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Capturing carbon in Australian soils: Potential and realities

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Abstract
An interest exists to enhance the amount of carbon contained in Australian soils because of the beneficial impacts on both soil productivity and atmospheric concentrations of greenhouse gases. There is no doubt that Australian soils have the capacity to capture additional carbon by altering current management practices. However, much debate remains over the potential rate and magnitude of carbon capture. It is unlikely that capturing carbon within soil will offset Australia's net greenhouse gas emissions, but it is likely that soils can contribute to reducing emissions within a broader set of strategies. A review of Australian research trials comparing traditional agricultural management practices with practices designed to retain addition carbon has indicated that, irrespective of the management practices applied, soil carbon values have continued to decline under agricultural production. However, the extent of SOC reduction was reduced under more conservative carbon friendly practices. This would result in an avoided emission, when compared to the business as usual scenario, rather than a net sequestration of carbon from the atmosphere. In an effort to extend our understanding of the magnitude of soil carbon change under different land use/management practices at a regional scale, a national soil carbon project has been recently established. This program will sample soils from the major combinations of soil and land use/management practices within defined regions across Australia. Land use/management impacts on differences in both the amount and composition of soil carbon will be defined.

Key Words
Measurement, modelling, scaling, accounting.

Why are we interested in changing the amount of carbon captured in soil?
Current interest in enhancing the amount of organic carbon captured in Australian soils exists for the following two reasons: the positive influence that soil organic carbon (SOC) has on a range of soil properties, and the potential to reduce Australia's net greenhouse gas emissions. SOC contributes positively to a variety of soil biological, chemical and physical properties and processes (Figure 1). Strong interactions (represented by the grey arrows) can exist between these different functions. For example, the biological function of providing energy for microbial activity may also result in improved structural stability and create organic materials that contribute to cation exchange and pH buffering.

A main determinant of agricultural productivity over much of Australia is the availability of water. Future predictions of climate change suggest that much of Australia's current agricultural land will be become warmer and drier. Under such scenarios, an enhanced capacity of soils to store plant-available water will be critical to maintain productivity. The application of pedotransfer functions derived by da Silva and Kay (1997) to the 0-10 cm layer of 80 Red Chromosols from South Australia indicate that increasing soil organic carbon content by 1% of the total soil mass (e.g. from 0.7% to 1.7%) would increase plant-available water holding capacity by 2 to 4 mm with the effect diminishing with increasing soil clay content (Figure 2). Beneficial changes in soil properties such as water holding capacity, and others depicted in Figure 1, provides the impetus to enhance the capture of carbon in soils for reasons beyond reducing net greenhouse gas emissions and carbon accounting purposes.

Do Australian soils have a capacity to capture additional carbon?
Soil provides a significant reservoir of organic carbon in Australia, 19 Pg C in the 0-30 cm soil layer (Grace *et al.* 2006) with an annual flux of 0.18 Pg C y^{-1} (Barrett, 2002), relative to the size of Australia's net greenhouse gas emissions, 0.15 Pg C y^{-1} (National Greenhouse Gas Inventory May, 2009). An annual 0.8% increase in the amount of carbon stored in the 0-30 cm layer across all Australian soils would offset Australia's net emissions. However, of the 769Mha of total land area within Australia, only 469 Mha are used for agriculture and of that, only 49.6 Mha are actively managed (24.6 for grazing of modified pastures and 25 for dryland cropping) (Bureau of Rural Sciences, 2001/2002). If the area available for capturing

carbon is limited to managed agricultural lands (49.6 Mha) and it is assumed that these lands, on average, contain three times more carbon per ha than other lands, an annual increase in soil carbon across all managed agricultural lands equivalent to 4.6% of current values would be required to offset all of Australia's emissions. This would be equivalent to an average increase in SOC stocks of 3.0 Mg C ha^{-1} y^{-1}. Given that estimates of average net primary productivity vary between 0.9 and 4.3 Mg C ha^{-1} (Roxburgh *et al.* 2004), it would appear unlikely that enhancing the capture of carbon within soils could completely offset Australia's net greenhouse gas emissions.

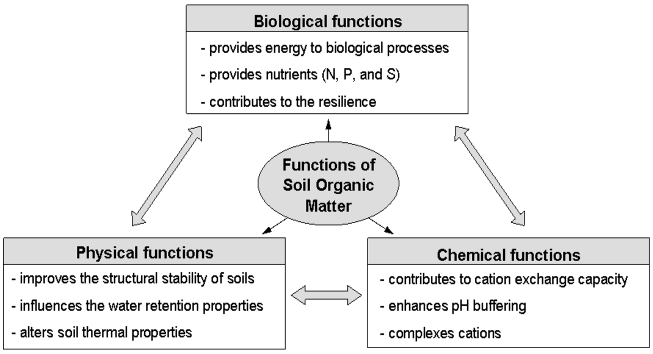

Figure 1. Functions performed by organic matter present in soils.

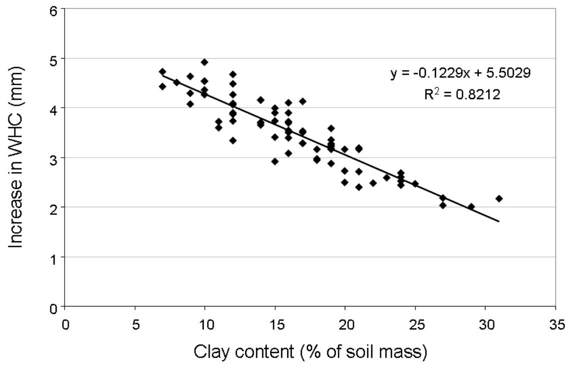

Figure 2. Magnitude of the estimated increase in soil water holding capacity (WHC) induced by increasing soil organic carbon content by 1% of total soil mass for red-brown earths of the mid-north of SA.

It remains possible, however, that capturing additional carbon within soil or reducing the extent of carbon emission from soil by altering land use and/or agricultural management practices could contribute significantly to a broad strategy aimed at reducing Australia's net greenhouse gas emission. This is particularly evident for cultivated soils where significant reductions in soil carbon can occur due to the initiation of agricultural production. Gifford *et al*. (1990) estimated that 39% of the native condition soil carbon stock has been lost over the 1860-1990 period and Guo and Gifford (2002) suggested that conversion of native forest and pasture to cropland reduced SOC stocks by an average of 42% and 59%, respectively. Such management induced reductions in soil carbon suggest that a capacity exists to recapture at least a portion of the carbon lost on initiating cultivation. Lal (1999) suggested that maximum levels of soil carbon under agricultural production would equate to 60-75% of that present under native condition.

