Resource-use efficiency explains grassy weed invasion in a low-resource savanna in north Australia

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Comparative studies of plant resource use and ecophysiological traits of invasive and native resident plant species can elucidate mechanisms of invasion success and ecosystem impacts. In the seasonal tropics of north Australia, the alien C₄ perennial grass Andropogon gayanus (gamba grass) has transformed diverse, mixed tree-grass savanna ecosystems into dense monocultures. To better understand the mechanisms of invasion, we compared resource acquisition and usage efficiency using leaf-scale ecophysiological and stand-scale growth traits of A. gayanus with a co-habiting native C₄ perennial grass Alloteropsis semialata. Under wet season conditions, A. gayanus had higher rates of stomatal conductance, assimilation, and water use, plus a longer daily assimilation period than the native species A. semialata. Growing season length was also ~2 months longer for the invader. Wet season measures of leaf scale water use efficiency (WUE) and light use efficiency (LUE) did not differ between the two species, although photosynthetic nitrogen use efficiency (PNUE) was significantly higher in A. gayanus. By May (dry season) the drought avoiding native species A. semialata had senesced. In contrast, rates of A. gayanus gas exchange was maintained into the dry season, albeit at lower rates that the wet season, but at higher WUE and PNUE, evidence of significant physiological plasticity. High PNUE and fire tolerance in an N-limited and highly flammable ecosystem confers a significant competitive advantage over native grass species and a broader niche width. As a result A. gayanus is rapidly spreading across north Australia with significant consequences for biodiversity and carbon and retention.

Keywords: alien invasive species, ecophysiology, water use, carbon uptake, weed invasion, trait-based comparisons, stable isotopes, carbon

Introduction

Alien plant invasions are considered a major threat globally to biodiversity and ecosystem function (Simberloff, 2011; Vilà et al., 2011; Strayer, 2012). Considerable research effort has gone into understanding the mechanisms that drive invasion success in order to direct effective weed management activities (Blumenthal, 2006; Barney and Whitlow, 2008; Catford et al., 2009).
Invasion drivers vary and are mediated or filtered by characteristics of the ecosystem being invaded, which can also differ in space and time (D’Antonio, 1993; Levine et al., 2003; Theoharides and Dukes, 2007). One of the major drivers of successful invasion is resource competition (Levine et al., 2003; Vilà and Weiner, 2004). Successful invaders are typically considered to possess a superior ability to acquire limiting resources (e.g., light, nutrients), and/or allocate resources to different plant parts for improved performance (Goldberg et al., 1999). Generally, high resource environments tend to be more invasible than low-resource environments (Gross et al., 1999). However, in a major review on resource-use explains grass invasion success have a competitive advantage over alien plants in low-resource environments (Funk, 2013). Generally, high resource environments tend to be more invasible than low-resource environments (Gross et al., 1999). However, in a major review on this topic, Gioria and Osborne (2014) found few studies that compared resource competition directly and most studies were undertaken in high resource environments. Many studies were also confounded by factors such as comparisons of different life forms or dominant alien versus subordinate native species. The effects on carbon sequestration and water use when species replacement is by another of the same life form will depend largely on individual species attributes and climate and may be difficult to predict (Cavaleri and Sack, 2010).

