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Repeated harvest residue removal reduces *E. globulus* productivity in the 3rd rotation in south-western Australia

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ABSTRACT

The use of biomass for energy is becoming increasingly popular, with many plantation forestry growers considering selling or using the biomass to generate renewable energy. It is known that this may lead to a net export of nutrients from the site, but the capacity of plantation sites to buffer this and sustain yield has not been quantified. In 2 long-term experiments, we explored the impact of repeated residue removal, retention, or retention of double the quantity of residues over 2 rotations of *Eucalyptus globulus* in south-western Australia. The 2 sites that we used had contrasting soil types, and we previously reported differential responses of plantation productivity to residue manipulation in the 2nd rotation. In this study we have shown that removal of harvest residues (and litter) into a 3rd rotation of *E. globulus* resulted in a significant impact on plantation productivity at both sites. It is important to note that a response to residue removal occurred even at a site that was highly productive in the first and second rotations, and which did not respond to residue removal or N fertilizer addition in the 2nd rotation. Retention of harvest residues and litter resulted in a significant increase in soil exchangeable cations at the higher productivity site, but the impacts on total soil C and N stocks were not as clear cut, with no significant changes to either of these, although a trend in the means for increased soil C under the residue retained treatments at the Red Earth site should be monitored into the future.

1. Introduction

Biomass is recognised as a significant potential contributor to renewable energy generation (Smeets and Faaij, 2007; Farine et al., 2012), and consequently plantation harvest residues can have considerable value as a renewable energy feedstock (IEA, 2002; Asikainen et al., 2002). If residues are retained on site, they can represent a fire risk, and/or lead to higher re-establishment costs because the residue material can be difficult to manage in highly mechanised operations. These factors have tended to influence management decisions toward removal of residues in many systems prior to replanting of the next rotation (e.g. Nambiar, 2010). However, removal of harvest residues has also been shown to have potentially detrimental effects on the site productive potential (Burger, 2002), mainly due to higher rates of nutrient and organic matter export, with the residue components (typically containing higher proportions of leaves, bark, branches and twigs) also having significantly higher concentrations of nutrients than the woody components (e.g. Sankaran et al., 2005). We have previously reported on the impacts of harvest residue removal on the productivity and soil properties at 2 second-rotation plantations in south-western Australia up to age 6 years (Mendham et al., 2003). That study showed that there were no significant effects of residue manipulation on 2nd rotation plantation productivity at a high fertility site, but that residue removal detrimentally affected productivity at the lower fertility site. There was no reported impact of residue management on soil carbon, nitrogen or exchangeable potassium in the 2nd rotation of Mendham et al. (2003). The aim of this study was to explore the impacts of harvest residue manipulation on plantation productivity and soil nutrients after the treatments were re-imposed into the 3rd rotation.

2. Materials and methods

2.1. Study sites and experimental treatments

Two sites in south-western Australia with differing harvest residue management treatments were used in this study. The sites were fully described in Mendham et al. (2003), but in summary they consisted of a higher fertility Red Earth site, and a lower fertility Grey Sand site. The sites contrasted substantially in

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productivity during the first rotation, with around 3-fold the yield of stem wood at the Red Earth site (189 Mg ha^{-1}) compared to the Grey Sand (62.7 Mg ha^{-1}) site (Mendham et al., 2003). Selected characteristics of the surface soils at each site are shown in Table 1, and selected soil chemistry to 1 m depth are shown in Table 2. The Grey Sand site has low clay content, but a similar level of organic matter to the Red Earth site. It also tended to have lower nutrient content, although it had higher magnesium content than the Red Earth soil, possibly attributable to the differing parent material at each of the sites. The soils in the weathered landscape of Western Australia are typically quite deep, and we would anticipate that the soils in these experiments would be deeper than 4–8 m, with roots of *Eucalyptus globulus* plantations typically extending to this depth within 4–5 years (Mendham et al., 2011).

The treatments imposed at the start of the second rotation were:

- Burn (B): Harvest residues and litter evenly distributed and burnt (not continued into the 3rd rotation, see below).
- Zero residues (0S): Residues and litter removed.
- Single residues (1S): Residues and litter evenly redistributed and retained.
- Double residues (2S): Double the quantity of residues and litter, which was achieved by moving the residues from the 0S treatment across to the 2S treatment.

The treatments were imposed in a replicated block design with 4 replications. Experimental plots were 18 m × 18 m, with 40 trees per plot. A single buffer row was maintained within the plot, with the inner measure plot comprising 24 trees. The second rotation was planted with seedlings in July 1995, and harvested when it was at age 9.5 (Red Earth) and 10 (Grey Sand) years.

