Explaining variability in soil carbon stocks based on farm management factors

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Abstract

There is limited information on soil carbon stocks for arable and vegetable cropping soils of New Zealand. Variability in the existing data is typically explained by soil and climate factors with little consideration given to land use and management history. We investigated the effect on carbon (C) of soil and crop management practices (crop type, sowing/harvest dates, tillage type and frequency during the previous 10 years), land use (sheep/beef pasture, and mixed arable, intensive arable, mixed vegetable, and intensive vegetable cropping), soil characteristics (order and texture) and climate (LENZ level 1). Soil C (0–15, 15–30 cm) and bulk density were measured on 453 paddocks on flat and rolling lands across seven New Zealand regions. The paddocks represent three major soil texture groups (loamy, silty and sandy) and six soil orders (allophonic, brown, gley, granular, pallic and recent) that comprise the dominant cropping soils in New Zealand. Results indicate that the inclusion of management history information can significantly improve our ability to predict soil C stocks. Our empirical model may be used to improve the accuracy of soil C predictions for use in soil C accounting, to identify soils with an inherently greater risk of soil C loss under intensification of cropping, and to help establish best management practices to mitigate soil losses under cropping in New Zealand.

Key Words

Soil C Stocks, Land use, tillage, crop rotation.

Introduction

Soil carbon (C), a major constituent of soil organic matter, is a function of environmental conditions (climate, soil acidity, drainage), parent material, and management (land use, tillage, crop rotation, compost additions). Soil organic matter is critical to maintaining soil structure, chemical fertility and in buffering extreme changes in pH. It is well known that C tends to decline under continuous cropping as organic matter breakdown is stimulated by cultivation and inputs of organic matter from crop residue are reduced compared with inputs under a pastoral system. Knowledge of how farm management affects C stocks is crucial to establishing best management practices that will mitigate soil C losses. The aim of this research was to determine (1) how much variation in soil C data can be explained by environmental (soil and climate) factors alone, and (2) investigate the contribution of land use and management factors (crop and tillage factors) to explaining soil C variability.

Methods

Soil C (0–15, 15–30 cm, LECO carbon analyser) and fine-earth (<4 mm) bulk density were measured on 453 paddocks on flat and rolling lands across seven New Zealand regions (Auckland, Waikato, Gisborne, Hawke's Bay, Manawatu, Canterbury and Southland). Soil order, soil texture class (hand assessment; grouped to texture class, loamy, sandy or silty using method of Milne et al. 1995), and the Land Environments New Zealand (LENZ) climate layer (Level 1) descriptors, which group together those sites with similar environmental conditions (Leathwick et al. 2003), were determined for each paddock. These factors (soil order, texture, LENZ level 1) are referred to here as the environmental factors. Detailed soil and crop management information was also collected for each paddock for the 10 years prior to soil sampling. The information collected included crop type and rotation, sowing and harvest dates, residue management practices, individual tillage passes (e.g. mouldboard plough, harrow, roll), irrigation and fertiliser inputs. This information was used to classify paddocks into land-use categories and also for calculation of crop and tillage scores. Land use classes were defined as follows: (1) Sheep/beef pasture (low-intensity dryland sheep or beef farming); (2) mixed arable crop (crop rotation included at least 2 consecutive years of restorative management, i.e. pasture or white clover, in the previous 7 years of continuous cropping, predominantly cereal crops grown); (3) intensive arable crop (crop rotation included less than 2 years of restorative management in the previous 7 years, predominantly cereal crops grown); (4) mixed vegetable crop (crop rotation included at least 2 consecutive years of restorative management, i.e. pasture or white clover, in the previous 7 years of continuous cropping, predominantly vegetable crops grown, e.g. potatoes, onions, salad greens, tomatoes); and (5) intensive vegetable crop (crop rotation included less than 2 years of restorative management in the previous 7 years, predominantly vegetable crops grown, e.g. potatoes, onions, salad greens, tomatoes).