This study focuses on the mechanisms facilitating the invasion of C₄ Andropogon gayanus Kunth. (gamba grass) in Australia’s mesic (>900 mm annual rainfall) savannas. Large areas (>200,000 ha) of invasion are occurring across the ‘Koolpinyah surface’ (Nott, 1995), a regional geomorphological formation that consists of ancient (Late Tertiary), leached, undulating sandy plains of low soil N and low organic carbon (Scott et al., 2009; Smith and Hill, 2011). Savanna ecosystems being invaded can be considered a resource-limited ecosystem due to these low fertility soils coupled with annual drought (6 months per year) and frequent fire (2 in 3 years) (Hutley and Setterfield, 2008). Despite the limiting resources, A. gayanus is one of a number of introduced pasture species that have become successful invaders in this region (Cook and Dias, 2006; Setterfield et al., 2013). Some drivers of A. gayanus invasion success have been previously demonstrated. For example, A. gayanus produces large amounts of seed annually compared to native grasses (Flores et al., 2005; Setterfield et al., 2005), resulting in high propagule pressure typical of successful invaders (Eppstein and Molofsky, 2007; Catford et al., 2009). Seedling establishment occurs in intact savanna but is greatly facilitated by both canopy cover and/or ground layer disturbance (Setterfield et al., 2005). Like many successful invaders, A. gayanus alters the abiotic characteristics of invaded sites to enhance its ability to colonize and survive (Catford et al., 2009). In this situation, the dominant fire regime changes as a consequence of the increased A. gayanus derived fuel loads and fire intensity (Rossiter et al., 2003; Setterfield et al., 2010) resulting in reduced canopy cover and ground layer vegetation and increased site suitability for establishment of the invader. In this study, A. gayanus is one of a number of introduced pasture species that have become successful invaders in this region (Cook and Dias, 2006; Setterfield et al., 2013). Some drivers of A. gayanus invasion success have been previously demonstrated. For example, A. gayanus produces large amounts of seed annually compared to native grasses (Flores et al., 2005; Setterfield et al., 2005), resulting in high propagule pressure typical of successful invaders (Eppstein and Molofsky, 2007; Catford et al., 2009). Seedling establishment occurs in intact savanna but is greatly facilitated by both canopy cover and/or ground layer disturbance (Setterfield et al., 2005). Like many successful invaders, A. gayanus alters the abiotic characteristics of invaded sites to enhance its ability to colonize and survive (Catford et al., 2009). In this situation, the dominant fire regime changes as a consequence of the increased A. gayanus derived fuel loads and fire intensity (Rossiter et al., 2003; Setterfield et al., 2010) resulting in reduced canopy cover and ground layer vegetation and increased site suitability for establishment of the invader. In this situation, the dominant fire regime changes as a consequence of the increased A. gayanus derived fuel loads and fire intensity (Rossiter et al., 2003; Setterfield et al., 2010) resulting in reduced canopy cover and ground layer vegetation and increased site suitability for establishment of the invader.
of from 0.01 to 0.11% (Day et al., 1979; Rossiter-Rachor, 2008). These soils are coarse textured and well drained, but with low water holding capacity.

The native grass understorey consists of perennial C4 grasses such as Allotropis semialata, Heteropogon triticeus, Chrysochroa fallax, Eriachne trieta Nees ex Steud., and C4 annual grasses such as Pseudopogonatherum irritans (Br.) and Sorghum sp. Following the release of a commercial seed supply in 1983, the alien grass A. gayanus (cultivar ‘Kent’) was planted at a range of locations across northern Australia (Oram, 1987) including near Mary River National Park and has since invaded vast areas of the high rainfall savanna (>1000 mm annual rainfall; Petty et al., 2012; Adams and Setterfield, 2013). It is now a dominant feature of the understorey in the northern section of the national park. A. gayanus can form dense monospecific sward up to 4 m high with a biomass of 20–30 t ha−1 in heavily invaded patches (Rossiter et al., 2003), with a sharp invasion front adjacent to non-invaded savanna (Figures 1A,B). Comparisons were undertaken at paired non-invaded, and invaded sites. Invaded sites had a minimum of 70% cover of A. gayanus in the understorey, whereas non-invaded sites had no A. gayanus and were dominated by A. semialata.

Leaf Gas Exchange

Leaf scale physiological traits of A. gayanus and A. semialata were compared using two approaches. Firstly, observations of diurnal patterns of leaf gas exchange were tracked for the two species using plants from three plots-pairs (A. gayanus vs native grasses) within the Mary River National Park. Measurements were made in situ during the wet (March) and dry seasons (May) using a portable photosynthesis system (Li-Cor 6400, Li-Cor Inc., Lincoln, NE, USA) on plants within adjacent sward of A. gayanus and A. semialata across an invasion front (Figures 1A,B). Ambient conditions were maintained within the leaf chamber with the instrument in standard measurements mode. Care was taken to ensure the exposure to incident radiation to a leaf was maintained during measurements. Afternoon air temperatures reached 35°C and heating of the instrument occurred requiring regulation of the chamber temperature which was set to 35°C to prevent artificial warming of leaves during measurement.

