Australian Government
Department of Agriculture

POLICY DELIVERY **ACTION ON THE GROUND 1**

Application ID: AOTGR1-[66]

FINAL REPORT – INCREASING SOIL CARBON IN TWEED VALLEY FARMLAND

DUE DATES

The final report and financial summary is due by 5 pm 30 September 2015

The final project report, peer reviewed publication and final financial statement is due within 90 days of the completion of the project.

The final report needs to include a signed statement by the peer reviewer(s) endorsing the report.

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FINAL REPORT

PROJECT TITLE:

Increasing soil carbon in Tweed valley farmland

PROJECT DESCRIPTION

The purpose of the project was to trial and to demonstrate innovative on-farm practices to increase sequestration of soil carbon through the use of organic amendments such as compost and reduce nitrous oxide emissions using biochar. The project aimed to improve understanding in the processes that improve soil organic carbon for agricultural productivity. This included promoting the use of organic soil amendments to increase soil carbon and investigate reducing emissions of nitrous oxide arising from application of nitrogen rich fertilisers in the production of sugar cane, banana, vegetable, perennial tree crops and livestock (dairy and beef) on 30 farms in the Tweed Local Government Area, New South Wales.

EXECUTIVE SUMMARY

Organic carbon is an important component of healthy soils and is essential for sustaining productive agricultural landscapes. Soil organic carbon (SOC) improves physical soil structure and stability, enables retention of soil moisture and nutrients and improves aeration essential for plant growth. Agricultural systems that have soils high in organic carbon are often more productive, more resilient to extreme weather events such as drought and experience lower rates of erosion and runoff that would otherwise transfer sediment and nutrients out of the farming system where it is required and into the surrounding environment where they can cause harm. Soil also has the potential to sequester significant volumes of carbon –dioxide originating in the atmosphere and therefore holds promise as a climate change mitigating strategy.

Much of Australia's agricultural soils, including those within the Tweed Local Government Area, have lost significant quantities of carbon to the atmosphere through historical land clearing and conventional land use practices. The loss of soil organic carbon has impacted on agricultural productivity, farm viability and community well-being. The reduction in mass of SOC below those prior to clearing provides opportunities however for agricultural industries to restore this important component of the soil, to take action to address greenhouse gas emissions associated with farming systems and to provide leadership on climate change mitigation. Farming for healthy soils and carbon sequestration will also increase farm productivity and enable more sustainable and viable agricultural industries, especially in areas such as the Tweed where SOC mass is substantially lower than prior to land clearance. The aim of this project was to increase SOC mass and reduce nitrous oxide emissions in Tweed valley farmland by applying organic soil amendments to conventional farming systems.

Thirty farms representing the diversity of Tweed's agricultural industries participated in the 3-year project, applying compost annually to a trial site within their existing production areas in order to determine the effects of organic amendments on soil organic carbon concentrations and other soil mineral components. The project also investigated the effects of organic amendments with biochar on nitrous oxide emissions, to inhibit this significant greenhouse gas pollutant, and the effects of organic amendments on crop yield

and health. Detailed soil sampling and analysis at the commencement and completion of the project provided a large data set. This data was then statistically analysed. Participating farmers made anecdotal records of crop performance against treatments including compost applications compared with conventional farming practices.

The project was developed on the premise that organic compost amendments would increase SOC mass and that changes in soil health would occur as a result of the organic amendment additions. The 30 participating farms were grouped into six land use types for the purpose of the project. All participant site control plots were sampled in 2012 prior to compost application. Compost was applied at 0, 10 and 20 wet tonnes/ha annually for three consecutive years in 2012, 2013, and 2014. At completion in 2015, all sites with the organic amendment and their control plots on each of the 30 farms were re-sampled.

The project found that land use type was the major determinant of nutrient sufficiency and the major demarcation in determining SOC concentration and mass/ha. The project highlighted the large differences in organic carbon concentrations between land use types, with the sweet potato farms on red ferrosols of the Cudgen plateau displaying extremely low SOC concentrations even after the organic amendment program, compared with much higher concentrations on dairy farms and in floodplain soils where sugar cane is grown. The project also found significant correlations between trends in nitrogen percentages and trends in SOC % and identified the linkages between SOC, soil microbial communities and soil nitrogen cycling. This was especially apparent on sites with higher carbon:nitrogen (C:N) ratios in the soil.

The project determined that there can be no general assumption made about improving soil carbon stocks based on compost application because each land use and management system will have a different response. Whilst the organic amendments had resulted in increased SOC % and a decrease in bulk density, the soils response to compost application was not easy to assess. The initial results suggested that the effect of compost on SOC stocks was generally minimal and in most cases not experimentally significant. Furthermore, the rate of compost applied did not produce a consistent, statistically significant effect on SOC concentration or mass. Additional statistical analysis also indicated that each of the six land uses should be assessed in relation to target SOC levels that include pre-clearing mass and determined by the individual land use and land management practices. Therefore comparisons on a general basis are not recommended.

The current study identified soil nitrogen as a significant factor in determining the response of SOC stocks to organic amendment addition. Thus nitrogen management was shown to affect SOC in this study. The impact of relatively high nitrogen concentrations is that nitrogen was not being cycled into SOC stocks, and therefore increased nitrogen acted to deplete SOC stocks. The reduction of SOC under the higher 20 T/ha organic amendment application rate is attributed to this factor, being in a cycle of using carbon stocks. Consequently in this study the best result was the 10 T/ha application which had greatest effect to increase SOC mass. Higher levels than 10 T/ha should not be adopted unless the C:N ratio of the organic amendment is matched to complement nitrogen fertiliser applications. The management practices that farmers can adopt that will build SOC are those that will not deplete the existing soil carbon stocks. An indicative baseline target when considering compost should be if SOC concentration in the surface 0-10 cm layer is below 4%, otherwise additional compost may deplete existing SOC stocks.

Analysis of nitrous oxide emissions from a cane farm subject to a range of organic amendments including compost and biochar mixtures gave inconclusive results. However it did reinforce the concept of biochar reducing microbial activity and in high nitrogen soil conditions less nitrous oxide was emitted and therefore carbon stocks would in theory be retained. Alternately, without biochar applied results did suggest that the 10 T/ha compost treatments produced slightly higher trends in nitrous oxide emissions. Thus biochar reduced the loss of nitrous oxide in areas where compost was applied however due to a lack of experimental replication the differences were not be shown to be significant.

There was experimental design issues with the project, including a lack of information about the compost types and current fertiliser regimes provided in the assessments. Almost every property used a different compost or compost application regime. Fertilisation types amounts and application strategies varied greatly among the 30 properties. These differences were not applied in the planning for statistical analysis in the form or a causative analysis and therefore more emphasis on collection and use of farm management information would have helped. Adding more discussion of these aspects would have improved this project with these aspects reflected in the discussions and extended into the experimental interpretations when the status of SOC stocks across the region was first defined in 2012. However a key advantage of the design was that it utilised ‘real’ world conditions likely to be encountered if organic amendment addition became a common land management practice. In this context, where real world conditions would operate in an adaptive process the adaptive cycle of management is one of seeking and searching for processes that offer continual improvement instigated on the basis of task formulation, monitoring, review and adaption.

Additionally, the project was successful in raising awareness of sustainable agriculture practices and the benefits of compost use in commercial agriculture. Whilst the project was unable to clearly demonstrate that compost applications increased soil organic carbon and that biochar reduces the loss of nitrous oxide to the atmosphere, the project did improve farmers' appreciation of the benefits of soil organic carbon and facilitated uptake of better management practices.

Whilst the project did not involve detailed analysis of crop yields and the relationship between compost application and productivity, a number of participating farmers reported improvements in crop yield and crop health in areas where compost was applied. This has led to significant changes in farming practices by some project participants who are adopting biological farming practices and phasing out more traditional and conventional methods that focused on costly chemical inputs and intensive soil preparation practices. As a consequence of the project some farmers have purchased equipment to enable them to produce and spread compost on their own farms. The project has assisted in changing land management practices even amongst traditional farmers.

Whilst compost application provides real opportunities for reducing input costs and sustainably enhancing intensive farming systems such as vegetable crops, its broad scale use in farming will remain limited while ever the costs of compost production and distribution outweigh the benefits. The project highlighted the need for locally produced and affordable organic amendments for use in local agriculture and has increased the demand for locally-produced compost. In response, Tweed Shire Council is in the process of designing a state-of-the-art food and organic waste processing facility close to the shire’s most important agricultural areas. The new system will compost the Shire's urban organic waste to produce an estimated 20,000 tonnes of high-grade compost each year.

The addition of organic amendments has not been found to markedly increase SOC content in Tweed’s agricultural production systems. We suggest this is not due to inadequate project objectives, but the project having inadequately identified the linkages and processes that would occur in soil between SOC and the other nutrient cycles driven by carbon as a consequence of the organic amendments. Alternatively, focus should now be directed toward identifying, promoting and assisting farmers to adopt those management practices that lead to increased SOC content such as improved knowledge in pasture management and enhancing biodiversity on-farm. This would also include assessment of the farms that were operating with high SOC stocks at the beginning of the project, that as a result of the organic amendments they had reduced those stocks.

Further research is also warranted on some if not all trial areas to determine if SOC decline occurs in the absence of continued organic amendments or under particular management practices. Closer scrutiny of land management practices such as tillage regimes and pasture condition is also required in order to better appreciate the effects of farm management practices on organic carbon and other soil properties. Coupled with this, farmers also require assistance to overcome barriers to adoption of better management practices that lead to healthier soils and the basis for sustainable agricultural industries.

METHODOLOGY

This was a comparative study with six land use types: beef, dairy, perennial tree crops (nut tree, avocado, banana), sugar cane, sweet potato and vegetables. The number of 'replicates' within each land use type ranged from 4 to 6. Assessment focused on characterising soil organic carbon at commencement and completion of the project (2012 and 2015).