The descriptive management information was converted into quantitative scores for inclusion in analysis. In the case of tillage, descriptive information (e.g. mouldboard plough, maxi-till, bed former) was quantified using the Soil Disturbance Rating (SDR) approach (US National Agronomy Manual 509). The SDR for each implement is based on the degree of soil disturbance (0 = no disturbance, -5 = high disturbance) associated with inversion, mixing, lifting, shattering, aeration and compaction. These scores were used to reflect the neutral to negative effects of tillage on soil quality. Disturbance scores were summed and multiplied by the proportion of the paddock affected by the implement to give the SDR (Table 1). SDRs for each implement were summed to give the total tillage score for each crop (Table 2). Crop-type information was quantified by generating a month-by-month calendar for each crop grown over the preceding 10 years. Crop scores
(Table 3) were derived by expert opinions based on crop rooting characteristics, organic matter returns and nitrogen (N) fixation potential and were applied on a month-by-month basis. As recent management events had a stronger influence on soil quality than more distant events, a linear monthly time weighting (based on 120 months) was applied to all tillage SDR and crop scores. Crop and SDR scores were then summed (separately) for each paddock for inclusion in analysis.

Forward stepwise regression procedures in GENSTAT v.10 were used to select the base model (environmental factors only). Additional management terms were added to the base model, and F tests were used to determine if these significantly improved the fit of the model. Model fitting was restricted to main effects and first-order interactions only.

Table 1: Examples of soil disturbance scores for different tillage implements that were used to derive soil disturbance ratings (SDR).

Tillage implement	Disturbance scores						Proportion of paddock affected	SDR
	Inversion	Mixing	Lifting	Shattering	Aeration	Compaction		
Direct drill	-1	-1	-2	-2	-1	-1	0.5	-4
Grubber	-4	-4	-3	-4	-4	-3	1	-22
Harrow	-2	-3	-1	-4	-3	-1	1	-14
Mouldboard plough	-5	-5	-5	-5	-5	-4	1	-29
Tyne	-1	-2	0	-2	-3	-3	1	-11

Table 2: Example calculation of the total soil disturbance rating (SDR) for a series of tillage passes used when preparing the seed bed for a barley crop.

	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Total SDR
Implements used	Mouldboard plough	Maxi-till	Maxi-till	Harrow	Roll	
SDR of implement	-29	-18	-18	-14	-4	-83

Table 3: Crop type scores for selected crops, based on a 0 to 4 rating scale (crops with higher values have most beneficial effect on soil C).

Crop type group	Example	Scores
Fine root	Grass, triticale	4
Cereal	Barley, wheat	2.5
Brassica	Broccoli, rape	2
Coarse root	Maize, sweetcorn	2
Tap root	Canola, mustard	2
Leafy vegetable	Lettuce, spinach	1
Root crop	Carrot, potato	1
Fallow/none	-	0

Results and Discussion

The number of paddocks sampled for each land use and soil order was unbalanced (n ranged from 37–133). Median C stocks in the top 15 cm of soil (Figure 1) were highest (61 t C/ha) under sheep/beef pasture and lowest (38 t C/ha) under intensive vegetable production. Soil under intensive arable cropping had, on average, 14 t/ha less C in the top 15 cm than sheep/beef pastures, while the intensive vegetable-cropping soils contained 23 t/ha less C than sheep/beef pastures. In general, brown and pallic soils had a narrower range of values than the allophanic, granular and recent soils. Median C stocks (0–15 cm) were highest for the allophanic soils (65 t C/ha), and lowest for the granular soils (43 t C/ha). The interaction between land use and soil order was also quantified (data not shown). For mixed arable cropping, the difference in C stocks between the 25th to 75th percentile was 16 t/ha for allophonic soils (n=11), 6 t/ha for brown soils (n=42), 18 t/ha for gley soils (n=30), and 6 t/ha for pallic soils (n=37). The corresponding values for intensive arable cropping were: 26 t/ha for allophanic soils (n=9), 9 t/ha for brown soils (n=28), 19 t/ha for gley soils (n=21), and 8 t/ha for pallic soils (n=34). This variation may be attributable to climatic differences and/or to the range of management practices that are applied within each land use category (e.g. direct drilling vs. full cultivation, residue incorporation vs. burning, use of green manure crops vs. winter grazing crops in cropping rotations).