Native grasses were not measured in the dry season as leaves had senesced by this phase of the seasonal cycle, whereas A. gayanus plants still supported green foliage enabling wet and dry season comparisons. Dry season measurements for A. gayanus were at the same site using the same population of plants and leaves. These diurnal gas exchange measurements provided in situ measurements of leaf performance over a range of leaf and air temperature and light conditions. Secondly, a further set of observations were made during the wet season (March) at an additional three sites within the Mary River National Park. This was undertaken to examine spatial variation of maximum net photosynthesis (Amax) and transpiration (Tmax) of both species under conditions of saturating light. Again, A. gayanus and A. semialata were sampled across an invasion front at these additional sites.

Gas exchange measurements were made on fully expanded, mature leaves approximately two thirds along the leaf lamina of five randomly selected individual plants. Measurements were made on three leaves per A. gayanus plant and two leaves per A. semialata plant, given the small plant and leaf size of the latter. This provided a total of 25 leaves sampled across both species per sampling run, which took approximately 1 h to complete. This sampling cycle was repeated continuously from 1000 to 1700 h local time. Variables collected per leaf included leaf temperature (Tleaf), leaf to air vapour pressure deficit (LAVPD), photosynthetically-active flux density incident at the leaf surface (PAR), assimilation (A), transpiration (T), and stomatal conductance (gs).

Gas exchange measurements were made at three additional sites under saturating light conditions with measurements occurring between 11 am and 1500 h local time. These measures were used for the analysis of instantaneous transpiration efficiency (ITE) and intrinsic water use efficiency (IWUE). ITE was calculated as μmol of CO2 assimilated per mol of water
transpired (A/T). IWUE was defined as the ratio of light saturated net assimilation rate to stomatal conductance (A/gs) which is thought to have low dependence on environmental parameters and reflects intrinsic plant physiological functioning (Jones, 1992). To determine the light compensation points, the light saturation point and apparent quantum yields light use efficiency, (LUE; Kuppers and Schulze, 1985), non-linear regressions \( A = a \times \ln(PAR) - b \) were fitted to the PAR and A data for each species. Instantaneous LUE of each species was quantified as \( \mu \text{mol of CO}_2 \text{ assimilated per } \mu \text{mol}^{-1} \text{ PAR} \) in the light limited region of the light response curves.

**Above-Ground Biomass and Leaf Area Index**

In March and May 2003, the above-ground live plant material (leaves and stems) of each species was harvested in three random 2 m × 2 m quadrats at each of the three paired invaded and non-invaded sites used in the gas exchange measurements. Plant material was dried and weighed to give above-ground biomass (AGB) and scaled to leaf area using allometric equations developed for *A. gayanus* (Rossiter, 2001). A generic allometric equation for native grass biomass and leaf area was used as a surrogate for *A. semiflata* as this relationship has been shown to hold across a range of northern Australian tropical savanna *C₄* grasses (Hutley and Williams, unpublished data). Native grass species used to derive the allometric equations were all *C₄* grasses common in these tropical savanna woodlands (Scott et al., 2012) and included * Aristida hygrometrica*, * Chrysopogon latifolius*, * Sorghum intrans*, * Heteropogon triticoides*, * Themeda triandra*, * Sclina nervosum*, *Sorghum plumosum*, * Chrysopon fallax*, * Bothriochloa apiculata*, * Pseudopogonatherum contortum* variously from four sites (Howard Springs, Claravale, Larrimah, and Katherine). Estimates of leaf area sampled from the 2 m × 2 m area enabled the mean leaf area index (LAI) for each site (invaded or non-invaded) to be estimated.