Based on these findings and indications, it can be concluded that soil carbon does have a potential place in emissions reduction but it will not provide the longer term solution on its own. Economic considerations related to implications on farm profitability will need to be investigated along with possible incentive payments in order to encourage adoption and effect significant change in Australian soil carbon stocks.

Management practices that can enhance SOC

A review of Australian field trial data available in peer reviewed journals has been completed as part of an ongoing project with the Australian government Department of Climate Change. In this review its was found that on average the absolute rate of change in soil carbon (defined as the change calculate using data collected temporally from individual sampling locations) was negative across a range of management practices considered to capture additional carbon within soils (Figure 3a). This finding suggested that, across the soils and management practices investigated, soil organic carbon was decreasing on average. However, it was also evident from this review, that relative to more traditional less soil carbon 'friendly' practices, soils under agricultural management practices considered capable of capturing additional carbon reduced rates of loss that lead to higher relative soil carbon contents even though on average declines in absolute terms were obtained (Figure 3b). As a result, the implementation of more carbon 'friendly' management practices appears to be avoiding emissions compared to the business as usual scenario.

Developing a national approach to defining soil carbon dynamics

The National Carbon Accounting System (NCAS) in Australia has adopted a Tier 3 approach to account for management impacts on soil carbon. A soil carbon simulation model based principally on a variant of the RothC soil carbon model (Jenkinson, 1990; Jenkinson *et al.* 1987) has been formulated. Variations from the original RothC model include the substitution of conceptual model pools with measurable pools (Skjemstad *et al.* 2004) and the inclusion of soil N cycling capabilities through assignment of C/N ratios to the various soil carbon fractions in a manner similar to that used in the Century soil carbon and nutrient cycling model (Parton *et al.* 1987; Parton *et al.* 1988). NCAS can be parameterised with measured values to define carbon dynamics at an individual point or a combination of default values and spatial data layers can be used to integrate carbon cycling over defined land areas. The latter approach is used to define the impact of land use and land use change on soil carbon for Australia's national greenhouse gas inventory.

A national soil carbon research program (SCaRP) has been established for Australia to define regional impacts of land use and management practices on the quantity of carbon present in selected agricultural soils. This program has adopted a consistent sampling and analytical methodology to ensure that directly comparable data sets are collected across the country. SCaRP will provide estimates of the actual distribution of soil carbon and its composition (attribution to the soil carbon fractions used in NCAS) and allow for the identification of management practices capable of enhancing soil carbon on a regional basis. A series of traditional (Figure 4) and more modern multivariate statistical approaches will be applied to the collected data to identify management impacts on soil carbon as well as some of the underlying mechanisms that account for the differences. Such information will be used to inform NCAS and identify regional combinations of soil type and management that optimise soil carbon accumulation. The program is also seeking to define the role that introducing perennial pastures into previously annual pasture systems can have on increasing soil carbon and to develop a cost effective methodology for quantifying soil carbon content and its allocation to fractions used to parameterise NCAS with a defined level of confidence in derived values.

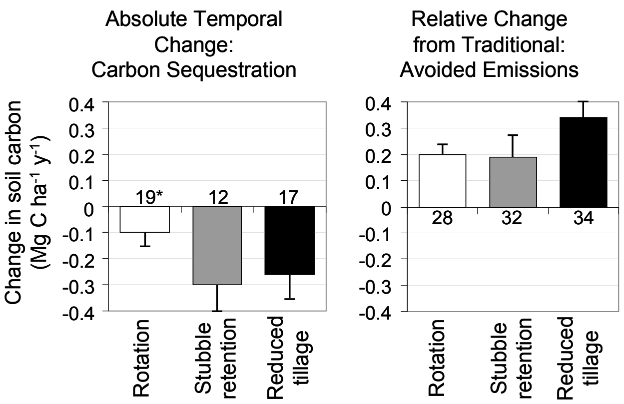

Figure 3. (a) Average absolute rate of soil carbon change under 'carbon soil carbon friendly' management practices and (b) relative difference in rates of soil carbon change between traditional and 'soil carbon friendly' management practices obtained in a review of Australia data appearing in peer reviewed publications. (* values indicate the number of studies included).

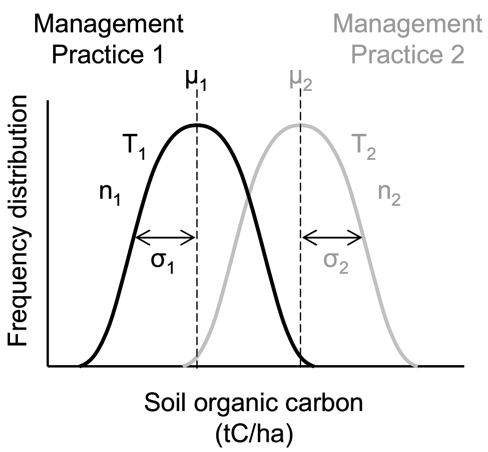

Figure 4. Schematic representation of one approach (the traditional statistical approach) to be taken within SCaRP to define the influence of agriculture (land use and management practices) on soil carbon.

References

Barrett DJ (2002) Steady state turnover time of carbon in the Australian terrestrial biosphere. *Global Biogeochemical Cycles* **16**.

Bureau of Rural Sciences (2001/2002). Land use of Australia, Version 3. http://adl.brs.gov.au/mapserv/landuse/docs/2001_02_Nat_Luse_Summary_Stats.pdf

da Silva AP, Kay BD (1997) Estimating the least limiting water range of soils from properties and management. *Soil Science Society of America Journal* **61**, 877-883.

Gifford RM, Cheney NP, Noble JC, Russel JS, Wellignton AB, Zammit C (1990) Australian lan use, primary production of vegetation and carbon pools in relation to atmospheric carbon dioxide concentration. In 'Australia's Renewable Resources: Sustainability and Global Change (Bureau of Rural Resources Proc 14)'. (Eds RM Gifford, MM Barson) pp. 151-188. (Australian Government Publishing Service: Canberra).

Grace PR, Post WM, Hennessy KJ (2006) The potential impact of climate change on Australia's soil organic carbon resources. *Carbon Balance and Management* **1**, 14-24.

