

Soil carbon and nitrogen dynamics in the first year following herbicide and scalping in a revegetation trial in south-east Queensland, Australia

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Abstract During revegetation, the maintenance of soil carbon (C) pools and nitrogen (N) availability is considered essential for soil fertility and this study aimed to evaluate contrasting methods of site preparation (herbicide and scalping) with respect to the effects on soil organic matter (SOM) during the critical early establishment phase. Soil total C (TC), total N (TN), hot-water extractable organic C (HWEOC), hot-water extractable total N (HWETN), microbial biomass C and N (MBC and MBN), total inorganic N (TIN) and potentially mineralizable N (PMN) were measured over 53 weeks. MBC and MBN were the only variables affected by herbicide application. Scalping caused an immediate reduction in all variables, and the values remained low without any sign of recovery for the period of the study. The impact of scalping on HWETN and TIN lasted 22 weeks and stabilised afterwards. MBC and MBN were affected by both herbicide and scalping after initial treatment application and remained lower than control during the period of the study but

did not decrease over time. While scalping had an inevitable impact on all soil properties that were measured, that impact did not worsen over time, and actually improved plant growth (unpublished data) while reducing site establishment costs. Therefore, it provides a useful alternative for weed control in revegetation projects where it is applied only once at site establishment and where SOM would be expected to recover as canopy closure is obtained and nutrient cycling through litterfall commences.

Keywords Soil carbon · Nitrogen availability · Site management · Scalping · Herbicide · Revegetation

Introduction

In Australia, revegetation efforts are increasing (Paul et al. 2002) and the main goals of restoration projects are to alleviate land degradation and biodiversity loss as a consequence of previous clearing of native vegetation, often as a consequence of mining operations and infrastructure projects. One of the major costs associated with revegetation during the establishment phase is site maintenance to reduce weed competition for resources (light, water and nutrients) as competition from unwanted plant growth is one of the primary causes of establishment failure. The effects of site preparation on soil organic matter (SOM) including carbon (C) pools and nitrogen (N) availability have been extensively investigated (Blumfield and Xu 2003; Xu and Chen 2006; Burton et al. 2007; Huang et al. 2008b; Xu et al. 2008) indicating a link between soil fertility and SOM (Roose and Barthès 2001). The above study shows that SOM variables are sensitive indicators to investigate the effects of site preparation practices particularly weed control methods on soil C and N availability.

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Repeat applications of herbicide are the most commonly used site preparation technique; this requires multiple visits before and after establishment and is thus expensive. Herbicides may also influence soil micro-organisms (Busse et al. 1996, 2006; Araújo et al. 2003) leading to an alteration of C and N pools (Huang et al. 2008a, b; Ibell et al. 2010). While herbicide application may not significantly affect SOM, it may not effectively control weeds either as the soil weed seed bank remains (Hosseini Bai et al. 2012a, b), and in the longer term, herbicide-resistant species may develop (Bailly et al. 2012). Alternative, nonherbicidal methods of weed control are therefore worth consideration. Removal of the top 10 cm of soil (scalping) is a potential alternative method which drastically reduces the soil weed seed bank. However, it also removes the top soil which contains the majority of the soil C and N pools. Furthermore, such soil disturbance may alter soil microbial activities due to changes in the abiotic soil components including both temperature and moisture (Hendrickson et al. 1985) and promote nutrient loss (Zabowski et al. 1994).

These site preparation techniques may affect plant early growth due to reduced weed competition (MacDonald and Thompson 2003; Graham et al. 2009) or alteration of nutrient cycling and availability (Ibell et al. 2010). It is important to understand how the contrasting methods of site preparation affect these variables following treatment application. Different measures of soil fertility may be used to evaluate soil C pools and N availability, including total C (TC), total N (TN), inorganic N, hot-water extractable organic C (HWEOC), hot-water extractable total N (HWETN), microbial biomass C (MBC), microbial biomass N (MBN) and potentially mineralizable N (PMN). These variables are indicators of soil properties associated with soil C and N cycling and availability as pointed out in various studies (e.g. Blumfield and Xu 2003; Chen and Xu 2005; Blumfield et al. 2006a; Burton et al. 2010; Hosseini Bai et al. 2012a, b). Those studies demonstrated that these variables reflected the productivity of an ecosystem and were highly influenced by soil disturbance. Studying the effects of radical treatments like scalping on these soil properties allows us to understand the changes in soil C and N pools and, consequently, the long-term implications of using these techniques. Our previous work did not show an improvement in soil C and N pools in the scalped areas during a 20-week period before planting (Hosseini Bai et al. 2012b). However, after tree planting, there may be an accelerated change in soil fertility. Therefore, there was a need to monitor soil C and N pools after planting for possible recovery in the scalped areas. This project was designed to explore the post-planting dynamics of soil C and N pools in the planted areas treated by herbicide and scalping compared to areas with no disturbance.

Materials and methods

Site characteristics

The experimental site was established at Laidley (27°40'31 S, 152°24'04 E), approximately 75 km west of Brisbane, south-east Queensland, Australia, and was an abandoned grass land dominated with *Chloris gayana* Kunth (Poaceae). The experimental site was established in December 2009. Soil at the site had 24 % clay, 25 % silt and 52 % sand content, and its pH was 5.8. Through the study, the average maximum daily temperature was 26°C ranging from 21 to 33°C, and in 2010, annual precipitation was 820 mm (Fig. 1).