**Leaf Nitrogen, Carbon, and Isotopes**

All leaves used in the gas exchange measurements of both species were collected, dried, pooled, and ground in a Culatti Type grinder (Model MFC CZ13) with a 1 mm screen. Percent elemental carbon (%C) and nitrogen (%N) and stable carbon (δ¹³C) and nitrogen (δ¹⁵N) isotope ratios were determined via Dumas combustion in an IsoChrom which was connected to an EA-1110 Elemental CHN-O Analyser. Analysis was conducted by the Australian National University stable isotope facility. Foliar nitrogen values (g N/g leaf) were divided by Aₘₜₐₓ for each leaf to calculate photosynthetic nitrogen use efficiency (PNUE). Foliar δ¹³C values indicate long term water use efficiency (LTWUE, Dawson et al., 2002). Foliar leaf δ¹⁵N values are somewhat indicative of nitrogen source and soil availability, with lower values suggesting preferential uptake of ammonium or higher soil ammonium to nitrate ratios (Handley et al., 1998).

**Statistical Analysis**

All statistical analyses were performed using SPSS Version 6.0 (2007, SPSS Inc., Chicago, IL, USA). Clear outliers (> 2 SD from the mean) were removed prior to analysis. Outliers were clearly identified from raw data plots and data points that were approximately 2 SD from a measurement run mean were examined. In the wet season, the percentage of outliers was larger than 5% and was 11% for *A. gayanus* and 10% for *A. semiflata*. None were identified for the *A. gayanus* dry season data set. Variable PAR conditions and shifts in temperature and VPD with cloud cover of the wet season resulted in a population of leaves that were not at a stable equilibrium when measured and were not included in calculations.

Diurnal leaf temperature, PAR, LAVPD, A, T, and gs, at each time period (10:00, 11:00, 13:00, 14:00, and 16:00 or 17:00) were analyzed using a one-way ANOVA to compare differences between the species/season factor (fixed). Data was normal (skewness, kurtosis values <2) and variances homogeneous (Levene’s significance test <0.05). Data for diurnal analyses were based on plants at one paired site only. Differences between species and seasons were assessed using the Student-Neumann–Keuls post hoc test. The species/season factor included three variables: *A. gayanus* in the wet season, *A. semiflata* in the wet season, and *A. gayanus* in the dry season.

Results of daily carbon uptake rates and water use per ground area (canopy scale fluxes) were determined by scaling up integrated diurnal measures of A and T, respectively, to rates per square meter ground area using site based LAI estimates. Extrapolation of leaf gas exchange parameters to the canopy scale using LAI is based on the assumption that for these grasses, canopy self-shading is limited and simple scaling using LAI to obtain canopy level estimates is feasible (Larcher, 2003). Leaf scale estimates and foliar δ¹³C, δ¹⁵N, foliar %N, foliar %C, foliar C:N, and PNUE (Aₘₜₐₓ/N per g leaf, PNUE) for each species/season were analyzed using one-way ANOVA and Student-Neumann–Keuls post hoc tests to assess differences between species and season (for *A. gayanus* data). Differences in ITE (A/T) and IWUE (A/gs) for each species/season (all sites data) were analyzed using a one-way ANOVA, Student-Neumann–Keuls post hoc tests and pair-wise comparisons with a Bonferroni adjustment.

The LUE of each species was determined as the slope of the linear relationship between PAR and A when light was limiting. Light limitation was assumed to have occurred at PAR <480 μmol m⁻² s⁻¹. Differences were analyzed using an ANCOVA with PAR as the covariate and species/season as the fixed factor. Differences in Aₘₜₐₓ, Tₘₜₐₓ, and gs for each species were determined from the light saturated leaves when PAR > 750 μmol m⁻² s⁻¹ for *A. gayanus* and *A. semiflata* in the wet season and PAR > 500 μmol m⁻² s⁻¹ for *A. gayanus* in the dry season. Differences were compared using ANCOVA, with PAR as the covariate and species/season as the fixed factor.

