). We expected that *relative* biomass allocation to roots (root biomass as a proportion of total biomass) would 2) decline with increasing light limitation (associated with low light availability below the grassland canopy, e.g. Gleeson & Tilman, 1992), 3) increase with increasing water limitation (in more arid sites, e.g. Hui & Jackson, 2006), and 4) decrease with nutrient enrichment particularly when multiple nutrients are added together (Yuan & Chen, 2012), as predicted by optimal allocation theory. Finally, we expected that 5) there might be statistical interactions among the factors predicting belowground biomass and allocation, due to the importance of environmental context in determining community responses to resource enrichment (Cleland & Harpole, 2010). Specifically, we expected that root biomass responses to nutrient enrichment would be constrained in sites where plant growth was limited by water (more arid sites), and that root biomass might even decline with nutrient addition at sites where there is strong competition for light, in favor of increased allocation to aboveground biomass.

Methods

This research was conducted within the Nutrient Network, a globally replicated network of sites manipulating nutrients (nitrogen – N, phosphorus – P, and potassium plus micronutrients– K_{μ}) and vertebrate herbivore exclusion (Borer and others, 2014a). The micronutrients were only added in year one, and included Ca, Mg, B, Cu, Fe, Mn, Mo, and Zn. For the effort described here, we analyzed data from 29 sites where the experimental treatments

had been applied for 3-5 years. At most sites plots were arranged in three blocks, each block containing the ten focal treatments: control unfenced & unfertilized, +N, +P, + K_μ, +NP, +NK_μ, + PK_μ, +NPK_μ, fenced & unfertilized, and fenced +NPK_μ. At each site, 30 plots (each 5 x 5 m) were sampled, except where noted in Supplementary Material, resulting in 874 plots sampled in total. For this manuscript, only data from the factorial nutrient addition treatments were analyzed (i.e. all fenced plots were excluded). The sites span four continents and, more importantly, wide environmental gradients in mean annual precipitation (274-2314 mm/year, summarized in Table S1). All sites are dominated by herbaceous vegetation but vary in the relative abundance of graminoids versus other functional types (Table S1). Vegetation types included, for instance, alpine meadows, prairie, pasture, savannah, and steppe, but we refer to these sites as grasslands for brevity.

Above- and belowground biomass were collected at the time of peak biomass in either 2011 (Northern Hemisphere) or early 2012 (Southern Hemisphere). According to Nutrient Network protocols (Borer and others, 2014a), aboveground biomass was destructively harvested in two 1 m x 0.1 m strips per experimental plot, sorted to separate the current year's production from litter, dried to constant mass, and weighed to the nearest 0.01 g. Immediately following the aboveground biomass harvest, five soil cores were taken to a depth of 10 cm in the harvest area. Root cores were collected using standard corers or sharpened PVC tubes with an inside diameter of 2.5 cm, for a total ground area of 24.5 cm². Exceptions to this protocol are noted in the Supplementary Material. All cores from each plot were combined in one sealed plastic bag, packed into coolers with cold packs, and sent via next day air to a central processing lab (USGS at Corvallis, Oregon, USA).

Total soil weights for each bulked sample were recorded, and a homogenized subsample comprising 1/5th of the total soil weight (20-150 grams) was weighed and sent to the University of California, San Diego for root extraction. Soil sub-samples were kept cool with icepacks throughout transit and refrigerated while in the lab until processing.

Live root biomass was estimated using a modification of the standard Long Term Ecological Research method for measuring standing fine root biomass in soil cores (Bledsoe and others, 1999). Soil subsamples were immersed in water; live roots were light in color and floated to the surface, while dead roots and organic matter were darker in color. Live roots were extracted with tweezers, rinsed to remove residual mineral soil, dried to a constant mass, and weighed to the nearest 0.001 g. Above- and belowground (to 10 cm) biomass estimates were expressed on a common scale (g/m²). Our key metric of proportional biomass allocation is the root mass fraction (RMF) following the method in Reich (2002). The RMF was calculated as the root biomass divided by the sum of root and aboveground live biomass on an equal area basis. Detailed methods are provided in Supplementary Material.

Our estimates of belowground biomass are based on one-time destructive harvests at the time of peak biomass; while this reflects a reasonable estimate of aboveground production, this is an underestimate of belowground production (Gill and others, 2002). Hence, we proceed with the caveat that this effort documents comparable patterns of shallow root biomass and allocation across plots and sites, but additional estimates of root turnover and deep root biomass would be needed to estimate total belowground production and allocation of net primary production. However, a survey of published and unpublished data on the distribution of root biomass at our sites shows that the majority of root biomass is captured by shallow root sampling efforts, such as ours (Table S2).

We assembled site-level metrics of water limitation and light availability at the soil surface, for inclusion as co-variables in our analyses. We extracted measures of the Global Aridity Index (CGIAR-CSI Global-Aridity and Global-PET Database, Zomer and others, 2008), based on data from the WorldClim database (Hijmans and others, 2005). Hereafter referred to as GAI, this index is calculated as mean annual precipitation divided by mean annual potential evapotranspiration, and hence accounts for both precipitation inputs and soil water loss due to high temperature, solar radiation, and wind. Low GAI indicates more arid sites with low soil water availability (low inputs and/or high rates of water loss). Using a linear multi-sensor light meter, we measured the proportional decrease in photosynthetically active radiation (PAR) from above the canopy to below the canopy as a proxy of light limitation. The proportion of PAR reaching the soil surface was calculated as the average of two PAR measurements taken at the soil surface perpendicular to one another in a 1 m² undisturbed subplot, divided by PAR measured above the canopy immediately afterwards, under full light conditions. We averaged the proportion of PAR reaching the soil surface across all years of measurement in the control plots from each site (unfenced, unfertilized) as a *site-level metric of the degree of light-limitation*. This metric is abbreviated hereafter as "light". Resource depletion is the key mechanism by which plants compete with neighbors (Goldberg 1990), and hence we use "light" as a proxy for community-level light depletion.

