Soil and plant growth benefits resulting from applying biosolids, poppy mulch and poppy seed waste as soil amendments to texture contrast soils in Tasmania

by

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Abstract

Organic materials are used as soil amendments in productive agriculture to increase or replace soil organic matter and provide essential plant nutrients. Two field trials were undertaken in Tasmania (a temperate region located between latitudes 40° and 44° south and between longitudes 143° and 149° east) over two years to quantify changes to biological, chemical and physical properties of soil and to determine crop responses from applying locally available organic materials to a texture contrast soil. Lime amended biosolids (LAB) and anaerobically digested biosolids (ADB) were applied at both sites with application rates calculated from local EPA guidelines. Lime and fertiliser (L+F) was applied at both sites, with application rates based on nitrogen requirement of the crop. Poppy mulch (PM) and poppy seed waste (PSW) were applied at one site only, with application rates based on industry recommendations.

Results showed that the application of bio-resources can produce equivalent cereal crop yields to inorganic fertiliser, for two successive seasons following application. LAB applied at 1NLBAR (for cereals) and PM applied at 17.5 wet t/ha increased soil pH by 0.9 and 0.6 units respectively within 9 months of application. Without further application of P, a season of growing cereals did not reduce soil Colwell P from pre-trial levels for the LAB treatment. However, an increase in Colwell P after the second year is of major concern for potential leaching and surface run-off of mobile P. A partial nitrogen balance after the first year showed that actual mineralised N from LAB was > 30% higher than calculated mineral N from EPA guidelines, whilst mineralised N from ADB was 19% lower than calculated mineral N from EPA guidelines. Furthermore, contrary to previous research, an inverse relationship was found between increasing rates of LAB and mineralised N according to partial N balances after the first season.

A further field trial and an incubation experiment were conducted to study nitrogen mineralisation kinetics of the different bio-resources. Results confirmed that current EPA guideline assumptions for application of ADB and LAB do not adequately reflect actual release of mineral nitrogen from either product. They also showed that eight weeks after application, PAN as a percentage of total N applied in PSW was 6 times higher than PAN from ADB, even though the application rate for ADB was 6 times higher than PSW and total N of the initial products were 4.1% and 4.2% respectively.

After 56 days incubation at 12.5° C (temperature of autumn/winter period when bio-resources are applied to soil) and constant soil moisture, PAN from total N applied in ADB, PSW and LAB was 35%, 49% and 62% respectively. The PM treatment showed a drawdown of PAN over the same period, suggesting that applying this product requires additional nitrogen to satisfy plant demand

A modelling component was included in the research program using APSIM (Agricultural Production Systems Simulator) with data from the field trials to interpret and improve understanding of the results obtained. The model simulation of mineral nitrogen accumulation in the soil following application of LAB was in good agreement with the measured data. However, measured mineral nitrogen for ADB and the higher application rates of LAB were not in agreement with the simulated model. This result together with partial nitrogen balances performed as part of this research suggests that the nitrogen equations used in the model may require additional information such as a constant that allows for the (non) uniformity of the soil to product contact when incorporated. This constant may then be used in general application guideline calculations to better reflect nitrogen release from bio-resources after application to soil.

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Table of Contents

List of Tables

List of Figures

List of Plates

1 Research Overview

1.1 Introduction

Cropping intensity has increased on texture contrast soils in Tasmania, Australia, resulting in soil structure decline and soil organic matter loss. Two regions dominated by such texture contrast soils are the Midlands and Coal River Valley. Bio-resources in the form of biosolids and poppy waste are currently used in these regions as soil amendments to replace organic matter and to supply essential plant nutrients in lieu of inorganic fertiliser. However, application rates of biosolids are currently determined by guidelines untested in the local environment, whilst application rates of poppy waste are based on an estimated release from total nutrients applied in the product.

The research presented in this body of work was undertaken to investigate and quantify any chemical, physical and biological impacts of adding specific waste organic materials to texture contrast soils in a temperate environment, particularly in relation to soil organic matter and plant available nutrients. This introductory chapter will provide an overview of the two regions of interest with respect to effects of increased cropping and irrigation on the soil type, and include a brief discussion of the mitigating strategies currently used. Background information regarding inorganic fertilisers and bio-resources in general will also be presented.

The subsequent chapter will be a more comprehensive review of the soil issues to be investigated and the bio-resources used in the research, in the context of the interaction between bio-resources and texture contrast soil. The literature review will:-

- Describe the main constraints of cropping texture contrast soils and subsequent relationship to soil health.
- Provide an extensive assessment of bio-resources (both general and project specific), including nutrient content, contaminants, current management, and effects on soil properties and subsequent plant response.
- Assess current regulatory guidelines with respect to determining application rates of bio-resources and subsequent nutrient (particularly nitrogen) release, acknowledging environmental effects such as temperature, soil moisture and rainfall, and

- Investigate the mineralisation kinetics of bio-resources when applied to soil and the use of kinetic equations in agricultural systems models to predict nitrogen release from applied bio-resources.

Outcomes of the literature review will form the basis of the specific research questions detailed for the experimental chapters that follow.

1.2 Background

Tasmania is located between latitudes 40° and 44° south and between longitudes 143° and 149° east, with a land area of 66, 288 square kilometres and a temperate climate. Following colonisation in 1803, a pastoral corridor was first established through the Midlands and Coal River Valley, with agricultural activities extending to the northwest and north east regions in the mid 1800's (ABS Year Book Australia, 1911). These latter areas contain deep gradational red clay soils (Ferrosols), which have become highly valuable for vegetable production in Tasmania. The soils in the traditional pastoral areas of the Midlands consist of texture contrast soils (Kurosols and Sodosols with variable depth sandy topsoils), together with isolated pockets of deep wind-blown sands (Tenosols), red shaley loams (Dermosols) and black cracking clays (Vertosols). The Coal River Valley soils include Kurosols, Sodosols and Vertosols.

Although dryland cropping and pasture establishment/renovation have occurred for more than fifty years, the soils of the Midlands and Coal River Valley have been subjected to an increase in irrigated cropping within the last thirty years, with the expansion of irrigation schemes and widespread adoption of centre pivot irrigation. This is despite sodicity and soil salinity being identified as a problem in the region as early as the mid 19th century and the subsequent introduction of The Tasmanian Waste Land Act of 1870 (ABS Year Book Australia, 1911). The act consolidated thirteen acts passed between 1860 and 1870, and highlighted the suitability of the soil for pastoral use only and not cultivated agriculture. Consequently, the recent increase in water application and frequency of cultivation events for crops such as poppies, onions and potatoes has presented soil management challenges for the farmers.

1.3 Texture contrast soils – definition and distribution

Texture contrast soils were first defined by Northcote (1960) as 'profiles dominated by the mineral fraction with a texture contrast of one and a half texture groups or greater between the A and B horizons. Horizon boundaries are clear – sharp.' Approximately 20% of Australia is covered by texture contrast soils with many of these being sodic and/or saline (Chittleborough, 1992).

Texture contrast soils are as diverse in their formation and pedology as the theories behind these processes (Chittleborough, 1992; Verboom and Pate, 2008). The three soil orders in Australia classified as texture contrast, vary according to the acidity and sodicity of their upper 'B' horizons; Kurosol – strongly acidic and **not** sodic, Chromosol – **not** strongly acidic and **not** sodic, Sodosol – **not** strongly acidic but sodic (Isbell, 2002).

In Tasmania, sodic soils have been estimated to cover approximately 23% of Tasmania's land area occurring primarily in the Launceston Tertiary Basin, the Derwent, Coal, Jordan and Huon River Valleys and on Flinders Island (Doyle and Habraken, 1993). This estimate was based on a limited data set and included sodic Kurosols, Chromosols and Vertosols. However, a recent study using a larger data set suggests that 1.6% of the land area in Tasmania contains Sodosols with 9.6% Kurosols and 5.3% Chromosols (Cotching *et al.*, 2009).

1.4 Challenges of increased cropping of texture contrast soils

The increase in water application and frequency of cultivation events for crops such as poppies, onions and potatoes on the texture contrast soils of the Midlands and Coal River Valley has resulted in soil structure decline and associated drainage problems (Cotching *et al.*, 2001; Doyle and Habraken, 1993). These problems can be exacerbated if the soil profile contains an unstable A_2 horizon. Mixing of the A_2 horizon with the A_1 by inappropriate deep tillage, may lead to poor surface drainage and pugging. Refer to Plate 1.1.

Plate 1.1 Pugging and compaction as a result of deep tillage (mixing A_2 + A_1) with high moisture content

Shallow top soils (cultivation restrictions) and low hydraulic conductivities of underlying horizons within the rooting depth of crops are also challenging characteristics of texture contrast soils and often lead to water logging (Fillery and McInnes, 1992). Other limitations to cropping include wind erosion, increased acidification (Coventry, 1992) and decreasing organic matter (Chilvers, 1996). These challenges were highlighted in a series of papers by Cotching *et al.* (2001; 2002a; 2002b) who found that of three soil types (Tenosols, Dermosols and Sodosols), Sodosols were the least resistant to change due to intensive cropping.

Tasmanian Irrigation was established in July 2011, by the Tasmanian Government. This is a single entity responsible for irrigation development and operation in the state as an initiative to enhance agriculture in the irrigation development regions. The main development regions in the Midlands and Coal River Valley are the Midlands scheme (56,000 ha), Coal River scheme (4,000 ha), Lower South Esk scheme (9,000 ha), Whitemore scheme (12,000 ha) and the Shannon Clyde scheme (8,000 ha) (http://www.tasmanianirrigation.com.au). However, the dominant soil type in many of these irrigation development regions are the Sodosols, Kurosols and Chromosols (texture contrast soils), potentially exacerbating existing cropping challenges of these soil types. Figure 1.1 shows the areas of Sodosols (red), Kurosols (blue) and Chromosols (green) in Tasmania adapted from Cotching (2009), and Figure 1.2 shows irrigation development areas (grey shaded) for the whole state taken from http://www.tasmanianirrigation.com.au.

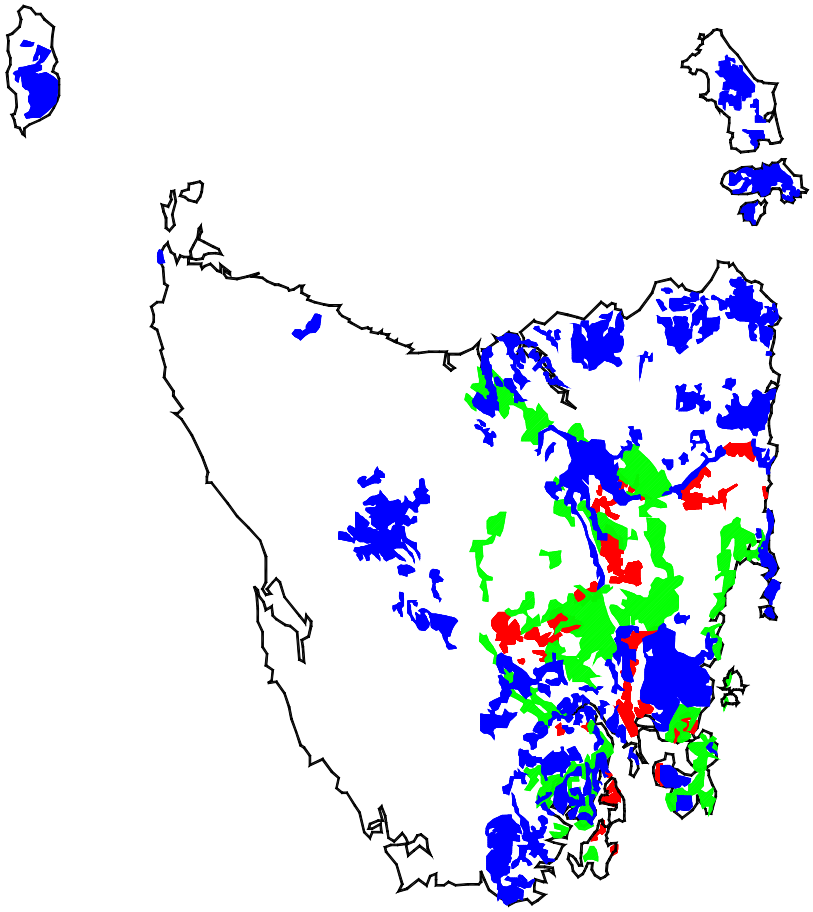

Figure 1.1 Sodosol (red), Kurosol (blue) and Chromosol (green) texture contrast soil distribution in Tasmania according to Cotching *et al.* (2009).

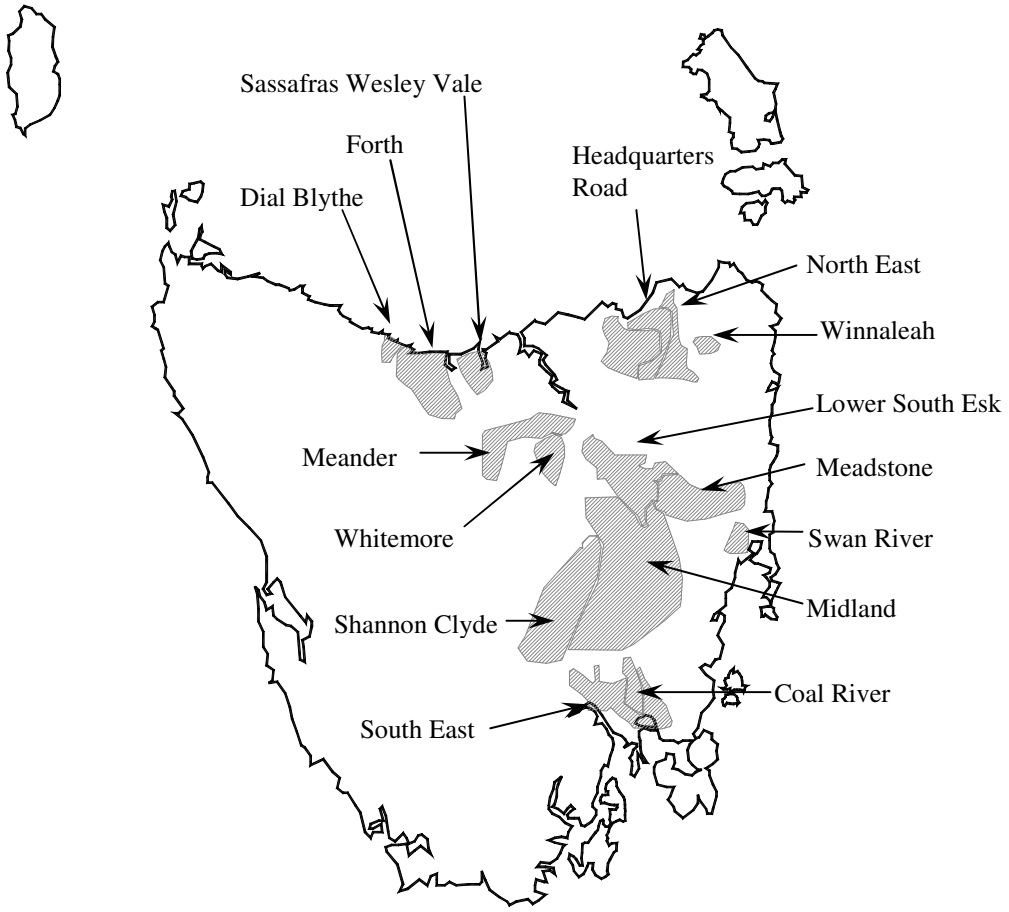

Figure 1.2 Tasmanian Irrigation, irrigation development areas (grey). Source: http://www.tasmanianirrigation.com.au

1.5 Mitigating effects of increased cropping of texture contrast soils

The consequences of declining soil organic matter, can be controlled, prevented, eliminated or mitigated in some way (György, 1989). Howard (1950) was of the view that to maintain structural integrity and fertility of soil used for agriculture, it was imperative to continuously restore the soil by manuring and applying appropriate soil management. A view supported by Hornick and Parr (1987). This management may include zero or reduced tillage (limiting oxidation of C), growing perennial crops or cover and green manure crops, retaining crop residues, and/or recharging the organic matter bank in the soil with the use of composts (Bot and Benites, 2005). An array of other organic materials have been researched for their potential to increase SOM including sewage sludge, animal manures, crop residues and industry waste (Armstrong *et al.*, 2007b; Moran *et al.*, 2005; Pardini *et al.*, 2008; Wallace *et al.*, 2009).

1.6 Soil amendments

1.6.1 Inorganic fertiliser

Since the advent of inorganic fertilisers in 1834 (Howard, 1950), the application of supplemental nutrients to soil has enabled crop production and yield to be increased and also the conversion to agricultural production of otherwise non-productive land (Byrnes and Bumb, 1998). The use of nitrogen fertiliser increased when factories fixing atmospheric nitrogen for manufacturing of explosives during the 1st World War, redirected their production of nitrogen to agricultural use (Howard, 1950). In Australia, inorganic fertilisers now account for over 12% of material and services inputs for productive agriculture, with the supply of inorganic N in fertilisers alone increasing four-fold between 1983 and 2005 (Fertiliser Industry Federation of Australia Inc., www.fifa.asn.au).

Nitrogen (N), phosphorus (P) and potassium (K) are periodically applied to soils to replace nutrients lost through crop removal, leaching and or soil erosion. Bronson and Fillery (1998) found that applied N can be lost by leaching and denitrification when texture contrast soils are waterlogged. In shallow sandy texture contrast soils in high rainfall or irrigated areas, P from applied fertilisers can potentially leach laterally over

impermeable subsoils (Bolland *et al.*, 1999). McCaskill and Cayley (2000) have also found that with high rates of superphosphate applied to texture contrast soils, Ca^{2+} in the product competed with K^+ for exchange sites, forcing the K^+ out of the 5-19cm soil layer and through the soil profile. Furthermore, Cadmium accumulation at a rate of 7.8 g ha^- yr^- has also been estimated after 44 years of high application rates of superphosphate to pasture in New Zealand (Gray *et al.*, 1999), and although mobilisation of Cd and other elements such as F is low, the potentially high level of plant uptake and accumulation in animals requires suitable management strategies to reduce this risk (Loganathan *et al.*, 2003). The appropriate use of fertilisers may improve crop production, however, cultivation and cropping continue to negatively affect soil organic matter and soil physical properties (Chilcott *et al.*, 2007).

The cost of inorganic fertiliser in Australia has also impacted on farm management decisions with urea and di-ammonium phosphate (DAP) almost doubling in price from 2006 to 2008, although there was some cost reduction in 2009 and 2010 due to the world economic downtown. The main advantage of inorganic fertilisers which ensures their enduring use is logistics. In contrast to organic materials used as soil amendments which often have a high volume to nutrient ratio, inorganic fertilisers have a high nutrient value to low volume ratio.

The escalating costs of inorganic fertilisers combined with challenges of cropping on texture contrast soils, have led farmers to seek alternatives to conventional crop production inputs. Consequently, organic materials applied to soil to replace lost nutrients and improve soil health have become more attractive (Larney and Pan, 2006).

1.6.2 Bio-resource soil amendments

Organic materials such as animal manures, crop residues, composts and sewage sludge have been used in agriculture since cultivation of crops began, to supply plant nutrients and improve soil properties. Traditional agriculture in India and China has always considered these products as part of the farming system and a natural cycling of nutrients (Howard, 1950). However, most developed nations have regarded agricultural residues and bi-products of urbanisation and industrialisation as waste products for disposal. Therefore, amendment availability and logistical limitations have often determined application timing and rate for agricultural use rather than the demand for

nutrients and organic matter (Bünemann *et al.*, 2006). For example, a study in Tasmania found that the economic viability of transporting biosolids is limited to within a 30 km radius from the product source (Cotching *et al.*, 2008). However, Sydney Water Corporation in Australia has been able to extend that distance to beyond 250 km by back loading gravel and other materials (Peters and Rowley, 2008).

Results of studies on the potential soil benefits and crop improvements from applied organic materials vary. A study by Slattery (2002) on the application of composted bovine manure to two texture contrast soils in Victoria found an increase in organic carbon, pH, Mg, Ca, N & K, with no detectable increase in surface Na, despite the compost initially containing excessive amounts of Na. It was suggested that soluble organic compounds, migrating down through the soil profile, were able to complex with the Na and remove the cation from the clay surfaces.

Maynard and Hill (1994) demonstrated that annual applications of compost can increase organic matter, subsequently leading to a change in soil physical characteristics. Changed physical characteristics included decreased soil bulk density, enabling plant roots to penetrate the soil more readily and scavenge a greater volume for nutrients, promotion of fine soil particle aggregation, reduced crusting after rains, and increased water holding capacity (Maynard and Hill, 1994). Ghosh (2008) found no change in microbial parameters from the application of organic residues to a black clay soil. Conversely, Kaur (2008) found that the application of various manures and wheat straw mitigated the effects of irrigating a sandy loam soil with sodic water, by reducing pH and bulk density and increasing microbial biomass carbon and water infiltration.

1.6.3 Nutrient release from bio-resources

If there is to be a change from conventional inorganic fertiliser inputs to organic material amendments, or a fusion of the two, to increase or maintain soil organic matter, the products and mechanisms of nutrient release from organic material amendments within the soil matrix need to be understood. For example, most nutrients contained in organic materials applied as soil amendments are in organic form. The decomposition rate and subsequent nitrogen mineralisation from applied amendments can vary greatly depending on a range of factors (Cabrera *et al.*, 2005). Aside from soil characteristics, moisture and temperature, the C/N ratio of an organic product was once considered a

good indicator of its decomposition potential (Albrecht, 1938). However, levels of other substances in the organic materials such as lignin and phenols have since been found to impact on decomposition rates and mineralisation of carbon and nitrogen (Oades, 1988).

1.7 Conclusion

In Tasmania, biosolids, poppy mulch and poppy seed waste are three organic matter products produced in sufficient quantity for application to agricultural land. Biosolids are by-products from the treatment of urban sewage, poppy mulch is the by-product of alkaloid production and poppy seed waste is the residue from poppy seed oil production. Although the annual state production of biosolids is by far the largest (about 40 000 wet tonnes), poppy mulch (10 000 wet tonnes) and poppy seed waste (5 000 wet tonnes) also contribute significantly to the overall organic matter resource available in the state.

The Tasmanian Biosolids Re-use Guidelines (Dettrick and McPhee, 1999) outline criteria required for application of biosolids to agricultural land. The current guidelines are based on interstate and overseas research and guidelines, and, as biosolids re-use has steadily increased over the last ten years, there is a need to 'localise' the science and address specific issues such as nutrient release and impact on soil properties.

There are no equivalent guidelines for the re-use of poppy mulch and poppy seed waste, and so application rates to date have been based on analysis of the product, "back of the envelope" calculations and other anecdotal evidence. Therefore, it is intended that the results of this research may form the basis of best practice guidelines for applying organic material wastes to agricultural land in a cool temperate environment and inform any revision of the existing biosolids re-use guidelines.

2 Literature Review – Interactions between texture contrast soils and bio-resources

2.1 Introduction

This review will describe the two main constraints of cropping texture contrast soils in Tasmania; soil organic matter (SOM) loss (Chilvers, 1996) and soil structure decline (Cotching *et al.*, 2001; Doyle and Habraken, 1993). The discussion will include historical changes over time in these two soil parameters and how they pertain to overall soil health of these soil types. Bio-resources have been identified to mitigate against soil structure decline and SOM loss (Pardini *et al.*, 2008; Wallace *et al.*, 2009), improve soil health (Cotching *et al.*, 2008; Ghosh *et al.*, 2008; Majumder *et al.*, 2008) and also to provide essential plant nutrients (Barbarick and Ippolito, 2007; Burgos *et al.*, 2006; Lagae *et al.*, 2009; McLaughlin *et al.*, 2008). In response, the intrinsic value, nutrient content and current management of bio-resources, including locally available biosolids, poppy mulch and poppy seed waste, will be examined. An assessment of the effect of bio-resources on soil chemical, physical and biological functions and plant response including contaminant loadings will also be presented in the context of application to texture contrast soils.