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. *Global Change*

Biology **8**, 345-360.
Jenkinson DS (1990) The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society B: Biological Sciences* **329**, 361-368.
Jenkinson DS, Hart PBS, Rayner JH, Parry LC (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. *Intecol Bulletin* **15**, 1-8.
Lal R (1999) Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Progress in Environmental Science* **1**, 307-326.
Parton WJ, Schimel DC, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal* **51**, 1173-1179.
Parton WJ, Stewart JWB, Cole CV (1988) Dyamics of C, N, P and S in grassland soils - a model. *Biogeochemistry* **5**, 109-131.
Roxburgh SH, Barrett DJ*, et al.* (2004) A critical overview of model estimates of net primary productivity for the Australian continent. *Functional Plant Biology* **31**, 1043-1059.
Skjemstad JO, Spouncer LR, Cowie B, Swift RS (2004) Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. *Australian Journal of Soil Research* **42**, 79 - 88.

Effects of long-term inputs of fertiliser and irrigation on soil carbon under grazed pasture

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Abstract
Soils constitute the largest pool of terrestrial carbon, and the development and adoption of methods designed to increase storage of carbon is an effective means of reducing atmospheric carbon dioxide. The main objective of this research project was to assess the effects of long-term irrigation and fertiliser inputs on carbon in stony soils developed under intensively grazed pasture in New Zealand. Replicated field trials were established at Winchmore in 1949-1952 to assess the input requirements of pasture under flood irrigation, and are the longest running of their type in New Zealand. Results revealed that despite substantial increases in pasture production in response to inputs of fertiliser and irrigation over 60 years, there was no significant sequestration of organic carbon in the soil profile to 1m, and soil profile carbon actually decreased with increased irrigation.

Key Words
Climate change, carbon sequestration, mitigation.

Introduction

Appropriately managing the ongoing and predicted impacts of climate change is widely recognized as the most important challenge facing New Zealand's future. Sequestration of atmospheric carbon dioxide as organic carbon in soil is widely acknowledged as a viable mechanism for climate change mitigation. Recent publications have suggested that declines in soil organic carbon in temperate agricultural regions over the past 20-30 years may be partly attributed to climate change (Bellamy *et al*. 2005; Schipper *et al*. 2007). In light of these research findings, and the significant role that organic matter plays in maintaining and promoting the sustainability of New Zealand's primary industries, it is critical that the effects of long-term pasture management on soil organic carbon be resolved and quantified. The objective of this project is to quantify the effects of long-term irrigation and fertiliser application on the distribution of organic carbon in stoney soils developed under intensively grazed permanent pasture in New Zealand.

Materials and methods

A total of 24 plots comprising of 4 replicate plots of three treatments from the long-term fertiliser and irrigation field trials located at Winchmore in mid-Canterbury were selected for this study (Figure 1). The fertiliser trial was initiated in 1952, and the treatments selected were the control (nil P), 188kg superphosphate /ha.yr (188PA) and 376kg superphosphate ha.yr (376PA). The fertiliser trial received rainfall (740mm) plus 500mm irrigation per annum. The irrigation trial was established in 1949, and the treatments selected were the dryland (rainfall), irrigated at 10% soil moisture (rainfall + 250mm irrigation/yr) and 20% soil moisture (rainfall + 500mm irrigation/yr), and all treatments received 250 kg superphosphate/ha.yr. Lime was applied to both trials at establishment, and in 1965 (irrigation trial) and 1972 (fertiliser trial) to maintain pH above 6. Sampling sites were selected at the same location within each plot. In addition, a single site was selected within the 'wilderness area', which is currently under broom (*Cytisus scoparius*). This area has never received irrigation or fertiliser, and therefore provided an unimproved reference.

The soil sampling at Winchmore was carried out in April 2009 when the fertiliser and irrigation trials had been running for 57 and 60 years, respectively. Twenty five pits were excavated using a mechanical backhoe to a depth of 1.5 meters. Each pit was approximately 1 m wide by 2m long. The exposed vertical soil profile was horizontally levelled using a 40 x 40 x 25cm (0.04 m^3) steel frame as a guide and each sampling depth (0-7.5, 7.5-15, 15-25, 25-50, 50-75 and 75-100cm) soil and stones were removed. The soil and stones from each depth were transported to a laboratory where they were weighed and then separated using a combination of sieves (2cm to 10cm). Approximately 3kg of fresh soil was taken from each depth for analysis, and the residual soil and stones were then returned to the pits before refilling. A total of 150 soil samples were taken, and soils were air dried and ground prior to determination of total carbon by mass spectrometry. The soil weight for each depth increment was combined with the carbon content (%) to determine the total quantity of carbon (t/ha). Statistical analysis of differences in soil carbon content and quantity between depths and treatments within each trial was carried out using Genstat v.11.

Figure 1. The Winchmore long-term filed trials, including the 'wilderness area' (bottom left).

Results

The available average annual dry matter yield (t/ha) data for the fertiliser (1952-1979) and irrigation (1960-2000) trials showed that relative productivity for the 376PA, 188PA and control treatments in the fertiliser trial were 100, 90 and 40%, respectively. The corresponding values for the 20% moisture, 10% moisture and dryland treatments in the irrigation trial were 100, 85 and 60%, respectively. Soil carbon concentrations (%) and quantities (t/ha) determined in soil taken form the fertiliser trial, irrigation trial and wilderness plots are shown in Tables 1 and 2, respectively. As expected, the concentrations and corresponding quantities of carbon in soil decreased significantly with depth on all treatments from averages of 4.22% and 28.96t/ha and 0.67% and 7.43t/ha in the 0-7.5cm and 75-100cm soil depths, respectively. In the fertiliser trial plots there were no significant differences determined in either carbon concentration or amount between treatments at all soil depths, except for the 25-50 cm soil layer where the amount of carbon was greater in the 376PA treatment (28.56 t/ha) compared with the 188PA (19.06 t/ha) and nil P (21.33 t/ha) treatments.

Table 1. Average concentrations (%) of carbon determined in soils taken from the Winchmore long-term trials and the adjacent 'wilderness area'.