The fractions of the community comprised by graminoids and by perennial species were calculated as two additional site-level metrics of species composition, based on visual percent cover estimates collected in 1 x 1 m plots adjacent to the biomass harvests described above. These values were calculated only from control plots at each site (unfenced, unfertilized).

Statistical analysis

Data analysis was performed in R version 3.01 (R Core Team, 2013). Pearson correlations were performed to evaluate associations among site-level parameters: aridity, light, live aboveground biomass (AGB), live belowground root biomass to 10 cm depth (BGB), RMF, graminoid fraction, and perennial fraction. Each data point in the correlation analysis was a site-level mean for each parameter, calculated for the control plots only.

Examination of the BGB data with Quantile-Quantile plots showed these data were lognormally distributed (Figure S2), as is common with ecological datasets involving measures of growth (Bolker, 2008), and hence the BGB data were natural-log transformed prior to analysis. The RMF data were continuous proportions bounded by 0 and 1 and, as expected, initial inspection with Quantile-Quantile plots indicated the data were non-normally distributed (Figure S3). Following the recommendation of Warton and Hui (2011) the RMF data were logit transformed. After transformation, BGB and RMF had normally distributed errors and were analyzed with a general linear mixed model using the lme call in the package nlme (Pinheiro and others, 2013).

To evaluate the responses of BGB and RMF to the addition of individual nutrients and their combinations, N, P and K_{μ} were each included as factorial fixed factors, site was treated as a random factor, and light and aridity were included as site-level covariates. As described above, our metric of light availability was based on site-level mean light penetration of the grassland canopy only in control plots, and hence was independent from aboveground biomass responses to nutrient enrichment (and resulting effects on light penetration through the canopy).

Significance for each factor was evaluated with Type II Wald chi-square tests using the Anova

function in the car package (Fox & Weisberg, 2011). Supplementary Information contains the R code for all tests.

Results

We found wide variation across sites in root biomass (BGB, 60-1675 g/m²) and proportional allocation of biomass to roots from 0-10 cm depth (RMF, 7-90%), as summarized in Table S1 in Supplementary Material. When considering mean values in control plots (unfenced, unfertilized) at each of the 29 sites across four continents, there were a number of correlations among response and predictor variables (correlation coefficients in Table 1). Aridity (GAI) was positively correlated with the proportion of perennial cover ($p = 0.03$, meaning annuals were more common in drier sites). At the site level, the proportion of PAR reaching the soil surface (light) was negatively correlated with AGB ($p = 0.001$), but was not associated with community composition (proportion of graminoid or perennial cover in control plots). AGB and BGB were not correlated, however both variables were positively correlated with RMF (as expected, because AGB and BGB are used in the calculation of RMF). There was low RMF in sites with low light beneath the grass canopy ($p = 0.02$, as expected, because of the negative correlation between AGB and RMF), but RMF was not correlated with GAI or community composition.

When analyzing the full data set (treatment plots as well as controls), both light and GAI were significant site-level covariates in the analysis (statistics in Table 2, parameter estimates for significant factors in Figure 1). GAI and light were both positive predictors of BGB, while only light was a significant predictor of RMF.

Previously, a synergistic increase in aboveground biomass with N and P addition was observed across the Nutrient Network sites (i.e. significant N x P interaction, Fay and others

2015). In contrast, N, P, and K_u each had an overall negative effect on BGB (parameter estimates for all terms shown in Table 2 and Figure S4). Only N addition had a statistically significant effect on BGB with the response characterized by a N x light interaction (Table 2); in sites with high light at the soil surface, N addition increased root biomass, but in sites where light competition likely limited growth (low light at the soil surface), N addition reduced root biomass (Figure 2).

Mean values calculated across sites for RMF in each of the Nutrient Network treatments are shown in Figure 3. Addition of N and P each significantly reduced RMF, with no interaction. As with BGB, there was a significant N x light interaction, where the reduction in RMF with N addition was greatest in sites where a lower proportion of incoming light reached the soil surface under control conditions (statistics in Table 2, significant parameter estimates in Figure 1).

Discussion

Across grasslands on four continents, N enrichment quickly (within 3-5 years) influenced community belowground biomass and allocation, and light availability at ground level was a key predictor of the response of belowground biomass allocation to N addition, despite significant variation among sites in plant community composition, climate, and soils. Interestingly, no other nutrient treatment positively affected absolute root biomass, and nutrient enrichment tended to lower proportional biomass allocation to roots. The findings of this analysis are consistent with the predictions of optimal allocation theory, demonstrating that allocation patterns predicted for individual plants scale to the community level, with total belowground allocation jointly influenced by nutrient enrichment and light-limitation predictably across wide climatic and environmental gradients.

342
343 *Variation in root biomass and root mass fraction across sites*

344 Similar to prior regional studies (i.e. Sims & Singh, 1978, Scurlock and others, 2002, Hui
345 & Jackson, 2006), this global study documents wide variation across sites in plant allocation to
346 belowground biomass. Based on prior syntheses we expected that root biomass and allocation
347 would vary with soil water supply (Hui & Jackson, 2006, Mokany and others, 2006, but see
348 Yang and others, 2009, Reich and others, 2014). Root biomass increased with increasing soil
349 water availability (high GAI), but the relationship with RMF was only marginally significant.
350 While most root production in grasslands occurs in shallow soil layers (Jackson and others,
351 1996), total belowground allocation was under-sampled in this study since we restricted our
352 sampling to the top 10 cm of soil, possibly contributing to the lack of a relationship between site
353 aridity and RMF. Under-sampling may have been relatively greater in dry sites; a global analysis
354 of rooting depths found that arid sites were more likely to have a greater proportion of roots
355 found at deeper depths (Schenk & Jackson, 2002).