Experimental design and treatments

The experiment was designed as a randomised split-plot complete block with four blocks and four replicates per treatment at each block. Each plot was divided to two sub-plots, and each sub-plots received either herbicide or scalping. The plots were 12 m×12 m consisting of six planting rows with eight plants in each row at approximately 1.5 m×1.5 m spacing. Each planting row was ripped to a depth of 30 cm. The three species, *Acacia concurrens* Pedley APNI (Fabaceae), *Melaleuca quinquenervia* (Cav.) S.T.Blake APNI and *Eucalyptus crebra* F. Muell. (both Myrtaceae), were planted in random order in the plots in December 2009. The first herbicide was applied in December 2009 prior to planting with subsequent post-planting herbicide application in February and October 2010 to suppress weeds. The first herbicide application was a mixture of glyphosate (1.5 kg ha⁻¹) and MCPA (2 l ha⁻¹) afterwards a selective herbicide, Fusilade at 3.3 l ha⁻¹, was applied. Approximately 10 cm of top soil was removed in the scalped areas by a road grader, with the blade angled to displace the soil into wind-rows, to control weeds and to decrease seed banks. Bare soil (control plots from now on) received neither of the treatments and was not planted either.

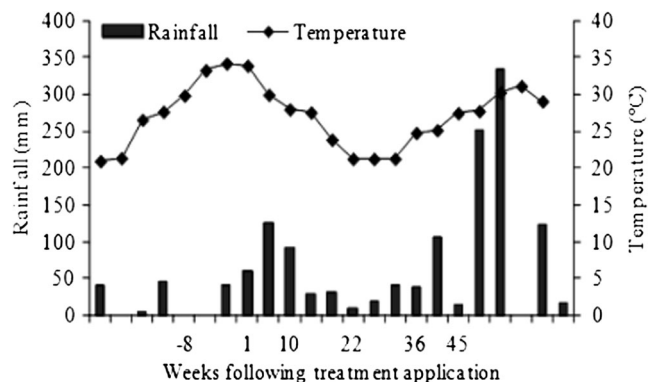


Fig. 1 Monthly rainfall (grey columns) and mean maximum daily temperature (close rhombus) of the experimental site located at Laidley, south-east Queensland, Australia, from June 2009 to April 2011

Soil sampling and analyses

The soil was collected six times: 8 weeks before (week -8) and 1, 10, 22, 36 and 45 weeks after treatment application from October 2009 to November 2010. The soil samples (0–5 cm) were collected at five positions in each plot using a 60 mm internal diameter auger. The sampled soils in each plot were bulked, well mixed and passed through a 2-mm sieve. A sub-sample of approximately half of the soil was air-dried, and the remainder was refrigerated at 4 °C and processed shortly after sampling.

Soil moisture content was assessed using 10 g soil which was kept in an oven at 105 °C for 24 h, and soil moisture content was calculated considering soil weight before and after oven-drying. Total C (TC) and total N (TN) of air-dried samples were determined. A fine powder of soil, approximately 20 mg, was weighed into tin capsules to measure TC and TN using a mass spectrometer (GV Isoprime, Manchester, UK; Blumfield et al. 2006b).

HWEOC and HWETN were determined by incubation method using a Shimadzu TOC-V_{CSH/CSN} TOC/N analyser (as described in Hosseini Bai et al. 2012a, b). To measure MBC and MBN, a fumigation–extraction method was used and the TOC and TSN of both fumigated and non-fumigated extractions were measured using a Shimadzu TOC-V_{CSH/CSN} TOC/N analyser (as described in Hosseini Bai et al. 2012a, b).

Soil NH₄⁺-N and NO₃⁻-N were determined in a 2 M KCl extraction using a SmartChem 200, discrete chemistry analyser (DCA) and total inorganic N (TIN) was the sum of these two parameters. To measure potentially mineralizable N (PMN), briefly, two sub-samples (5 g) of air-dried sample were weighed. One sub-sample was added to 25 ml water and incubated at 40 °C for 7 days. After incubation, 25 ml of 4 M KCl was added to the samples, and the suspension was shaken for 60 min and centrifuged for 20 min at 2,000 rpm. After centrifuging, the samples were filtered by a Whatman No. 42 filter paper. The second sub-sample of soil was added to 50 ml of 2 M KCl and processed as above but without incubation. Inorganic N of both samples were determined using SmartChem 200 DCA, and the PMN was measured as described in Blumfield et al. (2006).

Statistical analysis

The initial difference between the two treatments and the control at week -8 were removed from all data set and then the variations in the control were also removed from sampling time to sampling time. The effect of this processing of the data was to statistically control for both differences existing before the treatment and also to remove variation over time. The derived variables are called control-standardised from now on and present as st(variable) in the text. Then, the control-standardised values for each sampling time (called ‘weeks’)

were plotted for each treatment. To indicate the immediate effect of the treatment, computation of the significance of differences (ANOVA) between each treatment and the control in week 1 was performed to indicate an immediate effect of treatments. Afterwards, the best fit polynomial curve (0.95 Conf. Int.) for each set of data from weeks 1 to 45 was fitted and a simple homogeneity of slopes regression for weeks 1 to 45 was examined (assuming all trends are linear) to assess the trends on the values for each soil variable over time for each treatment. Where the regression of effect over weeks is evidently not linear, a piecewise regression was applied. All analyses were performed using an IBM SPSS statistic 20.