	Fertiliser Trial			Irrigation Trial			*Wilderness*
Depth (cm)	*Nil P*	*188PA*	*376PA*	*Dryland*	*10%*	*20%*	
0-7.5	4.12	4.35	4.25	4.42	4.25	3.92*	*4.50*
7.5-15	3.10	3.01	2.91	3.20	3.13	2.66*	*3.23*
15-25	2.14	2.04	2.22	2.09	2.18	1.84	*2.39*
25-50	1.35	1.22	1.38	1.20	1.35	0.90*	*0.87*
50-75	1.10	1.07	1.05	1.00	0.85	0.89	*0.62*
75-100	0.76	0.76	0.73	0.64	0.56	0.58	*0.95*

*indicates that means for 20% treatment were significantly different (P <0.05) compared with dryland and 10% treatments

Table 2. Average amounts (t/ha) of carbon determined in soils taken from the Winchmore long-term trials and the adjacent 'wilderness area'.

	Fertiliser Trial			Irrigation Trial			*Wilderness*
Depth (cm)	*Nil P*	*188PA*	*376PA*	*Dryland*	*10%*	*20%*	
0-7.5	27.96	30.84	29.25	29.94	28.99	26.77	*24.94*
7.5-15	20.54	17.77	17.91	27.81	17.49*	13.59*	*15.63*
15-25	20.63	17.26	20.13	25.27	22.35	23.03	*22.10*
25-50	21.33	19.06	28.53*	21.45	24.31	15.69*	*25.06*
50-75	9.07	10.49	10.09	12.28	16.21	7.76*	*14.79*
75-100	7.48	5.48	8.32	8.78	8.37	6.14	*11.27*
Profile	107.01	100.90	114.23	125.53	117.72	92.98*	113.73

*indicates that means for indicated treatment were significantly different ($P < 0.05$) compared with other trial treatments

Conversely, consistent significant differences in the amounts and distribution of carbon in soil were observed between treatments in the irrigation trial plots. In particular, levels of carbon were consistently lower in soils under the 20% irrigation treatment compared with the 10% irrigation and dryland treatments at most depths. Carbon concentrations in the 0-7.5, 7.5-15 and 25-50 cm soil depths under 20% irrigation (3.92, 2.66, 0.90) were significantly lower compared with either the 10% irrigation (4.25, 3.13, 1.35) or dryland (4.42, 3.20, 1.20) treatments. The corresponding data for carbon quantities revealed significantly lower levels under the 20% irrigation treatment in the 7.5-15, 25-50 and 50-75cm soil depths. In the 7.5-15cm soil, amounts of carbon were lower in both the 20% irrigation (13.59 t/ha) and 10% irrigation (17.49 t/ha) treatments compared with dryland (27.81t/ha). Only 15.69 t/ha of carbon was present in the 25-50cm soil under the 20% irrigation treatment compared with 24.31t/ha and 21.45 t/ha under the 10% irrigation and dryland treatments, respectively. Concentrations and amounts of carbon present in the wilderness site soil to 50cm were generally similar to the values determined in corresponding soils in the fertiliser and irrigation trials (except for the 20% irrigation treatment). However, quantities of carbon in the 50-100cm soils were higher in the wilderness area compared with the trial plots, especially in the 75-100 cm soil depth. Differences in carbon determined in various soil depths described above were reflected in the derived data for total soil profile carbon (Table 2). There were no significant differences observed in soil profile carbon levels between the treatments included in the fertiliser trial (100.90-114.23 t/ha). However, the amount of carbon determined in the soil profile under the 20% irrigation treatment (92.98 t/ha) was significantly lower compared with either the 10% irrigation (117.72 t/ha) or dryland (125.53 t/ha) treatments. Thus soil profile carbon to 1m under the 20% irrigation treatment was 21 and 26% lower than the corresponding amounts determined under the 10% irrigation and dryland treatments, respectively.

Conclusions

The findings of this study showed that despite significant increases in pasture production over 60 years there was no significant accumulation of organic carbon in the soil profile to 1 metre on the Winchmore plots. This was surprising given the magnitude of the response to inputs, where yields on the control treatments were only 40-60% compared with the corresponding fertiliser and irrigation treatments. Results from the irrigation trial revealed that profile soil carbon was significantly lower under the higher irrigation rate compared with the lower irrigation and dryland treatments. It is likely that soil carbon dynamics were influenced by the quality of organic carbon inputs rather than quantity, which in turn may be related to differences in pasture composition related to fertiliser and irrigation inputs. Ongoing studies are investigating this further.

References

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978-2003. *Nature* **437**, 245-248.

Schipper LA, Baisden WT, Parfitt RL, Ross C, Claydon JJ, Arnold G (2007) Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. *Global Change Biology* **13**, 1138-1144.

From source to sink – A national initiative for biochar research

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Abstract
A large national and collaborative interdisciplinary biochar project ("From source to sink – a national initiative of biochar research") funded by the Department of Agriculture, Forestry and Fisheries (DAFF) is currently in progress in Australia. The project is 3 years in duration and consists of a combination of laboratory- and field-based research activities. The DAFF project brings together leading scientists in Australia in the research areas of biochar, bioenergy, soil science, emissions management and life-cycle assessment. This national biochar initiative aims to address key aspects of biochar production and application in Australian agriculture. Research objectives are grouped in three broad categories which are closely linked with each other and which will focus on identical materials and standardised measurements: Biochar-soil interactions; Biochar and GHG mitigation; Biochar/bioenergy production and life-cycle assessment. The outcomes of this project are intended to directly benefit the Australian agricultural community and provide the scientific community, funding agencies, the Australian public and policy makers with peer-reviewed assessment of biochar production and application to soil.

Key Words
Biochar, soil carbon, climate change, carbon sequestration.

Background and introduction
Agriculture is a significant component of greenhouse gas emissions from land use and land-use change. Globally, these emissions account for carbon-equivalent emissions equal to that of transport. Since agricultural emissions are affected by fertilizer application, emissions are – as for transport – expected to increase at a faster rate then population growth *per se*, as a function of wealth creation and dietary requirements. However, the fact that agricultural land is actively managed means that the emissions can potentially be mitigated, or reversed.