The project comparisons were based on an experimental methodology reliant on the different types of productive land use, without site replication and ignoring any differences that may occur due to soil type, topography, climate or the choice of compost used. The key consistent factors were a zero, a medium (10 T/ha) and a high compost application rate (20 T/ha) onto adjacent 'plots' and the use of the National Soil Carbon Research Programme (SCaRP) methodology for sampling and analysis (Sanderman et al, 2011). Interpretation then required assumptions for uniformity in compost selection (type) and on-farm application, and uniformity in soils and sites location. Consequently, project comparisons were representative of general adoption of organic amendment application under 'real-world' conditions (where it was assumed one-size fits all), rather than the soil response as a function of specific types of organic amendment. The key advantages of this approach were that it is representative of a real life situation and different strategies for assessing the results could be adopted. Two aspects relevant to this project include: composts vary in composition between suppliers and among batches from the same supplier and land management and fertiliser use vary markedly among individual properties within the same land use type.

Farm selection

At project commencement Tweed Shire Council sought expressions of interest from farmers interested in participating in the project. Thirty landholders were selected based on land use type, geographic location and willingness to collaborate and commit to the 3-year project. Landholders included six cane farmers, six sweet potato growers, six beef producers, five dairy farmers, two banana growers, three vegetable growers and three fruit and/or nut growers. Farms selected for the project contained a variety of soils including coastal floodplain alluvials, Cudgen plateau volcanics and metamorphic-derived clays on hillslopes. The landuse type was frequently clustered on specific soils and landforms. For example sugarcane properties are all on coastal alluvial sites. The sweet potato properties are all on red ferrosols on the Cudgen Plateau.

Compost treatments and application

The study looked at the six land use types and three application rates of organic compost amendment (Table 1).

Table 1. Landuse types were grouped with compost treatment 0, 10, 20 wet tonnes/ha

1	2	3	4	5	6
Beef	Dairy	Perennial Horticulture	Sugar cane	Sweet potato	Vegetables

A range of soil organic amendments which included commercial compost blends, compost manufactured by Tweed Shire Council using green waste and biosolids, as well as fresh chicken manure were applied to the thirty farms participating in the project. Commercial grade composts manufactured to *Australian Standard AS4454 (2012) Composts, soil conditioners and mulches* were sourced from the following manufacturers: Mara Seeds Pty Ltd, Northern Rivers Waste (Lismore City Council), MI Organics Landscape Supplies and SoilLife Australia. The complete application program including products and timing of application is included at Attachment 3 – Compost specifications and application details.

A 3ha trial area was selected within each farm and divided into three 1ha treatment areas that received either 10 T/ha or 20 T/ha of compost per annum with the third, untreated area remaining as a control. Land managers continued with routine agricultural practices across all three treatment areas over the course of the project including typical fertiliser and pesticide applications and tillage regimes. The 3 one hectare treatment areas occurred adjacent to each other in order to ensure as much consistency in soil type, land use history and management practices as possible. Additionally the plots ran up and down slopes so that the sampling areas could be in approximately the same landform location.

The timing of compost application was dependent on the cropping cycle however the majority of applications were applied in spring. For sugar cane this meant application at planting of new cane (Year 1 of the project for all sugar cane sites) or harvest of the ratoon (Years 2 and 3). For sweet potato, application occurred prior to planting of runners in the summer whereas for tree crops, application occurred following harvest in autumn/winter for macadamias and avocadoes. For vegetables (garlic, mixed market garden vegetables) application typically occurred in the spring when it suited current crop rotation cycles but applications varied between crop types. Compost was applied on pastures (i.e. dairy and beef) in the spring with no delays as a result of farming practices. All dairy and beef farms did not receive a compost application in Year 1 due to delays experienced in producing compost on-farm at these sites. As a result of these delays, dairy and beef farms received double the treatment volume in Year 2 (i.e. 20 T/ha and 40 T/ha instead of 10 T/ha or 20 T/ha) to compensate. One vegetable farm did not receive any compost applications in Year 1. In Year 2, 20 tonne or two times the annual rate was applied to the Treatment 1 plot and 40 tonne was applied to the Treatment 2 plot in a single application event.

In addition to compost applications, a SoilLife 'Soil builder' microbiological solution was applied to the 10 beef and dairy farms at a rate of 30L/ha diluted in a 10:1 water:microbial solution and applied annually to compost-treated areas but not to control plots. The nutritional content of this product was not tested but it is considered unlikely to have had any measurable effect on soil chemistry including soil organic carbon content. However the results at the end of the study indicate this additional microbial solution may have contributed to the loss of SOC due to the soil mining process.

Pasture improvements

In addition to compost applications, the six beef producers and five dairies also seeded Shaw's creeping vigna (*Vigna parkeri*) throughout the treatment areas at a rate of 300g/ha during Year 2 of the project.

Soil sampling

Soil sampling at project commencement (August 2012) and completion (February 2015) was subcontracted to a certified professional soil scientist and project partner Dr Peter Bacon from Woodlots and Wetlands Pty Ltd with field assistance provided by Tweed Shire Council's Sustainable Agriculture Program. Sampling was conducted in accordance with the National Soil Carbon Research Programme (SCaRP) methodology (Sanderman et al, 2011). Soil organic carbon data were reported as % SOC and SOC mass where mass = SOC% x mass of soil. Measuring soil mass also enabled assessment of the impact of the organic amendments on bulk density.

Soil sampling consisted of selection of a 25x25m area considered representative within each 1ha treatment area. For each sampling event (i.e. project commencement and completion) a total of 10 cores and 1 additional core for bulk density were collected from each 25x25m grid using Dormer 400mm split tube samplers. Soils were sampled at three depths in accordance with the SCaRP methodology by dividing each core into 3 sub-cores (i.e. 0-10cm, 10-20cm, and 20-30cm) with each sub-core bulked with the other 9 sub-cores belonging to the same depth, from the same treatment. The 10 sub-cores were then manually homogenized and a minimum 500g sub-sample sent for laboratory analysis.

Soil analysis

All soil analysis including Total Organic Carbon (SCaRP method) was conducted by the Environmental Analysis Laboratory, Southern Cross University at Lismore, NSW using LECO and bulk density.

Information collected for the 2012 and 2015 sampling included SOC% from 30 sites each with 3 organic amendment application rates (0, 10 and 20 wet T/ha) and 3 depths 0-10, 10-20 and 20-30 cm (total 270 samples), bulk density (Mg/cubic m) (total 270 samples) and calculated mass of SOC (T/ha) for a total of 270 samples. These data provided for a comparison of soil carbon stocks for different soil depths to a total depth of 30 cm. In total 990 samples were taken over 30 farms at each sampling event in order to determine soil characteristics including soil organic carbon and bulk density.

In 2012, the surface 10 cm samples from the control plot at each of the 30 landholdings were also analysed for a wide suite of soil chemical properties including pH, salinity, Bray no 1 available P, total N, Exchangeable Ca, Mg, Na, K, Al and H+. Other elements analysed included zinc, manganese, iron, copper, boron, molybdenum, cobalt, selenium and silicon. In 2015 the surface 10cm samples from all three treatments at each of the 30 landholdings were also analysed for the same soil chemical properties. In 2015, all 90 plots (30 landholdings x 3 treatment areas) were also assessed for soil biological and physical health using the Northern Rivers Soil Health Card developed by SoilCare Inc.

Compost analysis

The chemical composition of composts used in the project were analysed by the Environmental Analysis Laboratory, Southern Cross University at Lismore, NSW.

Soil data statistical analysis and interpretation

Interpretation of the soil test results was initially undertaken by Dr Peter Bacon (Woodlots & Wetlands Pty Ltd) and peer-reviewed by Dr Jane Aiken (Consulting and Environmental Services Pty Ltd). A project technical report (Bacon, 2015) and project review report including supplementary analyses (Aiken, 2015) detail the range of data interrogations conducted through the project (See Attachment 4 & 5). Analyses for soil attributes included the soil mineral properties of macro and micro nutrients, trace elements and data compiled with the Northern Rivers Soil Health Card.

Comparisons for change in SOC concentration and mass due to treatment were initially assessed on the single time-point data of 2012 and 2015 by Before-After Control-Impact (BACI) type analysis using a one way analysis of variance with the three plots from each farm as a single block. In this case, SOC concentration as a percentage of mg/kg and mass is the amount of SOC on the basis of soil bulk density. Measuring soil mass enabled assessment of the impact of the organic amendments on bulk density.

This approach was applied to the 30 farms x 3 treatment areas for each farm. The analysis also included assessment of changes in soil bulk density, pH and nutrients in response to the application of organic soil amendments.

All results for SOC, soil and plant health scores, macro, micro and trace elements were depicted using bar chart graphics, and notated with analytical interpretation that defined whether derived values were within thresholds indicating adequacy or deficiency, and known indicative adequacy ranges for fertility and limiting growth thresholds (Bacon, 2015). All results were presented for each compost application rate (zero, 10 T/ha and 20 T/ha), for each land use group and collated for each farm and grouped to provide an interpretation based on land use type. The consequence of this methodology was that statistical assessments were focused on assessing the effect of organic amendment treatment grouped by land use. The statistical analysis was based on univariate ANOVA using the 30 landholder farms as replicates.

The project experimental design was then retested to accommodate multivariate components using the determinations of change in SOC mass T/ha for soil at 0-30 cm and testing for the influence of land use type with PERMANOVA (Anderson, 2005). This statistical program tested the simultaneous response of one or more variables to one or more factors in an ANOVA experimental design on the basis of any distance measure, using permutation methods.

Land use types and compost treatments for the PERMANOVA were (1-6) with compost treatment 0, 10, 20 T/ha wet application. The number of farms in each land use type was 5, 5, 6, 5, 5, 4 and when reformatted to a balanced design this was 5, 5, 5, 5, 5, 5 (Table 2).

