Using the multivariate data set of SOM quality to assess the management-induced changes in forest soils

Yan He[A], Jiachun Shi[A], Zhihong Xu[B], Chengrong Chen[B] and Jianming Xu[A]

[A]Zhejiang Provincial Key Laboratory of Subtropical Soil and Plant Nutrition, College of Environmental and Natural Resource Sciences, Zhejiang University, Hangzhou 310029, China, Email jcshi@zju.edu.cn and jmxu@zju.edu.cn
[B]Centre for Forestry and Horticultural Research, Griffith University, Nathan, Brisbane, Queenland 4111, Australia, Email zhihong.xu@griffith.edu.au

Abstract
Successful soil organic matter (SOM) quality assessment is needed to improve our ability to manage forest soils sustainably. Our objective was to use a multivariate data set to determine whether the land-use conversion from native forest (NF) to hoop pine plantation and the following rotation and site preparation practices had altered SOM quality at three adjacent sites of NF, first (1R) and second rotation (2R, including tree planting row (2R-T) and windrow of harvest residues (2R-W)) of hoop pine plantations in southeast Queensland, Australia. Knowledge of PCA based on the refined set of 41 SOM quantitative and qualitative parameters identified that principal component 1 (PC1), which explained 55.7% of the total variance, was most responsible for the management induced changes in soil processes. This was reflected by the dynamics of SOM regarding the aspects of total stock, soil basal and substrate induced respirations, gross and net N mineralization and nitrification, and microbial biomass, microbial diversity of C utilization patterns. Further, the macroaggregates ($F_{250\text{-}2000\mu m}$) and the C/N ratio of acid extracts of SOM physical fractions, which represented the most informative and unique variables loading on PC1, might be the most promising physical and chemical measures for SOM quality assessment of land use and management impacts in subtropical Australian forests.

Key Words
SOM quality assessment, land use and management impacts, physical fractions, CPMAS ^{13}C NMR, sequential hot water extraction and acid hydrolysis, forest.

Introduction
Three well-studied adjacent NF, 1R and 2R hoop pine plantation forest sites that exhibited different responses in whole soil chemical and biological processes to different forest types, rotation practices and residue management were selected as the study area. Our objectives were (1) to investigate the complex interactions between forest management practices and SOM quality, and (2) to screen and explore the most informative and unique SOM quality parameters which underpin the changes of soil chemical and biological processes induced by forest management. We hypothesized that the chemical analyses on physical soil separates could reveal more meaningful differences in soil C and N physical protection and biochemical recalcitrance in response to land use and management changes. To test these hypotheses, we carried out a combination of physical (wet-sieving and density) fractionation and structural chemical analyses (CPMAS ^{13}C NMR spectroscopy and sequential hot water extraction and acid hydrolysis) of the fractions obtained.

Methods
Site description
The NF and hoop pine plantation study sites were located in Yarraman State Forest, southeast Queensland, Australia. The 1R plantation was converted from NF in 1952. The 2R hoop pine was planted in 2000 after the clearcut harvest of part of the 1R plantation in 1999. Post harvest residues from the 1R plantation were formed into windrows approximately 6 m apart, and areas between windrows were then used as tree-planting rows for the 2R plantation. Hence, the three NF, 1R and 2R hoop pine plantation areas are adjacent to each other, and the 2R plantation area was divided into the following two treatments based on the residue management practices, (1) tree planting row (2R-T) and (2) windrow of harvest residues (2R-W).

Identification of the quantitative and qualitative parameters of SOM fractions
Cross-polarization magic angle spinning ^{13}C nuclear magnetic resonance (CPMAS ^{13}C NMR) spectroscopy and sequential hot water and acid hydrolysis were conducted on SOM fractions separated by wet-sieving and density fractionation procedures to characterize SOM quantitative and qualitative relevant parameters, including carbon (C) functional groups, C and nitrogen (N) contents, C/N ratios, and C and N recalcitrant indices.