356 Past studies have found that variation among species could contribute to variation in the
357 proportion of biomass allocated belowground (Craine and others, 2003). For instance, eudicots
358 had higher fractional allocation aboveground compared with monocots in a comprehensive meta-
359 analysis (Poorter and others, 2012), and perennial species in some systems allocate more to roots
360 than annuals (Reynolds & D'Antonio, 1996). Functional composition of the grasslands in this
361 study varied widely; however, neither the fraction of perennial species nor the fraction of
362 graminoids present in control plots was correlated with RMF, suggesting these coarse metrics of
363 community composition did not contribute in a predictable way to the variation in RMF observed
364 across sites.

Across the wide range of site conditions, canopy light depletion was the aspect of environmental context most important for predicting variation in RMF; we observed higher proportional allocation aboveground (low RMF) in sites with low light availability beneath the grassland canopy. This effect was driven by AGB, which was negatively correlated with RMF (BGB and AGB were not correlated). This pattern is consistent with a shift from light limitation in highly productive sites to limitation by belowground resources (nutrients, water) in low-productivity sites (Gleeson & Tilman 1992), thus providing a new empirical lens into the context-dependence of root allocation.

Root biomass responses to nutrient addition

Across the Nutrient Network sites, aboveground net primary production (estimated by peak aboveground live biomass) responded positively and synergistically to the additions of N and P in approximately 75% of the sites examined (Fay and others 2015), and hence we expected that while *absolute* root biomass (BGB) would also increase in response to additions of these nutrients, root biomass as a *fraction* of total biomass (RMF) would decline with nutrient addition. Instead, our analysis shows an average decline in BGB with N addition, although the direction and magnitude of the BGB response depended on light availability (N x light interaction), with the greatest declines in BGB observed at sites with lower average light availability beneath the grassland canopy. These results are still consistent with the expectations of optimal allocation theory, whereby plants would be expected to allocate to roots when limitation by aboveground ground resources (e.g. light) is small relative to limitation by belowground resources (nutrients). Importantly, increasing nutrient supply reduced the absolute

biomass of shallow roots, with important implications for carbon and nutrient cycling in grasslands (Sposito, 1989, Jobbagy & Jackson, 2001).

While other recent experiments in both temperate (Bardgett and others, 2009) and semi-arid (Zeng and others, 2010) grasslands have documented declining root biomass in response to N addition, our findings are in direct contrast to recent meta-analyses finding no response (Liu & Greaver, 2010), or positive responses of fine root biomass to N addition (Xia & Wang, 2008). Some of this variation may reflect different expectations for effects of fertilization on standing pools of biomass versus on productivity. Nadelhoffer and others (1985) showed that forest communities with high rates of N mineralization (high N supply) had low standing pools of fine root biomass, but high rates of annual root production, due to higher rates of root turnover in the more fertile sites. A recent meta-analysis of fine root productivity based on root ingrowth cores found positive and synergistic influences of N and P addition on fine root production (Yuan & Chen, 2012). Because their root production responses were smaller in magnitude than the response of aboveground productivity, their analysis found lower proportional allocation belowground with N and P addition. Therefore, while we document an average decline in standing root biomass with N addition dependent on light, we recognize this is a static measurement, and that additional measures of root longevity and turnover would be required to predict the responses of ecosystem productivity across these sites.

Our results show that variation in root biomass response to N addition (but not P or K) was predictable based on light-limitation at the site level. This finding is consistent with prior studies demonstrating that light becomes increasingly limiting to growth as nutrient limitation is alleviated through fertilization (Hautier and others, 2009). It also demonstrates how community and ecosystem responses to nutrients are context dependent. Other studies within the Nutrient

Network have also highlighted the role of context-dependence; for instance, Borer and others (2014b) found greater diversity loss with nutrient enrichment at sites with low light penetration below the canopy, and Fay and others (2015) found that aboveground biomass did not respond to nutrient addition in 25% of the sites included in their analysis, which they suggested was potentially due to water-limitation.

Root mass fraction response to nutrient addition

When considering relative root biomass allocation (RMF), our results were consistent with the predictions of optimal allocation theory (Thornley, 1972, Wilson, 1988), with additions of both N and P reducing RMF. As with BGB, there was an interaction between N and Light, where the greatest reduction in RMF with N addition occurred in sites with low light penetration through the canopy. Because there was not a significant impact of P addition on BGB we infer that the reduction in RMF with P addition was caused by an increase in aboveground biomass (Fay and others, 2015). Together these results suggest that the predictions of optimal allocation theory with respect to N limitation are robust across wide environmental gradients, but interestingly, that allocation responses to P limitation are not as strong. Given the high – and increasing – rates of N and P fertilization of Earth’s ecosystems (Falkowski and others, 2000), the mechanisms underlying these differences are worthy of further investigation.

Potential mechanisms underlying belowground responses to nutrient enrichment

In addition to the plastic allocation responses already discussed, allocation to roots, stem and leaves can also vary with the size of an individual according to allometric scaling theory (Weiner 2004). An analysis of a global forest biomass dataset found intraspecific variation in

allocation along environmental gradients consistent with optimal allocation theory, but not intraspecific variation in allocation, and suggested that allometric changes with individual plant size could be responsible for unexplained variation in allocation (McCarthy and Enquist 2007). With respect to our analysis, allometric scaling rules associated with increasing plant size could potentially explain the proportional decline in RMF with N enrichment, but could not explain the absolute decline in root biomass.

Shifts in species diversity and composition could also alter community-level allocation of belowground biomass as a result of nutrient enrichment, particularly at the multi-year timescales considered in this study (Olf, 1992, Dybzinski & McNickle, 2013, Mueller and others, 2013). Species with high root allocation tend to grow slowly but are often competitively dominant (Gurevitch, and others, 1990, Aerts and others, 1991), particularly under low resource supply, due to their ability to draw down levels of soil water and nutrients (Tilman & Wedin, 1991). With nutrient enrichment and a shift towards light limitation, species with lower allocation to roots but a capacity for faster aboveground growth are likely to shade and competitively suppress slower growing, lower-statured species (Grime and others, 1991).