Existing biosolids regulations in Australia, New Zealand, United States of America (US) and the European Union (EU) use nutrient loadings as a basis for calculating application rates (http://www.biosolids.com.au/forms/ANZBP-Summary_sml.pdf). Application of other bio-resources such as manures, composts and mulches are at the discretion of environmental protection authorities (EPA's) in each jurisdiction, with application rates often guided by potential or perceived nutrient loadings and leaching, as well as pathogens. Release of nutrients (particularly nitrogen) from any bio-resource is dependent on its composition, temperature, soil moisture, rainfall (irrigation) and other soil management conditions (i.e. incorporation). Using these parameters, agricultural systems modelling is emerging as a cost effective research tool to predict nutrient release from bio-resources. Consequently, the review will further discuss mineralisation kinetics of bio-resources in soil, with a closer examination of N mineralisation kinetic equations and their basis in relation to use in agricultural systems models.

2.2 Soil organic matter

Soil organic matter (SOM) is derived from plant and animal matter and, although consisting of products along a decomposition continuum, can be conceptualised as being composed of at least three pools: the living, the dead and the nonliving (Ohno *et al.*, 2009). The living pool contains plant parts and organic materials resulting from microbial activity, the dead pool contains materials of identifiable tissue (i.e. incorporated leaf litter, crop residues), and the non-living pool consists of substances that have undergone decomposition to such an extent that they are no longer recognisable from their original state. The non-living pool is further divided into sub-pools identified by their resistance to microbial degradation. The largest of these is referred to as soil humus.

Soil humus contains both humic substances, which are complex organic substances defined as humin, humic acid and fulvic acid, and non-humic substances, which have defined properties (Bot and Benites, 2005). The non-humic substances include polysaccharides and polyuronides, and are more susceptible to microbial degradation than the humic substances. The remaining sub-pools include the active or labile pool containing dissolved and particulate organic matter (Baldock and Skjemstad, 1999), and a small pool that includes charcoal and charred plant materials often termed inert or recalcitrant SOM, that are refractory in nature and resistant to breakdown with very slow turnover time (Falloon and Smith, 2000). Most analytical techniques used to measure SOM actually measure soil organic carbon (SOC) and not SOM. An estimate of SOM is then obtained by using a conversion factor to account for the portion of SOM not containing carbon (Baldock and Skjemstad, 1999).

However, new spectroscopic techniques are continuing to be developed to measure molecular changes to unfractionated and fractionated SOM, particularly with respect to introduced organic materials (Francioso *et al.*, 2000; Ohno *et al.*, 2009). Regardless of whether SOM or SOC components are measured, Baldock and Skjemstad (1999) have suggested that relative to soil type, soil functions attributable to specific SOM/SOC components and SOM/SOC as a whole need to be identified and the impacts of changes to SOM/SOC and its fractions due to management quantified.

2.3 Functions of soil organic matter

SOM contributes to three broadly classified groups of soil functions, namely biological, physical and chemical (Figure 2.1).

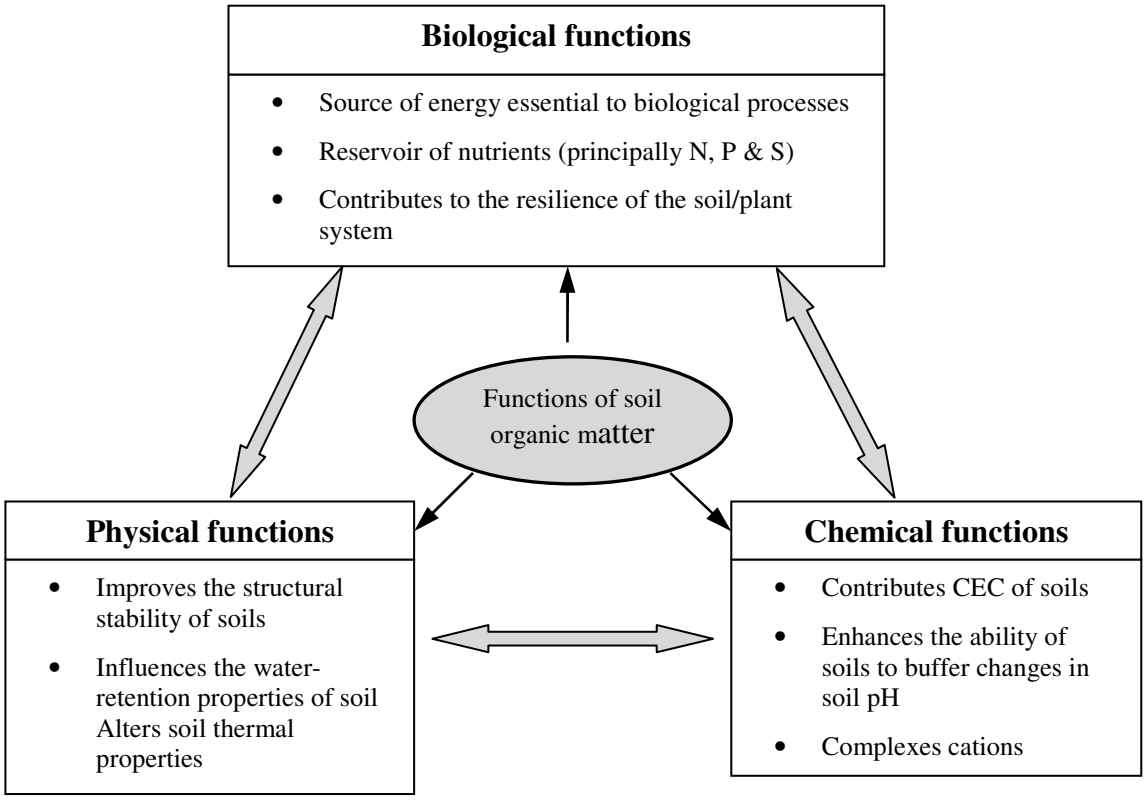

Figure 2.1 Functions of soil organic matter (taken from Baldock and Skjemstad, 1999)

These functions do not work independently, but interact with each other. For example, the biological health and activity of a soil can directly affect soil physical functions such as compactibility, aggregation and water holding capacity (Carter, 2002) as well as contributing to the soil's cation exchange capacity via decomposing organic matter (Baldock and Skjemstad, 1999).

Carter (2002) suggests that the regulation of SOM functioning in soil is related to organic matter additions or inputs. Furthermore he outlines that soil physical processes, nutrients and erodibility are specifically related to SOM in particles and aggregates, whilst physical functions such as compactibility, water holding capacity and soil friability are related to SOM in the whole soil (Carter, 2002). However, Janzen *et al.*

(1997) warn that the sensitivity of SOM means that on the one hand it can be increased in a relatively short period with alternative agronomic management (i.e. organic inputs), but on the other hand be as rapidly decreased if the alternative management is not maintained. Furthermore, the paradox of SOM is that soil aggregates are stabilised from slaking by the presence of organic matter while flocculation of soil particles and consequently the formation of surface seals are assisted by organic particles adsorbed on the clay (Quirk and Murray, 1991).

This contrasts to an assertion by Pagliai (2004) that based on manures and composts improving soil aggregation and porosity, the addition of organic materials plays an important role in preventing soil crust formation. They further suggested that results from their study confirmed the possibility of adopting alternative tillage systems to prevent soil physical degradation and that application of organic materials was essential to improve the soil structure quality.

2.4 Soil structure

Aggregation of particles is one of the most important physical properties of soil, as it is essential in maintaining good soil structure for plant growth (Ibrahim and Shindo, 1999). Tisdall and Oades (1982) theorised that aggregates could be divided into micro (<0.25mm) and macro-aggregates (>0.25mm) and that a strong correlation existed between overall stability and organic matter content. This theory described organic matter as increasing concomitantly with a rise in aggregate stability, and, conversely, soil organic matter decreasing (i.e. under intensive cropping) with a corresponding deterioration in soil structure and aggregate stability. Furthermore, the authors suggested that the contributing factors from organic matter that affect stabilisation of aggregates include organic C, N, carbohydrates, dithionite-citrate-bicarbonate (DCB) soluble Al and hyphae.

Haynes (1990) expanded the theory and described the formation of stable soil aggregates as occurring in two phases. The first phase was the aggregation phase involving exocellular microbial polysaccharide mucigels and the second was a stabilising phase involving humic materials. Aggregation of the soil particles was by the production of mucigels by microorganisms and stabilising of the aggregates was due to

the build-up of soil humic material over time. It was further suggested that a pool of carbohydrate from organic matter was involved in the formation of stable aggregates. Biological and physical-chemical (abiotic) processes contribute to the formation of soil aggregates; the physical-chemical processes being associated with clays and consequently finer texture soils and the biological processes associated with sandy soils with little clay content (Brady and Weil, 1999).

In their paper on sodicity and soil structure, Rengasamy and Olsson (1991) suggested that the stability of soil aggregates, and hence pore systems was largely determined by the attractive and repulsive forces from interactions between the soil solution and soil particles. They further stated that energy released from these interactions when a dry soil aggregate was placed in water was partly used to structurally transform the clay surfaces in the aggregates. The transformations subsequently damaging the aggregates and hence soil structure by mechanisms such as slaking, swelling and clay dispersion.

Rengasamy and Olsson (1991) stated that as the soil aggregates dry, the structural damage causes swollen and dispersed clay particles to settle in the pores by parallel orientation and may seal the pathways of air and water resulting in slow permeable clods of soil. The restriction of air and water (rainfall or irrigation) movement consequently may reduce crop growth and development (Jayawardane and Chan, 1995), and make the soil difficult to work when wet or dry (Rengasamy and Olsson, 1991).

Soil pores vary in size from >5mm down to <0.1μm and can be generally grouped as macropores (>0.08mm) and micropores (<0.08mm). Macropores allow the movement of air, plant roots, certain soil animals and the gravity drain of water. Larger micropores retain plant available water after drainage and accommodate fungi, root hairs and most bacteria, while smaller micropores (<5μm) are found largely in clay groupings (Brady and Weil, 1999). Continuous cropping and the associated structural damage and reduction in organic matter can reduce macroporosity (Pagliai *et al.*, 2004). This was confirmed by Cotching *et al.* (2001) who found a 47% decrease in dry aggregates > 9.5 mm and a 175% increase in dry aggregates 0.25 - 1.0 mm in Sodosols under cropping (with potatoes in the rotation) compared to long term pastures.

Low permeable soils with sodic properties are often associated with low macroporosity. Macroporosity can be increased by loosening soil through tillage (Jayawardane and

Chan, 1995). However, the macropore instability of the loosened soil often leads to deterioration of pore structure causing re-compaction from activities such as farm trafficking and flood irrigation (Jayawardane and Chan, 1995).

2.5 Historical changes to soil structure and SOM in texture contrast soils

Texture contrast soils or 'duplex soils' occupy approximately 20% of the land area in Australia, with many of them occurring in the cropping areas (Chittleborough, 1992). Leading up to 1992, eight years of collaborative research by CSIRO Crops and Soils Program and the Western Australian Department of Agriculture was conducted on cropping duplex soils or texture contrast soils in Western Australia, because at that time approximately 60% of crop production occurred on these soil types (Turner, 1992). The research confirmed that duplex soils with shallow sandy topsoils are prone to waterlogging and secondary salinisation (Tennant *et al.*, 1992). Furthermore, cementing agents within and trafficking of duplex soils result in hardsetting and high soil strength respectively (Tennant *et al.*, 1992). The research programme also investigated potential management options for the texture contrast soils, with McFarlane and Cox (1992) recommending the use of both above and below ground drains to remove excess water from duplex soils with a caveat that more research was needed in solute transport, salinity and soil structural changes after drainage was installed. Lucerne was also advocated as a potential ameliorant of duplex soils, both in providing soil nitrogen and enhancing soil structure (Turner, 1992).

Concurrent research on duplex soils in Hamilton, Victoria, showed that waterlogging of conventional cultivar wheat reduced the yield from 4.67 t/ha (drained) to 1.82 t/ha (undrained), with water logging occurring in the stem elongation period (Gardner *et al.*, 1992). Gardner *et al.* (1992) concluded that poor soil structure exacerbated the water logging and that perched watertables on the B horizon restrict root development in the tight clay subsoils limiting crop production on these soils. Bleached subsurface soil layers are indicative of constant waterlogging, whilst fluctuating water table results in rapid denitrification, limiting PAN in spring as crop growth rates increase (Gardner *et al.*, 1992), and recognised as the major mechanism in reducing crop yields (Fillery and McInnes, 1992). Research conducted by Carter (1992) on a red duplex soil, found

cultivation over a ten year period increased soil bulk density and decreased soil carbon in the sandy clay loam surface soils. Carter and Mele (1992) found that the long term effect of direct drilling and stubble retention on a duplex soil in North East Victoria provided only a small but significant increase in aggregate stability.

A seventeen week grazing experiment on red duplex soil in WA found that controlled grazing of pastures, where sheep were removed before the soil plastic limit was reached, reduced hardsetting and structure deterioration compared to a set stocking rate (Proffitt *et al.*, 1995). Soil structure parameters measured were dry bulk density, infiltration rate, tensile strength and image analysis of resin-impregnated soil blocks. In their study of the effects of agricultural management on a texture contrast soil in Tasmania, (Cotching *et al.*, 2001) found problems of hard setting and compaction when harvesting potatoes from soil with higher than desirable moisture content. Cotching *et al.* (2001) also found a 32% reduction in total organic C and a 27% decrease in readily oxidised C in Sodosols under cropping (with potatoes in the rotation) compared to long term pastures.

Recent research of texture contrast soils has focussed on potential management options to mitigate negative changes from cultivation. Five years of research by Bakker *et al.* (2005) found that averaged over the study period, the use of raised beds decreased bulk density in the cultivated depth of the soil, compared to control. Advocated as an option by Turner (1992), Latta and Lyons (2006) found that lucerne in a wheat rotation was a productive option for sodic duplex soils for its ability to increase water deficit to provide a buffer against waterlogging.

The alternative to cropping texture contrast soils is an extended pasture phase, which has been well documented to improve soil organic matter levels and many soil physical properties for these and other soils (Carter, 2002), and hence maintain soil quality and health. However, net yield is still the major factor in the economic viability of a farming operation, and, depending on commodity prices, grass/animal production may not always be the most profitable enterprise. So, to ensure the sustainability of cropping fragile texture contrast soils, further understanding is required to manage soil organic matter and soil structure decline concomitant with maintaining yield.

2.6 Health of texture contrast soils

Soil performs many functions in the ecosystem including serving as a reservoir of water and plant nutrients (Ludwick *et al.*, 1995), a purifying medium, a major sink for waste materials, an organic waste decomposer, a detoxifying agent and a means by which biological systems obtain their required major nutrients (Doran, 1994). The physical, chemical and biological properties of a soil collectively reflect its quality, whilst the capacity of soil to function as a vital living system within ecosystem and land-use boundaries is a measure of soil health (Doran and Zeiss, 2000). Agricultural practices such as cultivation has shown a significant decline in the quality of many soils (Doran, 1994). However, adopting zero tillage with residue removal may also decrease soil health over time (Govaerts *et al.*, 2007). Following a study of the effects of cultivation on a red texture contrast soil in NSW, Australia, Pankhurst *et al.* (2002) suggested that microbial biomass was an important indicator of soil quality and health. Cultivation resulted in a bacteria dominated microbial biomass, whilst zero tillage with residue retention resulted in a fungi dominated microbial biomass (Pankhurst *et al.*, 2002). However, Spedding *et al.* (2004) warn that this measure of soil health should be used with caution due to temporal changes in soil conditions throughout a growing season (particularly relevant to waterlogging in duplex soils). Gonzalez-Quinones *et al.* (2011) recognised the subsequent difficulty in interpreting absolute microbial biomass values and suggested a possible framework for measuring and interpreting results. Cotching *et al.* (2001) found that farmers of Sodosols perceived their cropping soils to be healthy unless potatoes were included in the rotation. This perception agreed with the results as Cotching *et al.* (2001) found a 33% reduction in microbial biomass C in cropping soils (with potatoes in the rotation) compared to long term pasture. They also found a significant correlation between microbial biomass C, total organic C and readily oxidised C.

Perennial wheat has been investigated for its potential to rectify declining soil carbon and improve health of soils with poorly structured and difficult to manage subsoils (Bell *et al.*, 2010); typical characteristics of texture contrast soils (Passioura, 1992). In order to address SOM loss, improve soil structure and supply plant nutrients (and ultimately maintain/improve soil health), farmers are seeking organic alternatives to inorganic fertilisers for productive agriculture (Larney and Pan, 2006). Based on consultation with

stakeholders in the wheat belt of Western Australia, a review by Chen *et al.* (2009) identified that decision support systems would be enhanced by improved understanding and application of physical and chemical soil tests, and evaluation of new fertiliser products, specifically N- management concepts.

2.7 Bio-resources

2.7.1 Introduction

Many bio-resources used in agriculture for soil amendments have not been manufactured for this purpose and contain many nutrients in an 'organic' form with unknown or variable degradation or release rates. Bio-resources such as animal manures and other organic materials are continually being investigated for use in agriculture (Dong *et al.*, 2005; Flavel and Murphy, 2006). The potential use of bio-resources, which are inherently voluminous materials, is limited by availability, commercial quantity and proximity to application site. In Tasmania, biosolids, poppy mulch and poppy seed waste are three organic materials produced in sufficient quantity for application as soil amendments to agricultural land. Limited information is available regarding these locally available products and their suitability for use in the areas of interest for this research. The following section will provide an overview of the three bio-resource materials used in this research, including the origins, treatment processes (where applicable) and current disposal or re-use programmes both locally and in a broader context. A more comprehensive review of bio-resources with regard to contaminants, nutrient release, interaction with soil functions and plant response will be presented in subsequent sections of the chapter.

2.7.2 Biosolids

2.7.2.1 ***Background***

The term 'biosolids' was created in 1991 by the Water Environment Federation (WEF) to differentiate between the usable 'solids' from municipal waste water or sewage treatment plants and the untreated raw sewage sludge from households, commerce and industry (Jenson, 1993 as cited by Moffet *et al.*, 2005). Treatment can involve either aerobic digestion (i.e. settling ponds) or anaerobic digestion. The anaerobically digested biosolids may be dewatered by presses, a centrifuge and/or polymers to reduce the

volume. After dewatering, biosolids can still have a consistency that varies from custard to moist soil (Shammas and Wang, 2007), with further treatment processes adopted such as pasteurisation and lime stabilisation to control odours and reduce pathogens (Brown *et al.*, 1997). Refer to Plate 2.1. Once treated, biosolids may then be disposed of by ocean dumping, landfill or incineration, or used beneficially for composting, remediation of contaminated mining sites or agricultural land application. Disposal methods of biosolids are controlled in order to **reduce** pollution, while beneficial re-use of biosolids has been defined as a sustainable practice that **protects** environmental, public and agricultural health while delivering economic, social and environmental **benefits** (Bethel, 1999).

Plate 2.1 Weighing lime amended biosolids prior to application to trial site at Cambridge

2.7.2.2 ***Biosolids disposal***

Prior to 1990, the preferred method for biosolids disposal from coastal cities around the world was ocean dumping: preferred because disposal cost through a long pipeline was considerably less than sophisticated land treatment systems (Wood *et al.*, 1993). Since that time, this disposal method has been outlawed by the United States (Schroder *et al.*, 2008), Australia and the European Union (EU). However, like some developing parts of the world, countries such as Canada continue to dump raw sewage into waterways and oceans unabated (Maclean, 2005).

Landfilling continues to be a preferred method of biosolids disposal despite the EU enacting a directive in 1999 to limit potential negative environmental impacts of this practice. Landfilling occurs because either the land is not available for surface application or the quality of the biosolids is below environmental protection authority (EPA) standards for beneficial re-use. In the US, landfilling of biosolids can accumulate carbon credits with methane extraction from the site providing additional sequestration benefits (Brown and Leonard, 2004).

Incineration of biosolids occurs where space for disposal is limiting, provided stringent environmental controls over toxic and particulate emissions are adhered to. However, more recently, incineration is gaining interest not only for disposal but for energy generation (Englande and Reimers, 2001).

2.7.2.3 ***Biosolids - beneficial re-use***

Composting and Site Remediation

Composting is a process of mixing and incubating different organic materials together in fixed proportions for use as a soil amendment. Maintained at a specific temperature and moisture content for a certain period, composting can convert materials to a form more readily incorporated into the soil (Crawford, 2006). Composting of many types of organic wastes, including biosolids, is a preferred treatment to reduce the overall mass to landfill, for reclamation of infertile soils (Raviv, 1998; Stratton and Rechcigl, 1998), and to reduce the risk of transmitting human pathogens (Sarooshi *et al.*, 2002). It has also been viewed as an option for degrading pharmaceuticals and personal care products

(PPCPs) and other organic contaminants found in biosolids (Xia *et al.*, 2005), and to stabilise the organic matter contained in the product (Brown and Leonard, 2004). Composting of biosolids may also prevent the bioaccumulation of pharmaceuticals in earthworms after application of biosolids (Kinney *et al.*, 2008). However, uptake of a contaminant by plants does not necessarily follow its accumulation in the soil (Wrigley *et al.*, 2008).

Surface land application of composted biosolids has been shown to stabilise soil after forest fires (Meyer *et al.*, 2004), and to prevent leaching of heavy metals (Gove *et al.*, 2002). However, Wrigley *et al.* (2008) observed that mixing composted biosolids with plant potting media at various ratios resulted in leaching of zinc and cadmium. Conversely, lime stabilised biosolids has been found to reduce phytoavailability of zinc and cadmium in smelter contaminated soils (Basta *et al.*, 2001). In the former example, leaching may be due to soluble complexes being formed between dissolved organic matter and metals ions contained in both the potting media and the composted biosolids. In the latter example, phytoavailability of heavy metals can reduce with an increase in pH (Basta and Sloan, 1999), but also the metal ions may be adsorbed to the introduced carbonates in the soil and subsequently immobilised. Plants have also assisted in removing heavy metals after application of biosolids to contaminated sites. Case studies outlined by Adriano *et al.*(2004) showed that the use of biosolids enhanced natural remediation of contaminated sites by increasing vegetative growth, which in turn removed soil contaminants via bioaccumulation.

Agricultural Land Application

Biosolids contain many of the macro and micronutrients required for plant growth as well as organic matter for maintaining or improving soil physical characteristics. Most countries where biosolids are re-used beneficially have EPA guidelines stipulating the application rates for agronomic benefit. Many states in Australia use the nitrogen limiting biosolids application rate (NLBAR) together with contaminant limiting biosolids application rate (CLBAR) to determine application rates, along with other soil constraints including hydraulic conductivity and pH. The level of final treatment and subsequent grade of biosolids also dictates the potential end use (Dettrick and McPhee, 1999).

Extensive laboratory and field trials were conducted between 2005 and 2009 across five mainland states of Australia under the banner of the National Biosolids Research Program, in which the benefits and risks to human and environmental health associated with applying biosolids to agricultural land was investigated (Broos *et al.*, 2007; McLaughlin *et al.*, 2008). Although this and other research has been undertaken espousing the benefits of biosolids for land application (Barbarick *et al.*, 2004; Cogger *et al.*, 2006), concerns continue to be raised about excess plant nutrients (i.e. phosphorus) and leaching (Alleoni *et al.*, 2008; Shober *et al.*, 2003), potential soil contamination from heavy metals (Oliver *et al.*, 2005; Stehouwer and Macneal, 2004), and accumulation of PPCPs (Kinney *et al.*, 2008; Xia *et al.*, 2005).