Biochar, as defined by the Australian and New Zealand biochar researchers' network (http://www.anzbiochar.org/index.html) is regarded as "the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment. Due to its highly aromatic structure, biochar is chemically and biologically more stable compared with the organic matter from which it was made." Due to the specific physical and chemical properties of some biochars (e.g. highly condensed aromatic structure, high porosity, high adsorptive capacity), this form of carbon can offer potential value to crop productivity through interactions with nutrients and soil mineral particles as well as offer benefits with regard to carbon sequestration. Any improvement to agricultural productivity and/or decrease in fertiliser use whilst retaining productivity has the potential to ease pressure on the soil resource, reduce energy consumption through decreased fertiliser production and aid in management of excess organic waste. It is in this context that biochar has emerged as a potential win–win strategy for climate change mitigation and food production at the global scale. Applying biochar to agriculture is proposed for three reasons: (1) application to soil is currently the most efficient and reliable way of utilising biochar beneficially and ensuring that the carbon remains sequestered through controlled application (product and rate), (2) there is potential for biochar to enhance soil health and productivity, and (3) suppression of CO_2 and non-CO_2 (e.g. N_2O) greenhouse gas release from soil (e.g. Sohi *et al.* 2009; 2010). However, the recognition that not all biochars have the same properties requires more thorough investigations into the specific usages of different biochar types (e.g. C sequestration versus productivity increase; summarized in Figure 1) as well as their interactions with different soil types. The DAFF-funded biochar project aims to close some of the current knowledge gaps.

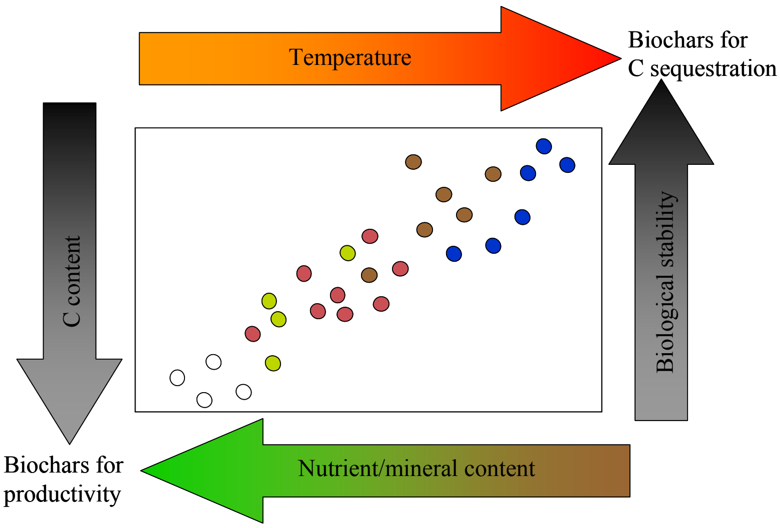

Figure 1. Example of properties of biochars produced from different feedstocks (coloured circles) at different temperature on C sequestration and productivity.

Project components and participants

The DAFF-funded biochar research project comprises three broad objectives:

- Biochar-soil interactions and characterisation
- Biochar and GHG mitigation
- Analyses of biomass stocks and life cycle assessment analysis
- Each project component is sub-divided in several tasks which are being achieved through a combination of field- and laboratory trials and analyses.

This project involves several Research Divisions from CSIRO (Land and Water: Evelyn Krull, Rai Kookana, Elizabeth Schmidt; Sustainable Ecosystems: Deborah O'Connell), Universities (UWA: Dan Murphy; UNE: Annette Cowie; USyd: Balwant Singh), State agencies (NSW Department of Industry and Investment: Lukas van Zwieten, Bhupinderpal Singh), Department of Agriculture and Food WA: Paul Blackwell) as well as agriculture groups (South Australian No-Till Farmer's Association: Greg Butler) and biochar producers/engineers (Pacific Pyrolysis: Adriana Downie; Anthroterra: Stephen Joseph). Evelyn Krull (CSIRO) is responsible for overall project management and delivery of project reports. PhD students and post-docs form an integral part of this project and project delivery.

Biochar-soil interactions and characterisation:

This task involves the characterisation of a large suite of biochars as a function of pyrolysis conditions and feedstocks. This task is collaboratively conducted in association with GRDC project CSO00041: A fundamental understanding of biochar - implications and opportunities for the grains industry. A sub-set of samples will be used to determine the interactions between biochars and different clay minerals to gain a process understanding of the organic-inorganic interactions. This will also include an assessment of the effect of aging on biochar properties. Finally, biochars will be analysed with regard to potential toxic elements and their bioavailability.

Biochar and GHG mitigation:

A combination of field trials (using in-field automated chambers) and laboratory trials (using intact soil cores) will be employed to assess the effect of biochar application on CO_2 and non-CO_2 (particularly N_2O) production. Detailed microbiological trials will be conducted to understand the effect of biochar addition on the microbial community, particularly with regard to nitrification and denitrification potential.

Analyses of biomass stocks and life cycle assessment analysis

Biochar production will be reviewed under the background of available biomass and in conjunction with bioenergy production in the Australian context. Life cycle assessment methodology will be employed to gain a comprehensive understanding of the full potential of GHG abatement using biochar in different scenarios. An analysis of current policies and future trends as well as an assessment of economic effects will be conducted as part of this task.

Outcomes
Increased knowledge of the soil benefits and GHG mitigation potential of biochar for a range of feedstock, production process and application scenarios.
Increased knowledge by landholders of the benefits and risks of application of biochar to soils as a soil conditioner and carbon sequestration tool.
Increased adoption (provided regulation is in place) by landholders of specific and appropriate biochars to improve soil condition and/or as a carbon sequestration tool.
Increased engagement between community (land holders, biochar producers), scientists and government on the risks and benefits of biochar, including building of long-term relationships.

References
Sohi S, Lopez-Capel E, Krull E, Bol R (2009) Biochar's roles in soil and climate change: A review of research needs. *CSIRO Land and Water Science Report 05/09*, 64 pp.
Sohi S, Krull E, Lopez-Capel E, Bol R (2010). A review of biochar and its use and function in soil, *Advances in Agronomy* (in press)

Nano-scale Secondary Ion Mass Spectrometry – Application to soil organic matter research

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Key Words
Image techniques, isotopes, carbon, nitrogen, ^{13}C, ^{15}N.