**Leaf Microclimate**

During the wet season, *A. gayanus* and *A. semiflata* leaves experienced a broadly similar microclimate in terms of Tleaf, leaf incident PAR and LAVPD, enabling direct species comparisons of physiological variables (Figure 2A, T, gₜ). Leaf temperatures
of both species were similar throughout the day, although at approximately 1400 h $T_{leaf}$ of $A. gayanus$ was higher than that of $A. semialata$ (Figure 2A). Levels of PAR were also similar for both species except at 1000 h, when PAR was significantly higher for $A. gayanus$ (Figure 2B). The diurnal range of LAVPD of $A. semialata$ leaves was similar to that of $A. gayanus$ from 1100 to 1600 h, although leaves of $A. gayanus$ had significantly higher LAVPD in the morning and afternoon (Figure 2C). By the dry season, early morning, and late afternoon $T_{leaf}$ and PAR were significantly lower for the persistent $A. gayanus$ compared to measurements in the wet season (Figures 2A,B). The LAVPD of $A. gayanus$ in the dry season was significantly higher than wet season measurements from 1100 to 1600 h (Figure 2C).

**Leaf and Canopy Scale Physiology**
Both species showed similar decreasing linear trends in $A$ throughout the day; however, in the wet season $A. gayanus$ assimilated carbon at significantly higher rates than $A. semialata$ (Figure 2D). Mean wet season rates of $A. gayanus$ $A_{max}$ and $T_{max}$ were 30% higher than $A. semialata$ (Table 1), with $A. gayanus$ maintaining a longer daily period of assimilation compared to $A. semialata$. $A. semialata$ exhibited net respiration by 1600 h while $A$ remained positive for $A. gayanus$ leaves until 1700 h (Figure 2D). Although lower than wet season rates, leaves of $A. gayanus$, were still assimilating carbon and transpiring in the dry season (Figures 2D,E) whereas $A. semialata$ was physiologically dormant. In the wet season,
morning levels of $T$ and $g_s$ for $A. gayanus$ and $A. semialata$ leaves were similar, however, by 1300 h, $A. gayanus$ had significantly higher rates than $A. semialata$. $A. gayanus$ was still transpiring water at 1700 h by which time $A. semialata$ rates of $T$ and $g_s$ was close to zero (still transpiring water at 1700 h by which time $A. gayanus$ had significantly higher rates than $A. semialata$). $A. gayanus$ had higher rates of $g_s$, water use and assimilation, although their leaves were similar, however, by 1300 h, $A. gayanus$ had significantly higher rates than $A. semialata$. $A. gayanus$ was still transpiring water at 1700 h by which time $A. semialata$ rates of $T$ and $g_s$ was close to zero (still transpiring water at 1700 h by which time $A. gayanus$ had significantly higher rates than $A. semialata$).

### Discussion

Along with land use change and climate change, alien plant invasion is one of the most threatening processes for the maintenance of biodiversity and ecosystem function. Interdisciplinary research is clearly needed combining ecology, eco-physiology, hydrology, and invasion biology to better understand differences between native and invasive alien species that will assist management and restoration of invaded ecosystems (Gioria and Osborne, 2014). Both instantaneous and time-integrated resource use efficiency (RUE) measures are required to assess performance on short-term (seasonal) as well growth cycles and phases of invasion. In this study, we used comparative measures of both instantaneous ($A_{max}$, $T_{max}$, $g_s$, ITE, LUE) and integrated measures of RUE (PNUE, LTWUE, LAI, biomass) to assess both resource acquisition and resource conservation performance in a highly seasonal environment.

Tropical savanna may represent a strong 'habitat filter' (after Weiker et al., 1998) as species grow and persist in a low $N$, annual drought affected, high water deficit, high VPD, and fire prone ecosystem. In such an environment, successful invasive species may exhibit similar resource conservation or RUE traits to native species that enable survival, however, this was not the case in this study. Under wet season conditions of high light, moisture, and $N$ availability, rates of stomatal conductance, $A$ and $T$ of the alien species were $30–40\%$ higher than the native species, with assimilation occurring for an additional 2 months of the year supported by a deep (up to 80 cm) and profusely branched, fibrous root mass (Rossiter-Rachor et al., 2009). Growth was maintained into the dry season with $A. gayanus$ stand biomass and LAI exceeding that of the wet season (Table 1). This finding is consistent with the meta-analysis of Cavalieri and Sack (2010) who found that invaders typically have significantly higher rates of $g_s$, water use and assimilation, although their analysis included few studies comparing invasive and native grasses.

