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Exploring trade-offs between water and carbon linked to woody encroachment in a native semi-arid grassland, Eastern Cape, South Africa

Weideman, C.[1]; Palmer, AR.[2]; Smart, K[3]

[1] Department of Environmental Science, Rhodes University, PO Box 94, Makhanda 6140, South Africa; [2] Institute for Water Research, Rhodes University, PO Box 94, Makhanda 6140, South Africa; [3] EFTEON, National Research Foundation, Pretoria

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Abstract

Woody encroachment has been widely documented in rangelands over approximately the last century. It is generally believed that this increase in aboveground biomass leads to increases in C sequestration, which, due to deeper rooting systems and leaf area of trees, implies a cost in terms of water availability due to increased evapotranspiration. To explore the evidence for this hypothesised trade–off in functionality, we installed a pair of identical eddy covariance flux towers in a native semi–arid C_4 grassland and an adjacent encroaching *Vachellia karroo* woodland in the Eastern Cape, South Africa, with otherwise similar site characteristics, and compared carbon © and water budgets over the period September 2019 to February 2022.

The woodland was marginally more productive than the grassland, but these C gains were offset primarily by disproportionately large dry season respiration effluxes, resulting in the grassland sequestering 65% more C than the woodland (389 g m^{-2} vs. 235 g m^{-2}) over ~20 months of concurrent data. Differences in water use were negligible, however, with the woodland evapotranspiring just 9% more water than the grassland (845 mm vs. 775 mm), equivalent to 78% and 70% of total rainfall (1103mm), respectively. Ecosystem water use efficiencies were essentially identical over the study period (2.7 g C m^{-2} [kg H_2O]$^{-1}$), with the grassland slightly more efficient in the dry season (2.6 vs. 2.5 g C m^{-2} [kg H_2O]$^{-1}$).

We found no evidence to support the hypothesis of a trade–off between C and water linked to encroachment at our sites. Given the complexity of ecohydrological and biogeochemical responses to vegetation shifts in these systems, however, and the wide variation in results reported in previous work, there is a clear need to replicate similar studies across broad environmental and climatic gradients towards improving understanding of these processes and developing coherent policy for rangeland management in the context of global change.

Introduction

Woody encroachment and proliferation has accelerated over the last century, understood to be a response to changing land management, biogeochemical, and climate drivers (O'Connor et al., 2014). This process has been particularly rapid in drylands, defined as regions with an aridity index of < 0.65 and characterised by open ecosystems typically comprising a dynamic complex of woody C_3 plant functional types and C_4 grasses (Archer et al., 2001). These systems account for nearly half the terrestrial land surface and, despite comparatively low levels of productivity relative to tropical and boreal forests, they play a major role in regulating the global C budget because they are so extensive globally, thus dominating the trend and inter-annual variability of the land sink (Ahlström et al., 2015).

Carbon dynamics in drylands are typically complex and non–linear, oscillating between net sources/sinks over seasonal and annual timeframes in response to management, high rainfall variability, and frequent drought. However, although the mechanisms are poorly understood and detailed accounting in many regions lacking (Biederman et al., 2017). Evidence of the effects of encroachment on C regulation in these systems is equivocal, and previous studies have reported increases, decreases, or no change in C sequestration rates relative to original vegetation types, because factors including rainfall thresholds, species functional traits, time since encroachment, and soil type all interact to mediate biogeochemical responses to varying degrees (Barger et al., 2011; Hughes et al., 2006).

Similarly, while increases in woody cover have been shown conclusively to lead to elevated water use and associated declines in catchment yields due to higher leaf area and deeper rooting systems of trees relative to grasses (Le Maitre et al., 2020), much of this work has focused on commercial forestry and alien invasive species in mesic and humid environments; the pattern is less clear in dryland systems. Impacts of vegetation shifts on the water balance tend to decrease with aridity, with semi–arid systems occupying a transitional zone along this continuum, and for which ecohydrological processes are least well understood (Huxman et al., 2005).

Despite these uncertainties, policy and planning relating to encroachment in drylands is often predicated on the assumption that higher aboveground biomass associated with increases in woody cover generally leads to increased C sequestration, reduced catchment runoff based largely on ecohydrological theory and extrapolation of data from different climatic regions and non-native species (Department of Environmental Affairs, 2019). Broad generalisations that do not account for the complexity of biogeochemical and ecohydrological responses to vegetation shifts in these systems hinders the development of effective responses to accelerating global change in these systems.