Introduction

Many microbial-mediated processes exhibit high spatial variability across a wide range of scales (nm to cm) and at this scale very little is known about the spatial organization of soil particles, soil organic matter, plant roots and microorganisms and their interactions. Understanding the link between the heterogeneity of the soil's physical/chemical environment and its impact on biological processes is a major challenge in soil science. Nano-scale secondary ion mass spectrometry (NanoSIMS) links a high resolution ion probe with isotopic analysis, which allows precise, spatially-explicit, elemental and isotopic analyses to be image mapped at the micro-scale (*ca*. 100 nm) (Herrmann *et al.* 2007a; 2007b). The power of NanoSIMS lies in the ability of the instrument to distinguish stable isotopes of elements with a high sensitivity, i.e. concentrations of sub parts per million can be detected. Here we illustrate the potential of NanoSIMS to examine plant root-bacterial and ectomycorrhizal competition for ^{15}N- and ^{13}C-labeled low molecular weight organic molecules. Amino acids are an important source of organic N for plants and C and N for microorganisms and as such these organic molecules are a major factor regulating ecosystem productivity. ^{15}N- and ^{13}C-labelled amino acids are often used to determine the relative competition between plants and microorganisms for dissolved organic matter. However, this has traditionally required bulk sample analysis (e.g. ground plant root material) which does not enable spatial resolution of the isotopes at a scale relevant to organic matter utilisation and competition by individual microbial and plant root cells.

As examples, we present data of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ NanoSIMS imaging to investigate (i) the competition between wheat root cells and bacteria for ^{15}N in the rhizosphere of an agricultural soil (Clode *et al.* 2009) and (ii) the flow of ^{15}N and ^{13}C across the ectomycorrhizal roots (mantle and hartig net) of the herbaceous plant *Polygonum viviparum* L.which has a widespread distribution in polar arctic and alpine regions. Enriched ^{15}N- and ^{13}C-labelled solutions of amino acid were injected into the soil surrounding the root zone of these plant species. Plant roots were sampled from individual plants over an uptake period of between 1 to 1000 minutes. Subsamples allowed the traditional bulk determination of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios for roots, soluble N pools and residual soil. In addition, samples were rapidly fixed and subsequently resin embedded so that $^{15}N/^{14}N$ and $^{13}C/^{12}C$ isotopic ratio image maps (10-30 μm^2) of cross-sections of bacterial-wheat root cell interactions or fungal-*Polygonum* root cell interactions could be obtained by NanoSIMS. Data will be presented to illustrate differential enrichment of root cells and microbes and show clear spatial patterns between the soil physical matrix (assessed as ^{28}Si), soil organic matter (assessed as ^{12}C), bacterial cells (^{15}N), fungal cells (^{15}N and ^{13}C) and plant roots (^{15}N and ^{13}C).

Conclusions

We conclude that NanoSIMS enables visualisation and isotopic ratio quantification of organic matter resource capture between competing plant and microbial cells. The ability to measure ^{15}N and ^{13}C enrichment within the rhizosphere at the sub-micron scale provides great opportunity to simultaneously quantify and image nutrient flow pathways in complex biological systems at a scale appropriate to the size of the competing organisms.

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References

Clode PL, Kilburn MR, Jones DL, Stockdale EA, Cliff JB, Herrmann AM, Murphy DV (2009) In situ mapping of nutrient uptake in the rhizosphere using nanoscale secondary ion mass spectrometry. *Plant Physiol.* **151**, 1751-1757.

Herrmann AM, Clode PL, Fletcher IR, Nunan N, Stockdale EA, O'Donnel AG, Murphy DV (2007a) A novel method for the study of the biophysical interface in soils using nano-scale secondary ion mass spectrometry. *Rapid Commun. Mass Spectrom.* **21**, 29-34.

Herrmann AM, Ritz K, Nunan N, Clode PL, Pett-Ridge J, Kilburn MR, Murphy DV, O'Donnell AG, Stockdale EA (2007b) Nano-scale secondary ion mass spectroscopy – a new analytical tool in biogeochemistry and soil ecology: a review article. *Soil Biol. Biochem.* **39**, 1835-1850.

Soil carbon and the New Zealand Agricultural Greenhouse Gas Research Centre

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Abstract
The New Zealand Agricultural Greenhouse Gas Research Centre was recently established. One of three core science areas will develop management guidelines for the conservation and, where likely, sustainable increase of soil carbon (C) storage associated with land-based food and fibre producing activities. It has been estimated that soils beneath grazed pasture store 85% of New Zealand's soil C to a depth of 0.3 m. Research has improved estimation at a national scale, but pastoral soils data remains fragmented, geographic coverage limited, and most samples obtained from a depth < 0.1 m. There has been little research about manipulating and verifying C storage rate in soils beneath grazed pasture. For these soils, C storage is already substantial including some from primal forest vegetation cleared by European settlers around 150 years ago. Modelling will develop better understanding of influential soil C cycling processes in grazed pasture systems. A potential for soil C storage will be estimated as well as the proportion that has been realised. Measuring and verifying the likely slow, relatively small and variable changes in soil C storage will be difficult. Connecting models and field measurements, accounting 'rules' are envisaged, guiding soil C storage management on New Zealand's farms.

Key Words
Pastoral agriculture, measurement, model, scaling, accounting.

Introduction
The New Zealand Agricultural Greenhouse Gas Research Centre was recently established for science to develop management guidelines for the mitigation of atmospheric change associated with land-based food and fibre producing activities. This synopsis begins with some New Zealand context to set the scene, then describes planned science about conserving and, where likely, sustainably increasing soil carbon (C) storage. Substantial additional work planned by the Centre about reducing enteric methane and soils nitrous oxide emissions will not be described here. For soil C, significant motivation comes from the realisation that organic matter underpins the provision (for example, water and nutrient supply) and regulation (for example, incubation and filtering) of the many valuable services from agricultural soils. In New Zealand, the most widespread land use is pastoral agriculture (11.1 M ha, 42% of total land area) with up to 85 M sheep and cattle fed by year round grazing. In contrast, agriculture in the forms of crop and horticulture production directly for human consumption involves ~0.5 M ha. It has been estimated that C storage in soils to a depth of 0.3 m beneath grazed pasture comprises 85 % of the national total for all land uses (Tate *et al.* 2005). These pastoral soils will be a major, initial focus of the proposed research.