2.7.2.4 ***Biosolids in Tasmania***

About 86 wastewater treatment plants (processing >100 kilolitres/day) operate in Tasmania (DPIPWE, 2009) servicing a population of around 500,000 people and producing approximately 10,000 dry tonnes of biosolids per year. As of 1st July 2009, these treatment plants came under the authority of three regional jurisdictions. The larger treatment plants servicing the cities of Hobart and Clarence produce anaerobically digested biosolids (ADB) and lime amended biosolids (LAB). Both products undergo anaerobic digestion and are dewatered with polymers and either a centrifuge or a belt press. For the LAB, the lime is added to the ADB (in the form of calcium carbonate or calcium oxide) just prior to entering a screw type conveyor contained in a tube, after which the final product is discharged into reuse containers for distribution (B. Hanigan *pers comms*).

2.7.3 Poppy waste

2.7.3.1 ***Background***

The poppy, *Papaver somniferum* L., is an annual herb native to Turkey and adjacent countries (Azcan *et al.*, 2004) and one of the oldest cultivated plants known to mankind (Fist, 2001). Plate 2.2 shows a commercial poppy crop at flowering.

Plate 2.2 Commercial poppy crop at flowering in the Northern Midlands of Tasmania.

Poppies are grown commercially for licit production of opium in Australia, India, Iran, Turkey, Pakistan, Bulgaria and Japan with illicit production in Afghanistan and parts of Southeast Asia. Since the first commercial production of opiate poppy crops in 1965, the Australian poppy industry has developed to currently supply approximately 50% of the world's morphine concentrate. Other concentrates produced from poppy straw include thebaine and codeine. Within Australia, the growing of commercial opiate poppies is restricted to Tasmania by a ministerial agreement between the Commonwealth and the States (Fist, 2001). Three companies (Tasmanian Alkaloids Pty Ltd, GlaxoSmithKline and TPI Enterprises Ltd) plant, harvest and process the poppies from an annual planted area exceeding 20,000 hectares, with GlaxoSmithKline the only company to send the raw straw out of the state for processing.

Planting of commercial opiate poppies occurs in late winter to spring with a planted density of approximately 100 seeds per square metre (J. Shaw, *pers comms*). Depending on final density, individual plants usually consist of a short primary head and one to two taller secondary heads. At maturity, the seed capsule and the upper 15 cm of the stem is harvested, and then threshed to remove the seeds. The seeds are not used in the extraction process as they do not contain significant amounts of the active ingredient required for the concentrates.

2.7.3.2 ***Extraction processes***

Poppy mulch

Poppy mulch (PM) is primarily poppy straw (capsule and stem) less the extracted active ingredient. However, final nutrient content of the mulch has the potential to be affected by the extraction process. The poppy straw processed by Tasmanian Alkaloids Pty Ltd undergoes a lime extraction using a warm solvent percolation system to remove the alkaloids, with the resulting concentrate containing between 40 and 80% of the active ingredient termed alkaloid (Fist, 2001). Calcium phosphates are precipitated with the straw at this stage in the process. The concentrate is then used in the manufacture of pharmaceuticals and is also sold as a raw narcotic material. The bi-product of the extraction process, the straw, has been termed 'poppy mulch'. Refer to Plate 2.3.

Plate 2.3 Poppy waste from Tasmanian Alkaloids Pty Ltd

This product undergoes a further process involving multi-layered live and static steaming to extract solvents used in the primary extraction process. The solvents are then re-used. Other additives used in the process include charcoal, diatomacous earth and spent mother liquors. Spent mother liquors are liquid waste from chemical refining processes and contain soluble calcium, phosphorus and potassium.

Poppy seed waste

The seeds of the poppy varieties containing morphine are used for culinary purposes and oil from the seeds used as edible oil, and in the manufacture of paints and cosmetics

(Azcan *et al.*, 2004). The seed coat or oilcake is used as cattle feed in Turkey (Azcan *et al.*, 2004) and has also been investigated for use as feed supplements for pigs and poultry (Akinci and Bayram, 2003; Statham, 1984). The seeds from the more toxic thebaine-containing poppy varieties are processed to extract the oil for commercial and industrial applications. The process used by Macquarie Oils Tasmania is called 'cold pressing' which uses only a small amount of water (R. Henry pers comms). Oil contents of thebaine poppy seed vary from 30% to 50% between varieties with protein levels varying from 20% to 30% (Azcan *et al.*, 2004). The bi-product of oil extraction is 'poppy seed waste' (PSW) sometimes referred to as poppy seed meal shown in Plate 2.4.

Plate 2.4 Poppy seed waste from Macquarie Oils Tasmania

2.7.3.3 ***Agricultural use***

The licit production of poppies for extraction of medicinal compounds is limited to the areas listed above, and so the re-use of the associated waste products is also limited. Most research around the world to date has focussed on the growth of poppies (Lisson, 2007), the production of alkaloids (Fist, 2001) and the nutritive value of edible poppy seeds (Eklund and Ågren, 1975) and poppy seed oil (Azcan *et al.*, 2004). Very little information has been published on the use of the bi-products of poppy production (i.e. poppy mulch and poppy seed waste), particularly in production agriculture. Some limited research has been undertaken in Tasmania using poppy mulch as a soil amendment growing spinach in a sandy loam soil (Hardie and Cotching, 2009). The

results indicated that soil pH and EC both increased, which consequently affected plant growth negatively due in part to the plants being intolerant of such soil conditions, and that planting occurred within the first 16 weeks after application of the product. However, soil carbon was found to significantly increase from 1.24 % to 1.57 % from the 200 m^3/ha application rate (Hardie and Cotching, 2009).

Anecdotally the suggested time frame for a positive soil and plant response from poppy mulch is eighteen months after application and incorporation, with a further recommendation to avoid growing potatoes and lettuces within that period (J. Aitken *pers comms*). This time frame is purported to allow the soil to neutralise the 'salts' in the poppy mulch (product used by Hardie and Cotching (2009) had an $EC_{1:5}$ = 7 dS/m).

2.7.4 Contaminants and bio-resources

Bio-resources may include industrial biosolids, industrial and agricultural by-products, municipal biosolids, municipal garden waste, composts, animal manures and crop residues. Contaminants in any of these products may include heavy metals, synthetic organic compounds (Haynes *et al.*, 2009) or high concentrations of plant derived compounds such as glycosides (Snyder *et al.*, 2009), with the presence and concentration dependent on the component source and/or the production process.

Industrial and agricultural by-products

Meal produced from pressing oil from brassicaceae seeds can contain up to 6% nitrogen, but when applied to agricultural land may be phototoxic to plants due to high levels of glucosinolates (Snyder *et al.*, 2009). Alternatively, meal from the oil seed *Limnanthes alba* contains glucosinolate degradation products and has potential as a biopesticide (Stevens *et al.*, 2008). Wood ash from energy production can contain high concentrations of cadmium, copper, chromium, lead and arsenic, but applied at rates below 10 t/ha can reduce possible toxicity (Pitman, 2006).

An alkaline by-product (bauxite residue) from crushing bauxite with caustic soda to produce alumina, when applied to soil, increased soil pH but reduced plant available P (Summers *et al.*, 2001). Eight weeks after application of poppy waste to a texture contrast soil, soil testing demonstrated that up to 57% yield losses of Bocane spinach

may have been due to an increase in pH and electrical conductivity (Hardie and Cotching, 2009).

Biosolids, composts and animal manures

Kinney *et al.* (2008) documented bioaccumulation of organic contaminants in earthworms after the application of biosolids (i.e. synthetic fragrances, pharmaceuticals and detergents) and swine manure (biogenic sterols). When applied to soil, manure borne estrogens have been found mobile enough to be transported to aquatic environments and effect reproductive biology of fish and vertebrates (Hanselman *et al.*, 2003). However, Peterson *et al.* (2003) found no accumulation of organic contaminants in either plants or soil after annual soil applications each of sewage sludge, household compost and solid pig manure over three years. Faecal coliforms were found in subsurface drainage within 40 minutes following irrigation of soil applied liquid swine manure in a study of preferential flow (Geohring *et al.*, 1998) . Rapid downward transport of soluble compounds from any product applied to soil is of concern particularly when irrigating dry texture contrast soils (Hardie *et al.*, 2011).

The bioavailability of heavy metals from biosolids was modelled following an extensive research programme in Australia (Warne *et al.*, 2008), which has enabled the development of heavy metal contaminant guidelines for application (Heemsbergen *et al.*, 2009). In addition, Cotching and Coad (2011) found that application rates of biosolids within current Tasmanian guidelines (Dettrick and McPhee, 1999) did not result in bioaccumulation of heavy metals in wheat or potatoes.

Crop residues

Crop residues have been incorporated back into soil to replace lost nutrients and increase organic matter since agriculture began (Albrecht, 1938). This includes burning of post harvest crop residues, which is still practiced worldwide (Zhang *et al.*, 2004). However, the unfettered use of crop residues, burnt, dried or green, may have negative impacts on soil properties. For example, ash has been shown to increase sorptivity of organic matter, which on the one hand is good for nutrient accumulation, but on the other retains pesticides and increases their persistence in soil (Zhang *et al.*, 2004). Plants also do not discriminate between nutrient sources in the soil (Burgess, 1992) and

providing temperature and moisture are optimum take up the required level of nutrients for continued growth. However, some plants such as spinach have been shown to take up heavy metals even under conditions of no extra loading from applied materials (Cotching and Coad, 2011).

Remediation of soil contaminants

In contrast to issues related to soil application of bio-resources with contaminants, bio-resources have been researched for their potential to remediate contaminated soil. A combination of lime, phosphate and compost has been shown to reduce the phytoavailability of lead and manganese in contaminated soil (Padmavathiamma and Li, 2010). Biosolids have also been documented to increase vegetative growth and subsequently remove soil contaminants in an environmental clean up through phytoextraction (Adriano *et al.*, 2004).

Although heavy metal contaminant loadings in some bio-resources used in Australia such as biosolids have concentration guidelines (Brown *et al.*, 2009; DEP *et al.*, 2002; Dettrick and McPhee, 1999; NSW-EPA, 1997; VIC_EPA, 2004), research continues to raise concerns about the fate of other contaminants in manures and biosolids such as persistent organic compounds (Haynes *et al.*, 2009; Overcash *et al.*, 2005). Ultimately, continued research into the persistence in soil and bioaccumulation in plants of land applied bio-resources will help to determine application rates to maintain human and environmental health.

2.7.5 Nutrient substitution of inorganic fertilisers by bio-resources

Bio-resources are often applied to soil in lieu of inorganic fertiliser to supply essential plant nutrients (Kidd *et al.*, 2007; Mohammad *et al.*, 2007). However, the inherent difficulty with using alternative materials is the variation and availability of nutrients depending on management, product composition and consistency. For example, Paschold *et al*. (2008) found that incorporating swine slurry reduced the mineralised N from 70% to 40% of total N applied and mineralised P from 100% to 60% of total P applied in the year of application compared to not incorporating. Ulen (1993) also found that composts containing manures had the potential to leach mineral nitrogen if not

incorporated. However, they reduced leaching by adding more dry straw to the base product (Ulen, 1993).

Weggler-Beaton (2003) found that although grain yield was similar between the application of air-dried biosolids and inorganic fertiliser, early P demand by the crop was not met by P supply from the biosolids. A laboratory incubation over 150 days by Flavel and Murphy (2006) using poultry manure pellets (PP), green waste compost (GWC), straw based compost (SBC) and vermicast (VER) applied at 24 dry t/ha to coarse textured sand, found that mineralisation of nutrients in regard to timing and amount was similar across all treatments providing at least a partial substitute for inorganic fertiliser. However, more nitrogen was released from the PP than was required for plant uptake, which has the potential for leaching (Flavel and Murphy, 2006). After growing two successive vegetable crops in twelve months on a red Chromosol soil, Sarooshi *et al*. (2002), found that elemental N, P and K in composted biosolids treated soils (applied at 125 dry t/ha) was significantly higher than soils fertilised with 1 t/ha 18:12:10.

In a greenhouse study of nutrient availability for plant growth, Wong *et al.* (2001) found that soil amended with biosolids without lime contained more nitrate and ammonium N, and major cations than soil amended with limed biosolids. However, dry weight yields of *Brassica chinensis* for the limed biosolids treatment was significantly higher (Wong *et al.*, 2001). Pu *et al.* (2008) found that sorghum dry matter production was significantly higher for soil amended with anaerobically digested and aerobically digested biosolids than for inorganic fertiliser. However, the study showed that higher application rates of biosolids increased mineral N concentration in the soil with little additional dry matter production. Furthermore, they calculated that the in-season mineralised N was 43 - 59 % of total organic N applied in the biosolids, which was much greater than guideline calculations (Pu *et al.*, 2008).

This disparity between rates and products demonstrates the inherent difficulty in making direct comparisons between inorganic and organic fertilisers. However, the management challenge of applying bio-resources to texture contrast soils is to match nitrogen supply with crop demand without excessive leaching and denitrification (Passioura, 1992).

2.7.6 Affect of Bio-resources on Soil Functions

Biological Functions

Nutrient release from applied organic amendments is dependent on decomposition processes. The soil fauna and flora which collectively are termed the microbial biomass (MB) are considered the primary and secondary consumers in the food chain, cycling nutrients from dead and decaying plant debris and other microfauna through the soil (Brady and Weil, 1999). Research conducted on surface applied biosolids to shrubland and grassland in the United States found an increase in MB six years after application (Barbarick *et al.*, 2004). However, Boyle and Paul (1989) found a significant decrease in MB after 20 weeks of incubating sludge treated soils. The soils were gathered from sites three years after eight years continued sludge application.

Brendecke *et al.* (1993) found that after applying anaerobically digested sludge at rates between 8.0 and 24 Mg/ha each year for four years to an arid soil, there were no significant adverse affects to microbial populations or their activity. They also found no significant changes to soil physical and chemical properties aside from elevated PO_4 – P, giving rise to their suggestion that microbial activity was not a good predictor of soil fertility. Plate counts of bacteria and fungi were also conducted and found to not be significantly affected by biosolids (Brendecke *et al.*, 1993). In their study of soil fungal and bacterial changes resulting from the addition of organic materials with different C/N ratios, Johannes and Erland (2007) found that bacteria increased with a lower C/N ratio material (alfalfa) whilst fungi increased with a higher C/N ratio material (barley straw). However, when they added N to balance the C/N ratio of the barley straw, fungi increased and bacteria was inhibited, against expectations (Johannes and Erland, 2007). This would suggest that the composition of organic amendments, other than the C/N ratio, may impact on bacterial and fungal activity and subsequent biological function.

In a five year glasshouse experiment conducted in Italy by Marchesini *et al.* (1988), fertiliser and compost treatments were applied to a sandy soil (85% sand) to examine possible benefits of long-term compost treatment of soil. Findings were that although yields were more for the compost treatments than the fertiliser treatments, microbial activity was similar across all treatments. However, it was suggested that the microflora developed in the composted mixes consisted of qualitatively different populations

offering more beneficial conditions for plant growth (hence, higher yields) and at the same time excluding the development of harmful organisms (Marchesini *et al.*, 1988).

In another greenhouse trial by Lupwayi *et al.* (1998), microbial biomass and bacterial diversity were analysed from residues of wheat, barley, canola, field peas and red clover incorporated into potted soils at equivalent rates of 5 tons an acre. The results indicated that fertiliser alone (without a carbon source) did not stimulate microbial growth, but rather, had an indirect effect by promoting growth, but only if plant residues were then incorporated into the soil (Lupwayi *et al.*, 1998). The authors also suggested that soil microorganisms perform many agriculturally important functions including decomposition and recycling of nutrients from dead organic material, nitrogen fixation, and maintenance of soil structure and detoxification of agrochemicals.

A study by Falih and Wainwright (1996) into the incorporation of sugar beet into soil found that the easily available carbon (from the beet) stimulated microbial and enzymatic activity . They suggested that amendments such as this could stimulate beneficial microbial processes in soil, such as P solubilisation. However, although it was considered that nitrification and S oxidation were mediated solely by chemo-autotrophic bacteria and hence not directly influenced by addition of C substrates, the authors concluded that the stimulated microbial activity by sugar beet could lead to nitrification, leaching and S immobilisation (Falih and Wainwright, 1996).

In a further study conducted by Cooper and Warman (1997) to assess microbial activity within both composted and fertilised plots, they found that compost application increased dehydrogenase enzyme activity DHA and organic C, whereas the fertiliser treatments resulted in a decrease in DHA without a corresponding decrease in organic C or pH. Conclusions were that microbial activity in the fertiliser treatments was possibly affected by factors other than organic C and pH. Various mechanisms that were suggested for decreased microbial activity in N fertilised plots included:-

- a direct inhibiting effect of nitrogenous compounds making C less available
- N increasing the retention of C and
- a partial sterilisation effect from the raised osmotic potential of the soil solution due to fertiliser salts (Soderstrom *et al.*, 1983 cited by Cooper and Warman (1997)).

The results of combined treatments referred to herein appear to support the theory that compost amendments resulted in increased qualitative microbial activity. However, it has not been so evident that inorganic fertilisers had a detrimental effect on the microflora (Marchesini *et al.*, 1988). These findings were in direct contrast to an older study by Pettersson and Wistinghausen (1979) who were of the view that to add mineral salts in soluble inorganic form essentially by-passed the activity of micro-organisms, considered by some as the most important function of soil, rendering them, superfluous. They continued to suggest that this inactivation of vital soil processes would lead to reduced product quality and plant dependence on a precisely regulated supply of minerals from the outside.

Soil Chemical Function

The soil chemical functions that may be affected by additions of organic materials include complexing of cations, CEC and pH. Cation complexes can enhance P availability, reduce concentrations of toxic cations, and promote the binding of organic matter to soil minerals (Baldock and Skjemstad, 1999). Adding compost and manures was shown by Schefe *et al.* (2008) and Whalen and Chang (2001) to increase P availability, although Pritchard *et al.* (2004) suggested that the increase in soil P availability after applying biosolids was from the release of inorganic P from biosolids and not soil organic P. Basta (2001) found that using alkaline organic amendments for rehabilitating mine sites reduced human exposure to Cd and Pb. However, Hue *et al.* (2001) found that Mn toxicity increased with the addition of organic amendments and Whatmuff (2002) found an increase in plant uptake of Cd and Zn after applying sewage sludge.

Soil salinity and sodicity are soil chemical attributes that can lead to a decline in soil physical function. Salinity is the presence of dissolved salts in the soil or water within the root zone (Shaw, 1999) and, although it can improve aggregation, it can inhibit plant growth through osmotic stress (Fitzpatrick *et al.*, 1994). Sodicity on the other hand is the presence of Na^+ ions within the soil matrix that when exposed to excess water can lead to a breakdown of soil aggregation and subsequent reduction in hydraulic conductivity.

Sodosols by definition are texture contrast soils that are only sodic and not acidic in the upper B horizon (Isbell, 2002). Mitigation of sodicity has generally been through the use of gypsum (Tillman and Surapaneni, 2002), which is problematic in Tasmania where (a) gypsum is expensive and not readily available and (b) it needs to be placed in the subsoil. However, Alan *et al.* (2008) have shown that problems associated with soil salinity and sodicity may be alleviated with the use of composts. Their research suggested that Ca^{2+}, Mg^{2+} and K^{+} in the compost treatments occupied the cation exchange sites on soil particles, which minimised adsorption and enhanced leaching of Na^{+} with rainfall/irrigation. This contrasts with Aoyama *et al.* (2006), who found an increase in $EC_{1:5}$ with lime treated sludge and surmised the cause as increased soluble salt from elevated levels of Ca^{2+}. Limited research has been conducted on the affect of biosolids on soils exhibiting saline and sodic properties, although some research has been conducted using sodic irrigation water or irrigated effluent (Tillman and Surapaneni, 2002) while others have investigated subsoil sodic remediation (Clark *et al.*, 2009).

Soil Physical Function

A decrease in soil organic matter (SOM) or soil organic carbon (SOC) can negatively affect soil physical functions including structural stability, water holding capacity and thermal properties (Baldock and Skjemstad, 1999). Such decreases can be exacerbated through conventional tillage and irrigation (Gwenzi *et al.*, 2009). However, applying organic amendments such as biosolids over a longer term has been shown to increase soil C within aggregates with subsequent improvement of aggregation and soil water retention (Wallace *et al.*, 2009). After five years, Tester (1990) found that penetration resistance and bulk density (soil properties that affect soil function) were less for biosolids and compost treatments compared to soil treated only with inorganic fertilisers. Mohammad *et al.*(2007) also found that organic amendments decreased bulk density and increased soil carbon. They observed cumulative effects on soil physical properties with continued organic additions, even though experiments were conducted in a hot humid tropical environment; normally associated with accelerated decomposition (Enger and Smith, 2004).

Armstrong et al. (2007a) found improvements to soil physical properties of Sodosols specifically, with the addition of composted pig bedding litter. Small unstable aggregates decreased concomitant with an increase in larger aggregates (Armstrong *et al.*, 2007a). After four years of applying urban waste compost Giusquiani et al. (1995) found an increase in porosity, increased water retention, a decrease in bulk density and improved soil structure. They concluded that soil structure was stabilised by a thin protective coating over the elongated pores, which subsequently prevented water damage and enhanced soil pore function.

2.7.7 Plant response to bio-resources

Plant response to soil amendments have been regarded by Warman (1998), as both qualitative and quantitative. The nutrient status of the plant has been noted as 'qualitative', while the growth and development has been noted as 'quantitative'. However, it was suggested that regardless of the source (quality) and amount of amendment applied to soils, seasonal variation in soil moisture and temperature seemed to have a greater influence on plant production (Warman, 1998).

Schuphan (1974) was of the view that conventionally fertilised soils were generally higher in P & K but lower than compost fertilised soil in C, Ca, Mg, Mn, Cu and Zn, and the availability of these nutrients to the plant was generally reflected in yield and quality. With respect to yield, it was shown that the use of compost and manure resulted in considerably lower yields than with conventional fertilisers, but was compensated by increases in protein, P, K, Fe and vitamin C (Warman, 1998). This view has been supported with studies concluding that food quality and storage performance (while reducing nitrates and improving the nitrate to vitamin C ratio), were positively affected from the use of compost, but yields were only lower than conventionally fertilised sites for two out of three years (Vogtmann *et al.*, 1993). However, earlier studies found inconsistency in results from compost and fertilizer comparative trials due to soil type, crop type and year of production (Warman and Fairchild, 1983).

From the results of a twelve-year study on the impact of compost on vegetable yields, Maynard and Hill (1994) suggested that compost amendments might not provide immediate effects to plants in one application. However, they found that sustainable

annual applications resulted in increased yields only after a minimum of five years. The cumulative effect of organic matter within the soil was thought to be the determining factor. Research by Golabi *et al.* (2007) concluded that increased yields from three subsequent crops of maize over two years was due to the cumulative effects of continuous application of organic material in the form of compost.

In a three-year study into yield, vitamin and mineral contents of organically and conventionally grown carrots, cabbage, potatoes and corn, no statistically significant differences were found between treatments (Cooper and Warman, 1997; Warman, 1998). The trials were conducted on sandy loam soils that had been unfertilised for five years previous and research plots were only used once with new plots each year, presumably to avoid the cumulative affect reported in Maynard and Hill (1994).

Cogger *et al.* (2001) studied the effects of annual biosolids applications over a seven year period to a forage grass. They found that yield increased concomitant with an increase in application rate with no detrimental effects.

In contrast to annual amendment applications, Cooper (2005) applied varying rates of lime amended biosolids and digested sludge once only to soil planted with wheat and triticale grown over a three year period. All biosolids treatments showed yield increases beyond the initial application year, indicating a long term nutrient release. These lasting effects, however, were not experienced by Armstrong *et al.* (2007b), who found that crop yields and quality declined three years after applying pig bedding litter.

2.8 Bio-resource management and regulation

The application of inorganic fertilisers to agricultural land has been at the discretion of industry advisors and agronomists. However in Australia, in recognition of the potential for inorganic fertiliser products to contribute to adverse environmental impacts throughout the supply chain, a joint initiative called Fertcare has been established between The Australian Fertiliser Services Association (AFSA) and The Fertiliser Industry Federation of Australia (FIFA). The main objective was to determine an industry standard for responsible use of fertilisers from advice to logistics (www.fertcare.com.au).