Results

Site-based differences in SOM quality: ANOVA and PCA results for fraction C pool, N pool and C/N ratio parameters

The minimum data set of overall SOM quality (constituted by 41 variables that retained from the ANOVA and PCA results of individual categories, data not shown) was assessed to screen for the most informative and unique variables that reflected the SOM quality changes induced by land use and management among the tested forest sites. In general, there were three significant PCs that together explained more than 81% of the total variance. PC1, which accounted for 55.7% of the total variance, contrasted $F_{250\text{-}2000\mu m}$ that showed relatively high loadings from other SOM fractions. The 27 parameters had significant loadings on PC1, among which the highest negatively weighted parameters in six physical fractions were absolutely achieved by the C/N ratio of acid hydrolysable extracts (C/N_{AC}) (Table 1). PC2, which explained 16.7% of the total variance, include 13 positively and five negatively significant weighted parameters that reflected chiefly the C and N content of acid and hot water extracts (C_{AC} and N_{AC}, and C_{HW} and N_{HW}) associated with $F_{53\text{-}250\mu m}$ and $F_{<53\mu m}$ (Table 1). Significant PC3 loadings explained 8.8% of the total variance and reflected mostly the C and N condition of non-hydrolysable residues (Table 1).

Table 1. Principal component scores based on 41 retained variables from all minimum data set categories. Only principal components with eigenvalues > 1 and that explain > 5% of the total variance were retained.

	Principal component		
	PC1	PC2	PC3
Eigenvalue	22.81	6.85	3.62
Proportion (%)	55.65	16.71	8.82
	Rotated scores of three retained eigenvectors[B]		
$F_{250\text{-}2000\mu m}$[A]			
C/N_{AC}	-0.92		
C/N_{HW}	-0.88		
N_{AC}	0.81		
C_{NON}	0.79		
N_{HW}	0.78		
C_{AC}	0.78		
C_{HW}	0.73		
N_{NON}	0.53		0.63
RI_N	-0.43		0.68
$F_{53\text{-}250\mu m}$			
C/N_{AC}	-0.93		
C/N_{HW}	-0.92		
N_{AC}		0.94	
C_{AC}		0.92	
C_{HW}		0.86	
N_{HW}		0.79	
C_{NON}		0.67	
$F_{<53\mu m}$			
C/N_{AC}	-0.8	-0.41	
RI_C	0.49		
C_{AC}		0.93	
N_{AC}		0.92	
C_{HW}		0.81	

	Principal component		
	PC1	PC2	PC3
Eigenvalue	22.81	6.85	3.62
Proportion (%)	55.65	16.71	8.82
	Rotated scores of three retained eigenvectors[B]		
$F_{<53\mu m}$			
N_{HW}		0.78	
C/N_{NON}			-0.71
RI_N			0.61
$LF_{<1.0}$			
C/N_{AC}	-0.6		-0.62
C/N_{HW}	-0.51	-0.42	-0.64
C/N_{NON}	0.46	-0.49	
$LF_{<1.6}$			
C/N_{AC}	-0.55		
C/N_{HW}	-0.47	-0.48	-0.54
RI_C	-0.43		
C/N_{NON}		-0.49	-0.77
RI_N			
$HF_{>1.6}$			
N_{AC}	0.77	0.48	
C_{AC}	0.74	0.5	
C_{NON}	0.74		
N_{HW}	0.72	0.46	
C/N_{AC}	-0.67		
C/N_{HW}	-0.6		-0.52
N_{NON}	0.6		0.57
C_{HW}	0.54	0.57	
C/N_{NON}			-0.87

[A]$F_{250\text{-}2000\mu m}$, 250-2000 µm size macroaggregate fraction; $F_{53\text{-}250\mu m}$, 53-250 µm size microaggregate fraction; $F_{<53\mu m}$, < 53 µm size silt and clay (S+C) fraction; $LF_{<1.0}$, the light fraction with density < 1.0 g cm^{-3}; $LF_{<1.6}$, the light fraction with density < 1.6 g cm^{-3}; $HF_{>1.6}$, the heavy fraction with density > 1.6 g cm^{-3}; RI_C, recalcitrancy indices of C; RI_N, recalcitrancy indices of N; C_{HW}/N_{HW}, hot water extractable C and N; C_{AC}/N_{AC}, acid hydrolysable C and N; C_{NON}/N_{NON}, non-hydrolysable C and N; C/N_{HW}, C/N ratio of the hot water extracts; C/N_{AC}, C/N ratio of the acid hydrolysable extracts; C/N_{NON}, C/N ratio of the non-hydrolysable residues;

[B]Only meaningful loadings (with absolute values > 0.40) were included in the interpretation of the PC; Scores were sorted by absolute size within each fraction.