Nutrient enrichment often reduces species richness (Suding and others, 2005, Bobbink and others, 2010). Across the Nutrient Network, local loss of species diversity in response to N addition was increased by light-limitation (Borer and others, 2014b), and individual species responses to nutrient enrichment were predictable based on a trade-off in growth-defense strategy (Lind and others, 2013). This suggests that species composition shifts contributed to the belowground biomass and allocation responses to N enrichment and light-limitation documented here, but without monocultures to supplement our naturally assembled diverse communities, it is not possible to quantify the relative contribution of intra-specific (plastic) versus inter-specific

responses to the observed shifts in allocation at the community level. Future work should aim to evaluate the influence of shifting species composition in community-level biomass allocation and resulting feedbacks to ecosystem function.

Conclusions: ramifications for understanding ecosystem responses to global change

Ecosystem responses to global environmental change have the potential to either dampen or intensify the magnitude of future climate change through C-cycle feedbacks (Field and others, 2007). Despite the importance of grasslands to the terrestrial C sink (Scurlock & Hall, 1998, Follett & Reed, 2010), belowground responses to environmental changes are often not considered in synthesis efforts (e.g. Elser and others, 2007, LeBauer & Treseder, 2007, Lee and others, 2010). Recent database efforts are aiming to address this need, for instance with the creation of the Fine Root Ecology Database (Iversen and others, 2017). This study demonstrates that global changes interact with the local environment to influence allocation above- versus belowground, that shallow roots respond in predictable ways to globally pervasive changes, and that measurements of allocation, root production, and turnover will be necessary to accurately predict the ramifications for ecosystem-level processes.

Supplementary Material

Supplementary material includes additional methods, tables, detailed statistical analyses and R code.

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References

- Aerts RR, Boog GA, Van Der Aart PJM. 1991. The relation between above- and belowground biomass allocation patterns and competitive ability. *Oecologia* 87: 551-559.
- Anderson JM. 1991. The effects of climate change on decomposition processes in grassland and coniferous forests. *Ecological Applications* 1: 326–347.
- Bardgett RD, Mawdsley JL, Edwards S, Hobbs PJ, Rodwell JS, Davies WJ. 1999. Plant species and nitrogen effects on soil biological properties of temperate upland grasslands. *Functional Ecology* 13: 650-60.
- Bledsoe CS, Fahey TJ, Day FP, Ruess RW. 1999. Measurement of static root parameters: biomass, length, and distribution in the soil profile. In: *Soils Methods for Long-Term Ecological Research*. New York, New York, USA, Oxford University Press. pp 413-436.
- Bloom AJ, Chapin FS, Mooney HA. 1985. Resource limitation in plants--an economic analogy. *Annual Review of Ecology and Systematics* 16: 363-392.

499 Blume E, Bischoff M, Reichert JM, Moorman T, Konopka A, Turco RF. 2002. Surface and
 500 subsurface microbial biomass, community structure and metabolic activity as a function
 501 of soil depth and season. *Applied Soil Ecology* 20: 171-181.

502 Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, Bustamante M,
 503 Cinderby S, Davidson E, Dentener F, Emmett B. 2010. Global assessment of nitrogen
 504 deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications* 20:
 505 30-59.

506 Bolker B. 2008. Chapter 4: Distributions, in: *Ecological Models and Data in R*. Princeton
 507 University Press, pp 103-146.

508 Borer ET, Harpole WS, Adler PB, Lind EM, Orrock JL, Seabloom EW, Smith MD. 2014a.
 509 Finding generality in ecology: a model for globally distributed experiments. *Methods in*
 510 *Ecology and Evolution* 5: 65–73.

511 Borer ET, Seabloom EW, Gruner DS, Harpole WS, Hillebrand H, Lind EM, Adler PB, Alberti J,
 512 Anderson TM, Bakker JD, Biederman L, Blumenthal D, Brown CS, Brudvig LA,
 513 Buckley YM, Cadotte M, Chu C, Cleland EE, Crawley MJ, Daleo P, Damschen EI,
 514 Davies KF, DeCrappeo NM, Du G, Firn J, Hautier Y, Heckman RW, Hector A,
 515 HilleRisLambers J, Iribarne O, Klein JA, Knops JMH, La Pierre KJ, Leakey ADB, Li W,
 516 MacDougall AS, McCulley RL, Melbourne BA, Mitchell CE, Moore JL, Mortensen B,
 517 O'Halloran LR, Orrock JL, Pascual J, Prober SM, Pyke DA, Risch AC, Schuetz M, Smith
 518 MD, Stevens CJ, Sullivan LL, Williams RJ, Wragg PD, Wright JP, Yang LH. 2014b.
 519 Herbivores and nutrients control grassland plant diversity via light limitation. *Nature* 508:
 520 517-520.

521 Cleland EE, Harpole WS. 2010. Nitrogen enrichment and plant communities. *Annals of the New*
 522 *York Academy of Sciences* 1195: 46-61.

523 Craine JM, Wedin DA, Chapin FS, Reich PB. 2003. Relationship between the structure of root
 524 systems and resource use for 11 North American grassland plants. *Plant Ecology* 165: 85-
 525 100.

526 Dybzinski R, McNickle G. 2013. Game theory and plant ecology. *Ecology Letters*, 16, 545-555.

527 Eilers KG, Debenport S, Anderson S, Fierer N. 2012. Digging deeper to find unique microbial
 528 communities: The strong effect of depth on the structure of bacterial and archaeal
 529 communities in soil. *Soil Biology & Biochemistry* 50: 58-65.

530 Elser JJ, Bracken ME, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom
 531 EW, Shurin JB, Smith JE. 2007. Global analysis of nitrogen and phosphorus limitation of
 532 primary producers in freshwater, marine, and terrestrial ecosystems. *Ecology Letters* 10:
 533 1115-1211.