Table 2. PERMANOVA Statistical groups – land use type

Group	1	2	3	4	5	6
Land-use	Beef	Dairy	Perennial Horticulture	Sugar cane	Sweet potato	Vegetables
30 Observations $_{\text{ORIGINAL}}$	5	5	6	5	5	4
30 Observations $_{\text{BALANCED}}$	5	5	5	5	5	5

PERMANOVA, two-way analysis of variance were run under the balance design, with subsequent post hoc pair-wise testing between groups (land use and compost treatment). PERMANOVA provides an option for pair-wise *a posteriori* comparison of levels for single factors. Response variables were SOC. Initially the SOC data were raw data not transformed or standardised, with permutation of residuals under the full model, and calculating a Monte Carlo probability. Then the ANOVA tests were run with standardisation of variables to z-scores. These two test designs were used to test the significance, if any for the rate of compost applied each with 5 replicates.

Supplementary variables were land use types: beef, dairy, perennial tree crops (nut tree, avocado, banana), sugar cane, sweet potato and vegetable and organic amendment or the three types of organic amendment and the explanatory variables included up to 31 soil chemical properties.

The scope of testing included – assessment of SOC mass T/ha 0-30 cm for both 2012 and 2015 and SOC % 0-10 cm for both 2012 and 2015. Those with PERMANOVA were used to determine the change in SOC mass T/ha 0-30 cm results testing comparisons for land use and for compost. Testing land use within a group by compost was undertaken first with distance-based multivariate analysis for a linear model (Anderson, 2004a), DISTLM. There was no significant difference in SOC concentration 0-30 cm when tested to determine the effects of compost application. As a result PERMANOVA pairwise tests were run to identify the pattern of land use response to each level of compost treatment.

The statistical data were interpreted to identify the patterns of experimental variance for the study using constrained principal components eigenvector values, canonical correlation values and variance percentages attributed to the experimental factors with testing of null hypotheses to $p < 0.05$ (Monte Carlo) (Table 3). For all tests the computation matrices were constrained on the basis of Bray-Curtis distance. For change in mass SOC between 2012 and 2015 (T/ha, 0-30 cm) data were not transformed or normalized due to some negative values, but for SOC % (0-10 cm 2015), the computations were transformed to z-values, which enabled a normally distributed correlation coefficient and thus Ho: $\rho = 0$ (Sokal and Rohlf 1995, p, 575). Permutations (or randomization) tests were either 999 or 4999, which gave the minimum precision of the probability statement at 0.001 (Legendre & Legendre, 1998, p 25). For all runs, 4999 permutations were used. The significance was determined by random assignment of the observations (Legendre & Legendre, 1998, p 26), testing statistical hypothesis that derive a Monte Carlo (randomized) probability values. A Monte Carlo p value represents a maximised unique number of permutation units giving a robust ρ-value. Where required a random seed value was used to commence the permutations.

CAP Canonical Analysis of Principal coordinates (Anderson, 2004) and CANOCO (ter Braak & Similauer, 2012) were used to conduct the assessment of canonical correlation analysis (CCA) in an investigation to assess causative associations. This was applied to the surface soil (0-10 cm) SOC %, 2015 sample collection. Data were grouped either by land use for each compost level to give 18 groups (5, 5, 6, 5, 5, 4; 5, 5, 6, 5, 5, 4; 5, 5, 6, 5, 5, 4) as a matrix of Y response variables totaling 90 observations, or grouped by compost application, with groups of 30 farm replicates for each level of compost treatment and therefore also 90 observations. The computation of CCA derived a correlation value for each soil property against the matrix of values for SOC.

Table 3. Multivariate Assessments conducted to determine the effect of compost and land type on SOC

Hypothesis Significance at: $\rho < 0.05$ (Monte Carlo)	Group[a]	Treatment[b]	Interaction	Pairwise testing	Method
H_o: null, no difference	Land use	Compost	Land use x Compost	Factor *a*, *b* and *b* within *a*	PERMANOVA[1]
H_o: null, no structure		Compost for each land use	-	% proportional variance assigned to treatment	Discriminant analysis, DISTLM[2]
H_o: null, no difference	The canonical analysis finds the axis (or axes) in the principal coordinate space that is best at discriminating among the *a priori* groups.			Eigenvector values	Canonical Analysis of Principal coordinates, CAP [3]
H_o: null, no effect of X on Y matrix	Perform a canonical analysis for the effect of **X** explanatory (predictor) variables of interest (e.g. environmental variables, if any, on **Y** SOC % 0-10 cm 2015 on the basis of any distance measure of choice, using permutations of the observations yielding a generalised canonical correlation analysis.			Correlation value	Canonical Correlation Analysis, CAP [3]
H_o: null, no linear correlation	Response variable	Predictor variables		% proportional variance and significance (ρ)	Constrained interactive forward selection CANOCO[4]

[1] PERMANOVA, Anderson (2004a)
[2] DISTLM, (Anderson, 2003)
[3] CAP, (Anderson, 2004b)
[4] CANOCO, (ter Braak and Similauer, 2012)

A CCA test was used to determine for a suite of 31 soil properties (X matrix predictor variables) a linear correlation against the SOC values (Y response variables). This computation produced linear relations between the two sets of variables as the multivariate extension of correlation analysis. In this computation there was a derived value of correlation for each of the soil properties in the X matrix and a test for significance to identify a direct linear correlation between the matrices. With this test it was possible to identify which soil properties were negatively or positively correlated to SOC in the surface soils. Correlation values were 1 to -1, with 0 indicating low correlation to SOC values. With an absolute value near one (1) indicating near perfect correlation Y increases as X increases, -1 indicates a very strong negative linear relationship between X and Y, if Y decreases then X increases. For 0 there is no linear relationship between X and Y, therefore Y does not tend to increase or decrease as X increases. Values at +/- 0.5 were taken as being moderate and +/- 0.3 as being weak (Sokal and Rohlf, 1998).

All CCA values were presented either grouped by tabulation from 1 to -1 and then in a second tabulated and ordered to alphabetical listing. The CANOCO program (ter Braak & Similauer, 2012) was also used to interpret the canonical correlation analysis for the tests groups by compost treatment. The analysis was 'Interactive-forward-selection', with Y variables SOC % 0-10 cm 2015 (T0, T10, T20 land-use nested). By being interactive it allowed for a choice of which variables to include in the computation. This program also generated a graphical representation of these canonical relationships.

RESULTS

The effect of compost application on soil organic carbon concentration between 2012 and 2015

The results of the initial univariate analysis of SOC concentration and soil bulk density before and after treatments are presented in Table 2. Overall, the control plots had an average increase in SOC mass of 1.7 T/ha (std dev = 24.4 T/ha) between 2012 and 2015, while the plots receiving 10 T/ha compost averaged 1T/ha increase and the plots receiving 20 T/ha compost averaged an increase of 14.1 T/ha (std dev = 30.7 T/ha). As detailed in Table 4, the univariate analysis revealed that the organic amendments resulted in increased SOC% and a decrease in bulk density but the differences in SOC between treatments and changes in SOC over time were not statistically significant.

Table 4. Effect of treatment on SOC components between 2012 and 2015

Treatment	Control	T10	T20	*P*
SOC% 0-10 cm, 2012	4.27	4.32	4.19	0.97
SOC% 0-10 cm, 2015	4.31	4.50	4.38	0.92
Change in %SOC 2012 to 2015	0.04	0.18	0.18	0.86
Soil bulk density 2012 T/cubic m, 0-10 cm	0.93	0.94	0.96	0.91
Soil bulk density 2015 T/cubic m, 0-10 cm	0.95	0.93	0.93	0.87
Difference in bulk density (T/cubic m, 0-10 cm) between 2012 and 2015	0.02	-0.01	-0.03	0.81
Mass of SOC T/ha 2015 0-10 cm	40.2	40.3	39.6	0.94
Mass of SOC T/ha 2012 0-10 cm	38.5	39.7	38.1	0.93
Mass of SOC T/ha 2015 10-20 cm	32.0	35.6	35.1	0.58
Mass of SOC T/ha 2015 20-30 cm	26.4	26.1	26.2	0.90
Mass of SOC T/ha 2015 0-30 cm	98.6	102.0	100.9	0.92
Mass of SOC T/ha 2012 0-30 cm	96.9	101.0	86.8	0.23
Difference in carbon mass (T/ha, 0-10 cm) 2012 to 2015	1.7	0.6	1.5	0.98
Difference in SOC mass (T/ha, 0-20 cm) 2012 to 2015	1.9	4.4	11.6	0.18
Difference in SOC mass (T/ha, 0-30 cm) 2012 to 2015	1.7	1.0	14.1	0.1

Compost application did not significantly change SOC concentration at sites where it was applied. The assessment of change in SOC concentration (T/ha for 0-30 cm) for both 2012 and 2015 and SOC% (0-10 cm) for both 2012 and 2015 using DISTLM revealed no significant differences as a result of compost application at either 10 T/ha or 20 T/ha. The average SOC concentrations for each land use and treatment (0-30cm soils) are shown in Figure 1. This also identifies the group trends and variability for each data class.