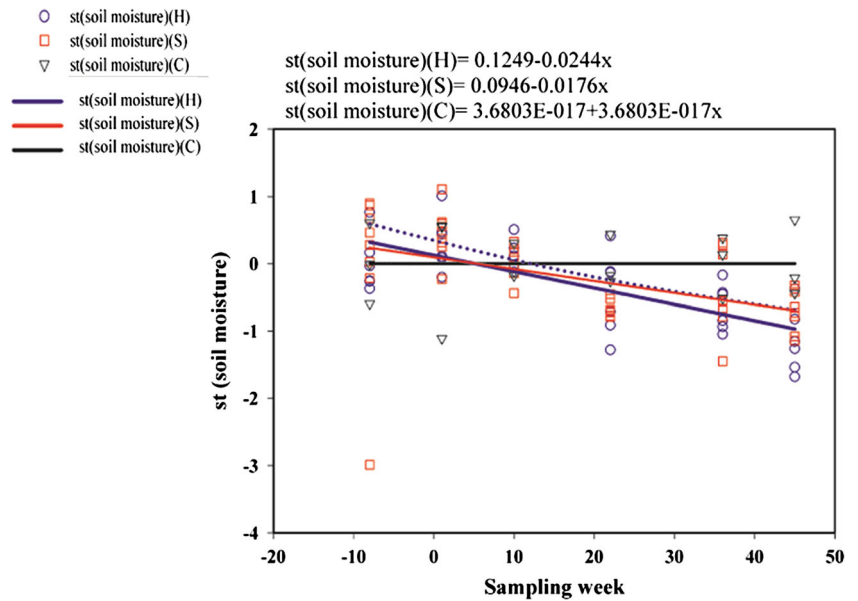
Results and discussion

Soil moisture

A scatter plot of control-standardised soil moisture indicated that soil moisture may have decreased in both herbicide and scalped plots relative to the control after week 1 (Fig. 2). The best fit was linear for both herbicide ($p < 0.01$; $R^2 = 0.51$) and scalping ($p < 0.01$; $R^2 = 0.21$). The difference between the treatments and control at week 1 indicated that there was no immediate effect of herbicide and scalping on soil moisture relative to control (Herbicide: $p = 0.34$ and scalping: $p = 0.58$). A simple homogeneity of linear slopes regression was computed for each of herbicide vs. control and scalping vs. control assuming linear regressions (Table 1). It does appear that soil moisture fell over the period of study more in the treated plots than in the control, but no immediate effect of herbicide and scalping was observed relative to the control. Soil moisture loss at both treatments continued and the values in the herbicide areas were lower than those of the scalped areas.

Our study suggested that soil moisture may have continued falling in both herbicide and scalping relative to control. Conflicting results have been reported regarding the impacts of weed control on soil moisture. For instance, weed control may decrease soil moisture due to sun exposure or wind (Close and Davidson 2003) or preserve it due to decreased demand for water by competitors (MacDonald and Thompson 2003). Huang et al. (2008b) found that weed control using herbicide did not affect soil moisture compared to control plots in a hardwood plantation in Australia. Water can be a limiting factor for plant growth, particularly, when plants are young. In the present study, it was important to know that the scalping had less effect on plant water availability than herbicide. Greater weed coverage in the herbicide areas than in the scalped areas (Hosseini Bai 2012) may have increased water usage by plants and also promoted evapotranspiration leading to faster reduction in water availability in the herbicide areas relative to scalping.

Fig. 2 Soil moisture content over 53 weeks in the control (C), herbicide (H) and scalped (S) plots in a revegetated ecosystem of south-east Queensland, Australia



TC, TN, HWEOC and HWETN

It was evident that st(TC) and st(TN) in the herbicide and scalped plots decreased between weeks -8 and 1, but it rose by week 45 (Fig. 3a, b). The comparison between the treatments and the control at week 1 indicated that herbicide did not immediately decrease st(TC) and st(TN) significantly, while values in the scalped areas were lower than those of the control plots ($p=0.01$ and $p=0.01$, respectively). A simple homogeneity of linear slopes regression was computed for each of herbicide vs. control and scalping vs. control assuming linear regressions (Table 1). Above analysis indicates that the level of st(TC) and st(TN) in the herbicide areas remained unchanged relative to the control during the period of the study. However, in the scalped areas, st(TC) and st(TN)

decreased after the initial treatment in week -8, and while some recovery was evident, it was not statistically significant.

There was little difference in st(HWEOC) between the herbicide and the control treatments, whereas st(HWEOC) in the scalped areas fell rapidly by week 1 and stayed well below the control values, through week 45 (Fig. 4a). The difference for st(HWEOC) in week 1 was only significant between the control and the scalped areas ($p<0.01$) suggesting that an initial application of herbicide had no detectable effect on HWEOC, but scalping dramatically reduced its levels.

The best fit polynomial curve for each treatment effect was a cubic curve (the significance of the cubic term was $p<0.01$ for herbicide data and $p<0.01$ for scalping; Fig. 4b). Both curves suggest an increase in st(HWEOC) relative to the control between weeks 1 and 10, a fall thereafter to week 36