The regulation and management of bio-resources in Australia is a reflection of the many and varied resources available for use on agricultural land. Biosolids re-use in Australia has been determined by guidelines for most states (Brown *et al.*, 2009; DEP *et al.*, 2002; Dettrick and McPhee, 1999; NSW-EPA, 1997; VIC_EPA, 2004), with most if not all reviewing their guidelines in response to an active research programme (McLaughlin *et al.*, 2008). A comprehensive review of biosolids regulations for Australia and New Zealand, comparing against US and EU regulations has also been prepared by Pollution Solution Designs Pty Ltd, commissioned by the Australian and New Zealand Biosolids Partnership (http://www.biosolids.com.au/forms/ANZBP-Summary_sml.pdf), to ensure sustainable and controlled use of this important resource. In Tasmania, application to land of class 2 and 3 biosolids must be in accordance with the Approved Management Method for Biosolids Reuse, 2006, which was approved by the Director of Environmental Management in accordance with regulation 12A(1) of the Environmental Management and Pollution Control Regulations 2000 (www.environment.tas.gov.au).

Compost standards in the EU, North America and Australasia were examined by Hogg *et al.* (2002) in the United Kingdom under the auspice of WRAP (Waste and Resources Action Programme). They determined that similar systems across the three regions were in place to protect human, animal and soil health by regulatory standards of production, governing standards of use and consumer systems of marketing (Hogg *et al.*, 2002). In Australia, the only guideline that exists for compost is the Australian Standard AS4454-1999 Soil Conditioners and Mulches, which only covers the production and not the regulation of its use.

In the 1990's, the potential for over-application of nitrogenous fertilisers, manures and organic wastes led many countries in Northern Europe to enacted legislation to protect groundwater and soil resources (Wilkinson *et al.*, 1998). In Tasmania the regulation and management of composts and other waste stream products (including biosolids) is undertaken by the Environmental Protection Agency (EPA), with protection of soil and water from contamination the main objective (www.environment.tas.gov.au).

The application rate of biosolids in Tasmania is determined by potential contaminant loading and nitrogen availability. Contaminants are detailed as heavy metals (Dettrick and McPhee, 1999) with tables defining maximum allowable concentrations in both the

product and the soil, prior to application. The nitrogen availability in biosolids is defined by a kinetic equation using total nitrogen of the product, total available nitrogen (ammonium and nitrate nitrogen) and the soil concentration. However, the release of nitrogen from biosolids and other bio-resources is also affected by temperature, moisture content and other soil management conditions before, during and after application.

2.9 Nitrogen mineralisation kinetics of bio-resources in soil

The nitrogen cycle in soil involves the mineralisation of organic nitrogen, uptake of the mineralised nitrogen by plants and the return of organic nitrogen to the soil from plant residues. Cultivated surface mineral soils typically contain about 0.15% nitrogen, with only 1.5 to 3.5% of this organic nitrogen mineralised annually (Brady and Weil, 1999). The total nitrogen content of each of the four bio-resources in Tasmania used for this study (lime amended biosolids, anaerobically digested biosolids, poppy mulch and poppy seed waste) is about 3 %, 4.6 %, 1.6 % and 5.1 % respectively, of which most is in organic form. The Tasmanian biosolids re-use guidelines (Dettrick and McPhee, 1999) suggest that only about 20 % of the organic nitrogen contained in dewatered biosolids is mineralised in the first twelve months following application. In NSW and SA, guidelines suggest 10%, 15% and 25% for composted, anaerobic and aerobically digested biosolids respectively (Brown *et al.*, 2009; NSW-EPA, 1997). In the US, suggested rates are 10%, 20% and 30% respectively with the onus on individual states to provide further application rate advice (US-EPA, 1994).

Cogger *et al.* (2004) found that 37% (± 5%) of total nitrogen in aerobic and 8 – 25% of total N in anaerobically digested biosolids was mineralised in the first year following application. Based on a field incubation study, Eldridge *et al.* (2008) estimated that 54%, 48% and 45% of the total N applied in granulated biosolids applied at 12, 24 and 48 dry t/ha respectively was mineralised as plant available nitrogen (PAN) within twelve months, with a laboratory incubation study showing that > 50% of the total PAN for the year was mineralised in the first 29 days. In their study where anaerobically and aerobically digested biosolids were applied to a heavy clay loam soil in South East Queensland, Pu *et al.* (2008) found that guideline calculation rates exceeded crop requirement for N and that 0.5 NLBAR (8 and 6 dry t/ha for anaerobically and

aerobically digested biosolids respectively) was sufficient to meet crop N demand. , Rigby and Smith (2008) revealed inconsistencies between actual nitrogen release from biosolids and guideline assumptions, whilst Rigby *et al.* (2010) determined that PAN from biosolids was dependent on the treatment process with lime amended, alum amended and dewatered biosolids cake mineralising 65.1%, 63.4% and 39.4% respectively of the organic N in the first season after application to an acidic sandy soil.

No published research has been found on the mineralisation rates of poppy mulch. However, materials found in the literature to have similar nitrogen and carbon contents to poppy mulch were composted green and straw wastes and vermi-cast (Flavel and Murphy, 2006). Flavel and Murphy (2006) found that annual nitrogen mineralisation rates for these products varied between 29 and 65 % of amendment organic N.

Poppy seed waste has been investigated by Statham (1984), Akinci and Bayram (2003) and Azcan *et al.* (2004) for its potential as an animal feed supplement, more specifically protein. Other seed waste or meals from sunflower, soybean and grape seed have also been studied by Irshaid *et al.* (2003) and Nicodemus *et al*. (2007) for a similar use. Research appears to only detail total nutrients in the products, as no published research has been found on nitrogen release rates from poppy seed waste or any other oil seed waste for land application.

Organic soil amendments in general have often been labelled 'slow release fertilisers' due to most nutrients being present in organic form (www.natureneem.com). However, Kara (2000) has suggested that the quality of introduced organic material can affect the nitrogen dynamics and SOM decomposition rate, with incorrect assumptions potentially leading to excess nitrate after plant harvest being lost by leaching and denitrification.

In soil, the rate of organic matter decomposition and subsequent release of nutrients such as N, P, C & S depends on soil properties, soil water content and temperature, and is driven by microbial growth (Neill and Gignoux, 2006; Singh and Kashyap, 2007). However, based on their study of biosolids, Douglas-fir litter, paper waste and wheat straw, Rowel *et al.* (2001) suggested that decomposition and nitrogen mineralisation from introduced organic materials is also related to the initial chemistry of the materials (a view supported by Herrman and Witter, 2008), or, as in the case of biosolids, the treatment process. Regarding biosolids, it was further suggested that N mineralisation

was not a result of whole material decomposition but of the labile protein pool in the product (Rowell *et al.*, 2001).

2.10 Agricultural systems models

Effective simulation of soil carbon and nutrient dynamics in a farming system requires the use of modelling tools that capture the key interactions between processes and biological, plant, management and environmental factors. Examples of these types of models include GOSSYM/COMAX (Mackinion *et al.*, 1989), MODCROP (Waldman and Richman, 1996), DSSATC (Jones *et al*, 2003) and APSIM (McCown *et al*, 1996).

Simulation models have been developed in an attempt to estimate N mineralisation rates from various organic products due to assessment difficulties of traditional soil testing (Chilcott *et al.*, 2007; Gilmour, 2009; Joshua *et al.*, 2001). Unfortunately the weakness of modelling organic matter is the dependence on decomposition rate constants and mechanistic or process assumptions (Krull *et al.*, 2003). In the APSIM model, there is also no provision for the changing microbial community to be represented by a concomitant change in nitrification rate (http://www.apsim.info/Wiki/SoilN.ashx). Furthermore, Morvan and Nicolardot (2009) warned of the difficulty in parameterising organic wastes because of no relevant relationships between model parameters and composition of wastes.

Cabrera *et al.* (2005) in their review of modelling research efforts, have suggested that more complex simulation models be developed that include processes and organisms and that further work is required to clarify nitrogen cycling from different organic residues, as most work has been done on SOM.

In an effort to provide backup data for organic amendment application recommendations, Gale *et al.* (2006) evaluated the model DECOMPOSITION with measured decomposition and N release from various composts for estimating the release of plant available nitrogen (PAN). Other models have also been assessed for their suitability to predict nutrient release particularly in relation to nitrate from applied amendments leaching into groundwater (Joshua *et al.*, 2001).

2.11 Conclusion

Bio-resources are used in agriculture as an alternative to inorganic fertiliser to supply essential plant nutrients concomitant with adding organic matter to the soil. However, broad scale use may be limited by carting and logistics, availability, nutrient loadings and consistency of product and contaminants. Bio-resources also behave differently depending on environmental (i.e. soil type, rainfall and temperature) and management factors (i.e. cultivation, irrigation, application timing). The literature review has identified three key areas that require further work to improve understanding of the behaviour of bio-resources when applied to texture contrast soils.

- The potential for bio-resources to replace soil organic matter and improve the health of texture contrast soils under current management regimes.
- Bio-resources as a substitute for inorganic fertiliser.
- Mineral nitrogen management from applied bio-resources

These key areas are highlighted in the following aims and objectives, which are addressed in the subsequent research chapters.

2.12 Aims of research

2.12.1 General objective

The general objective of the research was to investigate agronomic and soil changes when biosolids, poppy mulch and poppy seed waste are applied to sandy texture contrast soils in a temperate environment.

2.12.2 Specific objectives

Chapter 4

- Compare and contrast residual soil chemistry between inorganic fertiliser and bio-resources, six and eighteen months after application.
- Determine short term influences on microbial biomass and soil organic carbon from applying LAB, ADB, PM and PSW to texture contrast soils.

- Assess the potential for the application of LAB, ADB, PM and PSW to affect the aggregate stability, bulk density and penetration resistance of texture contrast soils in the short-term.
- Determine the impact of applying LAB, ADB, PM and PSW on soil pH and electrical conductivity of the A horizon of texture contrast soils.
- Determine the plant nutrient uptake and yield potential associated with the application of LAB, ADB, PM and PSW to texture contrast soils in Tasmania.

Chapter 5

- Quantify soil residual chemistry from different application rates of LAB and lime and fertiliser after two years of growing cereals on texture contrast soils.
- Determine short term influences on microbial biomass and soil organic carbon from different application rates of LAB to texture contrast soils.
- Determine the impact of different application rates of LAB on pH and electrical conductivity of the surface layer of texture contrast soils.
- Determine the plant nutrient uptake and yield potential associated with the different application rates of LAB to texture contrast soils in Tasmania.
- Determine the impact that spreading but not incorporating LAB at guideline rates may have on soil pH, EC, yield and plant nutrient uptake of texture contrast soils.

Chapter 6

- To quantify the N mineralised from soil applied LAB, ADB, PM and PSW as compared with L+F whilst growing a cereal crop on texture contrast soils in a temperate region.
- To determine the peak N mineralisation periods of LAB, ADB, PM and PSW after application in late autumn/winter for comparison with crop N requirements.
- To assess the mobility of N in the top 20 cm of texture contrast soils after application of LAB, ADB, PM and PSW as compared to L+F.

Chapter 7

- To quantify the rate of N release from PM. PSW, LAB and ADB when mixed with a sandy loam soil at a temperature typical of the Tasmanian climate in autumn and spring.
- To determine the peak mineralisation periods of the different products, that may be used to influence application timing to match crop demand.
- To determine the effect of the slow reactive $CaCO_3$ on N release to compare with N release from LAB.

Chapter 8

- Compare the simulated crop growth, development and yield, and key soil nutrient (N and C) responses to soil-applied organic materials against field results in a different set of environments.
- Assist the interpretation of results by demonstrating the potential application of Systems Models in bio-resource application to agricultural land.
- Assess the risk of off-site nitrogen losses when bio-resources are applied to texture contrast soils.

2.12.3 Thesis synopsis

The thesis is presented in the sequence shown in Figure 2.2. The diagram represents pictorially the development of the research throughout the project, from identifying the issues, through research conducted and subsequent understanding.

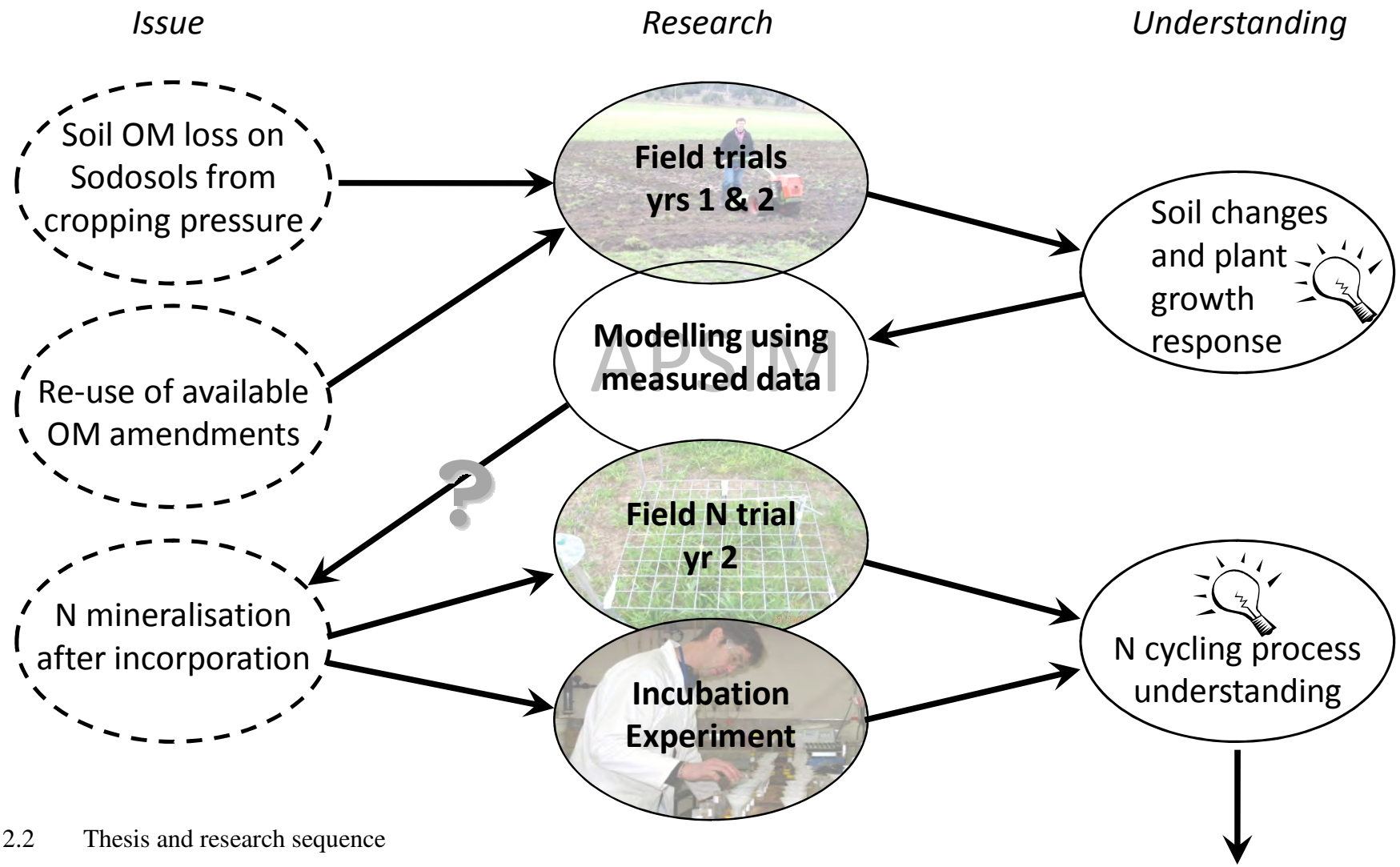

Figure 2.2 Thesis and research sequence

3 Materials and Methods – Field Trials

3.1 Introduction

Field trials were established on Brown Sodosols (Isbell, 2002) at two sites in Tasmania over two growing seasons. The first site was at Cambridge (E535360, N5260590) in southern Tasmania and the second site was at Cressy (E497257, N5375856) in the Northern Midlands. Both sites had been sown to pasture for a minimum of three years prior to trial establishment. In the first year of the trial, wheat (*Triticum aestivum* cv. Brennan) was planted at a rate of 90 kg/ha at Cambridge in July 2007 and barley (*Hordeum vulgare* cv. Gairdner) planted at a rate of 130 kg/ha at Cressy in September 2007. Prior to planting the first year, the Cambridge site was heavily grazed, mouldboard ploughed once and cultivated three times with an S-tine cultivator prior to planting. The Cressy site was sprayed with 2.0 L/ha Roundup CT, left for three weeks, disced twice and cultivated twice with an S-tine cultivator. Land preparation was consistent with traditional practice in both areas.

After Year 1, the Cambridge site was sprayed with 2.0 L/ha Roundup Powermax, with all regrowth, residues and remaining stubble burnt four weeks later. In September 2008, barley (cv. Gairdner) was direct drilled at a rate of 130 kg/ha. There was very little crop regrowth or weed growth at the Cressy site after the first year, so the site was cultivated with an S-tine cultivator to a depth of 10 cm three times in different directions to incorporate residues and remaining stubble. Although all care was taken at the time to avoid cross contamination between adjacent plots, some stubble roots and soil was retained on cultivator tines and did transfer across plots. Wheat (cv. Brennan) was then planted at a rate of 120 kg/ha in June 2008, after which the site was rolled to ensure seed soil contact.

3.1.1 Climate and irrigation schedule for years 1 and 2

Long term mean annual rainfall at nearby recording stations was 562 mm at Cambridge airport and 600 mm at Cressy Research Station (www.bom.gove.au). Rainfall below the long term average during the July – December growing period was experienced in both years (22 and 31 mm at Cambridge; 54 and 66mm at Cressy for 2007 and 2008 respectively). Refer to Figure 3.1 and Figure 3.2 for temperature and rainfall respectively measured at the Cambridge airport. Figure 3.3 and Figure 3.4 show temperature and rainfall respectively measured at the Cressy Research Station. Supplementary irrigation was applied to ensure that the crops did not experience soil moisture deficits in the growing months.

Irrigation applied in 2007 at the Cambridge site was: 34 mm, 31 mm and 17 mm on 16 Oct, 7 Nov and 4 Dec respectively. In 2008 at the Cambridge site, 15 mm irrigation was applied on each of 18 Sep, 25 Sep and 11 Nov. In 2007 at the Cressy site, irrigation applied was 20 mm, 11 mm, 46 mm, 24 mm and 23 mm on 5 Nov, 8 Nov, 25 Nov, 3 Dec and 14 Dec respectively. In 2008 at the Cressy site, 30 mm irrigation was applied on 6 Nov.

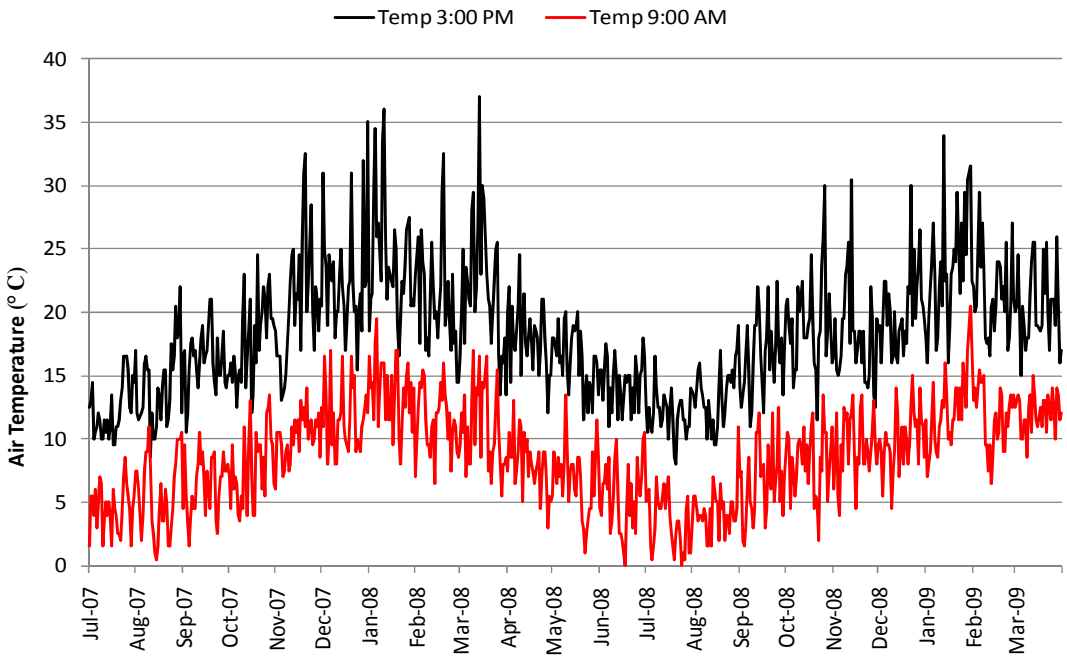

Figure 3.1 Maximum and minimum air temperature recorded at the Cambridge Airport (http://www.dnr.qld.gov.au/silo)

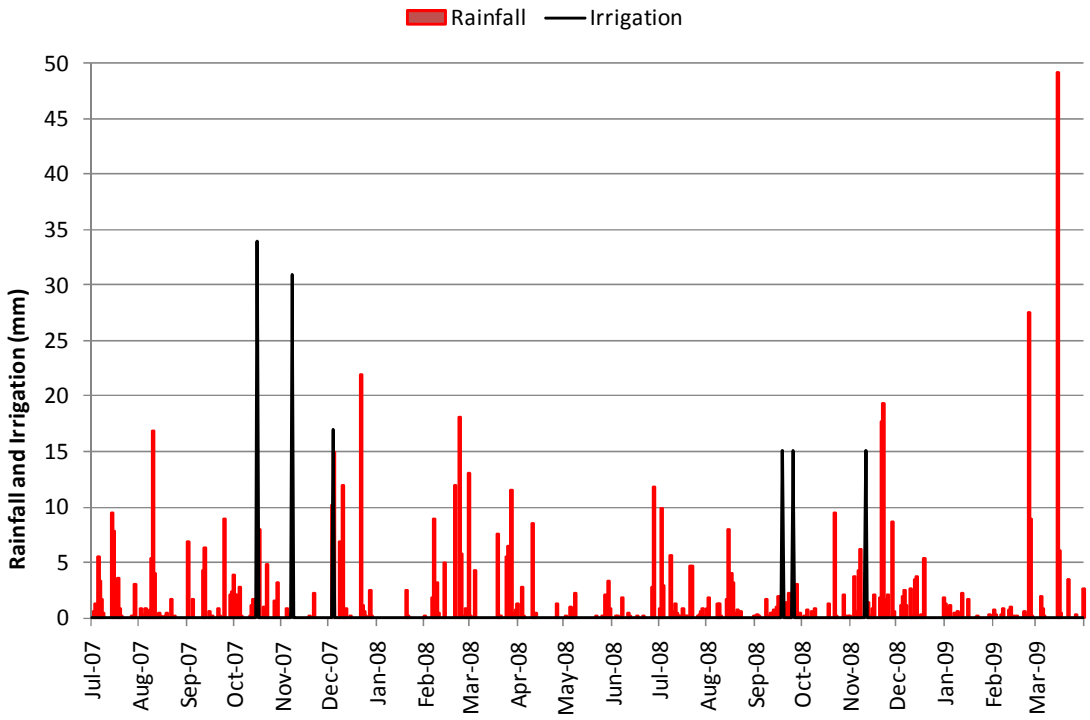

Figure 3.2 Rainfall recorded at the Cambridge Airport (http://www.dnr.qld.gov.au/silo) and irrigation recorded at the Cambridge trial site.