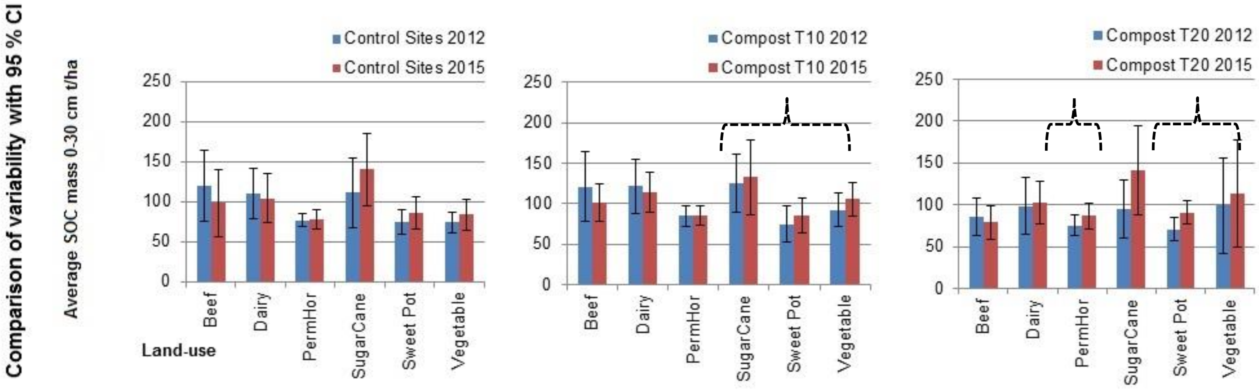

Figure 1. Plot of average land use SOC mass T/ha 0-30 cm trends due to compost application (note, brackets indicate the land use with a positive response due to compost)

Subsequent PERMANOVA pairwise tests, run to identify the pattern of land use response to each level of compost treatment, revealed that overall there were significant differences between the control (0 T/ha) and 10 T/ha treatments (ρ = 0.0024), but not between the control and 20 T/ha or 10 T/ha and 20 T/ha.

This method enabled a determination of the significance of the testing proportion of variance explained by the correlation structure in the experimental methodology. Overall, the variance explained by the experimental design in relation to the SOC values (mass and or concentration) when grouped by land use was between 19% and 24% and this was significant at ρ< 0.001 for all SOC data (Table 5). When each land use was tested for effect from compost the variance proportion was low and generally not greater than 12% for all 0-10 cm soils in 2015 and 0-30 cm soils in 2012 and 2015. In all cases the effect of land use on variance in SOC was not significant ρ> 0.05 (Table 6).

Table 5. Proportion of variance explained for land use SOC % 0-10 cm and 0-30 cm by mass.

Proportion of Variance Explained Testing by Land use Group					
0 - 10 cm		0 - 30 cm			
2015		2012		2015	
% Variance	p value	% Variance	p value	% Variance	p value
24.34	0.001	17.6	0.004	19.3	0.002

Table 6. Proportion of variance explained for compost application in soil organic carbon

Proportion of Variance Explained in SOC mass[1] for Compost Application 0, 10, 20 T/ha	Year	Land use	1 Beef	2 Dairy	3 Perennial Horticulture	4 Sugar cane	5 Sweet potato	6 Vegetable
0-10 cm	2015	% Variance	5.65	1.19	8.04	0.46	0.49	4.17
		ρ value	0.735	0.967	0.571	0.992	0.757	0.785
0-30 cm	2012	% Variance	12.8	7.75	7.05	8.93	1.16	11.3
		ρ value	0.440	0.629	0.566	0.593	0.950	0.610
0-30 cm	2015	% Variance	10.6	3.82	5.69	0.5	2.41	12.8
		ρ value	0.524	0.829	0.638	0.989	0.887	0.565

[1] 0-10 cm by % (concentration) and 0-30 cm by mass.

The variation presented in Table 6 was attributed to the variation within the farm replicates on all sites that could be assigned without compost application as shown by Figure 2 for SOC 0-30 cm in each sampling year (2012 and 2015).

This spread of variation is also evident in the patterns derived using the CAP Canonical determinations for land use and compost treatment. Figure 2 depicts the compost treatments for the 0-10 cm SOC concentration in the surface soils (0-10cm) sampled in 2015. In this case pattern and spread of the eigenvector values (no units) occurs across all treatments and it is difficult to assign land use types or relate this response to high or low SOC values.

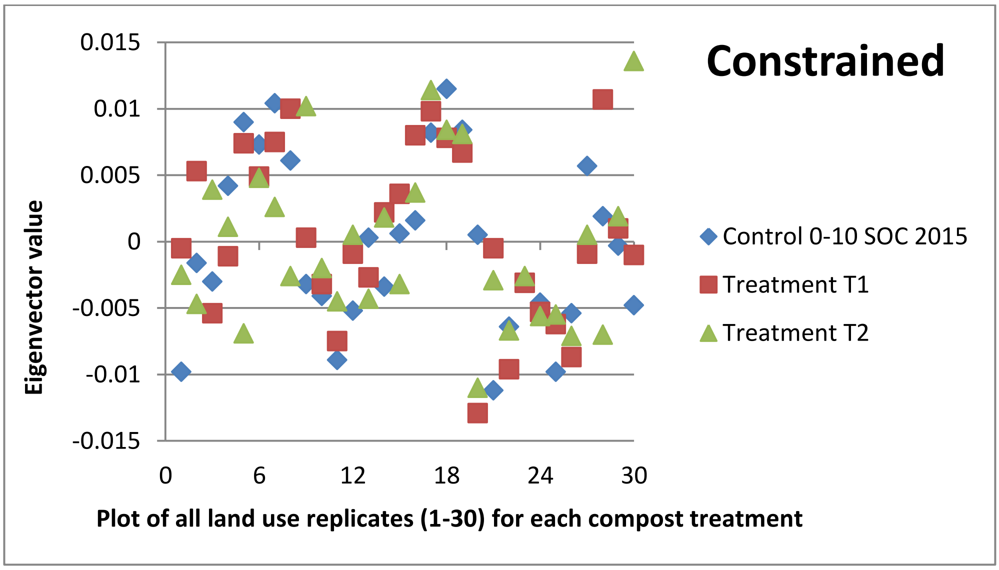

Figure 2. Constrained ordination plot for canonical analysis of principle components 0-10 cm

When depicted by average and 95% confidence intervals this variation occurs as a range between 60 to 160 T/ha as average values for each sampling site and each land use. Figure 3 depicts the range in values of SOC stocks in the Tweed Valley before any compost treatments were applied. The control plots in 2015 are also shown. Red lines show the range between 60 to 160 T/ha as average values for each sampling site and each land use.

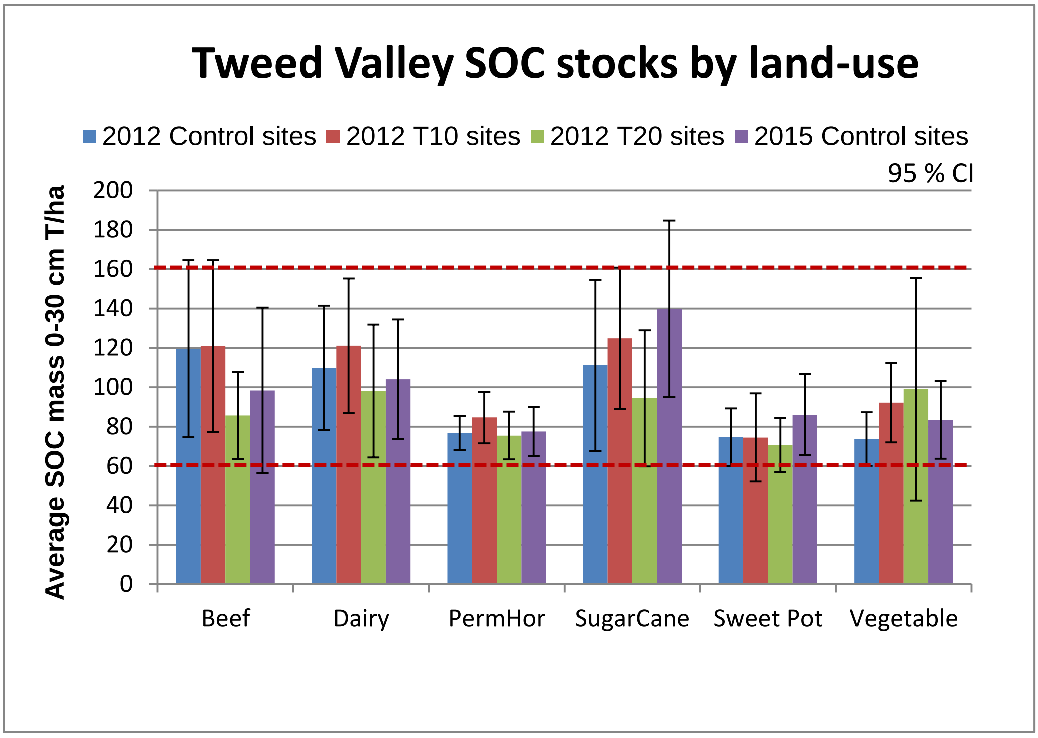

Figure 3. Plot of Average SOC stocks T/ha, 0-30 cm for Tweed Valley soils (no compost)

The effect of land use on soil organic carbon mass between 2012 and 2015

The mass T/ha of SOC varied between land uses as shown in Figure 1. Sugar cane and dairy farms tended to contain the highest SOC mass whereas sweet potato production areas contained comparatively low SOC mass.

There were significant differences in SOC mass between land uses but these could not be attributed to compost application alone. PERMANOVA comparisons for land use and compost treatment confirmed that for 0-30 cm SOC mass, T/ha, the 2015 results were statistically significant for land use ($\rho = 0.0011$) and compost application ($\rho = 0.0024$), but without interaction ($\rho = 0.9953$).

Investigation of the statistically significant difference between land use types ($\rho = 0.0011$) revealed that the significant difference for change in SOC mass T/ha (for soils 0-30 cm depth between 2012 and 2015) existed only between beef and dairy, beef and vegetable, all groups pairing with sugar cane and with perennial horticulture systems, but not for the comparisons between beef and sweet potato, dairy and sweet potato, dairy and vegetable, and sweet potato and vegetable land uses (Table 7). Thus statistically significant differences did not occur for the comparisons beef and sweet potato, dairy and sweet potato, dairy and vegetable, sweet potato and vegetable (Table 7).