In South Africa, approximately 10 % of the land surface has experienced woody encroachment to varying degrees since the 1990s, with highest rates recorded in semi-arid and dry sub-humid grasslands and savannas with annual rainfall > 500 mm (Skowno et al., 2017). *Vachellia karroo*, a deep–rooted nitrogen fixing legume, is among the most prolific of approximately 40 identified encroaching species in the northern and eastern parts of the country. We compared ecosystem C and water budgets using paired eddy covariance technology in a native semi–arid C_4 grassland and adjacent encroaching *V. karroo*–dominated woodland in the Eastern Cape Province of South Africa over a period of ~30 consecutive months, to evaluate potential trade–offs in functionality linked to woody cover increases in these systems.

Methods

A pair of identical open–path eddy covariance systems was installed on a commercial livestock ranch near Adelaide in the Eastern Cape, South Africa, (-32.742, 26.471; ~770 m.a.s.l), and data analysed for the period 1st September 2019 to 28th February 2022. The towers provide high frequency (10 Hz) measurements of mass (CO2) and energy (sensible and latent heat) exchanges above vegetation canopies averaged over 30-minute intervals and integrated over footprint areas of several hectares.

The flux sites are separated by a distance of 890 m and located on flat or gently undulating topography. Soils are shallow (~0.75 m) and consist of a clay/loam complex over Beaufort Series sandstones. Mean annual precipitation is 730.4 (±158) mm, with mild dry winters (JJA) and hot, relatively humid summers (DJF) (Koppen classification *Cfa*). Rainfall is strongly seasonal, with ~70 % occurring over the austral spring and summer/early autumn months (Oct–Mar). Mean annual temperature is 17.7 (±3.2) ºC, with warmest temperatures in January (22.5 [±0.8] ºC) and coolest in July (13.2 [±1.5] ºC).

Vegetation at the grassland comprises a variety of perennial C_4 grasses, with several dwarf shrub species present in low abundances, and a sward height of ~0.4 m in the growing season. The woody component at the encroached site is dominated by *V. karroo*, with cover ranging from ~20–40 % and a mean canopy height of ~5 m; the herbaceous layer comprises largely continuous cover by a range of C_4 grass and forb species. Both sites are utilised for grazing by domestic livestock and wild game at stocking rates of ~4 ha LSU^{-1}.

Results

Daily net ecosystem C exchange (NEE), gross primary production (GPP), ecosystem respiration (R_{eco}), and evapotranspiration (ET) at each site are shown in FigureA; intermittent power and sensor failures over the total 912 days of measurement resulted the loss of 28% of data (254 days) from the grassland tower (GRA), predominantly during the 2020/2021 and 2021/2022 growing seasons, and 5% of data (43 days) from the tower at the woodland site (VKA) in the 2019 dry season; a total of 615 days concurrent data were obtained, comprising 230 and 385 days of growing and dry season data, respectively.

Both systems generally functioned relatively similarly in terms of C and water regulation, with similar flux phase and amplitude over the 615 days of concurrent data. Near–complete failure of late spring rains in 2019, corresponding with the end of a severe multi–year regional drought, resulted in a truncated 2019/2020 growing season, with marked declines in physiological activity well into summer of that year, but with some recovery evident from January 2020 onwards. VKA was almost uniformly marginally more productive than GRA over the 615 days, with 8% higher total gross photosynthetic uptake (2278 vs. 2103 g C m^{-2}). These C gains were offset by relatively larger respiration losses at VKA, however, with a total efflux of 2042 g C m^{-2} relative to 1713 g C m^{-2} (16%), resulting in 65% more C sequestered at GRA (389 vs. 236 g m^{-2}) over the 615 days. Water use at the two sites reflected differences in productivity, with just 9% more ET measured at VKA than GRA (845 vs. 775 mm), equivalent to 78% and 70% of total rainfall, respectively, over this period (1103 mm), and the difference assumed to have been converted to surface runoff.

The bulk of the difference in the C and water budgets between the two systems is explained primarily by dry season physiology, however; while both gross C uptake and ecosystem respiration were higher at VKA in both seasons, the difference in total dry season respiration efflux between the two systems was double that measured in the growing season (220 vs. 109 g C m^{-2}, respectively), resulting in 93% more C fixed in the dry season at GRA (114 vs. 8 g C m^{-2}) relative to 17% more in the growing season (275 vs. 228 g C m^{-2}) (Figure 1). Seasonal differences in water use between the two systems reflected this trend, with 16% more ET measured at VKA in the dry season (341 vs. 288 mm at VKA and GRA, respectively) relative to 3% more in the growing season (504 vs. 487 mm).