Across New Zealand's South (aka main) and North islands, grazed pasture area was recently classified according to the land's dominant slope as < 15º called lowland and the rest hill country (Dr Andrew Manderson, pers. comm.). This distinction reflected the different animals and farming intensity, the latter commonly involving significantly greater stocking density and fertiliser application. The lowland area was 5.9 M ha, equally split between the two islands. Lowland dairy farms are the most intensive with ~1.5 M ha of grazed area countrywide during the 9-month-long milking season. Another ~0.7 M ha supports these farms by supplemental cattle feed production and spelling of grazed land during winter when the cows are not milked. Some cattle from dairy farms become involved in beef production. For beef cattle and sheep, there are intensive lowland fattening and finishing farms but mostly, these animals extensively graze the hill country (5.2 M ha with 56% located in the North Island). To illustrate C flowing through a pastoral agriculture system in New Zealand, indicative dairying estimates will be presented as an example. Gross photosynthesis sequestered 20 t C/ha/y from the atmosphere. Approximately half returned to the atmosphere by plant respiration, so the net C assimilation rate was 10 t C/ha/y. This was split equally between herbage utilisation (5 t C/ha/y ~ 12 t DM/ha/y where DM denotes dry matter or biomass) and plant litter and roots. For the consumed herbage, respiration was 2.7 t C/ha/y, faeces 1.5, milk and meat 0.5, methane 0.2 and urine 0.1 t C/ha/y. This suggested 1.6 t C/ha/y returned to the soil as dung and urine. Roots were reckoned to be 1 – 2 t C/ha/y, so plant litter was 3 – 4 t C/ha/y, the largest contribution to the soil.

Soil C has come from plants. In principle, farmers can increase the net C assimilation rate of pasture plants by, for example, applying fertiliser. Farmers can increase herbage utilisation by increasing the animal stocking density and vice versa. Following Parsons et al (2009), combination leads to a potential rate of C 'entering' soils, the difference between net C assimilation and herbage utilisation rates (Figure 1). Thus, increasing net C assimilation or decreasing net herbage utilisation should increase the potential C flow rate to the soil surface and vice versa. While valuable as an illustration of some involved principles, simultaneous changes in C assimilation and herbage utilisation complicate prediction.

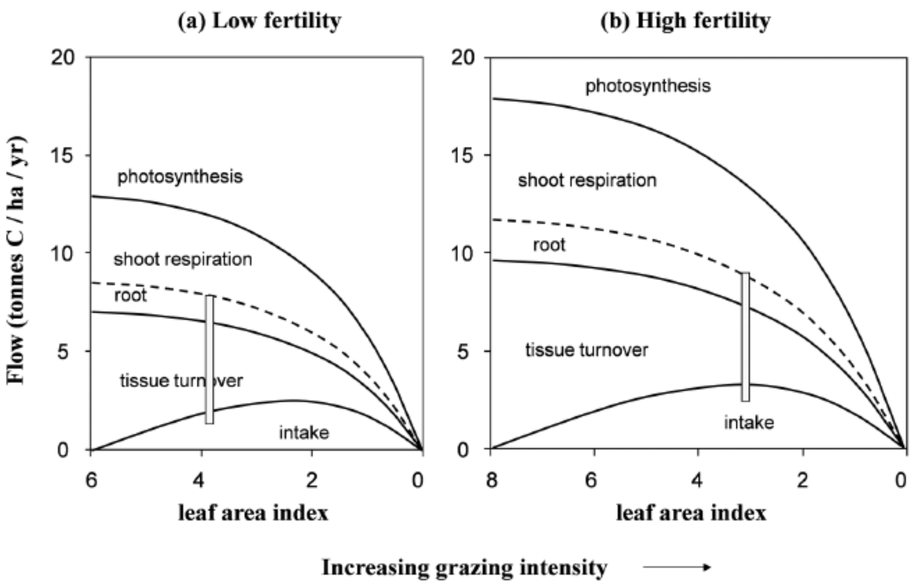

Figure 1. Relations between C flow rates through plants and animals (intake) in a grazed pasture system and grazing intensity, indicated by the pasture leaf area index, for soils of relatively low and high fertility. The vertical bars are examples, showing potential C flow rates to the soil surface (after Parsons *et al.* 2009).

The fate of C in soils has been classified using 'pools' on the basis of decomposition rate. Commonly, and risking impertinence by subsuming the complexity in a classification system, three pools have been associated with fast (annual), slow (decadal to centennial) and passive (millennial) rates. Such pools can be useful to determine the fate of C in soils (Stout and Goh 1980), including C from the primal vegetation (Tate *et al.* 1994). As an example, stable aggregates can form in soils containing particulate organic C, reckoned to be in the slow pool. Though undoubtedly challenging, if likely with reasonable accuracy and certainty, there could be considerable merit in connecting measurements and pools using models (Stewart *et al.* 2008).

In New Zealand, the quantity of C stored in soils beneath grazed pasture is already substantial. For example, soil was sampled repeatedly to a depth of 1 m on 23 dairy farms in the North Island by Schipper *et al.* (2007). Soil C storage averaged 232 ± 92 and 219 ± 109 t C/ha (± standard deviation) in the years 1983 and 2004, respectively (Dr Louis Schipper, pers. comm.). Thus, over 21 years, C storage changed by -14 ± 37 t C/ha, the negative sign indicating a net loss. With no change as a null hypothesis and a two-tailed test, the average change was significantly different ($p < 0.10$). The average change was considered a minimum detection limit estimate of 6 ± 16% ([14/232]*100 = 6%) over 21 years. It will be challenging to credibly verify the maintenance of soil C storage over time and relatively small changes that may be spatially variable.

Given context, we move on in the next section to briefly describe the Centre's proposal of a 5-year soil C research plan. Development began with a situation analysis. Scientists and stakeholders agreed there will be major challenges and a research strategy was needed.

Research strategy

The Centre's proposed work has been designed to understand the processes driving C storage rate in pastoral agriculture soils. In this C cycling system, processes include capture (net C assimilation) and supply, including amendment, as well as transfer in soils, incorporation and stability. The research will be evaluated regularly by policy stakeholders. The aspiration is an outcome, enabling farmers to conserve and, where likely, sustainably increase the rate and stability of C stored in soils. This provides another level of evaluation including, prior to recommendation, the establishment and verification of a practice's efficacy.

Envisaged first steps will be estimating a potential for sustainable C storage in soils, the current, relative position and the uncertainties. Questions can be helpful, so in short, 'how much?', 'how stable?' and 'can C storage rate be increased sustainably and verified?' (Table 1). Measurements will be undertaken in systems that can be manipulated, and measurements that can be connected to models will be most valuable, both fit for purpose. Measuring and verifying the likely slow, relatively small and variable changes in soil C storage will be difficult. Though challenging, measurements must be involved with models for acceptable accounting rules to credibly verify C storage rates as well as responses to manipulation.