Table 7. Pairwise a posteriori comparisons of land use for change in SOC mass t/ha, 0-30 cm between 2012 and 2015.

	Land use						
Land use		Beef	Dairy	Perennial Horticulture	Sugar cane	Sweet potato	Vegetable
	Beef		***0.011***	***0.0024***	***0.0437***	***0.1313***	***0.0030***
	Dairy			***0.0387***	***0.0015***	0.8111	0.1955
	Perennial Horticulture				***0.0135***	***0.0014***	***0.0053***
	Sugar cane					***0.0058***	***0.0035***
	Sweet potato						0.3188
	Vegetable						

Values in bold for comparison were different at ρ < 0.05
Values in ρ_Monte Carlo

Investigation of statistical difference for factor 2 (compost) nested in factor 1 (land use), identified that compost rate to dairy soils produced a significant difference in the SOC concentration for 0-30 cm soil between 10 and 20 t/ha with a highly significant ρ = 0.0010 (Table 8). This is a statistical result that explains the non-significant interaction between land use and compost.

Table 8. Summary for pairwise comparison for compost application with land use

		Land use					
Land use		Beef	Dairy	Perennial Horticulture	Sugar cane	Sweet potato	Vegetable
	Beef	ND[1]					
	Dairy		**2,3[2]**				
	Perennial Horticulture			ND			
	Sugar cane				ND		
	Sweet potato					ND	
	Vegetable						ND

1 ND, no difference monte carlo ρ < 0.05 (actual ρ = 0.001)
2 Compost application 10 T/ha
3 Compost application 20 T/ha

There was however, significant differences between land use for each compost application rate (0, 10, 20 T/ha). Table 9 depicts a summary of all pair-wise tests as a comparative matrix with significant values (ρ< 0.05) shown in bold. This pairwise analysis provided additional detail to the observed significant effects in the change in mass of SOC for 0-30 cm soils between 2012 and 2015 for land use type and organic amendment reported in Bacon (2015).

Table 9. Summary for pair-wise testing land use by compost application

Land use	Compost – Control Land use 1	2	3	4	5	6
1		**0**	**0**			**0**[2]
2			**0**	**0**		
3					**0**	
4						
5						
6						

Land use	Compost 10 t/ha Land use 1	2	3	4	5	6
1				**10**		
2			**10**		**10**	
3				**10**		**10**
4					**10**	
5						**10**
6						

Land use	Compost 20 t/ha Land use 1	2	3	4	5	6
1			**20**		**20**	
2			**20**			
3				**20**		
4					**20**	
5						**20**
6						

[1] Land use 1-Beef, 2-Dairy, 3- Perennial Horticulture, 4-Sugar cane, 5-Sweet potato, 6-Vegetable.
[2] Values in bold for comparison were significantly different at $\rho < 0.05$.

Relationships between soil organic carbon and other soil properties

Canonical Analysis of Principal (CAP) coordinates (Anderson, 2004b) and CANOCO (ter Braak & Similauer, 2012) were used to conduct the assessment of canonical correlation analysis (CCA). The computations by CAP tested for a linear relationship between the listed 31 soil chemical properties relative to the SOC concentration at 0-10 cm soil depth in 2015. Results are an indicative linear association between the values of SOC and the range of soil properties. Tested as a whole matrix the linear correlation was not significant at $\rho = 0.097$ for land use or at $\rho = 0.86$ for compost. However in this computation the value of variance described was 90.354% in one canonical axis and correlation values against each of the 31 chemical properties proved useful to identify which variables had the most potential for an association with SOC concentrations. The values of correlation to this canonical axis are summarized in Aiken (2015, Tables 2-8 and 2-9). These represent the tabulation of SOC 0-10 cm soil depth to each soil property listed by correlation values from 1 to -1.

Further information was derived by the interactive forward selection to support the observations from the correlation values (Table 10). Being interaction this test enabled a choice of variables. These were used to confirm which soil properties were described with the most variance and if these were statistically significant. Soil variables with ρ values <0.05 are identified in a data set grouped into organic treatments (Table 10).

Table 10. Confirmation of soil properties influencing SOC for surface soils 0-10 cm 2015

Analysis 1	'Interactive-forward-selection',				
Forward Selection	X Y SOC % 0-10 cm 2015 (T0, T10, T20 Land use nested)				
Name	Explains %	Contribution %	pseudo-F	P	P(adj)
ExchAl	21.3	21.4	23.8	0.0002	0.0084
Nitrogen%	61.4	61.6	309	0.0002	0.0084
Silicon	2.5	2.5	14.7	0.0004	0.0156
Ammon	0.5	0.5	2.7	0.0994	0.0994
ExchPot%	1.6	1.6	10.4	0.0028	0.007
Copper	1	1	7	0.0146	0.02086
ExchPot	1.1	1.1	8.3	0.0046	0.00833
pH	1	1	8.1	0.005	0.00833
Boron	0.3	0.3	2.9	0.0854	0.09489
Nitrate	0.6	0.6	5.4	0.028	0.035
Total variance %	**91.3**	**91.6**			
Analysis 2	'Interactive-forward-selection'				
Forward Selection	Results:				
Name	Explains %	Contribution %	pseudo-F	P	P(adj)
Nitrogen%	72.6	72.8	233	0.0002	0.00215
CNratio	26.1	26.2	1782	0.0002	0.00172
SoilType.Light Clay	0.2	0.2	13.2	0.0006	0.0086
Landuse.Sugar Cane	<0.1	<0.1	6.6	0.012	0.129
Landuse.Dairy	<0.1	<0.1	0.5	unknown	unknown
SoilType.Medium Clay	<0.1	<0.1	2.4	unknown	unknown
Total variance %	**98.9**	**99.2**			
Analysis 3	'Interactive-forward-selection'				
Forward Selection	Results:				
Name	Explains %	Contribution %	pseudo-F	P	P(adj)
Nitrogen%	73.3	73.9	159	0.0002	0.0021
ExchAl%	11.2	11.3	41.2	0.0002	0.0014
SoilType.Medium clay	1.7	1.7	7	0.0166	0.08715
SoilType.Light medium clay	0.7	0.7	3.1	0.102	0.4214
BrayP	0.7	0.7	3.2	0.079	0.3318
sulfur	0.2	0.2	0.9	0.3276	0.9282
CNratio	11.1	11.2	563	0.0002	0.0014
SoilType.Light clay	<0.1	<0.1	4.4	0.0416	0.1248
SoilType.Clay loam	<0.1	<0.1	3.1	0.0804	0.1876
Treatment.Control	<0.1	<0.1	0.7	0.3968	0.50524
Treatment.T2	<0.1	<0.1	0.7	0.409	0.50524
Total variance %	**98.9**	**99.7**			

Figure 4 shows the result of a canonical correlation analysis in the mode of forward selection to depict an association between soil variables with the grouping for each compost treatment. Of interest is a similarity between the control and (T20) T2 both opposite to (T10) T1. This is interpreted as the 10 t/ha SOC response was different, to that of the control and a 20 t/ha application of compost. For the 10 t/ha application the soil properties pH and Bray P, the trace elements zinc, manganese and molybdenum, and the ratio of calcium to magnesium, were the predictor variables for SOC.

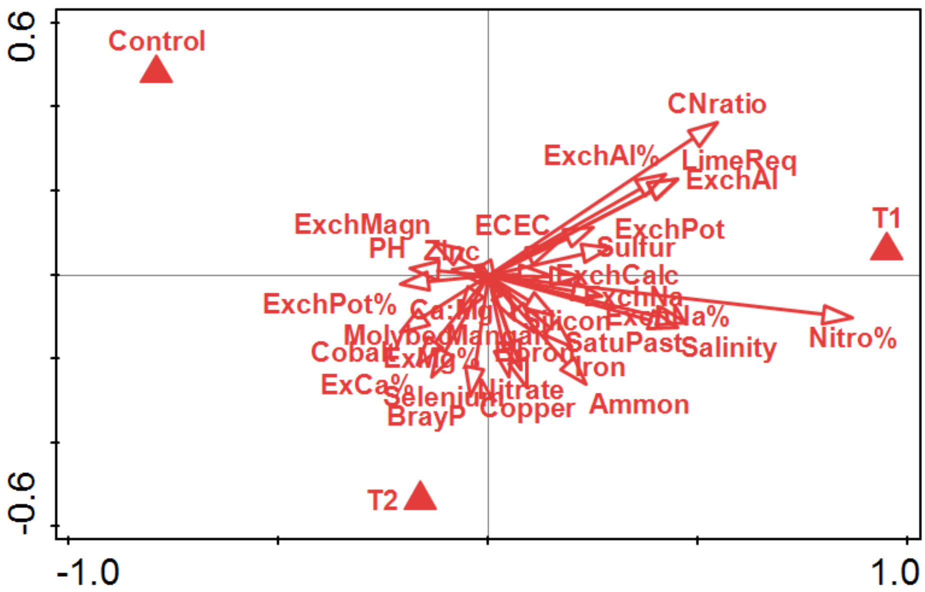

Figure 4. Ordination plot of soil properties associated to compost applications

This difference between the 10 t/ha and the control and 20 t/ha compost applications is also evident in the correlation values (Aiken, 2015, Tables 2-8 and 2-9) and is a result which provides support to use of a 10 t/ha compost application. Bacon (2015) notes that although for 0-10 cm soils the response to organic amendments was slight there were increases in SOC achieved for beef, dairy, perennial horticulture and vegetables, and only with the 10 t/ha application. Consequently, these data support the investigation for interpreting general assumptions for benefits in either a 10 t/ha and 20 t/ha compost applications.