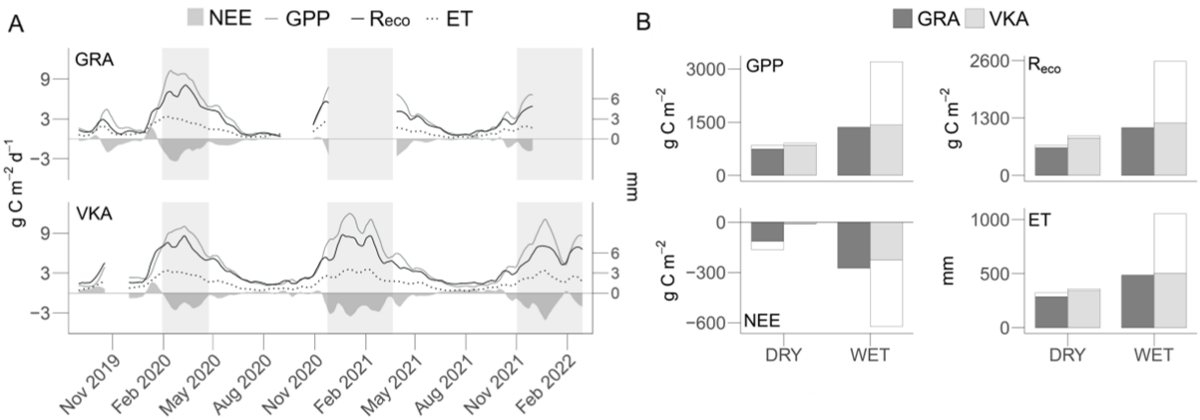

Figure 1: Daily NEE, GPP, R_{eco}, and ET measured at GRA and VKA over the study period; vertical grey bars indicate growing seasons (A). Total C and ET fluxes measured in dry (n = 385 days) and wet seasons (n = 230 days) over periods of concurrent data availability; white bars indicate sums calculated based on all available data at respective sites (B).

Growing season evaporative indices, calculated as the ratio of ET to precipitation, were almost identical (0.62 and 0.64 at GRA and VKA, respectively), with effectively all available rainfall utilised in the dry season (0.9 and 1.07, respectively), although the ratios of E:T in respective systems and seasons are undetermined. Ecosystem water use efficiencies (WUE_E), expressed as the ratio of daily GPP (g C m^{-2}) to ET (kg H_2O m^{-2}), over the study period were essentially identical (2.7 g C m^{-2} [kg H_2O]$^{-1}$); GRA was marginally more efficient in the dry season (2.6 vs. 2.5 g C m^{-2} [kg H_2O]$^{-1}$), however, with growing season values of 2.8 g C m^{-2} [kg H_2O]$^{-1}$ at both sites.

Discussion

Despite higher levels of productivity linked to increases in woody biomass at VKA, the grassland sequestered significantly more C than the woodland, attributable primarily to disproportionately larger dry season respiration effluxes at the former. The source of the additional dry season C losses at VKA is unclear, but since differences in GPP measured in each system were consistently relatively marginal, we anticipate that these likely originated from microbial decomposition of soil organic matter and necromass, although the underlying mechanisms would require further investigation. Reflecting differences in productivity, differences in total water use between the two systems were negligible and presumably explained by shallow soils and the absence of subsurface water at the flux sites, which constrains competitive advantage in terms of access to water conferred by deeper tree rooting systems relative to grasses in semi-arid environments. In this regard, topoedaphic and physiographic (upland vs. riparian) contexts are likely to be key factors in predicting the water use impacts of woody cover increases in water limited systems (Huxman et al., 2005).

Our data do not support claims of increased C sequestration and water use linked to encroachment in these systems, with the grassland sequestering 65% more carbon than the woodland at similar water use efficiencies. Given the complexity of ecohydrological and biogeochemical responses to vegetation shifts in drylands, and wide variation in results reported in previous work (Barger et al., 2011; Biederman et al., 2017; Hughes et al., 2006), our results underscore the need to replicate similar studies across environmental and climatic gradients to improve understanding of these processes and develop coherent policy for effective rangeland management in the context of global change.

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