534 Falkowski P, Scholes R, Boyle E, Canadell J, Canfield D, Elser J, Gruber N, Hibbard K,
 535 Högberg P, Linder S, Mackenzie FT. 2000. The global carbon cycle: a test of our
 536 knowledge of earth as a system. *Science* 290: 291-296.

537 Fay PA, Prober SM, Harpole WS, Knops JMH, Bakker JD, Borer ET, Lind EM, MacDougall
 538 AS, Seabloom EW, Wragg PD, Adler P, Blumenthal DM, Buckley YM, Chu C, Cleland
 539 EE, Collins SL, Davies KF, Du G, Feng X, Firn J, Gruner DS, Hagenah N, Hautier Y,
 540 Heckman RW, Jin VL, Kirkman KP, Klein J, Ladwig LM, Li Q, McCulley RL,
 541 Melbourne BA, Mitchell CE, Moore JL, Morgan JW, Risch AC, Schütz M, Stevens CJ,
 542 Wedin DA, Yang YH. 2015. Grassland productivity limited by multiple nutrients. *Nature*
 543 *Plants* 1: 15080.

544 Field CB, Lobell DB, Peters HA, Chiariello NR. 2007. Feedbacks of terrestrial ecosystems to
 545 climate change. *Annual Review of Environment and Resources* 32: 1-29.

546 Follett R, Reed D 2010. Soil carbon sequestration in grazing lands: societal benefits and policy
 547 implications. *Rangeland Ecology Management* 63: 4–15.

548 Fox J, Weisberg S 2011. *An R Companion to Applied Regression*, Second Edition. Thousand
 549 Oaks, California.

550 Friedlingstein P, Joel G, Field CB, Fung IY. 1999. Toward an allocation scheme for global
 551 terrestrial carbon models. *Global Change Biology* 5: 755-770.

552 Gill RA, Kelly RH, Parton WJ, Day KA, Jackson RB, Morgan JA, Scurlock JMO, Tieszen LL,
 553 Castle JV, Ojima DS, Zhang XS. 2002. Using simple environmental variables to
 554 estimate belowground productivity in grasslands. *Global Ecology and Biogeography* 11:
 555 79–86.

556 Gleeson SK, Tilman D. 1992. Plant allocation and the multiple limitation hypothesis. *American*
 557 *Naturalist* 139: 1322-1343.

558 Goldberg, DE. 1990. Components of resource competition in plant communities. In: *Perspectives*
 559 *on plant competition*, pp. 27-49.

560 Grime JP, Campbell BD, Mackey JMI, Crick JC. 1991. Root plasticity, nitrogen capture and
 561 competitive ability. In: *Plant Root Growth: an Ecological Perspective*. In: Atkinson D. ed.
 562 Oxford, Blackwell Scientific Publications.

563 Gurevitch J, Wilson P, Stone JL, Tees P, Stoutenburgh RJ. 1990. Competition among old-field
 564 perennials at different levels of soil fertility and available space. *Journal of Ecology* 78:
 565 727-744.

566 Harpole WS, Ngai JT, Cleland EE, Seabloom EW, Borer ET, Bracken MES, Elser JJ, Gruner
 567 DS, Hillebrand H, Shurin JB, Smith JE. 2011. Nutrient co-limitation of primary producer
 568 communities. *Ecology Letters* 14: 852-862.

569 Hautier Y, Niklaus PA, Hector A. 2009. Competition for light causes plant biodiversity loss after
 570 eutrophication. *Science*, 324, 636-638.

571 Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated
 572 climate surfaces for global land areas. *International Journal of Climatology* 25: 1965–
 573 1978.

574 Hooper DU, Johnson L. 1999. Nitrogen limitation in dryland ecosystems: responses to
 575 geographical and temporal variation in precipitation. *Biogeochemistry* 46: 247 – 293.

576 Hui DF, Jackson RB. 2006. Geographical and interannual variability in biomass partitioning in
 577 grassland ecosystems: a synthesis of field data. *New Phytologist* 169: 85–93.

578 Iversen CM, McCormack ML, Powell AS, Blackwood CB, Freschet GT, Kattge J, Roumet C,
 579 Stover DB, Soudzilovskaia NA, Valverde - Barrantes OJ, Bodegom PM. 2017. A global
 580 Fine-Root Ecology Database to address belowground challenges in plant ecology. *New*
 581 *Phytologist* 215: 15-26.

582 Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze ED. 1996. A global
 583 analysis of root distributions for terrestrial biomes. *Oecologia* 108: 389-411.

584 Jackson RB, Schenk HJ, Jobbágy EG, Canadell J, Colello GD, Dickinson RE, Field CB,
 585 Friedlingstein P, Heimann M, Hibbard K, Kicklighter DW. 2000. Belowground
 586 consequences of vegetation change and their treatment in models. *Ecological*
 587 *Applications* 10: 470-483.

588 Jastrow JD. 1996. Soil aggregate formation and the accrual of particulate and mineral-associated
589 organic matter. *Soil Biology and Biochemistry* 28: 665-676.

590 Jobbagy EG, Jackson RB. 2000. The vertical distribution of soil organic carbon and its relation
591 to climate and vegetation. *Ecological Applications* 10: 423-436.

592 Jobbagy EG, Jackson RB. 2001. The distribution of soil nutrients with depth: Global patterns and
593 the imprint of plants. *Biogeochemistry* 53: 51-77.

594 LeBauer DS, Treseder KK. 2008. Nitrogen limitation of net primary productivity in terrestrial
595 ecosystems is globally distributed. *Ecology* 89: 371–379.

596 Lee M, Manning P, Rist J, Power SA, Marsh C. 2010. A global comparison of grassland biomass
597 responses to CO₂ and nitrogen enrichment. *Philosophical Transactions of the Royal*
598 *Society of London B: Biological Sciences* 365: 2047-2056.