Observations from the canonical correlation analysis (CCA) were values grouped by land use (Tables 2-8, 2-9) and interpreted only for correlation values from moderate to strong (i.e. + 0.5 to + 1). Generally the outcome was that different correlation values that were positive predictors for SOC and those which were negative predictors were varied for each of the six land use systems. Where positive the correlation values occur as a response-increase in SOC (%) 0-10 cm. For those negative correlations against the response of SOC was a decrease, in association with an increase in the predictor variable.

Soil variables with ρ values < 0.05 identified in a data set grouped into organic treatments were Exch Al, Nitro%, Silicon, Exch Pot%, Copper, Exch Pot, pH, Nitrate, C:N ratio and Soil Type.Light Clay. Together these highlight the predictors of an association to SOC within the general overview by compost treatment for the SOC (%) 0-10 cm 2015 soils.

Soil properties with association to SOC

Canonical correlation analysis revealed relationships between SOC concentration at 0-10cm soil depth in 2015 and various soil properties for each land use. In summary, these results have identified the importance of nitrogen values to the interpretations for SOC sequestration with compost applied and identified that each different land use will have different variables which correlate to predicting SOC. They also raise the potential for comparisons of soil types, fertiliser use and choice of compost.

Both nitrogen % and nitrate were significant factors associated with the SOC % in surfaces soils (0-10cm). When the correlation value was positive it was nitrate in sweet potato (0.7) and for nitrogen % in perennial horticulture (1.0) and vegetable (0.9). When negative correlation values for nitrogen % were for beef (-0.8), dairy (-0.7), and sugar cane (-0.9), the negative correlation values were also indicative of negative values for carbon:nitrogen ratio. Lime requirement and exchangeable aluminum were important for perennial horticulture and sugar cane each with high negative values indicative of an associated reduction in SOC (Aiken, 2015, Table 2-8).

On beef farms, there was a positive correlation between SOC concentration and cobalt, copper, iron, and exchangeable magnesium. Negative correlations were boron, Ca:Mg, manganese, exchangeable sodium %, exchangeable potassium, carbon:nitrogen ratio, nitrogen %. Thus for beef increases in SOC % in surface soils were positively associated with increases in the concentrations trace elements cobalt, copper iron and magnesium. Conversely decreases in SOC% were associated with increased exchangeable potassium, exchangeable sodium, and nitrogen.

On dairy farms, there was a positive correlation between SOC concentration and silicon, cobalt, exchangeable calcium, effective cation exchange capacity, zinc, exchangeable magnesium and nitrate. Negative correlations were with exchangeable magnesium %, exchangeable potassium, molybdenum, selenium, exchangeable potassium %, nitrogen %, carbon:nitrogen ratio. Thus for dairy, increases in SOC in surface soils were associating with mobile nitrogen (nitrate), trace elements silicon, cobalt, zinc and magnesium, decreases associated with exchangeable cations magnesium, potassium, and trace elements molybdenum and selenium, and nitrogen.

For perennial horticulture, there were positive correlations between SOC concentration and nitrogen %, zinc, exchangeable calcium, pH, exchangeable potassium, salinity, copper, nitrate, effective cation exchange capacity, exchangeable calcium, molybdenum. Negative correlations were with exchangeable magnesium %, exchangeable aluminum %, exchangeable aluminum, lime requirement, carbon:nitrogen ratio, exchangeable sodium, sulfur, exchangeable sodium %. Thus, for perennial horticulture, increases in SOC in surface soils were associating with trace elements copper, molybdenum and zinc, calcium, nitrogen and pH, and decreases were in association with the cations sodium, potassium and magnesium, and lime requirement. Therefore soluble calcium availability is important for these soils.

For sugar cane, there were positive correlations between SOC concentration and cobalt, pH, exchangeable magnesium, zinc, effective cation exchange capacity, and exchangeable calcium. Negative correlations were with salinity, calcium:magnesium ratio, iron, exchangeable potassium, exchangeable magnesium, sulfur, exchangeable aluminum, carbon:nitrogen ratio, molybdenum, exchangeable aluminum %, lime requirement, and nitrogen %. Thus for sugar cane, increases in SOC were associated with trace elements cobalt and zinc and the cations calcium and magnesium, whilst decreases were associated with aluminum and molybdenum, and other cations potassium, magnesium and also lime requirement and nitrogen.

For sweet potato, there were positive correlations between SOC concentration and iron, nitrate, exchangeable potassium %, Bray phosphorus, nitrogen %, and copper. There were no negative correlations i.e. no values that were limiting. Thus trace elements iron and copper, with nitrogen which was not in excess (Bacon, 2015, Figure 15), the cation potassium and phosphorus were associated with increasing SOC. In this situation, there were no predicting variables to produce any negative correlations.

For the vegetables land use type, there were positive correlations between SOC concentration and nitrogen %, pH, carbon:nitrogen ratio, zinc, exchangeable potassium, exchangeable calcium, and effective cation exchange capacity. There were no negative correlations i.e. no values that were limiting. Thus nitrogen and calcium were positive drivers for SOC in these soils.

DISCUSSION

The intended project outcomes were to reduce nitrous oxide emissions, increase carbon stored in soil, trial innovative practices and technologies to reduce agricultural greenhouse gas emissions and increase carbon stored in soil. The data set and subsequent analysis provided an opportunity for assessment of a range of questions including:

- Would use of compost on Tweed Valley properties increase carbon sequestration?
- Does compost application result in any significant changes in soil constituents or in soil 'health'?
- Does the extent of carbon sequestration vary among the different Tweed Valley land use types?
- Does changing compost application rate significantly change carbon sequestration or any other soil characteristic?

The project determined that land use type is the main determinant of soil organic carbon (SOC) concentration in Tweed Valley soils. Dairies and coastal floodplains farmed for sugar cane contained the highest concentrations of SOC whereas sweet potato sites on the intensively farmed red ferrosols of the Cudgen plateau contained the lowest SOC concentrations. The addition of organic amendments in the form of compost did not significantly influence SOC concentration in any of the land use types tested despite the apparent positive influence of compost on SOC when applied at the lowest rate of 10 T/ha. Typically the soils response to compost application was not easy to assess with results indicating that effect of compost on SOC stocks was generally minimal and in most cases not statistically significant. Compost treatments not only produced increases in SOC but also decreases in SOC. Decreases occurred in the beef and dairy pasture systems and with no change for the perennial horticulture systems.

The project identified relationships between some soil constituents, especially nitrogen and the positive or negative change in SOC concentration. The use of compost appeared to increase the loss of nitrous oxide from a sugar cane ratoon crop with the addition of biochar seemingly reducing nitrous oxide loss although the effects could not be statistically validated.

The effects of compost applications on soil organic carbon concentrations in agricultural systems have been shown to vary as a result of a number of factors including soil type, soil fertility and management history. Yang (et al 2014) report increases in SOC and total nitrogen stocks accruing from a single compost addition a decade earlier, but the degree of increase depends strongly on compost type and addition rate. More recent studies in Australia suggest the relationship between soil type, soil chemical and biological interactions and management practices including fertiliser use complicate our understanding of carbon sequestration in soils (Cowie, et al 2013; Robertson, et al 2015).

A comparison of SOC stocks under various tillage, residual management and rotation treatments found varied results (Robertson, et al 2015). Zero tillage and stubble retention increased SOC in some situations but not others whereas inclusion of a bare fallow reduced SOC compared with continual cropping. Robertson (et al, 2015) report that responses in SOC to these management treatments were likely to be due in part, to differences in nitrogen and water availability (and their effects on carbon inputs and decomposition) and, in part, to other unidentified, interactions. They suggest that significant increases in SOC are possible under some circumstances through the long-term use of multiple beneficial practices.

Several propositions can be forwarded on the basis of the project results. Firstly, there were no apparent statistically significant changes in SOC stocks as a result of compost applications. In this study the effect of compost on SOC stocks was generally minimal and in most cases not experimentally significant. For example, perennial horticulture had an increase in SOC with 20 T/ha compost applications, which was also the case for sugar cane, sweet potato and vegetable, but this increase had also occurred for the control and 10 T/ha applications. Investigation of statistical difference for compost nested in land use, identified that compost rate to dairy soils produced a significant difference between 10 and 20 T/ha in the SOC concentration for 0-30 cm soil. This is a statistical result that explains the non-significant interaction between land use and compost. However, there was significant difference present between land use for each compost application rate (0, 10, 20 T/ha).

Secondly, land use type is a significant factor in the assessment of SOC concentration in Tweed Valley soils. In summary these assessments confirmed that for 0-30 cm SOC mass/ha the 2015 values could be assigned to comparisons for land use type $\rho = 0.0011$ and compost application $\rho = 0.0024$, but without interaction $\rho = 0.9953$. By pairwise testing (for each group a compost application rate), the computation revealed that the significant difference between groups $\rho = 0.0024$ existed between the 0 and 10 T/ha, but not between the 0 and 20 T/ha or 10 T/ha and 20 T/ha. The significant difference between groups $\rho = 0.0011$ for change in SOC mass T/ha 0-30 cm soil depth between 2012 and 2015 existed between beef and dairy and beef and vegetable all groups pairing with sugar cane and perennial horticulture systems. However statistically significant differences did not occur for the comparisons beef and sweet potato, dairy and sweet potato, dairy and vegetable, sweet potato and vegetable.

Thirdly, different compost application rates were producing different response combinations for different land use types. This difference between the 10 T/ha and the control and 20 T/ha compost applications is also evident in the correlation values (Tables 2-8 and 2-9) and is a result which provides support to use of a 10 T/ha compost application. Bacon, 2015, section 7.2.2 notes that although for 0-10 cm soils the response to organic amendments was slight there were increases in SOC achieved for beef, dairy, perennial horticulture and vegetables, and only with the 10 T/ha application. Consequently, these data support the investigation for interpreting general assumptions for benefits in either a 10 T/ha and 20 T/ha compost applications.