The relative significance of SOM quality parameters accounting for the changes induced by land use and management

Specific relevance of SOM quality parameters in conjunction with soil processes were identified through the correlation of PC scores of PCA with 22 chemical and biological parameters of whole soil (grouped into five categories, indicating the status of C pool, N pool, C transformation, N transformation, and microbial quantity and diversity, respectively) that were obtained in our previous studies (data now shown). The results showed that of the three retained PCs, only the scores of PC1 related significantly to all 22 referred parameters (Figure 1).

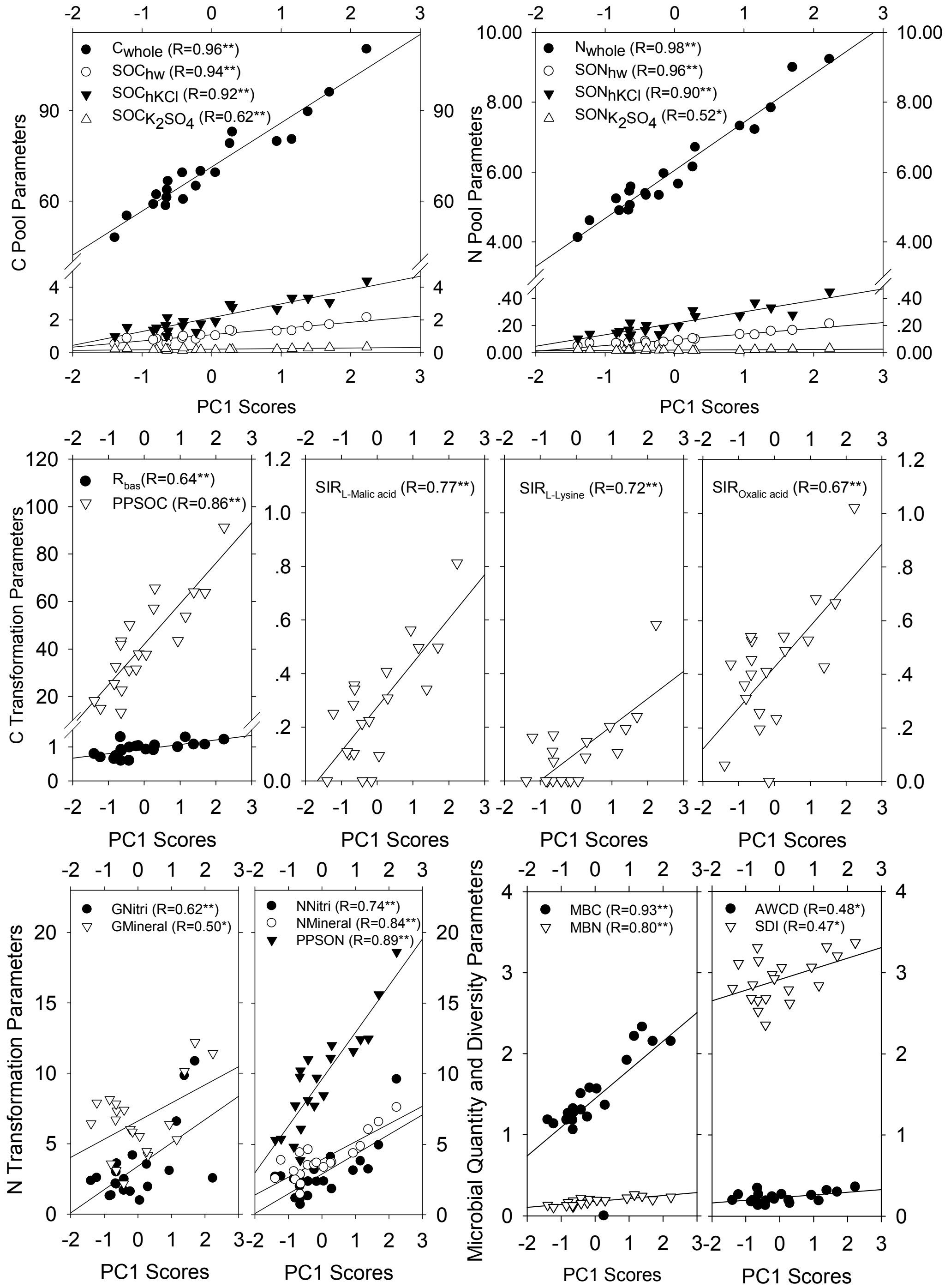

Figure 1. Correlations between the PC1 scores and the chemical and biological properties of whole soil (n = 20). C_{whole}/N_{whole}, total C and N of the whole soil, mg/g; SOC_{hw}/SON_{hw}, 70 ^oC hot water extractable soluble organic C and N, mg/kg; SOC_{hKCl}/SON_{hKCl}, hot 2M KCl extractable soluble organic C and N, mg/kg; SOC_{K2SO4}/SON_{K2SO4}, 0.5 M K_2SO_4 extractable soluble organic C and N, mg/kg; R_{bas}, soil basal respiration, µg CO_2-C/g/hr; PPSOC/PPSON, potential production of soluble organic C and N calculated based on a 7-day anaerobic incubation, mg N/kg; SIR, soil MicroResp^{TM} C source substrate induced respiration (for individual C substrates), µg CO_2-C/g/hr; GNitri, gross N nitrification, mg N/kg/d; GMineral, gross N mineralization, mg N/kg/d; NNitri, net N nitrification, mg N/kg/d; NMineral, net N mineralization, mg N/kg/d; MBC/MBN, soil microbial biomass C and N, mg/kg; AWCD, average well colour development of Biolog^{TM} GN plate after 96 h incubation; SDI, Shannon's diversity index. ** and * indicate the correlations are significant at the 0.01 and 0.05 probability level, respectively.

Discussion

On the PCA plots, separate clusterings were found for NF, 1R, 2R-T and 2R-W respectively. The comparison of the PC scores between NF and 1R, 1R and 2R-T, and 2R-T and 2R-W identified that only PC1, which explained three and seven times the variance explained by PC2 and PC3, was capable of accounting for all the complex differences among the tested forest sites simultaneously. And the optimum competence of candidate PC1 for best indicating the changes of SOM quality resultant from the land uses and management practices were further confirmed by its good relevance with all the whole soil chemical and biological processes (Figure 1). Therefore, all the quantitative and qualitative SOM fraction parameters with significant loadings on PC1 were the most informative measures that would be responsible for the complex impacts of land use and management on SOM quality in the tested forest ecosystem.