599 Leith HHF. 1978. Primary productivity in ecosystems: Comparative analysis of global patterns.
600 In: Leith HFH, ed. *Patterns of primary production in the biosphere*. Stroudberg, PA
601 USA., Dowden, Hutchinson and Ross. pp. 342

602 Lind EM, Borer E, Seabloom E, Adler P, Bakker JD, Blumenthal DM, Crawley M, Davies K,
603 Firm J, Gruner DS, Harpole WS. 2013. Life-history constraints in grassland plant species:
604 a growth-defence trade-off is the norm. *Ecology Letters* 16: 513-521.

605 Liu L, Greaver TL. 2010. A global perspective on belowground carbon dynamics under nitrogen
606 enrichment. *Ecology Letters* 13: 819-28.

607 Lu M, Zhou X, Luo Y, Yang Y, Fang C, Chen J, Li B. 2011. Minor stimulation of soil carbon
608 storage by nitrogen addition: a meta-analysis. *Agriculture, Ecosystems &*
609 *Environment* 140: 234-244.

610 Mack MC, Schuur EA, Bret-Harte MS, Shaver GR, Chapin FS. 2004. Ecosystem carbon storage
 611 in arctic tundra reduced by long-term nutrient fertilization. *Nature* 431: 440-443.

612 McCarthy MC, Enquist BJ. 2007. Consistency between an allometric approach and optimal
 613 partitioning theory in global patterns of plant biomass allocation. *Functional Ecology* 21:
 614 713-720.

615 Mueller KE, Hobbie SE, Tilman D, Reich PB. 2013. Effects of plant diversity, N fertilization,
 616 and elevated carbon dioxide on grassland soil N cycling in a long - term experiment.
 617 *Global Change Biology* 19: 1249-1261.

618 Michaletz ST, Cheng D, Kerkhoff AJ, Enquist BJ. 2014. Convergence of terrestrial plant
 619 production across global climate gradients. *Nature* 512: 39-43.

620 Mokany K, Raison RJ, Prokushkin AS. 2006. Critical analysis of root : shoot ratios in terrestrial
 621 biomes. *Global Change Biology* 12: 84–96.

622 Nadelhoffer KJ, Aber JD, Melillo JM. 1985. Fine roots, net primary production, and soil nitrogen
 623 availability: a new hypothesis. *Ecology* 66: 1377–1390

624 Norby RJ, Luo Y. 2004. Evaluating ecosystem responses to rising atmospheric CO₂ and global
 625 warming in a multi-factor world. *New Phytologist* 162: 281-293.

626 Olff H 1992. Effects of light and nutrient availability on dry matter and N allocation in six
 627 successional grassland species. *Oecologia* 89: 412-421.

628 Pinheiro J, Bates D, Debroy S, Sarkar D, R Core Development Team. 2013. nlme: Linear and
 629 Nonlinear Mixed Effects Models. R package version 3.1

630 Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L. 2012. Biomass allocation to
 631 leaves, stems and roots: meta-analyses of interspecific variation and environmental
 632 control. *New Phytologist* 193: 30-50.

633 R Core Team 2018. R: A language and environment for statistical computing. Vienna, Austria, R
634 Foundation for Statistical Computing.

635 Rasse DP, Rumpel C, Dignac MF. 2005. Is soil carbon mostly root carbon? Mechanisms for a
636 specific stabilisation. *Plant and Soil* 269: 341–356.

637 Reynolds HL, D’Antonio C. 1996. The ecological significance of plasticity in root weight ratio
638 in response to nitrogen: Opinion. *Plant and Soil* 185: 75–97.

639 Reich PB. 2002. Root-shoot relations: optimality in acclimation and adaptation or the ‘Emperor’s
640 New Clothes’. In: *Plant Roots: The Hidden Half*, pp. 205-220.

641 Reich PB, Luo Y, Bradford JB, Poorter H, Perry CH, Oleksyn J. 2014. Temperature drives
642 global patterns in forest biomass distribution in leaves, stems, and roots. *Proceedings of*
643 *the National Academy of Sciences* 111: 13721-13726.

644 Schenk HJ, Jackson RB. 2002. The global biogeography of roots. *Ecological Monographs* 72:
645 311-328.

646 Scurlock JMO, Hall DO. 1998. The global carbon sink: a grassland perspective. *Global Change*
647 *Biology* 4: 229–233.

648 Scurlock JMO, Johnson K, Olson RJ. 2002. Estimating net primary productivity from grassland
649 biomass dynamics measurements. *Global Change Biology* 8: 736-753.

650 Sims PL, Singh JS. 1978. The structure and function of ten western North American grasslands:
651 III. Net primary production, turnover and efficiencies of energy capture and water use.
652 *Journal of Ecology* 66: 573-597.

653 Smithwick EA, Lucash MS, McCormack ML, Sivandran G. 2014. Improving the representation
654 of roots in terrestrial models. *Ecological Modelling* 291: 193-204.

655 Sposito G. 1989. *The chemistry of soils*, New York, New York U.S.A., Oxford University Press.

656 Suding KN, Collins SL, Gough L, Clark C, Cleland EE, Gross KL, Milchunas DG, Pennings S.
 657 2005. Functional-and abundance-based mechanisms explain diversity loss due to N
 658 fertilization. *Proceedings of the National Academy of Sciences of the United States of*
 659 *America* 102: 4387-4392.

660 Thornley JHM. 1972. A balanced quantitative model for root: shoot ratios in vegetative plants.
 661 *Annals of Botany* 36: 431-441.

662 Tilman D, Wedin D. 1991. Plant traits and resource reduction for five grasses growing on a
 663 nitrogen gradient. *Ecology* 72: 685-700.

664 Warton DI, Hui FK. 2011. The arcsine is asinine: the analysis of proportions in ecology.
 665 *Ecology*, 92, 3-10.

666 Weiner, J. 2004. Allocation, plasticity and allometry in plants. *Perspectives in Plant Ecology,*
 667 *Evolution and Systematics* 6: 207-215.

