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Research paper

Growth and carbon sequestration by remnant *Eucalyptus camaldulensis* woodlands in semi-arid Australia during La Niña conditions

Rhiannon Smith[a,*], Michael Renton[b], Nick Reid[a]

[a] *Ecosystem Management, School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia*
[b] *School of Plant Biology, The University of Western Australia, Crawley, WA 6009, Australia*

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A B S T R A C T

Recent research has shown the value of native vegetation in semi-arid regions for sequestering large amounts of carbon (C), particularly in La Niña years. In 2011, above-average rainfall led to significant vegetation growth and a 'greening' of inland Australia. During the period 2008–2012, we measured aboveground growth rates, biomass accumulation and C sequestration by river red gums (*Eucalyptus camaldulensis*), a commonly occurring tree species in riparian and floodplain ecosystems in semi-arid inland Australia. We measured trees representing the full range of ages, stand densities, canopy conditions and landscape positions. Our data suggest that river red gums can grow up to 6 cm (diameter at 1.3 m aboveground) per year, with most trees growing at a rate of <3 cm per year and sequestering on average, just over 2.5 t C $ha^{-1} yr^{-1}$ in aboveground woody biomass during high-rainfall and flood conditions. In general, trees in riparian zones grew faster than trees on the floodplain and trees in dense stands grew more slowly than widely-spaced trees. Sites with high aboveground woody biomass at the start of the study had the highest growth and C sequestration rates, indicating that those sites had not reached their C carrying capacity. Healthy crown condition was associated with faster growth in trunk diameter. While stem increment decreased with tree size, C sequestration increased in aboveground woody biomass, illustrating the importance of mature and old-growth trees as C sinks. This study highlights the contribution of semi-arid riparian woodlands for sequestering large amounts of C in aboveground woody biomass during above-average rainfall periods and the need to factor this important sink into global C budgets.

1. Introduction

The semi-arid regions of Australia, South Africa and South America have been highlighted as important contributors to an anomalous global carbon (C) sink, after above-average rainfall and flooding associated with La Niña conditions in 2011 triggered significant vegetation growth and C sequestration (Ahlström et al., 2015; Poulter et al., 2014). At the global scale, approximately 4.1 ± 0.9 Pg of C was sequestered by land-based C sinks in 2011, compared to the decadal average of 2.6 ± 0.8 Pg C yr^{-1} (Poulter et al., 2014). Approximately 840 million tonnes of C was sequestered by Australian ecosystems in 2011 alone, much of that attributable to woody vegetation recruitment and a 'greening' of semi-arid regions (Poulter et al., 2014). Weather events such as those recorded in 2011 have the potential to change the trajectory of emissions scenarios and climate change predictions, and have drawn attention to the need for more research into C sequestration in semi-arid ecosystems.

Riparian ecosystems, defined as land that adjoins, directly influences, or is influenced by a body of water (Boulton et al., 2014), are the most productive and biologically diverse ecosystems in semi-arid regions worldwide (Hamilton et al., 2015; Lee and Rotenberry, 2015; Naiman and Décamps, 1997). A sharp gradient in plant composition and productivity exists between riparian and floodplain ecosystems as a result of more mesic conditions, more reliable access to surface and ground water, and elevated nutrient levels derived from sediments and organic matter deposited by successive flood events close to the river (Naiman and Décamps, 1997). As such, riparian ecosystems in semi-arid regions are likely to

* Corresponding author.
E-mail addresses: rsmith66@une.edu.au (R. Smith), michael.renton@uwa.edu.au (M. Renton), nrei3@une.edu.au (N. Reid).

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sequester significant amounts of C, but few studies have quantified this benefit (but see Dean et al., 2012; Scott et al., 2004).

River red gums (*Eucalyptus camaldulensis*) occur in the riparian zone of most arid and semi-arid inland river systems in all mainland Australian states (Boland et al., 2006). These trees live for up to 1000 years and can attain diameters (diameter at breast height, DBH) of up to 4 m (Boland et al., 2006; Colloff, 2014). River red gums are widely grown in plantations around the world (NAS, 1980) and have very fast growth rates and moderately dense, termite-resistant hardwood (Boland et al., 2006; Doran and Wongkaew, 2008). In plantations in tropical regions, annual seedling diameter growth rates can be 4–6 cm (Doran and Wongkaew, 2008).

Studies show the positive relationship between water availability and river red gum growth, health, biomass accumulation and therefore C sequestration in riparian and floodplain woodlands in south-eastern Australia (Bacon et al., 1993; Catelotti et al., 2015; Doody et al., 2015; Horner et al., 2010; Robertson et al., 2001). Published C sequestration rates in regenerating river red gum woodlands in south-eastern Australia vary from 1.6 to 7.2 t C ha^{-1} yr^{-1} depending on age, tree density and flood frequency (Horner et al., 2010; Robertson et al., 2001). However, the growth or biomass accumulation rates of old-growth river red gum stands are uncertain (but see Robertson et al., 2001).