Digging the information suggested by Table 1 more deeply, we can find that most of the $F_{250\text{-}2000\mu m}$ associated C and N aspects were exclusively reflected by the PC1, with the absolute higher loading scores than other SOM fractions. Thus the $F_{250\text{-}2000\mu m}$ might be excavated as the most unique SOM physical indicator that PC1 represented for the illustration of land use and management induced changes. This possibly resulted mainly from the special structures of macroaggregates that have been tested dependent on live binding agents, generally do not exhibit long-term stability, and are sensitive to changes in land use and management practices (Six *et al.* 2004). In contrast, microaggregates, mineral-associated organic matter and organic matter entrapped at sites inaccessible to microbial attack or physically protected within heavy fractions belong to more stable organic matter pools with a turnover time from decades to centuries and thus resist the impact from outside (Helfrich *et al.* 2006).

Additionally, if taking a further consideration on the loading scores of PC1, we can also conclude that the C/N ratio of acid hydrolysable SOM might be another most promising SOM chemical indicator that PC1 represented for the illustration of land use and management induced changes, since the C/N_{AC} raitos of all the test physical fractions were always highly weighted variables loading on PC1 (Table 1). Possible explaination might be that acid hydrolysis by 6 M HCl is the simplest and most reproducible method to differentiate the labile from the recalcitrant SOM fractions, as evidenced in various relevant studies (Refs not shown). Therefore, the decomposition degree (as indicated by the C/N ratio) of acid extracts conducted on SOM fractions with different physical protection might be another promising chemial measure for SOM quality assessment of management impacts in the tested forest ecosystem.

Conclusion

Results from PCA based on 41 retained minimum data set and excavation of their dependence on 22 soil chemical and biological parameters that reflected whole soil processes revealed that the PC1 was most responsible for the complex changes induced by the land uses and management practices, on which the most informative and unique loadings, the macroaggregates ($F_{250\text{-}2000\mu m}$) and the C/N ratio of acid extracts of SOM physical fractions might be the most promising physical and chemical measures for SOM quality assessment of land use and management impacts in subtropical Australian forests.

Acknowledgments

We acknowledge the funding support from Australian Research Council. The joint support funding from National Natural Science Foundation of China (40971136 and 20707020), and the Science and Technology Projects of Zhejiang Province (2009C33119) are also acknowledged.

References

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* **79**, 7-31.

Helfrich M, Ludwig B, Buurman P, Flessa H (2006) Effect of land use on the composition of soil organic matter in density and aggregate fractions as revealed by solid-state ^{13}C NMR spectroscopy. *Geoderma* **136**, 331-341.