Table 1. Themes, projects and key questions of a proposed research plan to enable the conservation and, where likely, sustainably increase of C storage rate in soils beneath grazed pasture.

Theme	Project	Question
Potential to increase C storage	C storage across New Zealand	How much C is stored currently and how stable is it?
	Geo-physical, geo-chemical, and climate limits	Are there upper limits for C storage?
Drivers of C storage rate	Forecasting C storage rate	Can process-based models elucidate the key drivers of C storage rate
	Determining C storage rate responses to manipulation	Can process-based models guide and verify the manipulation of C storage?
Measuring C storage rate	Verification methods	Can measurements be connected to models for acceptable accounting rules to verify C storage rate responses to manipulation?

Process-based model development and application will be major, on-going activities involving inter-disciplinary collaboration of numerate soil, plant, animal and climate scientists. Models will be essential for examining the drivers of C storage rate in soils. As stated, models and measurements will interact to identify and test hypotheses during field and controlled-environment trials. Models and measurements will also be used to develop and evaluate management practices to conserve C storage in soils and, where possible, sustainably increase the C storage rate (Table 2).

Table 2. Potential intervention practices to manipulate inputs and processes determining C storage in soils beneath pasture grazed by farmed animals with examples in brackets.

	Manipulation	Description
Inputs – C capture & supply	Land use	Land uses across a farm (feed production)
	Land practice	Fertiliser and water (precision application), functional plant traits (root: shoot ratio) and community composition (biodiversity), grazing management (herbage utilisation), pasture renewal (no tillage).
	Adding external carbon	C-rich amendments (bio char)
Processes – C transfer, incorporation & stability	Soil environment	Physical (stock density), chemical (lime) and biological (earthworms)
	Amendments	Substances (allophane) to affect the stable C pool

In closing, the Centre has been created for the people actually managing C in soils on New Zealand's farms. The planned science will be challenging, but the outcomes can be worthwhile. The sustainability of profitable pastoral agriculture depends on natural capital including what can be a wealth of C stored in soils.

References

Parsons AJ, Rowarth J *et al.* (2009) Managing pasture for animals and soil carbon. *Proceedings of the New Zealand Grassland Association* **71**, 77-84.

Schipper LA, Baisden WT *et al.* (2007) Large losses of soil C and N from soil profiles under pasture in New Zealand during the last 20 years. *Global Change Biology* **8**, 1138-1144.

Stewart CE, Plante AF *et al.* (2008) Soil carbon saturation: Linking concept and measurable carbon pools. *Soil Science Society of America Journal* **72**, 379-392.

Stout JD, Goh KM (1980) The use of radiocarbon to measure the effects of earthworms on soil development. *Radiocarbon* **22**, 892-896.

Tate KR, Ross DJ *et al.* (1994) Carbon storage and turnover, and respiratory activity, in the litter and soil of an old-growth southern beech (*Nothofagus*) forest. *Soil Biology and Biochemistry* 25, 1601-1612.

Tate KR, Wilde RH *et al.* (2005) Soil organic carbon stocks and flows in New Zealand: System development, measurement and modelling. *Canadian Journal of Soil Science* **85**, 481-489.

Towards truly sustainable cropping systems from a soil science perspective

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Introduction

Agricultural practices based on 'back-to-nature' ideas lead to drastic decline in yields, undermine the development of new and efficient production methods, and ultimately jeopardize the survival of mankind. For example, biological nitrogen fixation and use of biological pest management are often suggested as alternatives to chemical options. Such "ecosystem services" should be cautiously used as a complement as they are often associated with negative side effects such as increased nitrogen leaching, higher emissions of greenhouse gases, and production of harmful bio-chemical substances. We must go beyond the ideas of organic agriculture and create systems that are truly sustainable over the long term (Kirchmann and Bergström 2008). Such agricultural systems must produce sufficient food of good quality for a growing world population with as little negative disturbances on the environment as possible. Sustainable production requires the following conditions (Kirchmann and Thorvaldsson 2000): (i) prevention of agricultural soils from being degraded by erosion, salinization, pollution, compaction, loss of fertility, and uncontrolled urbanization; (ii) nutrient recirculation and equitable redistribution; (iii) control of soil-bound pathogens and pests; and (iv) management of soil-water status suitable for crop production. It also presumes efficient use of all types of production inputs.

List of key components for sustainable development

The following examples are identified as key components in future crop production systems with focus on soils:

- extraction of nutrients from urban wastes to produce inorganic fertilizers, which contributes to closing nutrient cycles and guarantees fertilizer quality;
- improving fertilizer use efficiency especially of phosphorus to optimize the use of a limited resource;
- separation of Cd from phosphorus fertilizers being achieved by metal extraction during fertilizer production;
- use of renewable energy for N fertilizer production;
- minimizing agricultural non-point source pollution of N and P by tailored mitigation measures; and
- development of pesticides that guarantee no toxic effect except for the target organisms.

Implementation

To reach long-term sustainability in agricultural production, we must go beyond the ideas of organic agriculture. Although 'ecosystem services' are important, research cannot ignore the need for a production increase, since food is not sufficiently provided for everyone today. This will certainly also be more critical in the future. In order to reach this critical goal for mankind, we must incorporate the message outlined in this presentation into political decisions made in society. Furthermore, we need a change in the public opinion that agriculture does not necessarily have a negative impact on the environment. It has often been proposed that many more people can be fed through a vegetarian diet, which is true. However, on-farm nutrient recycling is decreasing in systems without animals. This is very critical for organic crop production, which to a large extent is relying on recycling of animal manure for nutrient supply. In other words, a vegetarian diet requires use of inorganic fertilizers or more land, which is not available in the world. Use of more land for agricultural production will undoubtedly be in conflict with preservation of biological diversity. We have to recognize that all agricultural systems are man-made irrespective if they are organic or conventional. Therefore, to mimic natural systems does not automatically mean that we create sustainable cropping systems. Solutions may therefore not be found in nature. To develop truly sustainable systems, we need to consider the complete set of conditions outlined above, and find creative scientifically-based solutions as the only guiding principle.

References

Kirchmann H, Bergström L (2008) Organic crop production – ambitions and limitations. Springer Science and Business Media. 244 p.

Kirchmann H, Thorvaldsson G (2000) Challenging targets for future agriculture. *Eur. J. Agron*. **12**, 145-161.