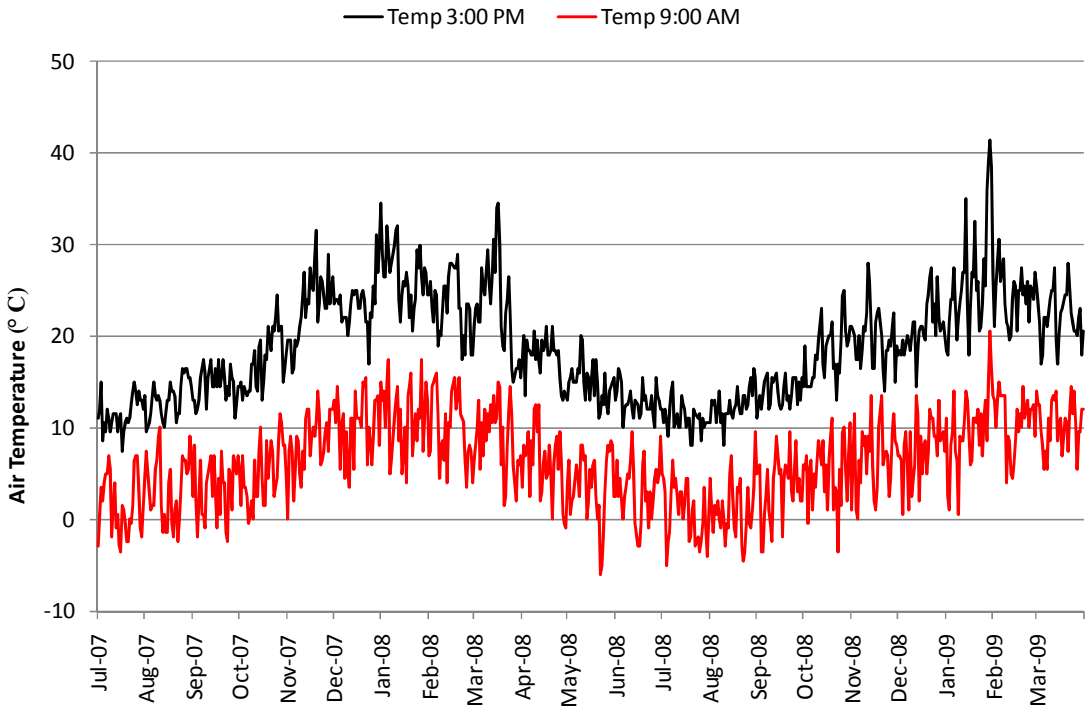

Figure 3.3 Maximum and minimum air temperature recorded at the Cressy Research Station (http://www.dnr.qld.gov.au/silo)

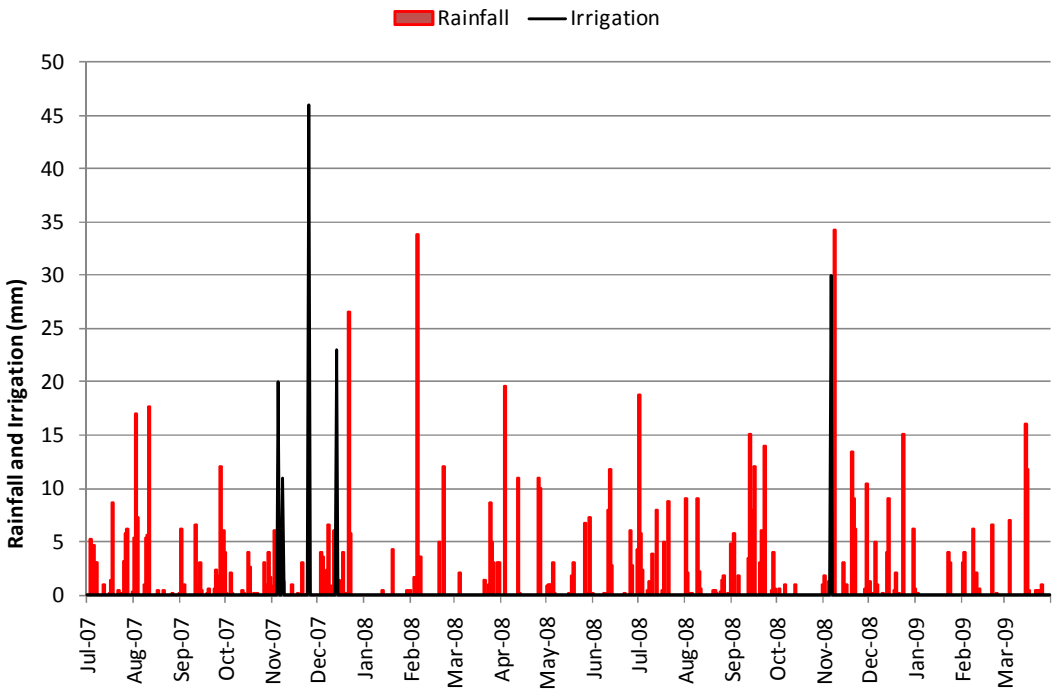

Figure 3.4 Rainfall recorded at the Cressy Research Station (http://www.dnr.qld.gov.au/silo) and irrigation recorded at the Cressy trial site.

3.1.2 Sampling and analysis in year 1

3.1.2.1 *Soil*

Soil characterisation and chemical and physical analysis

A 1.5 m deep pit was excavated at both sites with the soil fully characterised and sampled (National Committee on Soil and Terrain 2009) prior to any cultivation or planting. Complete soil descriptions are shown in Plate 3.1 and Plate 3.2 for Cambridge and Cressy sites respectively. The A1 horizon at Cressy consisted of 51% fine sand, 20% coarse sand, 16% silt and 13% clay, and the A horizon (A1 and A2 not clearly defined due to previous cultivation) at Cambridge consisted of 50% fine sand, 25% coarse sand, 6% silt and 19% clay. Duplicate samples using 65 mm diameter x 65 mm long stainless steel cores were taken per horizon and assessed for bulk density, total porosity and volumetric and gravimetric water content using methods adopted by Cotching *et al.* (2001). Sub-samples for each horizon were then ground to pass a 2 mm sieve, and analysed at CSBP Soil and Plant Laboratory, Western Australia.

Soil was analysed for organic carbon (Walkley and Black, 1934), Colwell P and K (0.5M $NaHCO_3$ extraction), Total P (H_2SO_4-K-$CuSO_4$ extraction), Olsen P (0.5M Na HCO_3 extraction), S (0.25M KCl extraction), pH (ratio of 1:5 soil:water suspension and 0.01M $CaCl_2$), EC (ratio of 1:5 soil:water extract), CEC, exchangeable Mg, Na, Ca & K (0.1M $BaCl_2$/0.1M NH_4Cl) and nitrate and ammonium N (1M KCl), using methods detailed on Rayment and Higginson (1992). P buffering index (PBI), a method to determine the P buffering capacity or fixing ability of a soil, was undertaken using 10 µg/ml P (Burkitt *et al.*, 2002). Site soil analysis is shown in Table 3.1.

Plate 3.1 Soil profile description for Cambridge trial site

Location: University farm, Cambridge, Tasmania.
Grid reference: 535134 E; 5257068N
Australian Soil Classification: Brown Sodosol
General Landscape Description:.Irrigated cropping & pasture for sheep grazing
Mapping Unit:
Site Description: Mid slope on alluvial fan
Geology: Tertiary + quaternary sediments
Soil Profile Morphology

Horizon	Depth (cm)	Description	Nitrate N (mg/kg)	Ammonium N (mg/kg)
A1	0-17	Very dark grayish brown (10YR3/2);sandy loam; weakly developed medium angular blocky structure; moderately weak consistence (dry); common very fine roots; sharp smooth boundary.	7	2
B21	17-34	Dark greyish brown (10YR4/2); medium heavy clay; moderately developed medium prismatic structure; moderately strong consistence (moist); common medium prominent dark yellowish brown mottles; few very fine roots; abrupt wavy boundary.	3	1
B22	34-48	Olive brown (2.5Y4/4); heavy clay; massive; very firm consistence (moist); few medium faint light olive brown mottles and few fine distinct dark yellowish brown mottles; few faint slicken sides; few very fine roots; clear smooth boundary.	2	1
B23	48-112	Light olive brown (2.5Y5/4); heavy clay; massive; moderately firm consistence (moist); few distinct slicken sides; few very fine roots; abrupt wavy boundary.	1	1
2C	112-150+	Light grey (2.5Y7/2); gritty light clay; massive; moderately weak consistence (moist); very few fine prominent black mottles and few very coarse prominent strong brown mottles.	1	3

Horizon	Horizon Depth cm	Sample depth cm	Bulk density Mg/m^3	15 bar v/v	DUL v/v	Saturation v/v	PAWC* v/v	K sat mm/hr	Sample Depth cm	pH water	pH CaCl2	EC dS/m	Org C	Exchangeable Cations					ESP
														Ca	Mg	K	Na	Total	
														Meq/100g					
A1	0-17	5-11	1.37	0.09	0.29	nd	0.20	39.3	0-17	6.3	5.4	0.12	2.81	5.99	2.69	0.59	0.46	9.73	4.7
B21	17-34	24-30	1.63	0.23	0.56	nd	0.33	< 0.1	17-34	5.7	4.6	0.14	1.13	5.25	9.52	0.23	1.31	16.31	8.0
B22	34-48	39-45	1.47	0.29	0.50	nd	0.21	< 0.1	34-48	6.7	5.8	0.25	0.68	5.69	15.32	0.22	2.54	23.77	10.7
B23	48-112	80-86	1.40	0.27	0.57	nd	0.30	< 0.1	48-112	7.8	6.9	0.62	0.34	6.13	18.62	0.32	5.44	30.51	17.8
2C	112-150	113-119	1.60	0.29	0.38	nd	0.11	< 0.1	112-150	8	7	0.85	0.24	4.64	12.74	0.52	4.71	22.61	20.8

* PAWC = (DUL-15 bar) x100

Plate 3.2 Soil profile description for Cressy trial site

Location: Bluegong, Cressy, Tasmania.
Grid reference: 497284E; 5375859N
General Landscape Description: Irrigated cropping & pasture for sheep grazing
Mapping Unit: Br – Brumby Assocation (Nicholls, 1958)
Site Description: Flat plain
Geology: Tertiary lake sediments
Soil Profile Morphology

Hor.	Depth (cm)	Description	Nitrate N (mg/kg)	Ammonium N (mg/kg)
A1	0-19	Very dark grayish brown (10YR3/2); fine sandy loam; weakly developed medium angular blocky structure; moderately firm consistence (moist); many very fine roots; abrupt wavy boundary.	8	7
A2	19-30	Pale brown (10YR6/3); sandy loam; massive; moderately weak consistence (moist); very few fine prominent dark yellowish brown mottles; few very fine roots; sharp wavy boundary.	5	1
B21	30-54	Dark yellowish brown (10YR4/6); heavy clay; massive; very firm consistence (moist); common medium prominent greyish brown mottles and few fine faint strong brown mottles; few very fine roots; clear smooth boundary.	20	3
B22	54-110	Dark yellowish brown (10YR4/6); heavy clay; massive; very firm consistence (moist); ; few fine distinct brown mottles and very few fine prominent strong brown mottles; few faint slicken sides; gradual smooth boundary.	12	2
C	110-130+	Light olive brown (2.5Y5/4); heavy clay; massive; very firm consistence (moist); many coarse faint dark yellowish brown mottles.	7	2

Horizon	Horizon Depth cm	Sample depth cm	Bulk density Mg/m^3	15 bar v/v	DUL v/v	Saturation v/v	PAWC* v/v	K sat mm/hr	Sample Depth cm	pH water	pH CaCl2	EC dS/m	Org C	Exchangeable Cations					ESP
														Ca	Mg	K	Na	Total	
														Meq/100g					
A1	0-19	6-12	1.4	0.08	0.36	0.47	0.28	3	0-19	6.7	5.9	0.06	2.04	6.73	0.58	0.17	0.15	7.63	2.0
A2	19-30	22-28	1.7	0.03	0.27	0.34	0.24	5	19-30	6.6	5.7	0.03	0.33	1.43	0.24	0.07	0.09	1.83	4.9
B21	30-54	40-46	1.2	0.29	0.53	0.53	0.24	< 0.1	30-54	6.3	5.4	0.12	0.79	4.93	9.61	0.14	0.93	15.75	5.9
B22	54-110	64-70	1.4	0.30	0.54	0.49	0.24	< 0.1	54-110	6.7	5.7	0.14	0.41	3.2	12.63	0.18	1.55	17.56	8.8
C	110-130								110-130	6.9	6.3	0.17	0.24	4.17	16.12	0.14	2.6	23.03	11.3

* PAWC = (DUL-15 bar) x100

Table 3.1 Pre-trial site soil analysis results for Cambridge and Cressy

Description	Cambridge A Horizon 170 mm depth	Cressy A1 Horizon 190 mm depth
Organic C (%)	2.8	2.0
pH (1:5 H_2O)	6.3	6.7
pH (1:5 $CaCl_2$)	5.4	5.9
$EC_{1:5}$ (dS/m)	0.12	0.06
PBI	66.5	65.1
NO_3^+ - N (mg/kg)	7	8
NH_4^- - N (mg/kg)	2	7
Total N (mg/kg)	nd	nd
Total P (mg/kg)	241	385
Olsen P (mg/kg)	57	29
Colwell P (mg/kg)	126	69
Colwell K (mg/kg)	234	64
SO_4^{2-} (mg/kg)	8.2	10.3
Exchangeable Ca^{2+} (cmol/ kg)	6.0	6.7
Exchangeable Mg^{2+} (cmol/ kg)	2.7	0.6
Exchangeable Na^+ (cmol/ kg)	0.5	0.2
Exchangeable K^+ (cmol/ kg)	0.6	0.2

Note: nd indicates analyte not determined

Soil nitrate and ammonium - Cambridge

At 81 d, 109 d, 147 d and 219 d after planting at the Cambridge site, four 50 mm diameter soil cores were taken per plot at 0 – 150 mm and 150 – 300 mm depths, with the cores combined for each depth, weighed and dried at 105 °C for 24 hours. Samples were re-weighed to determine gravimetric moisture content (GMC). Sub-samples of the 0 – 150 mm depth were taken prior to drying and frozen until analysis. At the end of the season samples were thawed and analysed for soil nitrate and ammonium by Analytical

Service Tasmania using 1:10 Soil:2M KCl. Extracts were then filtered using Whatman No. 42 filter paper and analysed for NO_3^- and NH_4^+ using the cadmium reduction procedure (Maynard *et al.*, 2008).

Soil penetration resistance, bulk density and aggregate stability

Soil penetration resistance was measured using a CP20 cone penetrometer (Rimik CP20; RFM Australia Pty Ltd, Brisbane) in four locations per plot at 81 d, 109 d, 147 d and 219 d after planting at the Cambridge site, and 195 d after planting at the Cressy site. Resistance in kPa was recorded at 15 mm increments through to 330 mm depth. Bulk density, gravimetric moisture content, soil penetration resistance and aggregate stability (Cotching *et al.*, 2001) were also measured post harvest at both sites.

Soil Chemistry

Post harvest, a composite of 10 core samples per plot (25 mm diameter x 100 mm deep) were taken from both sites, dried at 40 °C, ground to pass a 2 mm sieve and chemically analysed as for pre-plant soil samples.

Soil Organic Carbon

A sub-sample from each plot was prepared as per Sparrow *et al.* (2006) and analysed for organic carbon (C) of the whole soil and the silt + clay fractions. Analysis was performed by DPI Victoria using a LECO CNS analyser. C of sand was calculated from difference. Twenty grams of each soil sample was dispersed by shaking for 18 h on a horizontal rotating shaker in 90 mL of sodium hexametaphosphate (5 g L^{-1}) containing 10 glass beads (5 mm diameter). The dispersed soil suspension was wet sieved with distilled water through a 53 µm sieve into a 1000 mL beaker and dried to constant weight at 50°C. The dried <53 µm fraction (silt + clay) was then homogenized by grinding with a mortar and pestle to pass a 0.5 mm sieve, and analysed for organic carbon using a LECO CNS analyser. Samples of whole soil were also analysed for organic carbon. The C concentration of the silt + clay was expressed on a whole soil basis (g kg^{-1} soil) with the value for the sand fraction calculated by difference from total soil organic carbon.

Microbial Biomass

At 81 d and 219 d after planting at the Cambridge site, and 195 d after planting at the Cressy site a composite of four cores (75 mm diameter x 100 mm depth) were taken and analysed for microbial biomass and fungi/bacteria ratio (Smart *et al.*, 2004). Respiration values of non-treated soil and different combinations of antimicrobial treatments mixed with soil were measured and compared. Replicate 2 g samples of soil (sieved to < 1 mm, and moisture content 15%), were mixed with 250 µl of antimicrobial treatments and incubated at room temperature for 1 hour. Each sample was then mixed with 100 µl of 1% glucose and incubated for a further 4 hours at room temperature in the dark. Respiration values of treated samples were then measured using an IR Gas Analyser and compared to non-treated (total biomass) measured control. Samples were stored at 4 °C and analysed within 14 days of sampling. Samples were taken from at least 1 m inside the plot boundaries.

3.1.2.2 ***Amendments***

The LAB and ADB were analysed by Analytical Services Tasmania for moisture % (ANZECC Method 102), organic carbon (Walkley and Black, 1934), Colwell P and K (0.5M $NaHCO_3$ extraction), Total P (H_2SO_4-K-$CuSO_4$ extraction), Olsen P (0.5M Na HCO_3 extraction), S (0.25M KCl extraction), pH (ratio of 1:5 soil:water suspension and 0.01M $CaCl_2$), EC (ratio of 1:5 soil:water extract), exchangeable Mg, Na, Ca & K (0.1M $BaCl_2$/0.1M NH_4Cl), nitrate and ammonium N (1M KCl) and Total N (Kjeldahl), using methods detailed in Rayment and Higginson (1992). Metal elements including Al, As, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Zn, Ca, Mg and Na were also determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and Hg by cold vapour atomic fluorescence spectroscopy (CVAFS) after nitric acid digestion.

The PM and PSW were analysed for Total N (Leco FP-428 Nitrogen Analyser), nitrate and ammonium N (1M KCl), Colwell P and K (0.5M $NaHCO_3$ extraction), Total P (H_2SO_4-K-$CuSO_4$ extraction), Olsen P (0.5M Na HCO_3 extraction), S (0.25M KCl extraction), organic carbon (Walkley and Black, 1934) , pH (ratio of 1:5 soil:water suspension and 0.01M $CaCl_2$), EC (ratio of 1:5 soil:water extract), Cu, Zn, Mn & Fe

(DTPA) and exchangeable Mg, Na, Ca & K (0.1M $BaCl_2$/0.1M NH_4Cl), using methods detailed in Rayment and Higginson (1992). Refer to Table 3.2 for bio-resource analysis for year 1. In year 2, LAB and inorganic fertiliser was applied to selected plots at Cambridge and LAB, PM, PSW and inorganic fertiliser was applied to selected plots at Cressy. A small scale nitrogen trial that commenced at Cressy in the second year received the same products as the large scale ongoing trial for year 2. Analysis for products applied in year 2 is shown in Table 3.3.

Table 3.2 Nutrient analysis for bio-resources applied in year 1

	Units (DMB)	LAB	ADB	PM	PSW
Moisture	% (w/w)	75.1	76.8	55.1	10.8
pH (H_20)‡		12	6.6	8.6	5.5
Electrical conductivity‡	µS/cm	12 000	5 290	7 800	4 460
Organic C	% (w/w)	21.0	35.0	26.1	34.6
NH_4^+ - N	mg/kg	3600	4400	12	99
NO_3^- - N	mg/kg	nr*	nr*	6	26
NO_2^- - N	mg/kg	nr*	nr*	nr	nr
Total N	mg/kg	37 000	41 000	16 000	42 000
Total P	mg/kg	15 000	12 000	2 196	5 114
Total Ca	mg/kg	161 000	20 100	32 241†	8 245†
Total K	mg/kg	5 160	1 010	4 040†	3 561†
Total Mg	mg/kg	6 270	2 060	11 493†	6 494†
Total Na	mg/kg	7 670	1 270	152†	148†
Total S	mg/kg	nr	nr	2 695	3 240

‡pH and electrical conductivity (EC) results from 1:5 soil:water suspension.

† denotes Exchangeable cations not total.

* separate nitrogen species were combined and reported as ammonium

Table 3.3 Nutrient analysis for bio-resources applied in year 2

	Units (DMB)	LAB	ADB	PM	PSW
Moisture	% (w/w)	70.1	80.3	55.1	10.8
pH (H_20) ‡		13	6.6	7.3	5.5
Electrical conductivity‡	µS/cm	8 820	6 590	7 690	4 460
Organic C	% (w/w)	15.0	13.6	26.1	34.6
NH_4^+ - N	mg/kg	1300	4300	8.6	46
NO_3^- - N	mg/kg	1.7	1.2	<1.0	20
NO_2^- - N	mg/kg	1.2	<1.0	1.6	6
Total N	mg/kg	30 000	46 000	16 000	51 000
Total P	mg/kg	18 000	11 000	9 300	15 000
Total Ca	mg/kg	248 000	20 700	89 400	23 600
Total K	mg/kg	5 190	1 070	9 530	8 530
Total Mg	mg/kg	6 150	3 460	8 470	5 160
Total Na	mg/kg	464	4490	167	54
Total S	mg/kg	2 500	7 310	5 470	3 240

‡pH and electrical conductivity (EC) results from 1:5 soil:water suspension.

3.1.2.3 ***Plant***

Single quadrat samples (500 mm x 500 mm) of whole plants from each plot were taken at 79 d, 108 d, 140 d and 199 d (pre-harvest) after planting at the Cambridge site and 87 d and 150 d (pre-harvest) after planting at the Cressy site. Plants were cut at 5 mm above the soil and weighed for fresh weight (FW), oven dried at 60 °C for 24 hours and then weighed again for dried weight (DW) to calculate biomass. Dried product (excluding pre-harvest sample) was then ground (<2 mm), and analysed by CSBP Soil and Plant Laboratory, Western Australia for total P, K, S, Na, Ca, Mg, Cl, Cu, Zn, Mn,

Fe, NO_3 and B using nitric acid digestion and multi-elemental analysis by ICPAES. Total N was determined using a Leco FP-428 Nitrogen Analyser.

At the Cambridge site only, a 200 mm diameter x 170 mm depth soil sample was taken from each plot centred across a planted row at 140 d after planting to assess root/shoot ratio, tiller height, tiller number, leaf number, seed head length and diameter. The plants were cut 5 mm above the soil and FW and DW measured as above. The roots were washed free of soil, rinsed in two distilled water baths for 20 seconds each, blotted dry and root FW and DW determined.

Agronomic assessments undertaken on the pre-harvest samples for both sites included quadrat weed weight (Cambridge site only), harvest index (seed weight/whole plant weight), % shattered heads (Cambridge site only) and heads per metre row. Grain yield and 1000 grain weights per plot were obtained at harvest, after which the grain was analysed by CSBP Soil and Plant Laboratory, Western Australia for total P, K, S, Na, Ca, Mg, Cl, Cu, Zn, Mn, Fe, NO_3 and B using nitric acid digestion and multi-elemental analysis by ICPAES. Total N was determined using a Leco FP-428 Nitrogen Analyser.

Non-destructive plant assessments were undertaken using a single 500 mm x 500 mm quadrat randomly positioned in each plot for the following observations and intervals.

- Visual assessment at 29 d, 82 d, 108 d, 115 d, 121 d, 128 d and 140 d after planting at Cambridge and 21 d, 44 d, 51 d and 59 d after planting at Cressy (scoring plants for plant health; 6-healthy; 5-leaf tip necrosis; 4-pale; 3-marginal necrosis; 2-marginal and interveinal necrosis; 1-dead).
- Zadoks (1974) decimal growth scale at 108 d, 115 d, 121 d, 128 d and 140 d after planting at Cambridge and 21 d, 44 d, 51 d and 59 d after planting at Cressy.
- Height at 115 d, 121 d, 128 d and 140 d after planting at Cambridge and 44 d, 51d and 59 d after planting at Cressy.