The additional statistical analysis with canonical and multivariate techniques has provided further understanding to the relationship of SOC for each land use in the study. Observations from the canonical correlation analysis (CCA) were values grouped by land use (Tables 2-8, 2-9) and interpreted only for correlation values from moderate to strong (i.e. + 0.5 to + 1). Generally the outcome was that different correlation values that were positive predictors for SOC and those which were negative predictors were varied for each of the six land use systems. Where positive the correlation values occur as a response-increase in SOC. For those negative correlations against the response of SOC was a decrease, in association with an increase in the predictor variable.

Consequently, the project was unable to demonstrate the benefit of compost application as a viable strategy for increasing soil organic carbon stocks on typical and all Tweed Valley properties.

Nitrous oxide

Assessment for nitrous oxide emissions was undertaken by Tweed Shire Council and NSW DPI for one sugar cane farm which had the three treatment areas plus an additional site with biochar pre-applied. Analysis of nitrous oxide emissions to a range of organic amendments including 10T wet compost/ha and biochar combined with compost suggested biochar can reduce nitrous oxide flux from areas where compost was applied. Results did suggest that the 10 wet T/ha compost treatments produced slightly higher trends in nitrous oxide emissions. Biochar reduced the loss of nitrous oxide in areas where compost was applied however differences were not significant. Due to the significant variability in nitrogen fluxes between and within treatments, it was not possible to ascertain with certainty whether compost and biochar influenced release of nitrous oxide from the sugar cane trial area. The variability of results are common in greenhouse gas emissions research and the trial demonstrated that in order to obtain meaningful information from the study there was the need for much greater trial replication than was originally specified through the project plan.

The research findings do confirm the relationship between rainfall and nitrous oxide loss and the need to apply nitrogen fertilizers at times that are suitable for the crop and to avoid losses through denitrification following rainfall events. Excess nitrogen use costs farmers money and results in the unnecessary release of pollutants to waterways and the atmosphere. Local research has shown that biochar applied to agricultural soils can reduce nitrous oxide emissions (van Zwieten, 2010).

Soil Nitrogen

The premise for this study was that compost application would contribute to increase SOC stocks and therefore it was important to achieve sequestration into the soils with the compost application. However, this result was not generally evident. The reason for lack of response is attributed to the compost applications being in addition to the nitrogen fertilised soils that are found across the Tweed Valley agricultural lands. This study found that management of soil nitrogen is an important factor for determining the most suitable compost application rate because high nitrogen values were not being cycled into SOC stocks.

High inorganic nitrogen is a carbon limitation and contributes to an increase in the mineralization process of the nitrogen cycle (Myrold, 1998) which depletes carbon stocks. Similarly the comparisons for compost through the values of the Northern Rivers Soil Health card (Bacon, 2015, section 7.1) also indicated that biological properties were not improved by compost applications, which is also indicative of a lack of carbon sequestered.

In this study, the compost applications were applied to soils where nitrogen totals were above 'adequate' concentrations (Bacon, 2015). Under these conditions soil organic carbon increases were not significant, with differences more notable as soil organic carbon decreases. In all cases, nitrogen % was a negative correlation except for vegetables, sweet potato, and perennial horticulture and with SOC increases due to the 20 T/ha compost applications. The implication for this study is that generally, SOC was being reduced and not being sequestered under high nitrogen conditions (see Bacon, 2015 Figure 15). The data of the correlation analysis based on compost groups supports this observation, particularly with the similarity between no compost applied and for compost applications at 20 T/ha, and because for the 10 T/ha compost applications there were no highly correlated values to nitrogen percentage. Thus it is reasonable to conclude that compost addition to soils containing high nitrogen concentration needs to be assessed because, under high nitrogen, there is a critical impact on the use of SOC by the microbial communities. Where SOC reductions occurred this also indicates a lack of efficiency in the system, with nitrogen not being converted by plants to SOC. Similarly, sweet potato had low nitrogen % compared with 'adequate' concentrations but this group did not respond with a significant increase in SOC due to the compost addition. One reason may be the C:N ratio of the organic amendment, which needed to be at 20:1 (Myrold, 1988).

Bacon (2015, Figure 9) shows an increase in SOC in 0-10 cm soils due to 10 T/ha applications for beef, dairy, perennial horticulture and vegetables. For soils receiving a 10 T/ha compost application there were no soil properties which had a significant correlation to the values of SOC, although silicon was moderately correlated and this was statistically significant. Alternately, the soils without compost applied and soils with compost applied at a rate of 20 T/ha had the same soil properties limiting increases in SOC. These were salinity1:5 and saturated paste, exchangeable aluminum percentage, lime requirement, carbon and nitrogen ratio and nitrogen percentage were either moderately or highly correlated and negative correlations, with nitrogen percentage the highest at -0.9 (Aiken, 2015, Table 2-8). Thus for a compost application to the nitrogen rich soils across the Tweed Valley agricultural lands, based on the information available from this study, a 10 T/ha is the preferred rate of application. Consequently, nitrogen percentage in all soils, either receiving compost or not receiving compost is a highly important factor in sequestering SOC and should be investigated prior to choice of compost and the subsequent application rate.

The soil analyses typically revealed excess levels of nitrogen in all production systems except for sweet potato. Furthermore, some sites were found to contain extremely high levels of available phosphorous. Excess of both nitrogen and phosphorous typically leads to eutrophication or pollution of waterways and results in unnecessary financial costs to the landholder.

Experimental design

The project sought to identify the potential of increasing soil organic carbon through use of organic compost amendments. Inherent in the study were two important assumptions being applied to the analytical interpretations. These were assumptions of uniformity of spatial location and representation of different farm sites, and the assumption of similarity in soil response to compost application.

The participating farms across the Tweed Valley were located across a 40 km range. Land use types tended to be clustered on broadly similar soils and localities. For example sweet potato crops were all located on ferrosols on the Cudgen Plateau. Sugar cane was typically grown on coastal alluvial soils. Beef cattle properties were typically on lower fertility soils in more undulating lands. Climate also varied slightly between the eastern and western ends of the catchment. Despite the underlying assumption that all composts were similar, the compost used did vary among the sites depending on supplier. Landholders in the southern portion of the catchment obtained compost from different suppliers to those in the northern and eastern parts of the catchment generating further complexity with the analysis.

In summary, project comparisons were based on an experimental methodology reliant on land use type for farm grouping, without site replication and ignoring any differences that may occur due to soil type, topography, climate or the choice of compost used. The key consistent factors were a zero, a medium and a high compost application rate onto adjacent 'plots' and the use of the SCaRP methodology for sampling and analysis. Any statistics conducted under an experimental design without replication would have risks of generating a type II error, where a type II error is acceptance of a false null hypothesis (Sokal and Rolf, 1995). Consequently, project comparisons were representative of general adoption of organic amendment rather than the soil response as a function of specific types of organic amendment. The key advantage of this approach was that it is representative of a real life situation as composts vary in composition between suppliers and among batches from the same supplier.

Project plan outputs

The project has highlighted the difficulty in obtaining scientifically rigorous and meaningful data from broad landscape scale trials such as this, without inclusion of a plan for multivariate statistical analyses. It also identifies that commonly held assumptions about compost are a good starting point, but assumptions that cannot be described systemically have little value in the long-term. In this study our aim was to be inclusive however in respect, undertaking the study based on reasoning using a deductive scientific method missed the causative effects of the soil systems. However a key advantage of the design was that it utilised 'real' world conditions that would likely be encountered if organic amendment addition became a common land management practice.

The project also revealed the difficulties in demonstrating nitrous oxide emissions reductions from compost and biochar treated areas and changes in soil organic carbon resulting from application of compost, when interpretations are independent of corresponding soil biological processes. However, the project has promoted and led to the adoption of improved farm management practices that are recognised elsewhere as methods for increasing organic carbon stores in soils, reduced environmental impacts, improved productivity and farm viability. Table 11 summarizes the status of intended project outputs as specified in the approved project plan.

Table 11. Status of intended project outputs as specified in the project plan.

Intended project output	**Status**
2700t of alternative soil amendments (compost, compost biochar blends, manures) applied to 30 farms	Complete
1800 soil samples taken over 3 years	Complete
A complete analysis program highlighting before and after treatment for: • TOC(SCARP) by LECO • bulk density • pH and EC (1:5 water) • Available (Calcium, Magnesium, Potassium, Ammonium, Nitrate, Phosphate, Sulphur) • Exchangeable (Sodium, Potassium, Calcium, Magnesium, Hydrogen, Aluminium, Cation Exchange Capacity) • Bray I and II Phosphorus • Colwell Phosphorus • Available Micronutrients (Zinc, Manganese, Iron, Copper, Boron, Silicon) • Total Carbon (TC) • Total Nitrogen (TN) • Organic Matter • TC/TN Ratio • Basic Colour • Basic Texture • Modified Emerson Aggregate (MEAT)	Complete
A peer reviewed final project report describing the on-farm practices trialled, on-ground monitoring and data collection, analysis, and communication activities	Complete
A database of soil health data (0-10cm,10-20cm, 20-30cm) for the 30 farms with data entered into the NSW Soils database - SALIS	Complete
A Nitrous Oxide assessment highlighting potential emissions reduction for dairy farms, cane farms using recycled farm resources compost and biochar.	Complete
Case Studies of participating farmers highlighting project outcomes and farmers feedbacks	A number of project partners have expressed interest in being the focus on a number of case studies about the project. These case studies have not yet been finalised but will posted to the Tweed Shire Council website once complete.
Increased knowledge, skills and collaboration of all partners in the project through participation at workshops, sharing of information and experiences between the farmers and TSC, NRCMA, DPI, SCU, Woodlots & Wetlands and products manufacturers.	A number of workshops have been held through the project relating to compost benefits, production methods, and other soil amendments.