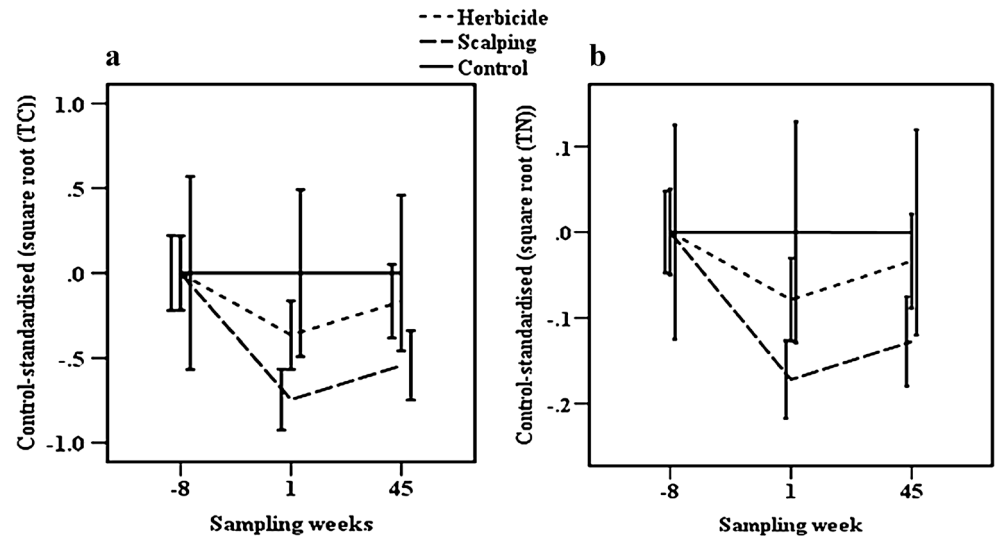
Table 1 Probability for univariate test of control standardised soil moisture, total C (TC), total N (TN), hot-water table organic C (HWEOC) and hot-water extractable total N (HWETN), microbial biomass C and N

(MBC and MBN), potential mineralizable N (PMN) and total inorganic N (TIN) for herbicide vs. control (H vs. C) and scalping vs. control (S vs. C) over sampling weeks

	Soil moisture		TC		TN		HWEOC		HWETN	
	H vs. C	S vs. C	H vs. C	S vs. C	H vs. C	S vs. C	H vs. C	S vs. C	H vs. C	S vs. C
Intercept	0.51	0.68	0.16	0.02	0.20	0.02	1.45	< 0.0001	0.37	0.007
Treatment (T)	0.51	0.68	0.16	0.02	0.20	0.02	1.45	< 0.0001	0.37	0.007
Sampling week (SW)	0.002	0.06	0.88	0.40	0.92	0.38	0.82	0.8	0.12	0.02
T × SW	0.002	0.06	0.88	0.40	0.92	0.38	1.82	0.8	0.12	0.02
	MBC		MBN		PMN		TIN			
	H vs. C	S vs. C	H vs. C	S vs. C	H vs. C	S vs. C	H vs. C	S vs. C		
Intercept	< 0.0001	< 0.0001	0.01	< 0.0001	0.14	< 0.0001	0.66	0.32		
Treatment (T)	< 0.0001	< 0.0001	0.01	< 0.0001	0.14	< 0.0001	0.66	0.32		
Sampling week (SW)	0.55	0.15	0.37	0.72	0.22	0.08	0.88	0.06		
T × SW	0.55	0.15	0.37	0.72	0.22	0.08	0.88	0.06		

Significant probabilities are presented in bold

Fig. 3 Soil a total C (TC) and b total N (TN) over 53 weeks in the control, herbicide and scalped plots in a revegetated ecosystem of south-east Queensland, Australia



and then another recovery. No effect of herbicide on st(HWEOC) was observed, while in the case of scalping, there

is an immediate reduction in st(HWEOC) values after scalping, and these values remained low for the period of the