3.1.3 Sampling and analysis – Year 2

3.1.3.1 *Soil*

Periodic soil sampling was conducted at the Cressy site throughout the second growing season on the LAB, ADB, PM, PSW and L + F plots from the first growing season. Five

20 mm diameter soil samples at 0 – 100 mm and 100 – 200 mm depths were taken at 63 d, 82 d, 112 d, 118 d, 125 d, 132 d, 146 d, 157 d, 171 d and 283 d after planting, combined per plot per depth and then frozen at -19 °C until the end of the trial. Frozen samples were then thawed to room temperature, before being extracted and analysed for nitrate and ammonium. Five grams of field moist soil was combined at a ratio of 1:10 soil:solution with 2M KCl and shaken on a horizontal rotating tumbler for 1 hour. Extracts were then filtered using Whatman No. 42 filter paper and analysed for nitrate and ammonium N using the cadmium reduction procedure (Carter, 2008). Gravimetric soil moisture (GMC) was measured on the same thawed samples by weighing out 10 – 15 g field moist soil, drying for 24 hours at 105 °C and re-weighing. Final nitrate and ammonium results were then corrected for moisture.

3.1.3.2 ***Plant***

At the Cambridge site, quadrat samples (500 mm x 500 mm) of whole plants from each plot were taken pre-harvest. Plant growth in areas of each plot at Cressy had been affected by an extended period of waterlogging and a late frost in the growing season, so quadrat samples (1000 mm x 1000 mm) of whole plants were taken from least affected areas, also pre-harvest. Plants were cut at 5 mm above the soil and weighed for fresh weight (FW), oven dried at 60 °C for 24 hours and then weighed again for dried weight (DW) to calculate biomass.

Agronomy assessments undertaken on the pre-harvest samples for both sites included quadrat weed weight, harvest index (a percentage of seed weight with respect to whole plant weight), and heads per metre row. Grain yield and 1000 grain weights per plot were obtained at harvest, after which the grain was analysed for total N using a Leco FP-428 Nitrogen Analyser.

3.1.4 Statistical analysis

Analysis of variance was calculated using Genstat to test for significant ($P \leq 0.05$) effects of treatments. Where significant treatment effects were indicated, significant difference between means were identified by least significant difference (LSD).

4 Agronomic and soil response from applying lime amended biosolids, anaerobically digested biosolids, poppy mulch and poppy seed waste as an alternative to inorganic fertiliser

4.1 Introduction

Bio-resources are used as soil amendments in productive agriculture to increase or replace soil organic matter and provide essential plant nutrients. Any response usually requires the amendment to be decomposed, or mineralised by micro-organisms. However, decomposition and subsequent mineralisation rates of these materials vary depending on amendment type, soil type, soil moisture and soil temperature. This chapter will present findings from two field experiments conducted at Cambridge and Cressy in Tasmania in the 2007 and 2008 growing seasons, where soil and crop responses to the application of locally available bio-resources (lime amended biosolids, anaerobically digested biosolids, poppy mulch and poppy seed waste) to texture contrast soils were studied.

4.2 Research objectives

The general objective of this research was to compare the impact of lime amended biosolids (LAB), anaerobically digested biosolids (ADB), poppy mulch (PM) and poppy seed waste (PSW) with inorganic fertiliser on biological, chemical and physical properties of the surface layer of two texture contrast soils.

Specific objectives were to:-

- Compare and contrast residual soil chemistry between inorganic fertiliser and bio-resources, six and eighteen months after application.
- Determine short term influences on microbial biomass and soil organic carbon from applying LAB, ADB, PM and PSW to texture contrast soils.

- Assess the potential for the application of LAB, ADB, PM and PSW to affect the aggregate stability, bulk density and penetration resistance of texture contrast soils in the short-term.
- Determine the impact of applying LAB, ADB, PM and PSW on soil pH and electrical conductivity of the A horizon of texture contrast soils.
- Determine the plant nutrient uptake and yield potential associated with the application of LAB, ADB, PM and PSW to texture contrast soils in Tasmania.

4.3 Materials and Methods

4.3.1 Trial sites

Two field trials were established in Tasmania at Cambridge and Cressy for cropping seasons 2007 and 2008. A full description of paddock preparation, planting, irrigation, and sampling and analysis methods adopted during the course of the trials, including treatment and pre-trial soil analysis are detailed in Section 3.

4.3.2 Treatments

The experimental design at both sites was a randomised block with three replications. Individual plot size was 4 m x 9 m with 1 m buffers between plots. Treatments were applied in the first year of each trial and are shown in Table 4.1.

Table 4.1 Treatments applied to the field trials at Cambridge and Cressy in Year 1

Treatment	**Description**	**Application Rate**	**Available Nutrients**	**Nutrient Analysis**
Control	Untreated	N/A		
L+F	Lime + Fertiliser	125 kg/ha DAP + 1330 kg/ha Lime + 60 kg/ha Urea	50 kg N 25 kg P 513 kg Ca	
ADB	Anaerobically Digested Biosolids at 1 NLBAR	22 wet tonnes/ha (5.1 dry tonnes/ha)	50 kg N #	Total N – 4.1 % Total P – 12000 mg/kg Total Ca – 20100 mg/kg
LAB	LAB at 1 NLBAR	23 wet tonnes/ha (5.8 dry tonnes/ha)	50 kg N # 513 kg Ca ¥	Total N – 3.7 % Total P – 15000 mg/kg Total Ca – 161000 mg/kg
PM*	Poppy Mulch	17.5 wet tonnes/ha (7.7 dry tonnes/ha)		Total N – 1.6 % Total P – 2200 mg/kg Exc Ca – 32370 mg/kg
PSW*	Poppy Seed Waste	1 wet tonnes/ha (0.92 dry tonnes/ha)		Total N – 4.2 % Total P – 5100 mg/kg Exc Ca – 8190 mg/kg

* indicates treatments at Cressy only.
# Application rates for Biosolids treatments were calculated in accordance with the Tasmanian Biosolids Re-Use Guidelines (Dettrick and McPhee, 1999), based on the nitrogen requirements for wheat and barley.
¥ denotes Ca^{2+} applied to biosolids as quicklime at 4% by wet volume – does not include exchangeable Ca^{2+} in base product.

The contaminant (heavy metals) and nitrogen loading of each biosolids product and their potential plant availability were estimated using equations for the contaminant limiting biosolids application rate (CLBAR) and the nitrogen limiting biosolids application rate (NLBAR). With respect to CLBAR, the biosolids were classed as grade B due to the concentrations of Cu and Zn in both LAB and ADB. This grade is suitable

for agricultural use (Dettrick and McPhee, 1999). The NLBAR calculations for the biosolids treatments were based on minimum crop nitrogen requirements for cereals, as follows:

Available Nitrogen (AN) = ammonia N + 0.15 (Total N – ammonia N)

Followed by:

NLBAR (of product) = Crop Requirement (kg/ha) / AN (kg/t)

For example:

Anaerobically Digested Biosolids (ADB)

Available Nitrogen = 4.4 kg / t + 0.15 x (41 kg / t – 4.4 kg / t)

= 9.89 kg / tonne

NLBAR (dry tonnes) = 50 kg / ha ÷ 9.89 kg / t

= 5.06 t / ha

Moisture content 76.8 % (solids 23.2%)

NLBAR (wet tonnes) = 5.06 x (100 / 23.2)

= 21.8 t / ha

The L + F application rate was calculated based on biosolids available N equivalent and the lime contained in LAB. Application rates for PM and PSW were based on suppliers' recommendations (J. Aitken *pers. comm.* and R. Henry *pers. comm.*). All treatments were incorporated with a rotary cultivator four days after application and three days prior to planting. Control plots were also cultivated to ensure uniform soil disturbance. In addition, N as urea at a rate of 60 kg/ha was applied to L + F plots of both sites at Zadoks stage 13.

It must be noted that the NLBAR estimation for calculating the application rate of biosolids, the use of supplier rate recommendations for PM and PSW treatments, and the inorganic fertiliser products applied (i.e. no additional trace elements or K) were used to satisfy the primary objective, which was to compare and contrast changes to soil and crop within a framework of traditional farming practice for the two regions of study. There is often a disparity between field results from scientific research and field

results from practical application (Carberry *et al.*, 2009), which may be due to uni-dimensional and/or limited multi-dimensional analysis used by scientists. It was hoped that by emulating traditional practice, the research would better reflect the whole system response in that context, and subsequently facilitate practical application of results.

4.4 Results and discussion

4.4.1 Soil chemical attributes – years 1 and 2

There were significant differences between treatment means for post harvest soil chemical attributes for both years 1 and 2 at Cambridge and Cressy (Refer to Table 4.2 and Table 4.3 respectively).

After two years of growing cereals at the Cambridge site with no extra P applied, Colwell P concentration for LAB (142 mg/kg) was significantly higher than Control (75 mg/kg). Using the pre-trial soil test for comparison (126 mg/kg), it would appear that there was significant drawdown of P reserves in the Control soil, but an increase in LAB. L+F at the same site also showed a drawdown of P reserves in the first (110 mg/kg) and second (94 mg/kg) years compared to the pre-trial Colwell P. ADB was not significantly different to any other treatment at the end of year 1 (107 mg/kg) or 2 (110 mg/kg). At the Cressy site Colwell P for the LAB (86 mg/kg), PM (77 mg/kg) and L+F (74 mg/kg) treatments were significantly higher than control (53 mg/kg), but only after the first year of growing a cereal crop. Similar to the Cambridge site, a drawdown of soil P reserves was observed after year 1 and 2 for the Control (53 and 52 mg/kg respectively) and ADB (59 and 52 mg/kg respectively) treatments when compared to the pre-trial soil test (69 mg/kg). All treatments at the Cressy site were lower than the pre-trial soil test after the second year, with no significant differences between treatments. Pritchard *et al.* (2004) suggested that P should be considered as well as N in calculating biosolids application rates in case of excess P applied to satisfy N crop requirements. Results from this research suggest that one application of biosolids may supply sufficient P to not draw on soil P reserves in the first year. However the increase in P, from the pre-trial value, after the second year of a cereal crop is of concern.

Table 4.2 Post harvest soil chemical analysis for seasons 2007 and 2008 at Cambridge after application of bio-resources to texture contrast soil

Analyte	Year	ADB	Control	L + F	LAB	LSD (P≤0.05)	Pre-trial*
pH $^{1:5}$ ($CaCl_2$)	2007	6.13[a]	5.93[a]	5.97[a]	6.83[b]	0.46	5.40
	2008	5.90[a]	5.87[a]	6.67[ab]	7.07[b]	0.84	
EC $^{1:5}$ (dS/m)	2007	0.14	0.13	0.13	0.20	ns (0.06)	0.12
	2008	0.13	0.14	0.19	0.20	ns	
Soluble NO_3^- (mg/kg)	2007	21.0[a]	14.3[a]	15.7[a]	39.0[b]	17.6	7
	2008	21.7[bc]	14.0[a]	15.0[ab]	24.7[c]	7.6	
Soluble NH_4^+ (mg/kg)	2007	3.33	3.00	2.33	3.33	ns	2
	2008	2.00	2.00	2.00	1.67	ns	
Total N (%)	2007	0.18	0.14	0.17	0.13	ns	nr
	2008	0.16	0.14	0.14	0.14	ns	
Colwell P (mg/kg)	2007	107	91	110	125	ns	126
	2008	110[ab]	75[a]	94[a]	142[b]	36	
Colwell K (mg/kg)	2007	192	179	175	164	ns	234
	2008	231	176	202	198	ns	
Ext SO_4^{2-} (mg/kg)	2007	16.0	11.2	10.3	13.2	ns	8.2
	2008	10.5	10.9	11.7	12.8	ns	
Exc Ca^{2+} (c mol/kg)	2007	7.28	7.44	7.31	9.24	ns	6.00
	2008	7.20	6.83	8.05	9.57	ns	
Exc K^+ (c mol/kg)	2007	0.42	0.41	0.38	0.38	ns	0.60
	2008	0.46	0.39	0.47	0.47	ns	
Exc Mg^{2+} (c mol/kg)	2007	3.00	4.20	2.76	2.78	ns	2.70
	2008	3.50	3.53	2.90	2.80	ns	
Exc Na^+ (c mol/kg)	2007	0.32[a]	0.44[b]	0.33[a]	0.33[a]	0.09	0.50
	2008	0.46	0.56	0.51	0.45	ns	

Note: different letters indicates significant differences between treatment means, ns indicates no significant differences, nr indicates no result, * denotes pre-trial soil test of whole site and not individual plots.

Table 4.3 Post harvest soil chemical analysis for seasons 2007 and 2008 at Cressy after application of bio-resources to texture contrast soil

Analyte	Year	ADB	Control	L + F	LAB	PM	PSW	LSD (P≤0.05)	Pre-trial*
pH $^{1:5}$ ($CaCl_2$)	2007	5.87^{a}	6.13^{ab}	6.33^{b}	6.87^{c}	6.80^{c}	6.00^{a}	0.27	5.9
	2008	6.17^{a}	6.80^{bc}	6.47^{ab}	7.07^{c}	6.53^{ab}	6.33^{ab}	0.51	
EC $^{1:5}$ (dS/m)	2007	0.11^{bc}	0.08^{a}	0.09^{a}	0.16^{c}	0.14^{bc}	0.11^{ab}	0.04	0.06
	2008	0.06	0.09	0.07	0.08	0.09	0.07	ns	
Soluble NO_3^- (mg/kg)	2007	33.0^{c}	18.0^{a}	23.0^{ab}	30.0^{bc}	33.0^{c}	28.0^{abc}	10.0	8
	2008	3.7	4.7	4.3	5.3	8.3	10.3	ns	
Soluble NH_4^+ (mg/kg)	2007	3.33	2.00	2.67	3.00	2.67	4.00	ns	7
	2008	2.33	2.00	1.67	2.00	3.67	2.67	ns	
Total N (%)	2007	0.18	0.16	0.18	0.17	0.20	0.19	ns	nr
	2008	0.16	0.15	0.15	0.14	0.19	0.17	ns	
Colwell P (mg/kg)	2007	59^{ab}	53^{a}	74^{bcd}	86^{d}	77^{cd}	64^{abc}	15	69
	2008	52	52	57	60	54	55	ns	
Colwell K (mg/kg)	2007	106	122	184	146	186	148	ns	64
	2008	82	105	96	85	108	94	ns	
Ext SO_4^{2-} (mg/kg)	2007	11.1^{ab}	7.5^{a}	8.1^{a}	14.5^{b}	13.9^{b}	9.7^{a}	3.8	10.3
	2008	5.37	5.30	5.10	5.23	7.13	5.00	ns	
Exc Ca^{2+} (c mol/kg)	2007	6.34^{a}	6.52^{a}	7.18^{a}	9.90^{b}	9.12^{b}	6.96^{a}	1.09	6.7
	2008	6.67	8.20	7.07	8.70	7.34	6.70	ns	
Exc K^+ (c mol/kg)	2007	0.23	0.26	0.41	0.34	0.43	0.34	ns	0.2
	2008	0.19	0.21	0.22	0.19	0.25	0.22	ns	
Exc Mg^{2+} (c mol/kg)	2007	0.69^{ab}	0.67^{ab}	0.66^{a}	0.77^{b}	1.03^{c}	0.74^{ab}	0.11	0.6
	2008	0.68	0.97	0.64	0.70	0.78	0.68	ns	
Exc Na^+ (c mol/kg)	2007	0.15	0.19	0.15	0.18	0.13	0.15	ns	0.2
	2008	0.13	0.22	0.11	0.13	0.12	0.11	ns	

Note: different letters indicates significant differences between treatment means, ns indicates no significant differences, nr indicates no result, * denotes pre-trial soil test of whole site and not individual plots.

Soil pH (1:5 0.01M $CaCl_2$) for LAB (6.83) was significantly higher than for L+F (5.97), ADB (6.13) and Control (5.93) after the first year at the Cambridge site (Refer to Figure 4.1). The lime application rate for L+F was calculated as equivalent to that supplied by

LAB, but interactions between the soils buffering capacity, the amendment and the liming material may have contributed to the differences after the first year. After the second year, soil pH for LAB (7.07) was significantly higher than ADB (5.90) and Control (5.87), but not significantly higher than L+F (6.67). This result suggests that there may be a slower response time for pH from lime applied as $CaCO_3$ in L+F compared to lime applied as CaO in biosolids.

Soil pH (1:5 0.01M $CaCl_2$) for LAB at the Cressy site after the first and second years (6.87 and 7.07 respectively) followed a similar trend to the Cambridge site, with both LAB and PM (6.80) significantly higher than Control (6.13) and L+F (6.33) after the first year (Refer to Figure 4.2). Unlike Cambridge, the L+F treatment (6.47) at the Cressy site remained significantly lower than LAB (7.07) after the second year. The high pH for Control in the second year appears inconsistent compared to between year increases of the other treatments, and may have been due to soil transfer from adjacent lime amended treatment sites during cultivation and planting of the second year crop.

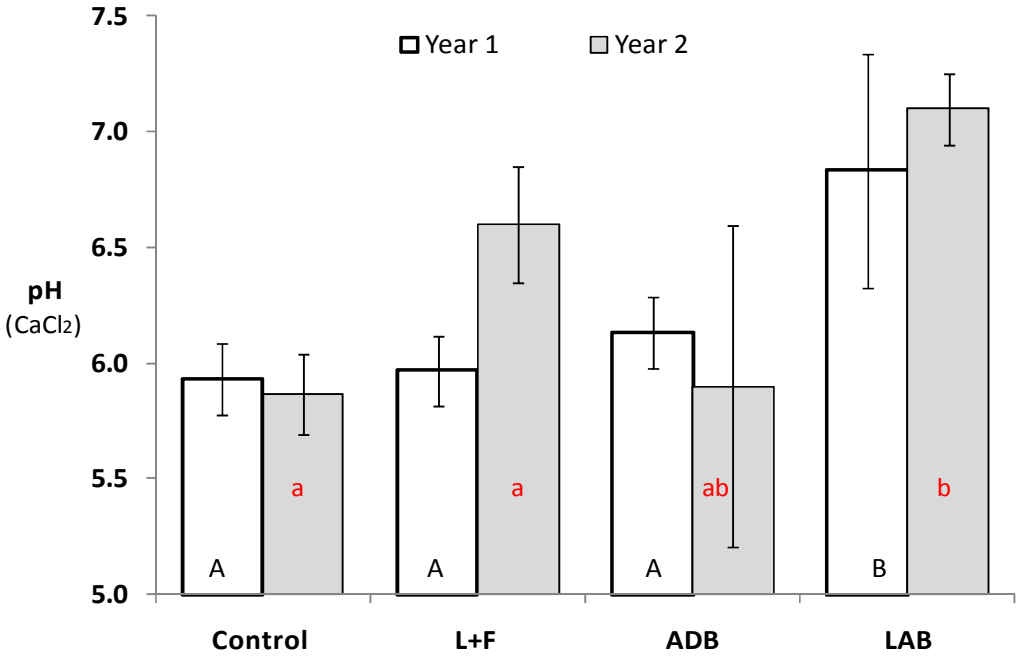

Figure 4.1 Post harvest soil pH at the Cambridge site for years 1 and 2 in response to application of bio-resources to texture contrast soil

Note: different capital and lower case letters indicate significant difference within each year, and error bars are standard error of the means.

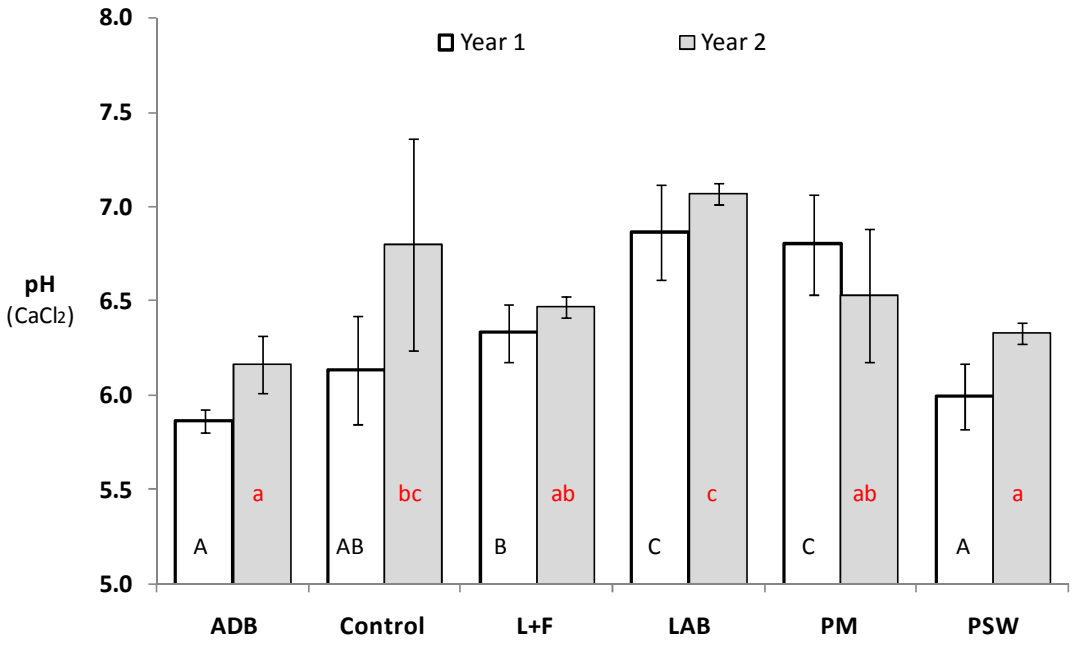

Figure 4.2 Post harvest soil pH at the Cressy site for years 1 and 2 in response to application of bio-resources to texture contrast soil

Note: different capital and lower case letters indicate significant difference within each year, and error bars are standard error of the means.

There were no significant differences in Colwell K between any treatment at either the Cressy or Cambridge sites for years 1 or 2. At the Cambridge site, all treatments (ADB – 192, Control – 179, L+F – 175 and LAB – 164) were much lower than the pre-trial analysis (234) after the first year with all but the Control treatment increasing after the second year (ADB – 231, Control – 176, L+F – 202 and LAB – 198). In contrast, the Colwell K for all treatments at the Cressy site, including control, was higher than the pre-trial analysis for both years. The majority of potassium in soil is contained in the primary minerals (mica and K feldspars), with less than 1% available in solution (Brady and Weil, 1999). Allison (1973) suggests that most potassium contained in plant residues is readily available for crop use once added to soil. This premise appears to hold when comparing residual K from PM (a plant residue) with LAB and ADB (9 530, 5 190 and 1 070 mg K/kg respectively). However, it doesn't hold with PSW (8 530 mg K/kg), which could also be considered a plant residue.

There were no significant differences in soil KCl extractable SO_4^{2-} at the Cambridge site for either year 1 or 2. However at the Cressy site, soil SO_4^{2-} for PM (13.9 mg/kg), LAB (14.5 mg/kg) and ADB (11.1 mg/kg) was significantly higher than L+F (8.1 mg/kg) and

Control (7.5 mg/kg). ADB, LAB, PM and PSW all showed a significant reduction in extractable SO_4^{2-} between the end of year 1 and the end of year 2 (Refer to Figure 4.3). Loss pathways include plant uptake in year 2 and leaching and transfer of labile S to the organic pool. An increase in organic S is often associated with an accumulation of organic matter from incorporating organic wastes and minimum tillage (Shaw, 1999). There were no significant differences between single rate treatments after the second year at the Cressy site.