Intended project output	Status
A Tweed soil carbon and sustainable farming mailing list	Complete. Tweed Shire Council has developed a stakeholder register with the contact details of all project partners, as well as farmers and rural land holders involved in previous projects, attendees to sustainable agriculture-related field days etc. These stakeholders are kept informed of council sustainable farming projects run by Tweed Shire Council and other organisations and information of relevance to their operations.
Extension and Communication of project practices, results, experiences and outcomes delivered though regular farm visits, the mailing list, TSC website and local media as well as a minimum of three workshops and field days and industry grower group information sessions.	On-going. Copies of media releases and media articles generated during the project are included at Attachment 2.

Productivity gains

Whilst the project did not involve a comprehensive analysis of production data and the effect of soil amendments on productivity, a number of farmers did report improvements in crop yield and health from sites where compost was applied. This was particularly the case in intensive vegetable production where growth rates and product quality could be easily observed.

Project communications

Throughout the project Tweed Shire Council has organized a range of workshops and field days to demonstrate and promote the benefits of compost use in agricultural systems. In February 2013 a workshop was held with Tweed landholders to present the results of the initial round of soil testing and to advise the community on the project activities and intended outputs. A final stakeholder workshop was held in April 2015 to present the preliminary findings of the final round of soil testing.

Project partners have become engaged in sustainable agriculture with many of the project partners now attending other workshops, field days and seminars run by Tweed Shire Council's Sustainable Agriculture Program on topics including effective pasture management and biological farming techniques. Some of the project partners have also been involved in a biological farm planning course as well as a sustainable grazing course currently being run by Tweed Shire Council's Sustainable Agriculture Program.

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IMPLICATIONS FOR AUSTRALIAN AGRICULTURE

Explain the significance of these findings for policy makers and the Australian agricultural industry.

The importance of soil organic matter and soil organic carbon for productivity in farming systems is well understood. It is also well recognised that soil organic carbon levels in Australian agricultural soils have been in a state of decline and are generally at very low levels. This reduces the productivity of agricultural soils and the sustainability of farming enterprises throughout the country. Whilst this project was unable to clearly demonstrate the benefits of compost applications to increase organic carbon content of agricultural soils and reduce nitrous oxide emissions, it is well known that management practices that result in long-term increases in soil organic carbon not only increase productivity but also provide opportunities to mitigate the effects of increased greenhouse gas emissions that are causing climate change. This project has demonstrated that the application of organic soil amendments, without clarification of their type and links to understanding of the soil biological processes is generally not an effective method for increasing soil organic carbon especially on nitrogen rich soils. That is, that carbon applied, does not automatically result in carbon retained in soil. However, in at least some situations compost application resulted in improved nutrient availability and possibly plant productivity.

The project findings highlight the value of industry, government and community collaboration on sustainable agriculture projects and the importance of demonstrating the economic, social and environmental benefits of particular better management practices in order to facilitate their adoption amongst industry.

The project has demonstrated that high quality composts can be produced for agricultural purposes, using municipal green waste and even biosolids and these materials may provide alternative resource opportunities for agricultural producers resulting in environmental and economic benefits. Australian agriculture will continue to benefit from further integration with the waste sector and garner the full benefits of this currently underutilised resource.

The project has greatly improved farmers understanding of Tweed valley soils and built capacity in sustainable agriculture including the use of organic soil amendments, and management practices that maintain and enhance the natural resource base. Whilst education is the initial step, in formulating the program to build knowledge, that knowledge needs to be applied as part of the process of hypothesis, testing, review and adaption to new knowledge. This needs to be supported by government policy and programs that help to continue the transition to a sustainable agriculture future.

ENDORSEMENT

See signed statement by the peer reviewer, Dr Jane Aiken, endorsing this report (Attachment 6).

ACKNOWLEDGEMENTS

Tweed Shire Council would like to acknowledge the funding provided by the Australian Government. Tweed Shire Council would also like to acknowledge the administrative support provided by the Sustainable Agriculture Branch of the Department of Agriculture.

Tweed Shire Council would like to acknowledge the significant contributions made by participating landholders and thank them for their involvement and on-going interest in the project. Tweed Shire Council would also like to acknowledge the remaining project partners including the former Catchment Management Authority (now North Coast Local Land Services), New South Wales Department of Primary

Industries for advice and services in relation to nitrous oxide emissions analysis, the Environmental Analysis Laboratory, Southern Cross University for its high-quality services in relation to soil analyses and contributions made at various workshops and field days throughout the project. The important contribution provided by Dr Peter Bacon and Dr Jane Aiken for data analysis and interpretation is gratefully acknowledged.

The contributions made by Tweed Shire Council to the project are also acknowledged. At project commencement Tweed Shire Council estimated a total in-kind contribution to the project to the value of $68,980. The actual in-kind contribution has been in excess of $183,000 including salaries and on-costs for the Program Manager and other staff involved in the project (i.e. financial management, media and communications personnel), office expenses and vehicle running costs.

ATTACHMENTS

1. Plain English Summary – limited to two pages, endorsed by the peer reviewer(s), summarising the key findings and outcomes of the project.
2. List all submitted publications arising from this project – Nil.
3. Compost specifications and application details.
4. Bacon 2015.
5. Aiken 2015.
6. Peer reviewer endorsement.

Note: No intellectual property was created or has arisen over the life of the project.
Consent to use photographic and audiovisual recordings are not currently required as no images or audiovisual recordings have been used in public materials generated through the project.

PLAIN ENGLISH SUMMARY

Please provide a Plain English summary for public release using the template below.

The summary will be uploaded to the department's website and should stand alone as a summary of the project that can be understood by people without expertise in the field.

PROJECT TITLE

Increasing soil carbon in Tweed valley farmland

PARTNER ORGANISATIONS

Tweed Shire Council was the lead organisation for the project with responsibility for project governance, planning and coordinating on-ground works and community engagement. Partner organisations included the North Coast Local Land Services, New South Wales Department of Primary Industries, Southern Cross University and private sector consultants who provided technical advice and expertise for various aspects of the project. The 30 participating landholders and various local agricultural industry bodies provided on-going support and cooperation throughout the project.

PROJECT SUMMARY

The project assessed the potential for using organic amendments to increase sequestration of soil carbon and reduce nitrous oxide emissions in agriculture. Thirty farms covering six major agricultural production systems in the Tweed Local Government Area of New South Wales participated in the project over a three-year period. Various rates of compost were applied to farms on an annual basis and soils analysed to determine changes in soil organic carbon and soil mineral properties over time. Significant differences in soil organic carbon concentration were observed between the six major land use types (dairy, beef, sweet potato, sugar cane, vegetables and perennial horticulture) however these could not be attributed to compost application alone. Annual applications of compost at 10 and 20 (wet) tonne/hectare did not result in a significant change in soil organic carbon concentration despite a trend of increased soil organic carbon sequestration over the three year study. The project determined the relationship between nitrogen and soil organic carbon with high nitrogen contributing to the biological process in depletion of soil organic carbon stocks. The project raised awareness of the soil health benefits of organic amendments and showcased farming practices that can increase soil carbon content and agricultural productivity and has built capacity in sustainable agriculture in the Tweed.

OBJECTIVES

The project objectives were to increase sequestration of carbon in agricultural soils through the application of composts and other organic amendments, investigate the potential to reduce nitrous oxide emissions using compost and biochar in agricultural soils, to demonstrate and raise awareness of the economic, environmental and social benefits of soil organic carbon, establish a network of sustainable agriculture operators, and improve understanding of the organic carbon status of agricultural soils in the Tweed Local Government Area.

KEY ACTIVITIES

The project involved the application of 2700 tonnes of compost on 30 farms over a three year period; the collection of over 1800 soil samples for analysis, a comprehensive soil analysis program to determine the chemical composition of soils before and after compost application, a nitrous oxide emissions assessment for cane farms using compost and biochar. A series of workshops, field days and other activities were held to increase knowledge, skills and collaboration amongst project partners, and improve understanding of the benefits of soil organic carbon through extension and community outreach.

OUTCOMES

Outcomes of the project included:

- Increased understanding of the productivity and environmental benefits of soil organic carbon amongst the farming community.
- Improved understanding of management practices that assist in sequestering atmospheric carbon in the soil i.e. minimal tillage, pasture management practices including stock rotations that do not result in overgrazing of the resource, timing of fertilizer applications to minimise nitrous oxide fluxes.
- Increased demand for large quantities of locally-produced organic soil amendments such as compost for use in commercial farming systems.
- Extensive community engagement and cooperation through establishment of a sustainable agriculture network.
- Successful interagency collaboration between local and state government departments with interests or responsibilities for sustainable agriculture.
- Opportunities for sustainable farming systems based around organic waste recycling practices.

IMPLICATIONS

The historical loss of soil organic carbon and nitrous oxide emissions from agricultural soils are impacting on productivity, farm viability and the environment.

The project has promoted practice change and demonstrated the benefits of adopting better management practices including the use of organic soil amendments as alternatives to traditional inputs for crop productivity and farm sustainability. Through extension, collaboration and landholder inclusion in research it is possible to shift management practices in traditional farming systems towards more economically, environmentally and socially sustainable approaches by demonstrating benefits at the local level.

The project highlights the importance of understanding soil characteristics systemically and the complex interactions that occur in soils in response to current and previous land use practice, the relationships between various soil properties and the effect of soil amendments. Such an understanding is essential for making the right management decisions including when making decisions with the aim of increasing soil organic carbon content.

This project has increased the demand for organic soil amendments such as compost amongst commercial farmers in the Tweed Local Government Area through a process of education and on-ground project involvement. The project has highlighted the variability in organic carbon content throughout the agricultural landscape and the importance of ensuring landholders are aware of the full range of soil health indicators, including total organic carbon, available to them and the effects that various management practices have on soil nutrient cycling that includes the microbial component to achieve soil health so that they can make timely and informed decisions as producers and land managers.