Internationally, there has been much recent discussion about growth rates (Bowman et al., 2013; Matsushita et al., 2015; Taylor et al., 2014), biomass accumulation and the value of individual large old trees for C sequestration (Stephenson et al., 2014). Previous assumptions that old-growth forests are C-neutral (i.e. net primary productivity or NPP is equal to heterotrophic respiration, Rh) and not sequestering C, came about after reductions in net ecosystem productivity (NEP = NPP − Rh, IPCC, 2000) were observed in aging plantation forests (Odum, 1969). This assumption was erroneously extended to individual trees in forest ecosystems (Stephenson et al., 2014). However, there is now growing evidence that while growth rates slow with tree age, biomass accumulation and C sequestration can continue to increase with tree size (and age) (Sillett et al., 2015; Stephenson et al., 2014). These findings draw attention to the potential value of old-growth trees for C sequestration (Baldocchi, 2008), in addition to their value for biodiversity conservation and provision of multiple ecosystem services (Daily, 1997).

Given the apparent potential for C sequestration in semi-arid regions, particularly in riparian ecosystems, tree growth and biomass accumulation rates with increasing tree size and age need to be understood, as well as the factors controlling growth and C sequestration rates. This paper reports the results of a 4-year study into growth, aboveground biomass accumulation and C sequestration in riparian and floodplain river red gum communities in semi-arid inland Australia. We investigated the effect of tree size, site position and crown condition (dieback severity) on tree growth to determine the impact of these factors on C sequestration rates. Using our tree growth data, we predicted tree ages at different sizes. Given the high rainfall owing to La Niña conditions during this study, aboveground growth and C sequestration rates are likely to be at a maximum, and our tree age–size predictions are likely to be modest (underestimates).

2. Methods

2.1. Study region

The study region was the lower Namoi catchment in northern New South Wales, Australia. Sites were located in the riparian zone and on the floodplain of the Namoi River between Boggabri (30.70°S, 150.03°E; 246 m asl) and Walgett (30.02°S, 148.12°E; 136 m asl) with most sites located east of Wee Waa (30.22°S, 149.44°E; 193 m asl: Fig. 1). Rainfall across the region is unreliable and sporadic, with mean annual rainfall decreasing from east to west from 600 mm at Boggabri to 470 mm at Walgett, with slight summer dominance (Supplementary material). The Namoi River is a highly regulated system with Keepit Dam and a series of weirs along the length of the river providing water for irrigation and flood mitigation (WRC, 1980). Groundwater levels are generally in decline across the region (Kelly et al., 2013).

The riparian zone of the lower Namoi River is dominated by a narrow band of river red gum forest or woodland, generally monocultural stands, occasionally with a shrubby understorey consisting of cooba (*Acacia salicina*) or river cooba (*A. stenophylla*). River red gums also occur away from the river channel on depressed floodplains and palaeochannels of the Namoi River. Dieback, a premature decline in crown health and death of river red gums, can be observed at various points along the river and is generally worse on the floodplain. Changes to flood frequency and duration as a result of river regulation and floodplain development are likely to have affected tree health, germination and recruitment dynamics of flood-dependent tree species such as river red gum in the region (Bunn and Arthington, 2002; Catelotti et al., 2015; Reid et al., 2007).

2.2. Field measurements

Permanent quadrats were established at nine sites in river red gum-dominated riparian and floodplain woodlands across the lower Namoi floodplain (Fig. 1). Quadrat area differed according to the density of stems at the site. Dense sites had quadrat areas of 25 × 25 m or 25 × 50 m while sparse quadrats were generally 100 × 100 m. Ninety trees were measured across the nine sites. Sites represented the range of land-use histories and stand condition states in the region. Initial diameters at breast height over bark (DBH, i.e. 1.3 m above ground level) were taken in late winter 2008 and repeat measurements were taken in early spring 2012. Rainfall during the study was average to above-average owing to La Niña weather conditions (Supplementary material). In 2010, annual rainfall across the region was 1.6 or 1.7 times the long-term average rainfall.

Aboveground woody biomass was measured in quadrats as reported in Smith and Reid (2013). Briefly, DBH was measured using a metal diameter tape for large trees or electronic digital callipers for small trees. Observer error was estimated using DBH measurements of dead trees, i.e. the difference in DBH of a dead standing tree between the first and second time periods gave an estimate of observer-based error, which was on average ≤0.5 mm. In addition to DBH measurements, site environmental variables were recorded, including position in the landscape (riparian or floodplain), the overall health of the site in terms of the severity of dieback based on crown condition (healthy, intermediate or severely dieback-affected) and the number of stems per hectare (stem density).

Tree growth rates were calculated as the difference in DBH over the 4-year period and are reported as average annual figures. Allometric equations (1–3 below) were used to calculate aboveground tree biomass (wood and canopy) from tree DBH measurements. Equations for forest (Eq. (1)) and woodland (Eq. (2)) trees developed by the Australian Greenhouse Office (Snowdon et al., 2000) were compared with an equation developed specifically for river red gums (Robertson et al., 2001: Eq. (3)). The river red gum specific equation (Eq. (3)) was used to calculate aboveground biomass of individual trees in this study as it gave the most conservative biomass estimates when the three equations were compared. The difference in standing biomass between time one (2008) and time two (2012) was assumed to be accumulated biomass, of which 50% was assumed to be C sequestered by the tree (Snowdon et al., 2000). Aboveground C accumulated by individual