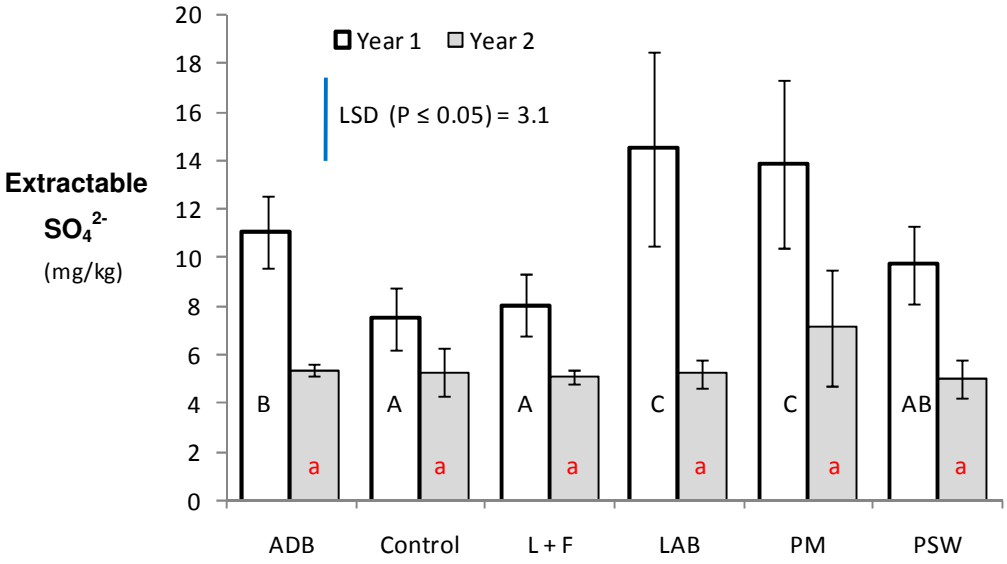

Figure 4.3 Cressy soil extractable SO_4^{2-} post harvest – Years 1 and 2 in response to application of bio-resources to texture contrast soil

Note: different capital and lower case letters indicate significant difference within each year, LSD is significant difference between years, and error bars are standard deviation of the means.

$EC_{1:5}$ for the LAB treatment was not significantly different (P=0.055) to all other treatments at the Cambridge site after the first year. However at the Cressy site LAB (0.16) was significantly higher than Control (0.08), L+F (0.09) and PSW (0.11) after the first year. According to Maas and Hoffman (1977), soils with $EC_{1:5}$ between 0.15 and 0.34 dS/m and 10 – 20% clay content are considered to have a medium salinity rating, suitable only for moderately tolerant crops such as barley (but not wheat). All but LAB were below this range. There were no significant differences between any of the treatments at either site in the second year, although L+F (0.19) and LAB (0.20) at the Cambridge site were in the range of medium salinity.

The exchangeable sodium percentage (ESP) for each site and each year was calculated using the sum of exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}), excluding the exchangeable H^{+} and Al^{3+}. These were excluded because (a) the pH (1:5 H_20) of the soils was above 6 and (b) analysis results for H^{+} and Al^{3+} were below 0.01 cmol / kg. The results showed that although there were no significant differences between treatments in the first year at Cambridge (Figure 4.4), LAB was significantly lower than all other treatments in the second year.

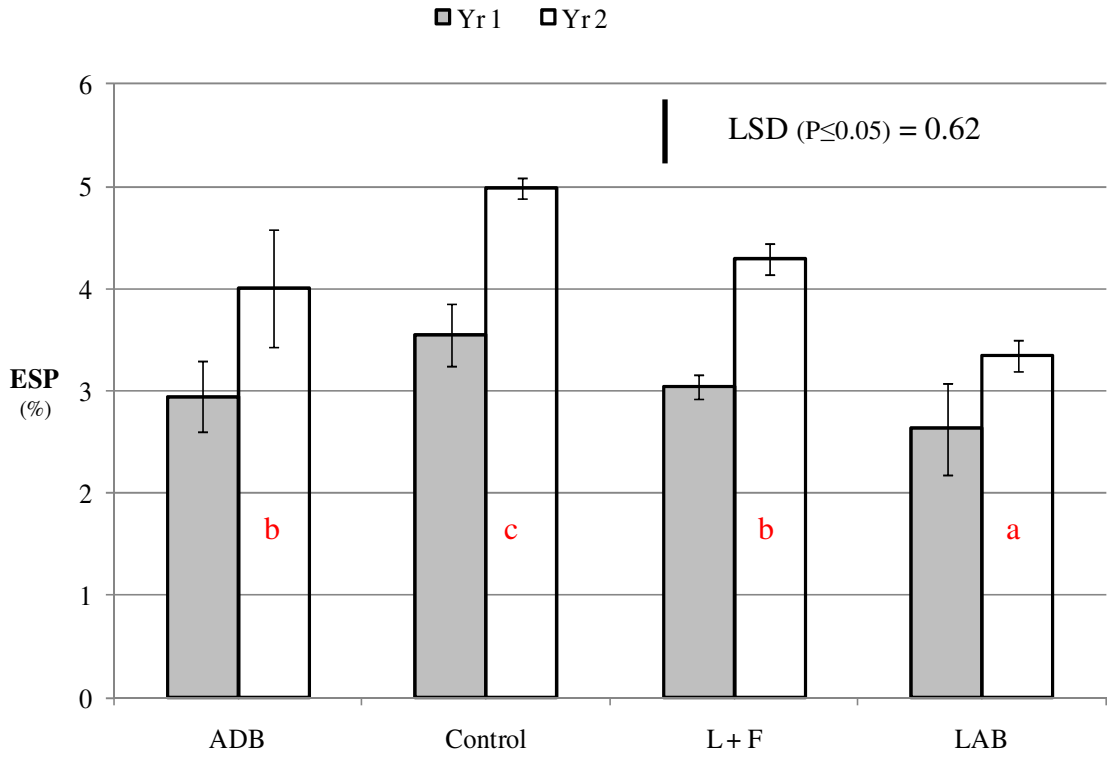

Figure 4.4 Post harvest soil exchangeable sodium percentage (ESP) at Cambridge for years 1 and 2

Note: different letters indicate significant difference between treatment means, LSD is significant difference within the year 2, and error bars are standard deviation of the means.

At Cressy, the ESP for PM was significantly lower than for PSW, ADB and Control, but not significantly different to L+F or LAB (Figure 4.5).

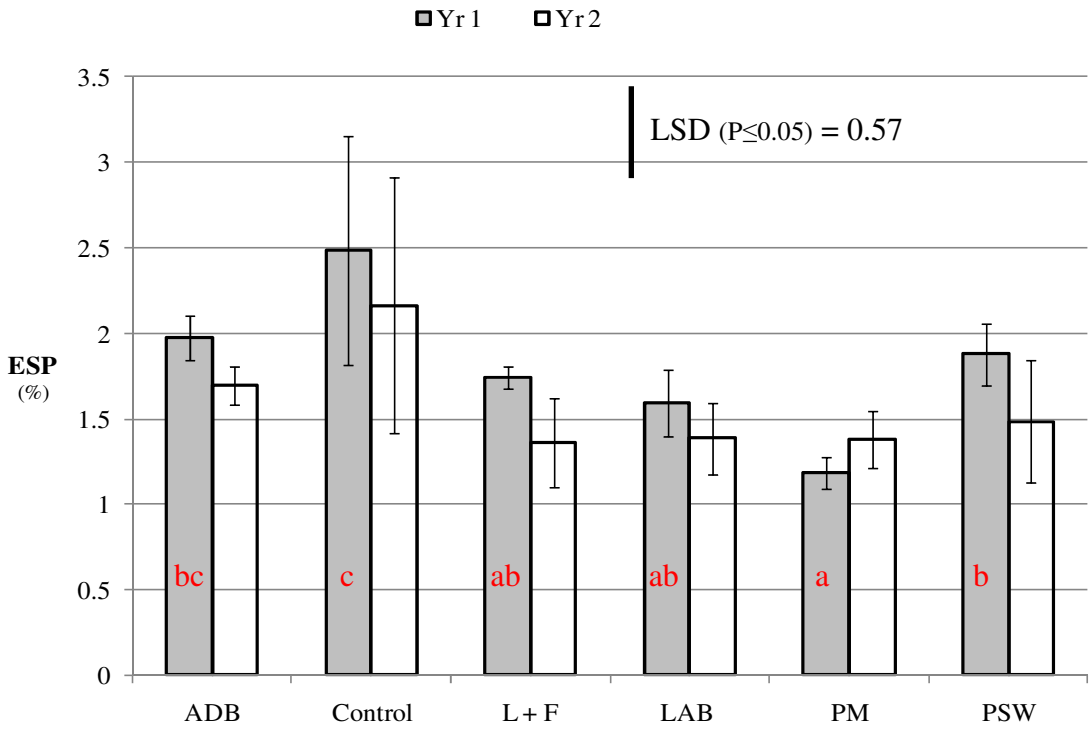

Figure 4.5 Post harvest soil exchangeable sodium percentage (ESP) at Cressy for years 1 and 2

Note: different letters indicate significant difference between treatment means, LSD is significant difference within the year 1, and error bars are standard deviation of the means.

The LAB treatment at the Cambridge site had significantly more soil NO_3^- (39 mg/kg) after the first year, than the ADB (21 mg/kg), Control (14.3 mg/kg) and L+F (15.7 mg/kg) treatments (Refer to Figure 4.6). However, after the first year at the Cressy site soil NO_3^- for ADB (33 mg/kg) and PM (33 mg/kg) was significantly more than the L+F (23 mg/kg) and the Control (18 mg/kg) treatments, with LAB (30 mg/kg) only significantly higher than Control (Refer to Figure 4.7). After the second year at the Cambridge site soil NO_3^- for LAB (24.7 mg/kg) was significantly higher than Control (14 mg/kg) and L+F (15 mg/kg) but not ADB (21.7 mg/kg). Although soil NO_3^- for PSW (28 mg/kg) at the Cressy site was not significantly different to any other treatment after the first year, PSW (10.3 mg/kg) was significantly higher than ADB (3.7 mg/kg) after the second year. This was despite the low application rate of PSW (1 t/ha) compared to ADB (22 t/ha) and similar total nitrogen of the two products (4.1% and 4.2% respectively).

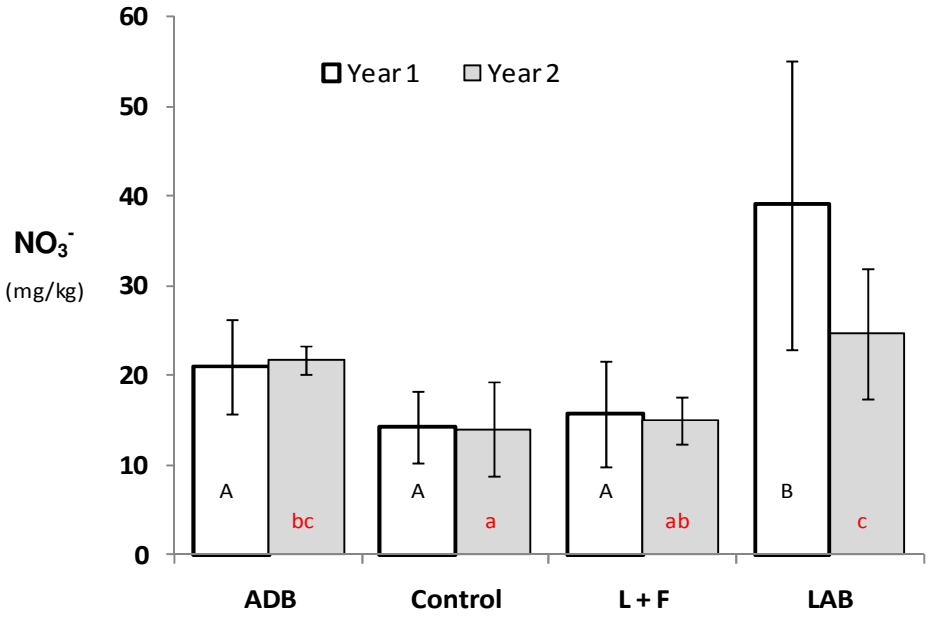

Figure 4.6 Post harvest soil NO_3^- at Cambridge trial site for years 1 and 2 in response to application of bio-resources to texture contrast soil

Note: different capital and lower case letters indicate significant difference within each year, and error bars are standard deviation of the means.

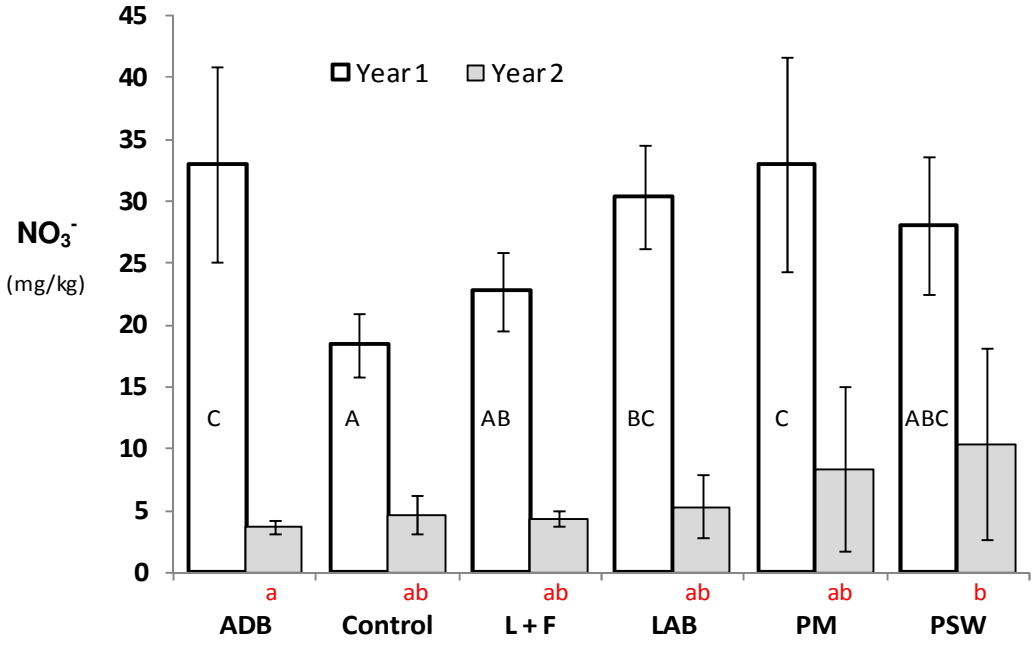

Figure 4.7 Post harvest soil NO_3^- at Cressy trial site for years 1 and 2 in response to application of bio-resources to texture contrast soil

Note: different capital and lower case letters indicate significant difference within each year, and error bars are standard deviation of the means.

The results suggest that bio-resources may be used as an alternative to inorganic fertiliser with respect to supplying plant nutrients, particularly N. Similar findings were reported by Kidd *et al.* (2007) and Mohammad *et al.* (2007) in their respective studies of sewage sludge and composted waste products. However, results also confirmed comments by Cabrera *et al.* (2005) and Bünemann *et al.* (2006) that the inherent characteristics of bio-resources make it difficult to match nutrient supply with plant demand. Inorganic fertilisers have known nutrient contents which are considered immediately or rapidly available to plants, whereas this research has shown that bio-resources and specifically LAB applied to agricultural land can result in more available N than plant demand with potential for N loss through leaching when applied in the late autumn/winter period. Australian EPA guidelines for biosolids application rates are based on an estimated N release of approximately 20% of total N within the first year, however Eldridge *et al.* (2008) questioned the "one-size-fits-all" approach to N management after finding more than 50% of plant available N was released within 2 months of application of granulated biosolids. In contrast, ADB (biosolids without lime) did not display the same characteristics as LAB.

4.4.2 Microbial biomass (MB) and soil carbon (SC)

Bacterial biomass at the Cressy site showed L+F and PM were significantly greater than Control and ADB (Table 4.5). This contrasts with studies by Peacock *et.al.* (2001) and Bittman *et. al.* (2005), who found that bacterial biomass decreased in the first year after application of inorganic fertilisers to no-till cropping and pastures respectively as compared with control and organic amendments, and Barbarick *et al.* (2004) who found an 11% increase in microbial biomass after application of biosolids. Sampling at the Cressy site occurred in a fallow period following harvest when the soil temperature was high and moisture low, which may have minimised microbial activity associated with the addition of organic material. However, Feng *et. al.* (2003) observed that changes in microbial community composition from tillage practices were more pronounced in fallow. There were no significant differences between treatments with respect to bacterial biomass at the Cambridge site (Table 4.4), perhaps due to even less soil moisture than the Cressy site.

Fungal biomass at the Cressy site showed ADB, LAB, PM and L+F were significantly greater than Control. Aoyama *et. al.* (2006) reported that water soluble Ca^{2+} associated with limed biosolids may decrease fungal biomass, however, the evidence presented here from the Cressy site shows no significant difference between limed (LAB) and un-limed (ADB) biosolids. There were no significant differences between treatments at the Cambridge site with respect to fungal biomass, however, the trend of LAB < L+F < Control < ADB supports the findings reported by Aoyama *et. al.* (2006).

Table 4.4 Bacterial and fungal biomass and total C of soil fractions sampled in March 2008 for treatments at Cambridge in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	LSD (P<0.05)
Bacterial Biomass (µg/g)	10.93 (3.35)	10.68 (3.50)	10.30 (0.95)	8.04 (0.95)	ns
Fungal Biomass (µg/g)	11.43 (2.93)	9.92 (2.78)	9.17 (1.52)	8.04 (2.93)	ns
Soil Moisture (%)	11.70	12.63	11.84	12.83	ns
Total C Silt and Clay	1.49 (0.10)	1.43 (0.26)	1.49 (0.29)	1.31 (0.23)	ns
Total C Sand	0.89 (0.08)	1.09 (0.14)	1.47 (0.31)	1.26 (0.54)	ns

Note: numbers in brackets are standard deviation from the means.

Table 4.5 Bacterial and fungal biomass and total C of soil fractions sampled in March 2008 for treatments at Cressy in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**PM**	**PSW**	LSD (P<0.05)
Bacterial Biomass (µg/g)	4.98 ^{a} (2.45)	6.09 ^{a} (2.57)	16.08 ^{b} (3.49)	10.96 ^{ab} (6.68)	16.91 ^{b} (8.10)	7.46 ^{a} (3.73)	7.22
Fungal Biomass (µg/g)	10.85 ^{c} (3.46)	5.55 ^{a} (1.68)	9.61 ^{bc} (2.32)	9.38 ^{bc} (3.39)	8.69 ^{bc} (3.62)	7.26 ^{ab} (1.59)	2.71
Soil Moisture (%)	13.98	13.73	13.59	13.11	13.93	13.75	ns
Total C Silt and Clay	1.15 (0.09)	1.07 (0.09)	1.07 (0.05)	1.08 (0.10)	1.19 (0.05)	1.20 (0.16)	ns
Total C Sand	0.82 (0.21)	0.80 (0.01)	0.75 (0.04)	0.83 (0.21)	0.93 (0.13)	0.83 (0.10)	ns

Note: different letters indicate significant differences between treatment means, numbers in brackets are standard deviation from the means.

Organic carbon was analysed for the whole soil and the silt plus clay fraction, with the value for the sand fraction calculated by difference. The analysis at the end of year 1 showed no significant differences between treatments at either site (Table 4.5). A recent study by Hardie and Cotching (2009) found a significant increase in soil carbon from 1.24% to 1.57% after applying poppy mulch (PM) at 200 m^3/ha (approximately 3 times that used in this trial), although no significant difference was found at lower rates equivalent to that used in this trial.

A change in soil management can affect the concentration of soil carbon. Studies by Sparrow *et al.* (1999) and Cotching *et al* (2001; 2002a) have found that intensive cropping management resulted in between 30% and 50% reduction in soil carbon compared to pasture management. Although this present study has demonstrated an upward trend in soil organic carbon associated with applying organic materials, Hardie and Cotching (2009) showed that much higher rates would need to be used to obtain any significant increase. Alternatively, more frequent applications of organic material have been shown to increase soil organic carbon (Hepperly *et al.*, 2009; Tian *et al.*, 2009).

There was no significant relationship between soil carbon and fungal or bacterial biomass less than 12 months after application and incorporation of bio-resources. However, biological responses may take longer to become established as Cotching *et al.* (2001) found a significant relationship between soil organic C and microbial biomass C in Sodosols in Tasmania under a range of management regimes that had been in place over many years.

4.4.3 Soil Physical Characteristics

Analysis of penetration resistance results measured at the Cambridge and Cressy sites post harvest year 1 showed no significant differences at 0 – 75 mm depth or 75 – 150 mm depth. Results from analysis of bulk density, and dry and wet aggregate stability measured at the same time also showed no significant differences between treatments at either the Cambridge site (**Error! Reference source not found.**) or the Cressy site ().

Although there were no changes in soil physical properties one year after application in this research, a response to applied amendments may take longer to appear. Tester (1990) assessed the effects of composted sewage sludge, beef cattle manure and

fertiliser amendments on a loamy sand soil and found a reduction in penetration resistance and bulk density over a five year period, for the compost compared to fertilised and control treatments. Other studies of long term amendment application (Angers and N'Dayegamiye, 1991; Christensen, 1986; Ibrahim and Shindo, 1999) found positive changes to soil physical attributes, specifically aggregation of particles.

Table 4.6 Soil physical parameters measured at the Cambridge site post harvest year 1 in response to application of bio-resources to texture contrast soil

		ADB	**Control**	**L+F**	**LAB**	**LSD** (P≤0.05)
Penetration Resistance (kPa)	0 – 75 mm	745	924	780	950	ns
	75 – 150 mm	1504	1240	1213	1484	ns
Water Content (%)	0 – 75 mm	8.84	8.09	8.78	8.34	ns
	75 – 150 mm	9.08	9.29	11.72	8.95	ns
Bulk Density (mg/cm^3)	0 – 75 mm	1.27	1.29	1.25	1.29	ns
	75 – 150 mm	1.39	1.37	1.35	1.38	ns
Dry Aggregate Stability (%)	> 2.0 mm	42.1	59.3	50.5	53.4	ns
	< 2.0 mm	57.9	40.7	49.5	46.6	ns
Wet Aggregate Stability (%)	> 0.25 mm	12.3	12.9	14.1	12.9	ns
	< 0.25 mm	87.7	87.1	85.9	87.1	ns

Table 4.7 Soil physical parameters measured at the Cressy site post harvest year 1 in response to application of bio-resources to texture contrast soil

		ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
Penetration Resistance (kPa)	0 – 75 mm	1201	1282	1268	1415	1297	1155	ns
	75 – 150 mm	1594	1930	1886	1788	1644	1556	ns
Water Content (%)	0 – 75 mm	13.98	13.73	13.59	13.11	13.93	13.75	ns
	75 – 150 mm	12.30	11.92	11.85	11.19	11.84	12.15	ns
Bulk Density (mg/cm^3)	0 – 75 mm	1.26	1.28	1.29	1.29	1.28	1.29	ns
	75 – 150 mm	1.40	1.41	1.43	1.42	1.40	1.42	ns
Dry Aggregate Stability (%)	> 2.0 mm	48.4	50.6	41.6	50.0	43.8	44.0	ns
	< 2.0 mm	51.6	49.4	58.4	50.0	56.2	56.0	ns
Wet Aggregate Stability (%)	> 0.25 mm	18.5	17.7	17.8	17.9	17.6	20.1	ns
	< 0.25 mm	81.5	82.3	82.2	82.1	82.4	79.9	ns

4.4.4 Crop growth and harvest assessments in response to soil applied bio-resources

Crop growth parameters were measured and harvest assessments undertaken each year at both Cambridge and Cressy. In year 1, wheat was grown at Cambridge and barley at Cressy. In year 2, barley was grown at Cambridge and wheat at Cressy. There were no significant differences in emergence or height and biomass at growth stage Z31 and Z71 at the Cambridge site (Table 4.8), despite the aerial photograph taken at growth stage Z71 showing colour differences between treatments (Plate 4.1). The differences evident in the individual plants from the 200 mm diameter core samples shown in Plate 4.2 was also not reflected in biomass and height results from quadrat samples taken at growth stage Z71.