668 Wilson JB 1988. A review of evidence on the control of shoot: root ratio, in relation to models.
 669 *Annals of Botany* 61: 433-449.

670 Woodward FI, Osborne CP. 2000. The representation of root processes in models addressing the
 671 responses of vegetation to global change. *New Phytologist* 147: 223–232.

672 Xia J, Wan S. 2008. Global response patterns of terrestrial plant species to nitrogen addition.
 673 *New Phytologist* 179: 428-439.

674 Yang Y, Fang J, Ji C, Han W. 2009. Above- and belowground biomass allocation in Tibetan
 675 grasslands. *Journal of Vegetation Science* 20: 177-184.

676 Yuan ZY, Chen HYH. 2012. A global analysis of fine root production as affected by soil
 677 nitrogen and phosphorus. *Proceedings of the Royal Society of London B: Biological*
 678 *Sciences* 279: 3796-3802.

679 Zeng DH, Li LJ, Fahey TJ, Yu ZY, Fan ZP, Chen FS. 2010. Effects of nitrogen addition on
680 vegetation and ecosystem carbon in a semi-arid grassland. *Biogeochemistry* 98: 185-93.

681 Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV. 2008. Climate change
682 mitigation: A spatial analysis of global land suitability for Clean Development
683 Mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment* 126:
684 67-80.

Table 1. Correlations among site-level values of aridity (GAI, see Methods), the proportion of photosynthetically-active radiation passing through the grassland canopy to reach the soil surface (Light), the proportion of community cover comprised by graminoids/monocots (gram.frac), the proportion of community cover comprised by perennial species (per.frac), the average root mass fraction (RMF), live aboveground biomass (AGB) and belowground biomass (BGB). Site-level mean values were used in this analysis, for control plots only (unfenced, unfertilized). Values are Pearson correlation coefficients with significant values in bold. Asterisks indicate level of statistical significance (*= $p < 0.05$, **= $p < 0.01$, ***= $p < 0.001$).

	Aridity	Light	gram.frac	per.frac	RMF	ABG
Light	-0.16					
gram.frac	0.05	-0.14				
per.frac	0.40 *	-0.24	0.35			
RMF	0.18	0.43 *	0.01	0.01		
AGB	0.17	-0.57 **	-0.02	0.32	-0.61 ***	
BGB	0.28	-0.14	0.19	0.15	0.70 ***	-0.07

Table 2. Analysis of deviance table (Type II tests) showing the regression parameter estimate (Est), χ^2 test statistic and p-value for each term in the mixed effects models described in the Methods. This analysis evaluated how factorial nitrogen (N), phosphorus (P) and potassium plus micronutrient (K_{μ}) enrichment influenced the proportion of biomass allocated to roots (RMF), and root biomass (g/m^2). Aridity and light (mean proportion of PAR reaching the soil surface) were included as site-level covariates, including their interactions with experimental treatments. Significant terms highlighted in bold.

Model term	RMF			root biomass (g/m^2)		
	Est	χ^2	p	Est	χ^2	p
Light	2.09	13.3	<0.001	0.28	1.43	0.23
Aridity	0.66	2.55	0.11	0.61	6.03	0.014
N	-0.38	26.31	<0.001	-0.53	2.11	0.15
P	-0.05	6.96	0.008	-0.07	0.69	0.41
K_{μ}	0.11	0.84	0.36	-0.21	0.04	0.84
Light:N	0.45	4.89	0.03	0.63	8.66	0.0032
Light:P	0.24	1.45	0.23	0.25	0.02	0.88
N:P	-0.27	0.01	0.98	0.36	0.03	0.86
Light: K_{μ}	-0.12	0.19	0.66	0.07	0.02	0.90
N: K_{μ}	-0.15	0.84	0.36	0.34	0.08	0.77
P: K_{μ}	-0.27	0.00	0.95	0.12	0.46	0.50
N:Aridity	-0.16	0.24	0.62	0.13	0.07	0.79
P:Aridity	-0.32	0.00	0.96	-0.05	0.44	0.51
K_{μ} :Aridity	-0.17	0.46	0.50	0.15	0.21	0.65
Light:N:P	-0.19	0.42	0.52	-0.33	0.68	0.41
Light:N: K_{μ}	0.23	0.16	0.70	0.03	0.06	0.81
Light:P: K_{μ}	0.25	0.19	0.66	-0.17	0.13	0.72
N:P: K_{μ}	0.26	2.65	0.10	-0.33	2.45	0.12
N:P:Aridity	0.59	1.81	0.18	-0.05	0.12	0.73
N: K_{μ} :Aridity	0.15	0.70	0.40	-0.25	2.25	0.13
P: K_{μ} :Aridity	0.37	0.08	0.77	0.05	0.04	0.85
Light:N:P: K_{μ}	-0.14	0.03	0.86	0.09	0.00	0.95
N:P: K_{μ} :Aridity	-0.63	2.42	0.12	-0.02	0.02	0.89

Figure 1. Mean parameter estimates and confidence intervals (thin and thick lines indicate 95% and 50% confidence intervals, respectively) for fixed effects in models evaluating the response of root mass fraction (RMF, in green) and root biomass (BGB, in black) to experimental addition of multiple nutrients, including nitrogen (N) and phosphorus (P). Average light availability at the soil surface in control plots and aridity (Global Aridity Index, see Methods) were included as site-level covariates. Only statistically significant parameter estimates from Table 2 are displayed (note the main effect of light on BGB is not significant, but is displayed because of the significant light:N interaction).