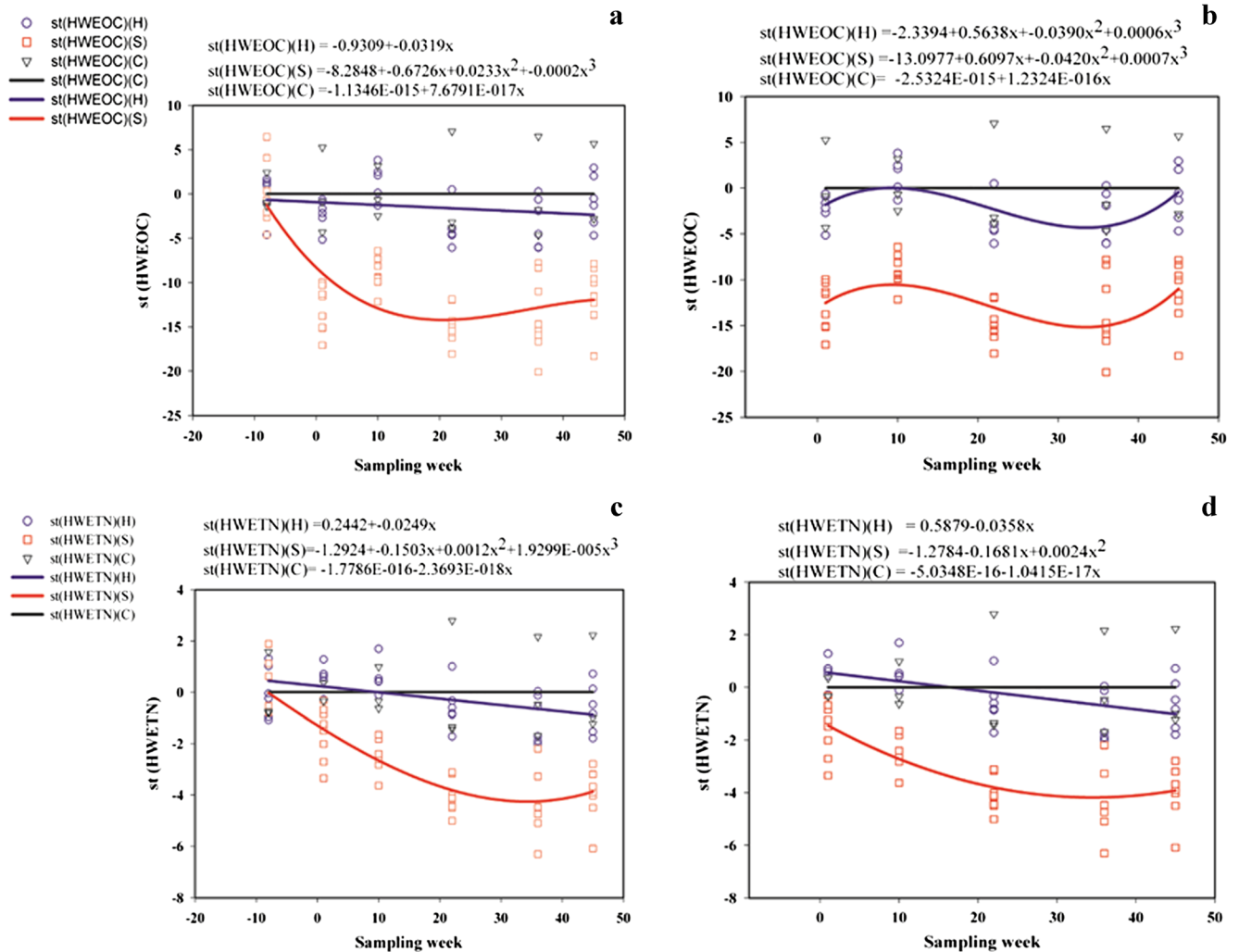


Fig. 4 Soil hot-water extractable organic C (HWEOC) (a, b) and hot-water extractable total N (HWETN) (c, d) in the control (C), herbicide (H) and scalped (S) plots in a revegetated ecosystem of south-east Queensland, Australia

study and did not show any recovery in the 45 weeks after the initial treatment of the site.

There was a significant effect of scalping on soil st(HWETN) at week 1 ($p < 0.01$) and our st(HWEOC) Fig. 4c indicates that st(HWETN) fell steadily to around week 22 and stabilised thereafter through week 45. The best fit polynomial curve for each treatment effect was a linear for the herbicide data ($p < 0.01$) and a quadratic for the scalped plots ($p_{\text{quadratic term}} < 0.01$) as shown in Fig. 4d. A simple homogeneity of slopes regression was computed for each of herbicide vs. control and scalping vs. control as reported in Table 1. There is no demonstrated effect of herbicide on st(HWETN), either initially or over time, and the herbicide values do not differ significantly from the control values at any time. In the case of scalping, there is, however, an apparent steady reduction in st(HWETN) values after scalping, and forcing a linear regression on the data suggested that they had continued to fall throughout the experiment, although the effect is not very reliable ($p_{\text{regression}} < 0.05$).

Inspection of Fig. 4c, d, indicates that st(HWETN) values in the scalped areas fell steadily to week 22 relative to the control and stabilised thereafter. Piecewise regression explored the homogeneity of slopes of these regressions vs. the control for the same weeks (Table 2). This analysis indicates that there is a strong and robust regression of st(HWETN) on sampling weeks for scalped plots (the level of st(HWETN), relative to the control, fell steadily) from week -8 to 22. The effect of scalping increased steadily over time, stabilising at about week 22.

In general, when pre-existing differences between site management practices, and variations over time in the control plots, were removed from the treatment data, no significant change in TC, HWEOC and HWETN was evident in the herbicide relative to control areas over the sampling period. Our results are consistent with studies that found no significant change in soil organic C in the first year following plantation establishment with *Eucalyptus globulus* in Australia (Mendham et al. 2002) and *Eucalyptus grandis* in

Brazil (Araujo et al. 2010). Soil organic C has been reported to take over a decade to change following plantation establishment (Sicardi et al. 2004), although this will depend upon many prevailing factors. In a hardwood plantation located in Australia, no significant difference in C pools was observed between herbicide and control plots 1 year following herbicide application (Huang et al. 2008b). Ibell et al. (2010) reported that soil labile C and N are attributed to the residue of weed biomass in *Pinus* spp., 7 years after the treatment application, in Australia. In our study, herbicide application was applied three times to control weeds, and it would appear that the residues of weed biomass in the herbicide areas plus the continued regrowth of weeds may have been sufficient to prevent a significant reduction of labile C and N inputs.

MBC and MBN

It is evident that st(MBC) and st(MBN) values fell, relative to the control, in both herbicide and scalped plots, but much more strongly in the scalped plots, and substantial losses were present by week 1 (i.e. losses were immediate upon initial treatment; Fig. 5a, b). The difference between the control and the treatment values at week 1 found that herbicide values were very little different to the control values but values in the scalped plots were significantly below the control values for both st(MBC) and st(MBN) ($p < 0.05$). We may conclude that an initial application of herbicide had little effect on MBC and MBN, but scalping reduced its levels considerably. After the treatment application, the best fit was polynomial for MBC but not for MBN (Fig. 5c, d). A ‘simple’ homogeneity of slopes regression was computed for each of herbicide vs. control and scalped vs. control, as reported in Table 1. Relative to the control, the level of st(MBC) and st(MBN) did not change from weeks 1 to 45, although the levels were significantly lower after the initial treatment (i.e. by week 1) in the herbicide plots and very much lower in the scalped plots. Both MBC and MBN stayed at significantly lower levels than the control through weeks 1 to 45, but did not show either worsening or recovery, and the effect of scalping was considerably greater than that of herbicide.