For the 3rd rotation, it was our intention to re-establish both sites with coppice, but the survival of coppice at the Red Earth site was poor due to an earlier thinning operation that had killed around 30% of the stumps. Thus the trees at the Grey Sand site were re-established by allowing the stumps to coppice, and the trees at the Red Earth site were replanted with *E. globulus* seedlings in July 2005. The remaining coppice regrowth at the Red Earth site was controlled at planting with glyphosate. The replanted genetic material was the latest deployment and more advanced than the 2nd rotation. The coppice trees at the Grey Sand site were reduced to 2 stems per stool at around age 2 years as per standard industry practice in Western Australia. Three of the experimental treatments from the 2nd rotation were re-imposed on the same plots after harvest (0S, 1S and 2S). The burn treatment was not reimposed because it would have compromised the intention to re-establish the stands with coppice regrowth.

An additional treatment of N fertilizer addition (+F) was added to the design at age 3 years. This treatment utilised spare plots within the design, which were available because of a +P treatment that had shown no response (data not shown) and had been discontinued early in the 2nd rotation (~10 years prior to the establishment of the 3rd rotation). The +F treatment had 250 kg N/ha applied in autumn as urea annually from age 3–6 years, and a harvest residue retention treatment equivalent to 1S.

Table 1
Selected site and surface soil (0–10 cm) characteristics of the study sites (after Mendham et al., 2003). Values for pH, carbon, nitrogen and exchangeable cations were averaged over all treatments, collected annually for the first 7 years of the 2nd rotation. Values for clay content were derived from a one-off sampling and are average values across all plots in the experiment. Standard deviation is shown in parentheses.

	Red Earth	Grey Sand
Site		
Location	34.3°S, 116.0°E	33.75°S, 115.1°E
Mean rainfall (mm y^{-1})	1023	825
Mean summer temperature (°C)	17.3	19.2
Mean winter temperature (°C)	10.2	12.3
Soil Type (FAO, 1998)	Rhodic Ferralsol	Haplic Podzol
Planting density (trees ha^{-1})	1250	1250
Soil (0–10 cm)		
Clay (%, <2 μm)	16.7 (2.8)	0.7 (0.4)
pH (1:5 H_2O)	6.4 (0.21)	5.2 (0.15)
Organic C (mg g^{-1})	44.0 (2.8)	40.1 (2.2)
Total N (mg g^{-1})	2.54 (0.16)	1.60 (0.14)
Exchangeable K (mg kg^{-1})	75 (39)	48 (16)
Exchangeable Ca (mg kg^{-1})	736 (202)	638 (82)
Exchangeable Mg (mg kg^{-1})	79 (22)	116 (12)

2.2. Climate data

Climate data was sourced from the SILO climate data service (Jeffrey et al., 2001), which provides interpolated daily climate information for the closest point on a 0.05° grid of Australia's land surface.

2.3. Plantation productivity

The trees were measured annually, with heights and diameters assessed for every tree within the inner measured plots. Standing volume was calculated by aggregating individual tree conical volumes (Rance et al., 2012).

2.4. Harvest residue nutrient content

Nutrient contents of the harvest residues at the end of the 2nd rotation were calculated as the sum of nutrients in the individual components (leaves, bark, twigs and branches). This was calculated using allometric relationships developed between nutrient content and tree dimensions on the same set of trees as were studied by Rance et al. (2012). The final tree measurement of the 2nd rotation (assessed in mid 2005, a few months before harvest) were used as the basis to predict harvest residue nutrient contents.

2.5. Soil sampling and analysis

Soils were sampled from each of the harvest residue management plots in 2012 and 2013. Mineral soil samples were taken from the 0–10 and 10–20 cm depth ranges, after removing the surface litter down to the mineral-soil interface. The surface 20 cm was chosen because it is the most actively cycling region of soil and is the most likely to be responsive to treatment effects. A total of 9 steel cores were inserted into the ground (to 20 cm depth) per plot, removed intact and returned to the laboratory where they were extracted, separated into the 2 depth intervals and air dried. Air dried soils were analysed by CSBP analytical laboratories (Bibra Lake, Western Australia) for exchangeable cations (Ca, Mg, K) on the 2012 samples, and for soil organic C and total N on the 2013 samples, all using the standard methods described in Rayment and Higginson (1992). Bulk density of the <2 mm fraction was calculated directly using the weight of soil in the sampled cores on a plot basis, sampled annually (as above) for the first 6 years of the 2nd rotation. The bulk density data did not change significantly over time, thus an average value was calculated per plot. Soil nutrient contents were calculated by multiplying bulk density by nutrient concentration on a plot level.

2.6. Statistical analysis

Treatment comparisons were tested using one-way analysis of variance for soil variables, and one-way analysis of covariance for stand productivity, using the first rotation stump diameters as