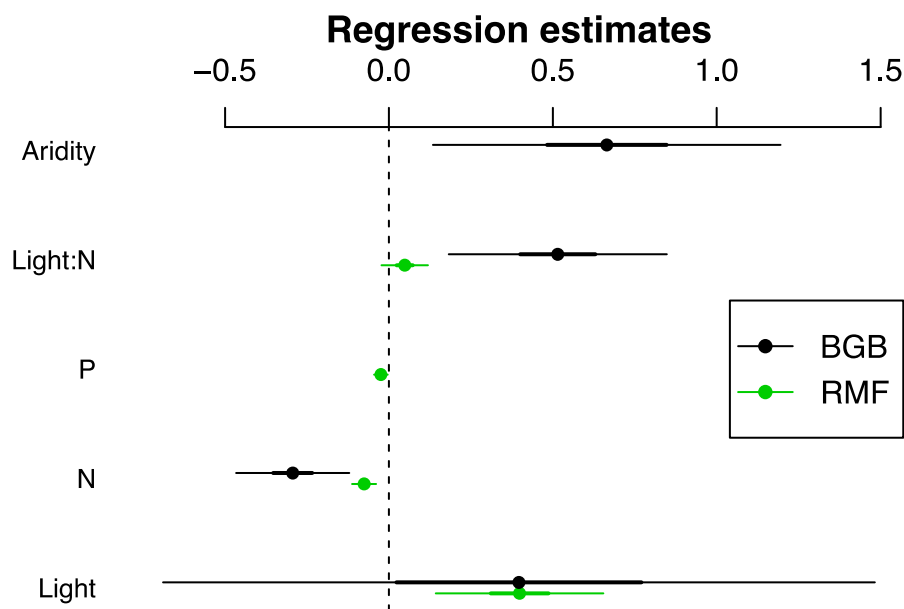


Figure 2. The root biomass response to N addition depended on site-level light limitation. Fractional light availability (light) is the proportion of photosynthetically active radiation passing through the grassland canopy. The natural-log response ratio of root biomass to N addition (LRR N addition) is equivalent to the average \ln -root biomass (g/m^2) in plots without N addition subtracted from the average \ln -root biomass (g/m^2) in N addition plots. The grey line indicates LRR=0 or no difference in root biomass between ambient and N enriched plots. Negative values indicate a decline in root biomass in plots with N addition compared to plots without N addition. Black trend line shows the best linear fit, indicating that N addition increased root biomass only where abundant light passed through the canopy. Data labels indicate site names as in Table S1.

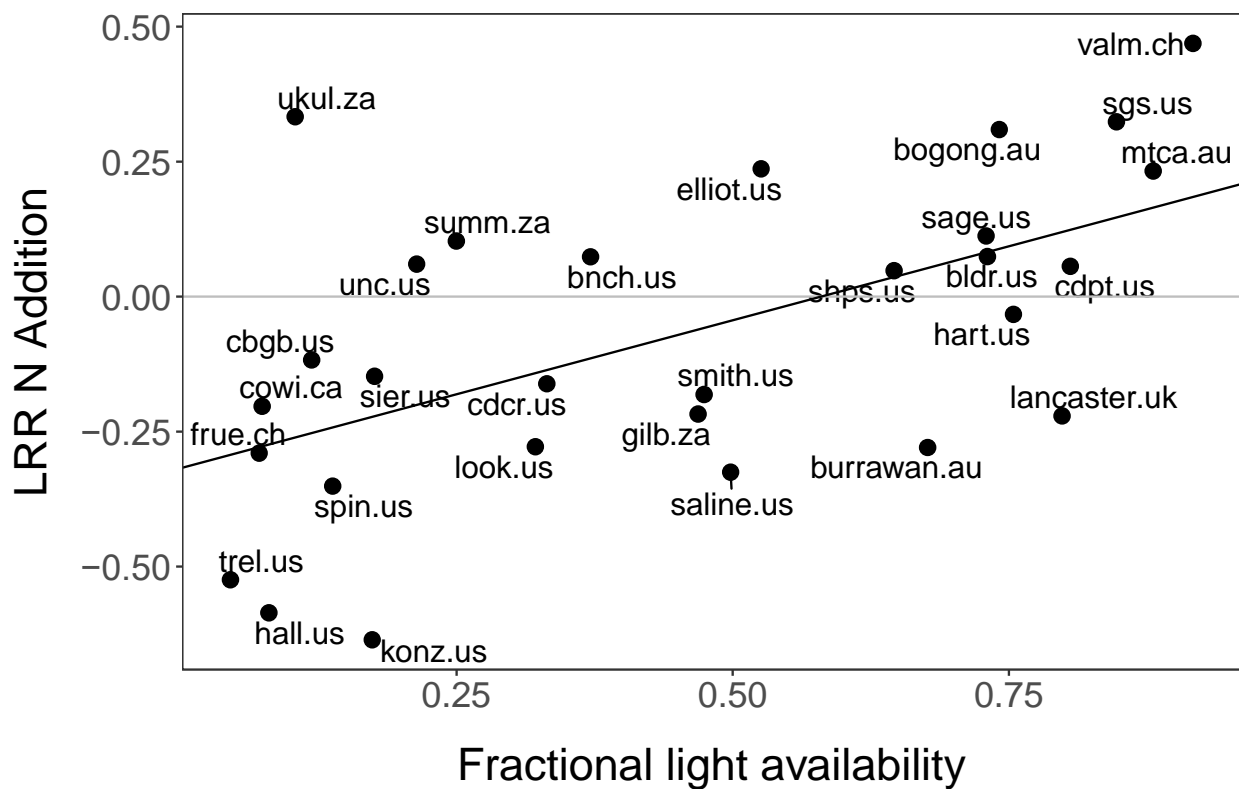


Figure 3. Mean root mass fraction (RMF) in each of experimental nutrient addition treatments, including nitrogen (N), phosphorus (P) or potassium plus micronutrients (K_{μ}), singly and in combination. Means are averages of plot level data across all sites, error bars indicate one standard error of the mean. Addition of N and P both resulted in a significant reduction of RMF (N and P as main effects, without significant interactions).