Both herbicide and scalping decreased MBC and MBN relative to the control plots but both remained stable following the initial effect for the remaining period of the study. There are contrary reports of herbicidal impacts on soil microbial communities. Busse et al. (2001) examined soil microbial activity and composition in a plantation subjected to repeated herbicide application and found no significant effect of herbicide on soil micro-organisms. They concluded that herbicide application at field rates may not be harmful for soil micro-organisms. An immediate decrease in microbial biomass upon initial herbicide application was observed in a slash pine plantation by Shan et al. (2001) and in a loblolly pine plantation by Rifai et al. (2010). Both studies suggested that this

Table 2 Probability for piecewise regression of control standardised hot-water extractable total N (HWETN) and total inorganic N (TIN) for scalping vs. control of week -8 to 22 and week 22 to 45

	HWETN		TIN	
	Weeks -8 to 22	Weeks 22 to 45	Weeks -8 to 22	Weeks 22 to 45
Intercept	0.005	0.04	0.69	0.03
Treatment (T)	0.005	0.04	0.69	0.03
Sampling week (SW)	< 0.0001	0.92	0.002	0.43
T × SW	< 0.0001	0.92	0.002	0.43

Significant probabilities are presented in bold

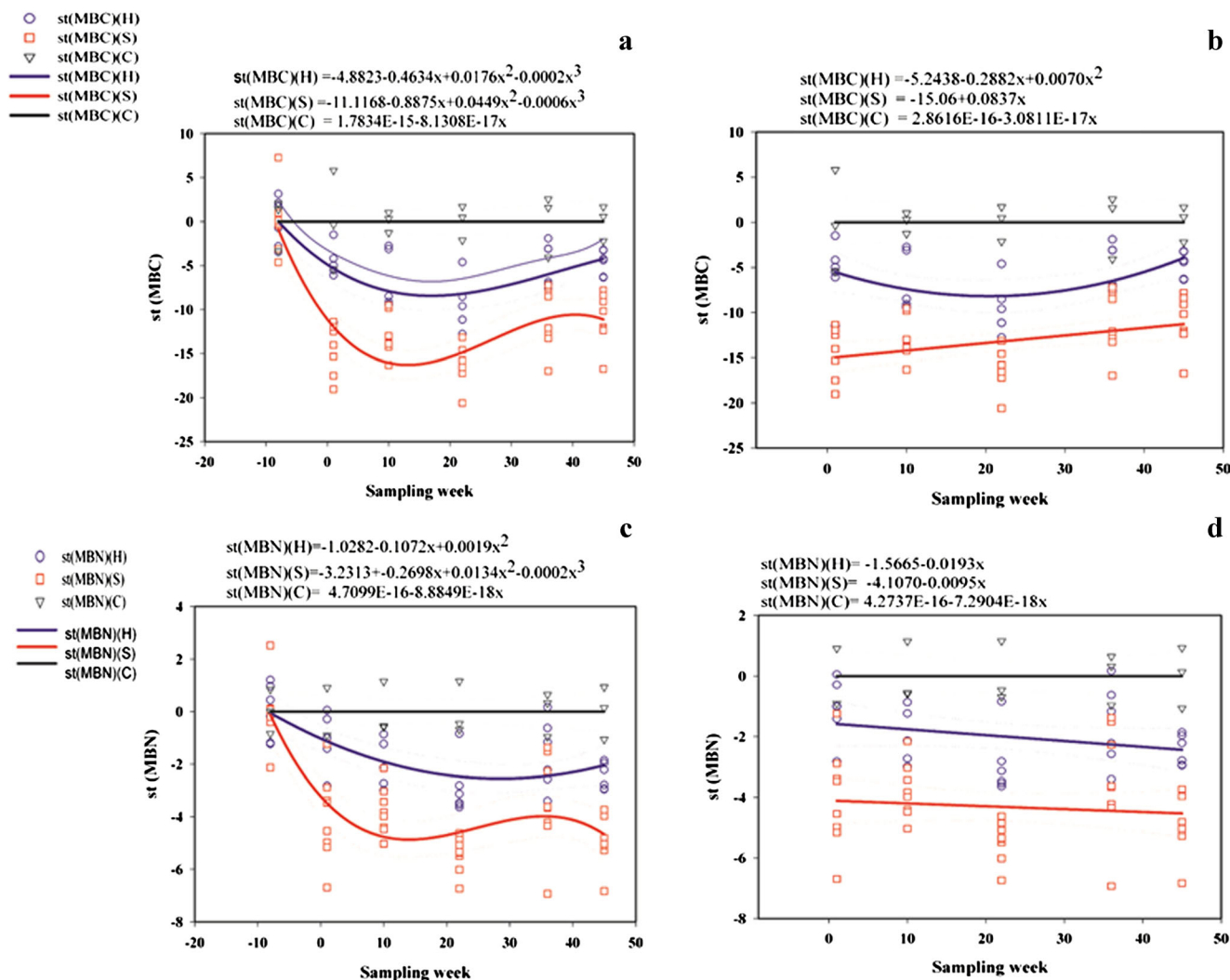


Fig. 5 Soil microbial biomass C (MBC) (a, b) and microbial biomass N (MBN) (c, d) before and after treatment application in the control (C), herbicide (H) and scalped (S) plots in a revegetated ecosystem of south-east Queensland, Australia

decrease may have been through the reduction in the C pool due to weed root mortality after herbicide application. Li et al. (2004) reported a decline of MBC following repeated application of Glyphosate, Imazapyr and Sulfometuron Methyl in a loblolly pine plantation in Canada. They concluded that herbicidal toxicity was not likely to be responsible for such a reduction and argued that reduced C inputs due to weed control was the main reason of the reduction. Weed control by herbicide may enhance the decomposable substrate due to plant die-back which may improve microbial biomass (Lupwayi et al. 2009). On the other hand, it has been argued that a reduction of microbial population at two vineyards after repeated application of herbicide in Australia was due to herbicidal toxicity (Whitelaw-Weckert et al. 2007). In our experiment, labile C and N did not vary in the herbicide areas relative to the control plots throughout the sampling period which, indicates that C and N input was not affected by herbicide application. Therefore, declines in