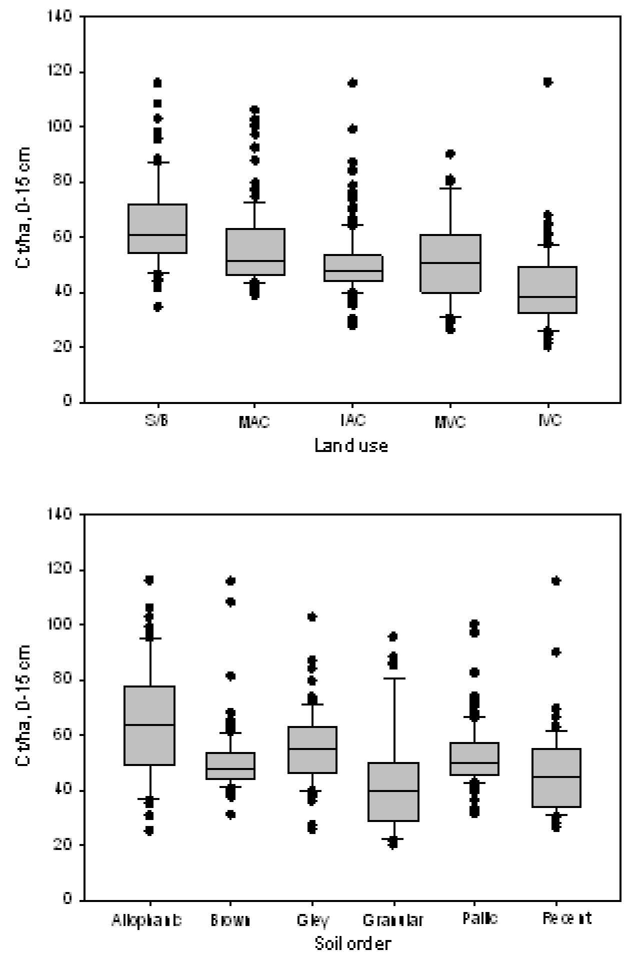

Figure 1: Effect of land use (a) and soil order (b) on soil carbon (t/ha, 0–15 cm). The bottom and top of the box represent the 25th and 75th percentile, while the bar near the centre of the box is median (50th percentile).
S/B = sheep or beef pasture, MAC = mixed arable crop, IAC = intensive arable crop, MVC = mixed vegetable crop, IVC = intensive vegetable crop.

The effects of environmental and land use/management factors on C stocks were assessed by determining the amount of variability in the data that was explained when each factor was included in the model. Environmental factors alone explained 38-48% of the variability in C stocks. Inclusion of management information (either in the form of land use or crop and tillage scores) significantly improved the amount of variability explained by the model. Farm management explained a greater proportion of the variation in C stocks for the 0–15 cm than the 15–30 cm depth (Table 4). Conversely, environmental factors explained a greater proportion of the variation in C stocks at 15–30 cm than at 0–15 cm.

Our land use category explained more of the variability in C stocks than the combined crop and tillage scores. This suggests that either (a) land use encompasses an influential management factor (e.g. residue management, irrigation) that is not captured by our crop and tillage scores, or (b) our crop and tillage scores or time weightings are not optimal (they were originally derived for Aggregate Stability, rather than C stocks). There is limited scope to include additional management factors due to risk of overparameterising the model. Figure 2 shows the relationship between measured and predicted soil C stocks when the model includes (a) environmental factors only, and (b) when environmental factors plus crop and tillage scores. The figure provides evidence that scores could be improved as C stocks are overestimated by the model when measured stocks are low, and underestimated when measured stocks are high (Figure 2).

Table 4: Model predictions of soil C stocks (t/ha) using different combinations of environmental and management factors.