### TABLE 1 | Mean eco-physiological traits of $A. gayanus$ and $A. semialata$ in the wet season, and $A. gayanus$ in the dry season.

<table>
<thead>
<tr>
<th>Species/season</th>
<th>AGB (g m$^{-2}$)</th>
<th>LAI (m$^2$ m$^{-2}$)</th>
<th>$A_{max}$ (µmol m$^{-2}$ s$^{-1}$)</th>
<th>$T_{max}$ (mmol m$^{-2}$ s$^{-1}$)</th>
<th>$g_s$ (µmol m$^{-2}$ s$^{-1}$)</th>
<th>C uptake (g m$^{-2}$ d$^{-1}$)</th>
<th>E (L m$^{-2}$ d$^{-1}$)</th>
<th>ITE (A/T)</th>
<th>LUE (A/ PAR)</th>
<th>PNUE (N/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A. gayanus$/Wet</td>
<td>183.9$^a$</td>
<td>0.82</td>
<td>18.31</td>
<td>6.35</td>
<td>0.27$^a$</td>
<td>2.68$^a$</td>
<td>2.51$^a$</td>
<td>1.73$^a$</td>
<td>0.017$^a$</td>
<td>0.06$^a$</td>
</tr>
<tr>
<td></td>
<td>(11.78)</td>
<td>(0.04)</td>
<td>(0.51)</td>
<td>(0.17)</td>
<td>(0.01)</td>
<td>(0.06)</td>
<td>(0.06)</td>
<td>(0.29)</td>
<td>(0.002)</td>
<td>(0.003)</td>
</tr>
<tr>
<td>$A. semialata$/Wet</td>
<td>44.8$^b$</td>
<td>0.22</td>
<td>11.8$^b$</td>
<td>4.88$^b$</td>
<td>0.16$^b$</td>
<td>0.54$^b$</td>
<td>0.46$^b$</td>
<td>2.37$^b$</td>
<td>0.022$^b$</td>
<td>0.1$^b$</td>
</tr>
<tr>
<td></td>
<td>(1.77)</td>
<td>(0.01)</td>
<td>(0.25)</td>
<td>(0.05)</td>
<td>(0.01)</td>
<td>(0.06)</td>
<td>(0.06)</td>
<td>(0.09)</td>
<td>(0.002)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>$A. gayanus$/Dry</td>
<td>405.5$^c$</td>
<td>1.11</td>
<td>3.31$^c$</td>
<td>1.42$^c$</td>
<td>0.03$^c$</td>
<td>0.97$^c$</td>
<td>0.70$^c$</td>
<td>2.53$^c$</td>
<td>0.008$^c$</td>
<td>0.31$^c$</td>
</tr>
<tr>
<td></td>
<td>(58.96)</td>
<td>(0.06)</td>
<td>(0.29)</td>
<td>(0.07)</td>
<td>(0.002)</td>
<td>(0.12)</td>
<td>(0.08)</td>
<td>(0.22)</td>
<td>(0.003)</td>
<td>(0.05)</td>
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<td>(b)</td>
<td></td>
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<tr>
<td>$A. gayanus$/Wet</td>
<td>15</td>
<td>15</td>
<td>94</td>
<td>94</td>
<td>3</td>
<td>3</td>
<td>210</td>
<td>18</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>$A. semialata$/Wet</td>
<td>15</td>
<td>15</td>
<td>59</td>
<td>59</td>
<td>3</td>
<td>3</td>
<td>108</td>
<td>8</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>$A. gayanus$/Dry</td>
<td>15</td>
<td>15</td>
<td>71</td>
<td>71</td>
<td>3</td>
<td>3</td>
<td>120</td>
<td>15</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Mean (SE) are given for above-ground biomass (AGB), leaf area index (LAI), maximum net photosynthesis ($A_{max}$), maximum transpiration ($T_{max}$), stomatal conductance ($g_s$), carbon uptake (C uptake), evaporation (E), instantaneous transpiration efficiency (ITE), instantaneous light use efficiency (LUE), photosynthetic nitrogen use efficiency (PNUE). Different superscripts in each column indicate significant differences at $P = 0.05$. $^b$Number of samples used to derive all variables.