MBC and MBN may have been caused by herbicidal toxicity.

Despite the fact that MBC and MBN decreased significantly through scalping, this effect did not increase during the period of study. Initial decrease of MBC and MBN in the scalped areas relative to the control plots is attributed to organic matter removal of the top-soil which was inevitable. These results are consistent with our previous finding in Hosseini Bai et al. (2012b). In this study, no significant change in MBC was observed between weeks 1 and 20 following treatment application due to lack of significant change in SOM. There is a positive relationship between microbial biomass and SOM (Li et al. 2004). In the current study, neither HWEOC nor HWETN recovered in the scalped areas, which may explain lack of recovery in MBC and MBN. However, scalping did not decrease MBC and MBN over time.

PMN and TIN

The $st(PMN)$ values differ little between the control and the herbicide treatment at any time, but, relative to the control, scalped plots show substantial losses by week 1 (i.e. losses were immediate upon the initial treatment). It is also apparent that $st(PMN)$ in the scalped plots may have shown some recovery after week 1 (Fig. 6a). The difference between control and treatment values in week 1 found that values in the scalped plots were below the control values ($p < 0.01$). We may conclude that an initial application of herbicide had little effect on $st(PMN)$, but scalping reduced its levels promptly and significantly.

The $st(PMN)$ had not changed relative to the control by week 1 where herbicide was applied, but fell where scalped, the stability of these levels from weeks 1 to 45 was further investigated (Fig. 6b). The best fit curve for each treatment effect was a linear regression for the herbicide data ($p < 0.05$) and for the scalped plots ($p < 0.01$) as shown in Fig. 6b. A simple

homogeneity of slopes regression was computed for each of herbicide vs. control and scalped vs. control, as reported in Table 1.

The above analysis demonstrates that, relative to the control, the level of $st(PMN)$ in the herbicide plots was unchanged, but in the scalped plots, it was reduced promptly after the initial treatment in week -8 and stayed at significantly lower levels than the control through weeks 1 to 45. While the charts in Fig. 6b suggest some steady recovery, analysis indicates that relative to the control, any recovery was not statistically significant ($p = 0.28$).

There is virtually no difference in $st(TIN)$ between the herbicide and the control plots (Table 1 and Fig. 6c). The $st(TIN)$ in the scalped areas appears to be at similar levels to the control in weeks -8 and 1, but falls steadily to week 22 and stabilises thereafter through week 45 (Fig. 6c). The difference between the control and the treatment values in week 1 found that neither herbicide nor scalped values were different to the control values.

