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Managing semi-arid woodlands for carbon storage: Grazing and shrub effects on above- and belowground carbon

Stefani Daryanto[a], David J. Eldridge[b,*], Heather L. Throop[c,1]

[a] Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia
[b] Office of Environment and Heritage, c/-Australian Wetlands, Rivers and Landscapes Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia
[c] Biology Department, New Mexico State University, MSC 3AF, Las Cruces, NM 88003, USA

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ABSTRACT

Shrub cover has increased in semi-arid regions worldwide. This change has generally been viewed as land degradation, due to shrub-induced declines in pastoral productivity. As a consequence, widespread management treatments to reduce shrub density have been applied in many pastoral areas. These treatments, however, often do not have long-term positive benefits for forage production. Alternative uses for shrub-encroached lands have received little consideration, but a recent move towards economic incentives for carbon (C) storage could lead to financially viable alternative land management strategies. We examined changes in above- and belowground C storage following 20 years of factorial land management treatments (grazing/no grazing and shrub removal/no removal) in an Australian semi-arid woodland. Disturbance by shrub removal (root ploughing) and/or livestock grazing significantly reduced the amount of soil organic carbon (SOC). The most disturbed treatment (grazed and ploughed) contained the least SOC (15.30 Mg C ha^{-1}) while protection from grazing and shrub removal led to the greatest SOC (28.49 Mg C ha^{-1}). Declines in SOC in shrub removal treatments (with and without grazing) were compensated, in part, by enhanced aboveground C accumulation, derived mainly from woody plants. Destocking currently grazed shrublands for two decades resulted in a net C accretion, over 20 years, in the order of 6.5 Mg ha^{-1}, almost entirely through increasing belowground C. At the current price for C in Australia, the economic benefit for C accumulation from removing livestock grazing would be similar to the economic benefit of grazing. The results suggest that C farming in this semi-arid woodland system may offer an economically viable alternative management strategy to grazing, although uncertainties in future climate, C credit value, and assessment protocols present hurdles for implementing alternative management aimed at C farming.

1. Introduction

Humans have had a substantial impact on the physical and biological features of Earth, with approximately 83% of all terrestrial environments experiencing some kind of direct human influence, including urban settlement, agricultural or pastoral land use, and transport networks (Sanderson et al., 2002), resulting in various degrees of ecosystem degradation. One of the most severely impacted ecosystems is arid and semi-arid environments ('drylands'), which cover about 40% of the globe and support 40% of its human population (Maestre et al., 2012). Although disturbance (e.g., fire) has been a natural part of many dryland systems, these systems are still prone to human-induced disturbance processes, largely brought about by the introduction of domestic livestock grazing, agricultural practices, and changes to natural fire regimes (Van Auken, 2009).

One globally widespread form of land cover change in drylands is the increase in the density of woody plants, which leads to dramatic declines in pastoral productivity in many systems (e.g., Oba et al., 2000; Van Auken, 2009). The apparent mechanisms behind woody encroachment range in spatial scale from local-to-regional (e.g., increases in grazing and reductions in fire frequency) and regional-to-global (e.g., changes in N deposition, atmospheric CO_2 concentration, and climate; Sankaran and Anderson, 2009). Long periods of heavy grazing suppress grass production, and the resulting decline in grass fuel loads can alter the frequency and severity of wildfire, which exerts a controlling feedback effect on shrubs (D'Odorico et al., 2012). Increasing atmospheric CO_2 may favour the

* Corresponding author. Tel.: +61 2 9385 2194; fax: +61 2 9385 1558.
E-mail addresses: s.daryanto@student.unsw.edu.au (S. Daryanto), d.eldridge@unsw.edu.au (D.J. Eldridge), throop@nmsu.edu (H.L. Throop).
[1] Tel.: +1 575 646 5970.

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establishment of C_3 shrubs at the expense of C_4 grasses (Polley et al., 1997), and deep-rooted C_3 shrubs may be more physiologically active in dry conditions than shallow-rooted C_4 grasses (Throop et al., 2012b). Furthermore, biological feedbacks may promote the dominance of shrubs following their establishment. Enhanced soil faunal activity and deposition of nutrients beneath shrubs leads to positive plant–soil feedbacks whereby shrub growth is promoted in the interspaces at the expense of herbaceous plants (Holmgren, 2009). With generally greater levels of erosion in the interspaces and the collapse of facilitatory mechanisms due to excessive herbivory (Pugnaire et al., 2011), grass seedling establishment is infrequent. These 'novel systems' (Bridgewater et al., 2011), characterised by a greater cover and density of woody plants, are more strongly resistant to human-induced disturbances than the original systems from which they were derived (Standish et al., 2009).

The structure and composition of Australian vegetation has changed substantially in the two short centuries since European settlement. Large areas of Australia's grassland and woodland matrix have become encroached by shrubs, resulting in substantial reductions in pastoral productivity (Noble, 1997), and encouraging many pastoralists to control shrubs chemically and mechanically (Harland, 1993). One popular mechanical method is blade-ploughing (*aka* root ploughing), which has been widely promoted by government agencies to control a range of woody species (e.g., *Dodonaea*, *Senna* and *Eremophila* spp.; Robson, 1995). However, this method has been largely unsuccessful for long-term shrub eradication, and the failure of small-scale shrub removal has been blamed on regional-to-global factors such as highly variable regional rainfall (Brown et al., 1997) and rising atmospheric CO_2 concentrations (Morgan et al., 2007). As an alternative to mechanical removal, attempts to convert shrublands to their original open woodlands structure by destocking have produced inconsistent results (Angassa and Oba, 2007; Trodd and Dougill, 1998).