Foliar $N$, $C$, and Isotopic Signatures

There was no significant difference between foliar $\%N$, $\%C$, or $\delta^{13}C$ for leaves of both species and nor between seasons for $A. gayanus$ (Table 2). $A. semialata$ and $A. gayanus$ foliar $\delta^{15}N$ values were similar in the wet season but were significantly lower than dry season values for $A. gayanus$ (Table 2).

Resource Use Efficiency Traits

Andropogon gayanus and $A. semialata$ had similar water use efficiency (WUE) according to three different measurements: IWUE (Figure 3), LTWUE ($\delta^{13}C$, Table 2) and ITE (Figure 4; Table 1). The PNUE and $A_{max}$, $T_{max}$, $g_s$ of $A. gayanus$ in the wet season were significantly higher than $A. semialata$ (Table 1). From the wet to dry seasons, $A. gayanus$ leaves showed significant increases in IWUE and ITE (Figure 4; Table 1); however, there was no change in LTWUE ($\delta^{13}C$, Table 2). By the dry season, $A_{max}$ of $A. gayanus$ leaves had decreased by 82% (Figure 5; Table 1) relative to wet season rates, while PNUE was significantly higher (Table 1). The LUE of $A. gayanus$ was significantly lower in the dry season compared to the wet season (Table 1; Figure 5).
TABLE 2 | Mean (SE) and ANOVA results for foliar percentage and isotopic nitrogen and carbon (%) of A. gayanus (n = 210) and A. semialata (n = 108) in the wet season and A. gayanus in dry season (n = 120).

<table>
<thead>
<tr>
<th>Variable</th>
<th>A. gayanus wet season</th>
<th>A. semialata wet season</th>
<th>A. gayanus dry season</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>% foliar N</td>
<td>1.1 (0.08)^a</td>
<td>1.14 (0.18)^a</td>
<td>0.99 (0.15)^a</td>
<td>( F_{(2,10)} = 3.78; P = 0.095 )</td>
</tr>
<tr>
<td>% foliar C</td>
<td>46.44 (0.10)^a</td>
<td>45.46 (0.39)^a</td>
<td>45.93 (0.27)^a</td>
<td>( F_{(2,10)} = 3.64; P = 0.065 )</td>
</tr>
<tr>
<td>% foliar C: N</td>
<td>42.92 (2.92)^a</td>
<td>42.24 (7.53)^a</td>
<td>51.00 (7.50)^a</td>
<td>( F_{(2,10)} = 11.67; P = 0.002 )</td>
</tr>
<tr>
<td>(^{15}N)</td>
<td>–3.28 (0.38)^ab</td>
<td>–2.37 (0.32)^a</td>
<td>–4.52 (0.44)^b</td>
<td>( F_{(2,10)} = 6.24; P = 0.017 )</td>
</tr>
<tr>
<td>(^{13}C) (LTWUE)</td>
<td>–11.18 (0.56)^a</td>
<td>–11.50 (0.29)^a</td>
<td>–12.00 (0.09)^a</td>
<td>( F_{(2,10)} = 0.65; P = 0.541 )</td>
</tr>
</tbody>
</table>

Different superscripts in each column indicate significant differences at \( P = 0.05 \).

While rates of \( A, T, \) and \( g_s \) were higher for the invader, there were no species differences in instantaneous water and light use efficiencies measures (IWUE, ITE, LTWUE, LUE), also consistent with meta-analysis of WUE of Cavaleri and Sack's (2010), even when this analysis was restricted to arid and semi-arid ecosystems (Funk, 2013). While both species are perennial grasses, in this environment leaf function (and age) is essentially annual, with leaf initiation, development, and gas exchange occurring only after the onset of wet season rainfall. This is followed by senescence after seed set in March–April (native species) or May–June (A. gayanus). As a consequence, leaves of both species develop in high water availability and low LAEV conditions with little difference in leaf-scale WUE. A. gayanus showed stomatal down-regulation and increases in IWUE and ITE (Figures 3 and 4) during the dry season, suggesting physiological plasticity in response to the higher LAEV and reduced soil moisture availability. Physiological plasticity has been demonstrated for a number of invasive species compared to native species in low-resource environments where resource availability fluctuates (Funk, 2008; Davidson et al., 2011). This is a favorable attribute for persistence in the seasonal tropics, which are characterized by large seasonal changes in resource availability, in particular available N, P, and moisture (Hutley et al., 2000; Soper et al., 2015).