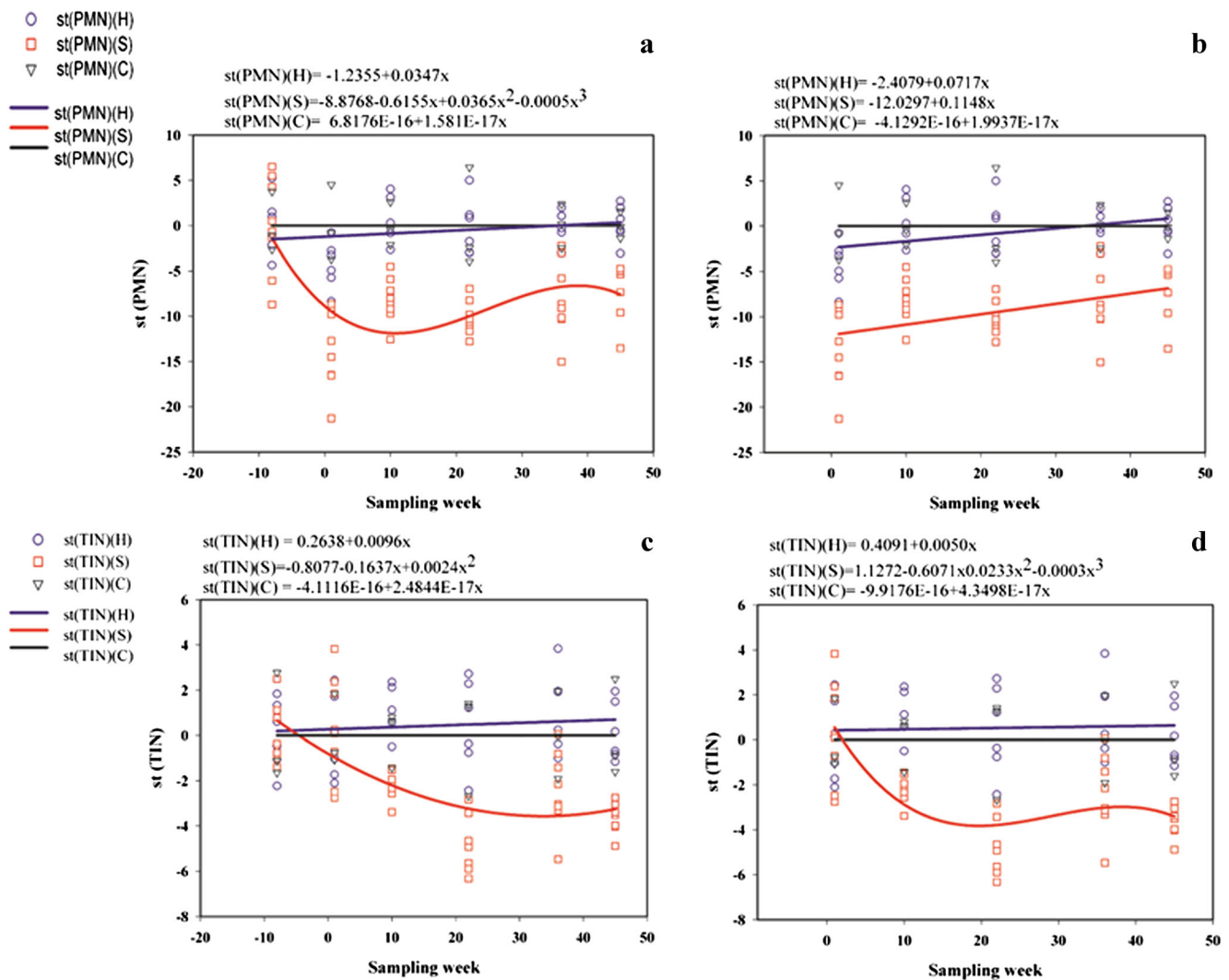


Fig. 6 Soil potential mineralizable N (*PMN*) (a, b) and total inorganic N (*TIN*) (c, d) in the control (C), herbicide (H) and scalped (S) plots in a revegetated ecosystem of south-east Queensland, Australia

There was evidently no effect on st(TIN) from applying herbicide, and even scalping did not have immediate effects.

There are very different dynamics of TIN in the scalped and herbicide plots (Fig. 6d) from weeks 1 to 45. A ‘simple’ homogeneity of linear slopes regression was computed for each of herbicide vs. control and scalped vs. control, as reported in Table 1. In the case of scalping, there is an apparent steady reduction in st(TIN) after scalping at least until week 22, although the effect is not very reliable (Table 2). Fig. 6d indicates that st(TIN) values in the scalped areas, relative to the control, may have fallen steadily to about week 22 and stabilised thereafter. Piecewise regression explored the homogeneity of slopes of these regressions vs. the control for the same weeks (Table 2). This analysis indicates that there is a strong and robust regression of st(TIN) on week for the scalped plots (the level of st(TIN), relative to the control, fell steadily) from weeks -8 to 22, but stabilised thereafter (Table 2) and remained significantly lower than control.

No effect of herbicide on soil TIN was observed in this study although other researchers have reported a decline in mineral N in soil of a 20-year pine plantation through weed control due to reduced C inputs (Rifai et al. 2010). Increased inorganic N was observed in the first year following the treatment application in a pine plantation and was attributed to decreased vegetation or decreased N immobilisation (Vitousek et al. 1992). The authors argued that weed control reduced organic matter input which resulted in decreased N immobilisation and increased N availability in the herbicide areas relative to control plots. Li et al. (2003) also observed higher N availability 2 years following site establishment than that seen after 5 years in a loblolly pine plantation due to decreased organic matter input and temperature variability. In our study, herbicide application did not affect organic matter input relative to control plots, which may have maintained a balance in N transformations (immobilisation and mineralisation) leading to an unchanged trend of N availability throughout the period of study.

Soil TN recovered slightly in the scalped areas between weeks 1 and 45 although this recovery was not significant. TIN analyses in the scalped areas indicated that the effects of scalping may have lasted for 22 weeks, and after that, it stabilised. There was also an improvement in soil PMN in the scalped areas but this was not significant. Vegetation removal may alter soil biotic and abiotic conditions leading to alteration of N availability (Gurlevik et al. 2004; Ibell et al. 2010). After vegetation removal, soil temperature may increase and N mineralisation may be stimulated (Frey et al. 2003; Gurlevik et al. 2004). We did not measure soil temperature in this experimental site; however, it was likely that soil temperature was higher in the scalped areas than the herbicide areas due to increased sun exposure. Possible PMN improvement in the scalped areas may have also been associated with improved soil temperature. All of these observations suggest that N loss may occur for a short period of time (22 weeks), but it should stabilise afterwards.

Conclusion

Scalping strongly reduced the TC, TN, HWEOC, HWETN, MBC, MBN and TIN to a level very significantly below the control, and these levels did not recover during the span of this study. However, it is important to note that scalping did not cause a further deterioration in SOM after the immediate decline following the treatment application. Improvement in SOM should occur due to C input through plant residue decomposition and root exudation leading to enhancement of metabolic activity of soil microbes (Xu et al. 2010). However, the period of SOM improvement would differ according to environmental conditions, land use history and vegetation type (Paul et al. 2002). At our site, the organic matter removed from the soil will be replaced through litter cycling once canopy closure is achieved, but determination of the recovery period requires a longer-term investigation. Scalping was a viable alternative to herbicide for the control of weeds at our revegetation site as it decreased site visits and even improved plant growth (Hosseini Bai 2012). In revegetation systems, scalping is applied only once. However, we do not recommend this method in short rotation plantations, where there may be insufficient time for the recovery of SOM between the treatments.

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