While the encroachment of woody plants is regarded by many as symptomatic of a degraded ecosystem (Grover and Musick, 1990), this view is mainly perpetuated in the grazing context. Considerable attention has been paid to the consequences of short- and long-term shrub removal on primary productivity (e.g., Daryanto and Eldridge, 2010; Robson, 1995). The ecological and economic consequences of shrub encroachment have received little research emphasis beyond pastoral impacts, despite evidence suggesting that encroachment can have positive impacts on multiple ecosystem functions (Eldridge et al., 2011; Maestre et al., 2009) or ecosystem 'multifunctionality' (Maestre et al., 2012). An emerging view is that encroaching shrubs, whether occurring in isolated patches or as extensive shrublands, can cause a state transition from historical grass dominance to an alternative, but stable, state (Standish et al., 2009). However, ecosystem multifunctionality in this altered stable state may still remain high (D'Odorico et al., 2012), even where herbaceous productivity is sparse or patchy. For example, shrubs may moderate surface micro-climate, reduce nutrient loss from erosional processes, enhance nutrient inputs via N fixation (Lajtha and Schlesinger, 1986), increase soil structure, stability, and the infiltration of water (Howard et al., 2012), and provide essential habitat for a range of shrub-obligate taxa (Daryanto and Eldridge, 2012; Eldridge et al., 2011; Howard et al., 2012; Maestre et al., 2009). Shrubs can also hasten the recovery of degraded systems by facilitating seedling establishment (Padilla and Pugnaire, 2006) due to their ability to moderate the effects of drought, and extremes of fire, salinity and frost (Booth et al., 1996; Richmond and Chinnock, 1994).

Carbon (C) uptake and storage may be substantially enhanced by shrub encroachment (Barger et al., 2011), and the potential ecological, economic, and atmospheric consequences of substantial shrub C uptake make this a key response variable. In North America, woody encroachment has been identified as one of the largest, albeit highly uncertain, components of the terrestrial C sink (Houghton, 2003; Pacala et al., 2001). This accumulation of C appears to be a function of enhanced below- and aboveground net primary productivity (NPP), low decomposition rates below shrubs, biochemical recalcitrance of woody litter, and organic matter stabilisation in protected soil aggregates (e.g., Knapp et al., 2008; Liao et al., 2006; Throop and Archer, 2007). Recent modelling using remote sensing data and measurements of C flux and vegetation growth as a function of climatic and soil data has identified a similar potential for C sequestration by shrubs in semi-arid system in Australian (e.g., Dean, 2011; Fensham and Guymer, 2009; Harper et al., 2007; Howden et al., 2001; Witt et al., 2011) and Mediterranean woodlands (e.g., Ruiz-Peinado et al., 2013). The magnitude of this C sink, however, is largely unknown. Also critical, but unknown, is the potential efflux of C that arises when existing shrubs are removed through management practices. This lack of information is surprising, given the large financial investment by regional and local governments in Australia in supporting the removal of shrubs from encroached woodlands on the expectation of enhanced pastoral (grazing) productivity (Robson, 1995). Recent legislation on a C price in Australia, financial incentives for landholders to sell or to lease their land for long-term C-sequestration schemes are likely (Prowse and Brook, 2011). Although shrublands typically sequester less C and are therefore less profitable than monocultural C plantations, a price on C should increase the development of 'biodiversity planting' (Prowse and Brook, 2011) or 'ecological carbon planting' through market-driven processes (Crossman et al., 2011). For Australian drylands, this ecological C planting may also provide a biodiversity and conservation co-benefit (Watson et al., 2011) and provide other ecosystem functions such as reduced salinisation and erosion (Scanlan et al., 1992).

Here we report on a study aimed at evaluating the long-term impact of different land management practices on above- and belowground C pools. In doing so, we re-evaluate the current paradigm that shrub encroached woodlands have low ecological and economic values. We do this by quantitatively assessing changes in plant and soil C stocks at different microsites in a shrub-encroached semi-arid woodland in eastern Australia subjected to varying combinations of grazing and mechanical shrub removal by blade-ploughing. We anticipated that the unploughed site from which grazing has been excluded for almost two decades would have greater total C than sites that were either ploughed or grazed, as both types of disturbance would decrease landscape-level pools of soil C. We expected therefore that the least-disturbed site would be valued more highly in terms of the ecosystem service of storing C; a service that has until recently not garnered much economic value.

2. Methods

2.1. Study area

The study was conducted at 'Wapweelah', an extensive grazing property about 35 km west of Enngonia near Bourke in north-western New South Wales, Australia (29°16′S, 145°26′E). The site falls within Gumbalie Land System (Walker, 1991), and is characterised by sandplain with low west–east trending sandy rises and dunes of Quaternary aeolian alluvium, and subject to moderate windsheeting and watersheeting. The slope is <1%, soil texture is sandy loam to loamy and the mean annual rainfall is about 312 mm, with 45% more rain falling during summer than winter (Robson, 1995).

The vegetation in the area is typical of areas in eastern Australia targeted for shrub removal by blade-ploughing (Harland, 1993).