Differences in leaf scale traits alone were unable to explain the 5–10 times greater stand scale biomass accumulation and fourfold increase in LAI of the invader at these sites (Table 1). The exception was PNUE, reflecting one of the most significant limiting resource in these mesic savannas, soil available N (Rossiter-Rachor et al., 2009; Soper et al., 2015). Most studies comparing nutrient-use efficiency in native and alien plants have found higher PNUE in the invasive species (Funk, 2013). For example, the alien African lovegrass (Eragrostis curvula) had a higher PNUE compared to native grasses in the low-nutrient soils of eastern Australia (Finn et al., 2012). Plant invasion is thought to mostly occur in resource rich environments, with invasion driven by altered growing conditions and release of resources via disturbance that differentially increases an invader’s competitive attributes (Daehler, 2003). Recent evidence suggests that invasion and persistence does often occur in low resource environments; however, drivers of this are poorly understood (Gioria and Osborne, 2014).

The invasive traits of A. gayanus identified in this study exhibit all three attributes suggested by Funk and Vitousek (2007) that are critical for invasion and perseverance in low-resource environments; (1) high resource acquisition and high RUE, (2) an active increase in resource availability following invasion, and (3) continued disturbance following invasion. Firstly, resource acquisition and RUE were exhibited by A. gayanus via higher rates of \( g_s, A, \) and \( T \), a longer growing season, high biomass and LAI and significantly higher PNUE. Secondly, an invasive species must actively increase resource availability. Comparative values of leaf \( ^{15}N \) (Table 2) suggested A. gayanus is likely to use more soil ammonium or have increase soil ammonium levels when compared to native grass dominated patches. This is consistent with findings of Rossiter-Rachor et al. (2009) who used labeled \(^{15}N\) experiments that showed A. gayanus’ preference for ammonium as an N source over nitrate. The presence of A. gayanus stimulated soil ammonification and potentially inhibited nitrification (Rossiter-Rachor et al., 2009). This mechanism drives a positive plant–soil feedback that promotes a broader niche width and improved habitat suitability for A. gayanus, in this N-limited ecosystem. Thirdly, Funk and Vitousek (2007) suggest an invader must promote continued disturbance that increases resource availability enabling persistence. A feature of A. gayanus invasion is high biomass (fuel) production and a shift to a high severity fire regime as described by Rossiter et al. (2003) and Setterfield et al. (2010). Severe invasion reduces woody cover by up to 80% within a decade post invasion (Brooks et al., 2010).
and initiates a grass-fire feedback. The loss in woody cover releases water, nutrient resources and increases radiation to the understory that further accelerates *A. gayanus* growth and invasion.

**Conclusion**

This study has shown that collectively, instantaneous, and time-integrated RUE traits, invasion-derived feedback loops combined with high propagule pressure confers substantial a competitive advantage to *A. gayanus* over both native grassy and woody lifeforms. These attributes largely explain its current invasiveness and persistence in Australia’s low-resource savanna ecosystems. This is an ecosystem transformation that is resulting in a rapid loss of biodiversity and significantly increasing fire risk (Setterfield et al., 2013). This study provides evidence from a seasonal tropical savanna ecosystem to support Funk’s (2013) assertion that invasive species in low-resource environments possess traits that allow both increased resource acquisition and resource conservation. This superior capacity of *A. gayanus* to compete for resources also supports modeling predictions of continued rapid invasion across the vast savanna region of northern Australia (Adams et al., 2015).
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References


Finn, J., Prober, S. M., and Buckley, Y. M. (2012). Plastic traits of an exotic grass contribute to its abundance but are not always favorable. PLoS ONE 7:4 e35870. doi: 10.1371/journal.pone.0035870


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