	C t/ha 0–15 cm		C t/ha 15–30 cm		C t/ha 0–30 cm	
Factor/Variate	*P* value	R^2 (%)	*P* value	R^2 (%)	*P* value	R^2 (%)
Environmental factors only	-	38	-	48	-	41
Environment factors + Land use category	<0.001	63	<0.001	64	<0.001	58
Environment factors + Crop Score	<0.001	56	0.007	53	<0.001	50
Environment factors + Tillage Score	<0.001	56	<0.001	55	<0.001	51
Environment factors + Crop and Tillage Score	<0.001	60	<0.001	61	<0.001	56

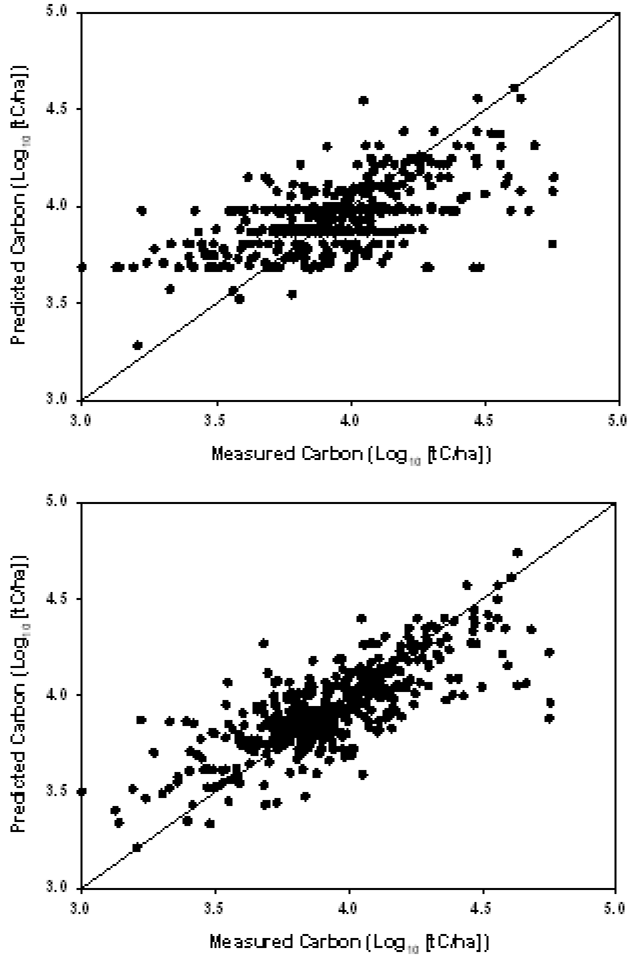

Figure 2: Model predicted verses measured values of soil carbon (t/ha, 0–15 cm) for all land uses where a) only environmental factors are included in the model, and b) environmental factors and crop and tillage scores are included. Line through middle of plots is the 1:1 line.

Conclusions

The inclusion of farm management information significantly improved our ability to predict soil C stocks. The detailed land use categories used in this work were more successful in explaining variability in soil C stocks than our crop and tillage scores. Future work should focus on refining crop and tillage scores for soil C prediction. Work in this area will help identify soils with an inherently lower risk of soil C loss under intensification of cropping. Moreover, knowledge of how management affects C stocks will enable us to identify best management practices to mitigate soil C losses and improve the accuracy of soil C accounting systems.

Acknowledgements

The authors thank Tina Harrison-Kirk, Peg Gosden, Lesley Corbett, Paul Johnstone, Nathan Arnold, Hayley Barlow and Charles Wright for assistance in sample collection and analysis; and Esther Meenken and Andrew Wallace for statistical advice. The research reported here has been funded by the MAF Sustainable Farming Fund, with co-funding from the Foundation for Arable Research, Horticulture NZ, Environment Canterbury, Environment Southland, Environment Waikato, and the Auckland, Hawke's Bay, and Horizons Regional Councils; and by funding from the FRST *Land Use Change and Intensification* (C02X0812) and *Sustainable Land Use Research Initiative* (C02X0813) programmes.

References

Leathwick J, Morgan F, Wilson G, Rutledge D, McLeod M and Johnston K (2003). Land environments of New Zealand. Ministry for the Environment, Wellington, New Zealand. 184 p.

Milne JDG, Clayden B, Singleton PL and Wilson AD (1995). Soil description handbook. Revised edition. Manaaka Whenua Press, Lincoln, Canterbury, New Zealand. Pp. 50–51.

United States Department of Agriculture (2002). National agronomy manual 509. Natural Resources Conservation Service, 3rd ed. Draft Report. June 1999.