Table 4.8 Wheat crop growth parameters at Cambridge for year 1 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**LSD** ($P \leq 0.05$)
Emergence (no/m^2)	63	53	46	46	ns
Height Z31 (cm)	54.3	61.7	57.3	64.0	ns
Biomass Z31 (t/ha)	1.99	1.34	1.75	3.21	ns
Height Z71 (cm)	70.7	74.0	76.7	74.0	ns
Biomass Z71 (t/ha)	3.86	3.29	3.94	6.13	ns

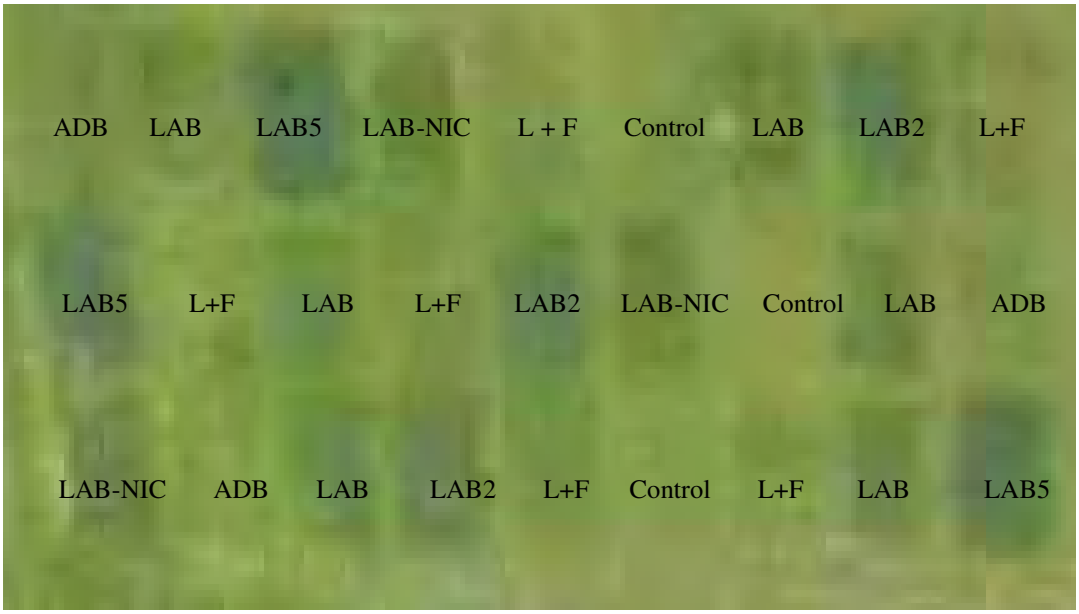

Plate 4.1 Aerial photograph of the Cambridge site in November 2007 at growth stage Z71 (treatments LAB2, LAB5 and LAB-NIC not included in this analysis)

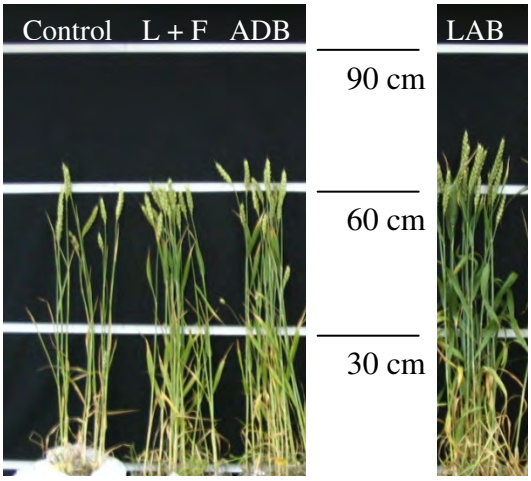

Plate 4.2 Wheat samples at growth stage Z71taken from 200 mm diameter core samples at Cambridge site in year 1

Specific plant growth parameters measured from the 200 mm diameter core samples showed that there were no significant differences in seed head diameter, length, shoot/root ratio or leaf number. However, tiller number for ADB was significantly higher than L+F and Control, with LAB greater than Control only (Table 4.9).

Table 4.9 Wheat crop growth parameters at growth stage Z71 at Cambridge for year 1 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**LSD** (P≤0.05)
Seed Head Diameter (mm)	10.4	10.5	10.9	11.0	ns
Seed Head Length (mm)	62.8	69.7	73.3	79.2	ns
Shoot/ Root Ratio	4.7	3.0	5.7	5.3	ns
Tiller Number (no)	16 [c]	9 [a]	11 [ab]	13 [bc]	4
Leaf Number (no)	4.9	4.1	4.5	5.1	ns

Note: different letters indicate significant differences between treatment means.

There was no significant difference between the yields of LAB and L+F treatments, however both were significantly higher than control (). Similar results were found by Weggler-Beaton *et al.* (2003) with increases in wheat and barley yields from relatively low rates of biosolids comparable with increases from conventional N & P fertilisers. There were no significant differences in harvest index, weeds or heads per metre row for year 1.

Table 4.10 Wheat harvest parameters at Cambridge for year 1 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**LSD** (P≤0.05)
Harvest Index (%)	51.2	54.4	52.9	48.3	ns
Weeds (%)	20.9	12.3	23.5	10.6	ns (0.09)
Heads per metre row (no)	36	36	41	55	ns
Yield (t/ha)	1.7 [ab]	1.4 [a]	2.0 [b]	2.2 [b]	0.5

Note: different letters indicate significant differences between treatment means, harvest index is grain weight as a percentage of whole plant.

In the second year at Cambridge there were no significant differences between treatments for harvest index, weeds, seed heads per metre row or yield. Although the yield data suggest a difference between treatments, the standard deviations (shown in brackets) indicate why there was no significance.

Table 4.11 Barley harvest parameters at Cambridge for year 2 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**LSD** (P≤0.05)
Harvest Index (%)	55.1	52.5	52.9	53.0	ns
Weeds (%)	8.0	15.3	7.7	20.3	ns
Heads per metre row (no)	77	57	83	69	ns
Yield (t/ha)	2.2 (0.8)	1.3 (0.1)	2.0 (0.6)	2.1 (1.3)	ns

Note: standard deviations from the means are shown in brackets.

At the Cressy site, plant height for the LAB treatment at growth stage Z32 was significantly higher than PM, PSW, L+F and Control, but not significantly higher than

ADB (Table 4.12). However, by growth stage Z71, biomass for ADB was significantly higher than all other treatments except LAB.

Table 4.12 Barley crop growth parameters at Cressy for year 1 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**PM**	**PSW**	**LSD** (P≤0.05)
Emergence (no/m2)	139	118	129	141	130	104	ns
Height Z25 (cm)	16.7^{abc}	15.0^{a}	18.0^{c}	17.3^{bc}	17.3^{bc}	16.0^{ab}	1.9
Height Z32 (cm)	42.7^{bc}	37.0^{a}	39.0^{ab}	44.3^{c}	37.0^{a}	36.7^{a}	4.5
Biomass (t/ha)	11.2 ^{c}	8.3 ^{ab}	9.3 ^{ab}	9.8 ^{bc}	8.1 ^{a}	9.4 ^{ab}	1.5

Note: different letters indicate significant differences between treatment means.

The visual differences shown on Plate 4.3 of plants at the Cressy site taken from a 200 mm diameter soil core at Zadoks 71 are not clearly defined relative to measured data from quadrats. However, note the subtle difference in height and density of PM relative to all other treatments. This is consistent with suggestions that the dissolved salts in PM can inhibit plant growth within the first 12 months of land application, after which time they neutralise (Aitken, 2007).

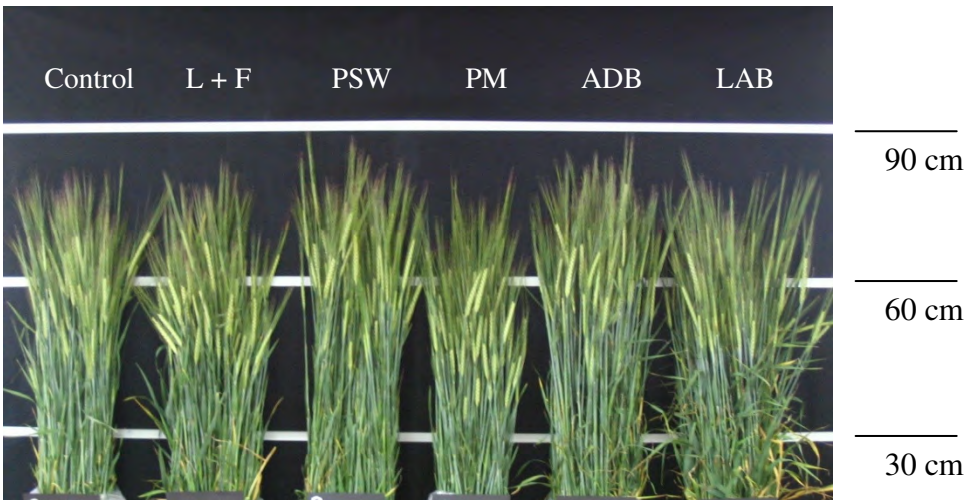

Plate 4.3 Barley samples at growth stage Z71 taken from Cressy site in year 1

In the first year at Cressy, all treatments yielded significantly higher than Control (Table 4.13). There were also significantly more seed heads per metre row for L+F than all other treatments except for ADB. There were no significant differences between treatments for harvest index or weeds.

Table 4.13 Barley harvest parameters at Cressy for year 1 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**PM**	**PSW**	**LSD** (P≤0.05)
Harvest Index (%)	59.3	59.7	58.8	51.0	57.4	58.8	ns
Weeds (%)	0	0	0	0	0	0	ns
Heads per metre row (no)	168 [ab]	134 [a]	199 [b]	151 [a]	158 [a]	138 [a]	36
Yield (t/ha)	6.1 [b]	5.5 [a]	6.5 [b]	6.5 [b]	6.4 [b]	6.3 [b]	0.4

Note: different letters indicate significant differences between treatment means, harvest index is grain weight as a percentage of whole plant.

There were no significant differences between treatments for any of the measured harvest parameters for year 2 (Table 4.14).

Table 4.14 Wheat harvest parameters at Cressy for year 2 in response to application of bio-resources to texture contrast soil

	ADB	**Control**	**L+F**	**LAB**	**PM**	**PSW**	**LSD** (P≤0.05)
Harvest Index (%)	48.6	47.9	46.3	44.2	43.1	46.3	ns
Weeds (%)	3.6	2.1	1.8	1.6	3.6	3.3	ns
Heads per metre row (no)	56	59	49	68	51	54	ns
Yield (t/ha)	1.76	1.82	1.65	2.04	1.68	1.80	ns

Note: different letters indicate significant differences between treatment means, harvest index is grain weight as a percentage of whole plant.

4.4.5 Biomass and grain analysis in year 1

Wheat biomass was analysed at growth stages Z13, Z31 and Z71 at the Cambridge site in year 1 (Table 4.19). There were no significant differences between treatments for P, S or Mg. However at Z13, LAB contained significantly more K in the biomass than Control and L+F and significantly more NO_3^- than all other treatments being 9 times L+F, 13 times Control and 11 times ADB values. At Z31, LAB contained significantly more K in the biomass than all other treatments. However, there were no significant differences between treatments with respect to K in biomass at Z71. Although there were no significant differences between treatments with respect to NO_3^- for Z31 and Z71, LAB contained significantly more total nitrogen than all other treatments at these two growth stages.

Table 4.15 Wheat biomass nutrients at Cambridge for growth stages Z13 (26/09/07), Z31 (25/10/07) and Z71 (26/11/07) in year 1 in response to application of bio-resources to texture contrast soil

Analyte	Date	ADB	Control	L + F	LAB	LSD (P≤0.05)
P (%)	26/09/07	0.48	0.48	0.47	0.44	ns
	25/10/07	0.37	0.35	0.38	0.33	ns
	26/11/07	0.25	0.25	0.24	0.20	ns
K (%)	26/09/07	4.61^{ab}	4.23^{a}	4.24^{a}	4.82^{b}	0.43
	25/10/07	2.70^{a}	2.62^{a}	2.86^{a}	3.52^{b}	0.56
	26/11/07	1.09	1.12	1.05	1.35	ns
S (%)	26/09/07	0.32	0.30	0.29	0.33	ns (P=0.06)
	25/10/07	0.18	0.17	0.17	0.21	ns
	26/11/07	0.14	0.14	0.12	0.13	ns
Ca (%)	26/09/07	0.33^{a}	0.31^{a}	0.31^{a}	0.40^{b}	0.03
	25/10/07	0.20^{a}	0.20^{a}	0.21^{a}	0.33^{b}	0.07
	26/11/07	0.12^{a}	0.11^{a}	0.12^{a}	0.17^{b}	0.03
Mg (%)	26/09/07	0.21	0.24	0.20	0.24	ns (P=0.06)
	25/10/07	0.17	0.19	0.17	0.23	ns
	26/11/07	0.14	0.14	0.13	0.15	ns
Total N (%)	26/09/07	3.9	3.7	3.8	4.9	ns (P=0.06)
	25/10/07	1.8^{a}	1.8^{a}	2.0^{a}	2.5^{b}	0.5
	26/11/07	1.0^{a}	0.9^{a}	1.0^{a}	1.4^{b}	0.3
NO_3^- (mg/kg)	26/09/07	47^{a}	40^{a}	60^{a}	540^{b}	121
	25/10/07	41	38	47	491(542)	ns
	26/11/07	40	40	39	46	ns

Note: different letters indicate significant differences between treatment means, number in brackets is standard deviation of the mean.

The calcium content of the plant biomass from the LAB treatment analysed from Z13, Z31 and Z71 samples was significantly higher than all other treatments at each growth stage. However, when harvested grain was analysed for calcium content, there were no significant differences between treatments (Table 4.16). Of the other key nutrients analysed in the grain, S and total N in the LAB treatment was significantly higher than all other treatments. The high total N in the grain for LAB suggests that the applied bio-resource may be releasing more N than predicted from calculations.

Table 4.16 Wheat grain nutrients at Cambridge for year 1 in response to application of bio-resources to texture contrast soil

Analyte	**ADB**	**Control**	**L + F**	**LAB**	**LSD** (P≤0.05)
P (%)	0.37	0.36	0.37	0.35	ns
K (%)	0.37	0.41	0.39	0.41	ns
S (%)	0.1163^{a}	0.1107^{a}	0.1163^{a}	0.1267^{b}	0.0103
Ca (%)	0.033	0.034	0.038	0.034	ns
Mg (%)	0.13	0.13	0.13	0.13	ns
Total N (%)	1.48^{b}	1.26^{a}	1.41^{ab}	1.74^{c}	0.18
NO_3^- (mg/kg)	38	38	39	37	ns

Note: different letters indicate significant differences between treatment means

The optimum nutrient concentrations for wheat grain to be used for stock feed have been suggested as P at 0.44%, K at 0.40%, S at 0.14%, Ca at 0.05% and Mg at 0.13% (Lardy and Bauer, 1999). Based on these values, all treatments contained less P, S and Ca. Only Mg and K were close to suggested levels.

At the Cressy site for growth stage Z71 (Table 4.17), PM contained significantly more P than all other treatments in the biomass and contained significantly more S than Control, L+F, LAB and PSW. Similar to the Cambridge site, the plant biomass at Z71 contained significantly more Ca than all other treatments. There were no significant differences between treatments for any other analyte in the biomass. This was emulated in the grain nutrient analysis (Table 4.18) in that there were no significant differences between any of the treatments for any of the analytes.

The optimum nutrient concentrations for barley grain to be used for stock feed have been suggested as P at 0.35%, K at 0.57%, S at 0.15%, Ca at 0.05% and Mg at 0.12% (Lardy and Bauer, 1999). Based on these values, all treatments were close to suggested levels except for Ca.

Table 4.17 Barley biomass nutrients growth stage Z71 at Cressy for year 1 in response to application of bio-resources to texture contrast soil

Analyte	**ADB**	**Control**	**L + F**	**LAB**	**PM**	**PSW**	**LSD** (P≤0.05)
P (%)	0.25 ^{ab}	0.26 ^{b}	0.23 ^{a}	0.25 ^{ab}	0.30 ^{c}	0.25 ^{ab}	0.03
K (%)	1.19	1.14	1.31	1.30	1.50	1.32	ns
S (%)	0.20 ^{bc}	0.16 ^{a}	0.17 ^{a}	0.18 ^{ab}	0.22 ^{c}	0.16 ^{a}	0.03
Ca (%)	0.26 ^{a}	0.21 ^{a}	0.26 ^{a}	0.32 ^{b}	0.22 ^{a}	0.22 ^{a}	0.05
Mg (%)	0.16	0.15	0.14	0.15	0.16	0.15	ns
Total N (%)	1.60	1.30	1.61	1.74	1.45	1.52	ns
NO_3 (mg/kg)	98	114	86	110	87	79	ns

Note: different letters indicate significant differences between treatment means.

Table 4.18 Barley grain nutrients at Cressy for year 1 in response to application of bio-resources to texture contrast soil

Analyte	**ADB**	**Control**	**L + F**	**LAB**	**PM**	**PSW**	**LSD** (P≤0.05)
P (%)	0.41	0.41	0.43	0.40	0.41	0.40	ns
K (%)	0.53	0.54	0.56	0.55	0.53	0.53	ns
S (%)	0.14	0.14	0.14	0.14	0.13	0.13	ns
Ca (%)	0.038	0.038	0.047	0.041	0.038	0.037	ns
Mg (%)	0.130	0.131	0.137	0.129	0.132	0.129	ns
Total N (%)	1.90	1.76	1.86	1.92	1.85	1.80	ns
NO_3 (mg/kg)	43.33	40.00	39.33	42.00	43.33	41.33	ns

4.4.6 Soil and crop nitrogen balance at Cambridge for year 1

Table 4.19 shows the total nitrogen and NO_3^- of the biomass at growth stages Z13, Z31 and Z71, together with soil nitrogen analysis undertaken at the same time in year 1. Soil NO_3^- for LAB was significantly higher than ADB and Control, but not L+F.

Table 4.19 Wheat biomass nitrogen and soil NO_3^- and NH_4^+ at Cambridge for growth stages Z13 (26/09/07), Z31 (25/10/07) and Z71 (26/11/07) in year 1 in response to application of bio-resources to texture contrast soil

Analyte	Date	ADB	Control	L + F	LAB	LSD (P≤0.05)
Biomass Total N (%)	26/09/07	3.9	3.7	3.8	4.9	ns (P=0.06)
	25/10/07	1.8[a]	1.8[a]	2.0[a]	2.5[b]	0.5
	26/11/07	1.0[a]	0.9[a]	1.0[a]	1.4[b]	0.3
Soil NO_3^- (mg/kg)	26/09/07	5.33[a]	4.17[a]	10.70[b]	12.67[b]	2.81
	25/10/07	3.43	3.37	3.60	5.60	ns
	26/11/07	6.30	4.53	5.03	12.63	ns
Soil NH_4^+ (mg/kg)	26/09/07	0[a]	0.43[a]	2.27[b]	0.40[a]	1.48
	25/10/07	1.83	1.47	5.47	3.77	ns
	26/11/07	0	0.37	0.60	0.37	ns

A partial nitrogen balance is shown in Table 4.20, using biomass (t/ha) from Table 4.8 and nitrogen analysis of soil and biomass from Table 4.19.

Table 4.20 Partial nitrogen balance relative to calculated nitrogen inputs from applied bio-resources and inorganic fertilizer at Cambridge for growth stages Z31 (25/10/07) and Z71 (26/11/07) in year 1

	Date	**ADB**	**Control**	**L + F**	**LAB**
B_t	25/10/07	1.99	1.34	1.75	3.21
	26/11/07	3.86	3.29	3.94	6.13
B_k	25/10/07	1990	1340	1750	3210
	26/11/07	3860	3290	3940	6130
B_{TN}	25/10/07	35.8	24.1	35.0	80.3
	26/11/07	38.6	29.7	39.6	85.8
S_{AN}	25/10/07	5.3	4.8	9.1	9.4
	26/11/07	6.3	4.9	5.6	13.0
$B_{TN} + S_{AN}$	25/10/07	41.1	28.9	44.1	89.7
	26/11/07	44.9	34.6	45.2	98.8
N_{PB} (kg/ha)	25/10/07	**-13.7**		**-10.7**	**+34.9**
	26/11/07	**-10.0**		**-9.7**	**+43.9**

B_t - Biomass (t/ha), B_k - Biomass (kg/ha), B_{TN} - Total N in Biomass (kg/ha), S_{AN} – Soil Available N ($NH_4^+ + NO_3^-$ kg/ha), N_{PB} (Nitrogen partial balance) = $B_{TN} + S_{AN} - BR_{AN} - S_{AN}$ (of control soil), BR_{AN} = 50 kg/ha (calculated value of available nitrogen from applied bio-resources and inorganic fertiliser).

These calculations demonstrate that by the flowering stage (Z71 – 26/11/07), of the 50 kg/ha of calculated available nitrogen applied from the ADB and L+F treatments, 10.0 kg/ha and 9.7 kg/ha respectively of nitrogen was unaccounted for from soil or plant biomass. Furthermore, the LAB treatment showed an additional 43.9 kg/ha of available nitrogen in the system beyond the calculated release. This represents an estimated 53.9 kg/ha difference of available nitrogen between LAB and ADB. Mahoney *et al.* (Mahoney *et al.*, 1987) found the addition of calcium in a biosolids digestion process enhanced microbial activity resulting in faster aggregation of biomass compared to a digestion process without calcium. The calcium released into soil solution from the pH

reactions when LAB was applied may be similarly enhancing microbial activity and consequently releasing more nitrogen. These results suggest that current guideline calculations (Dettrick and McPhee, 1999) do not adequately reflect the different nitrogen release rates from biosolids with and without lime (LAB and ADB respectively), although both products have undergone similar treatment processes (i.e. anaerobically digested and dewatered) up until the addition of lime (added in the worm drive to deposit product in distribution container). They also raise potential concerns about nitrogen exiting the system through leaching or volatilisation.

Table 4.21 shows that grain for the LAB treatment contained significantly more total nitrogen than all other treatments.

Table 4.21 Wheat grain nitrogen and soil NO_3^- and NH_4^+ at Cambridge for year 1 in response to application of bio-resources to texture contrast soil

Analyte	**ADB**	**Control**	**L + F**	**LAB**	**LSD** ($P \leq 0.05$)
Grain Total N (%)	1.48^{b}	1.26^{a}	1.41^{ab}	1.74^{c}	0.18
Grain NO_3 (mg/kg)	0.38	0.38	0.39	0.37	ns
Soil NO_3^- † (mg/kg)	10.20	6.77	9.07	16.33	ns (P=0.06)
Soil NH_4^+ † (mg/kg)	0	0	0	0	ns

† soil tests conducted six weeks after harvest

A partial nitrogen balance relative to calculated nitrogen inputs from applied bio-resources and inorganic fertilizer at Cambridge following harvest in year 1 is shown in Table 4.22. The caveat in the calculations is that soil tests were conducted six weeks after harvest. Whole plant nitrogen analysis was not undertaken, therefore, based on results obtained by Austin *et al.* (1977) using 47 genotypes of wheat, 68% of the total nitrogen in the whole plant was assumed to be contained in the grain. The remaining 32% is shown in the table as B_{ETN}.

Table 4.22 Partial nitrogen balance relative to calculated nitrogen inputs from applied bio-resources and inorganic fertilizer at Cambridge following harvest in year 1

	ADB	**Control**	**L + F**	**LAB**
G_t	1.7	1.4	2.0	2.2
G_k	1700	1400	2000	2200
G_{TN}	25.2	17.6	28.2	38.3
B_{ETN}	11.9	8.3	13.3	18.0
S_{AN} †	10.2	6.8	9.1	16.3
$G_{TN} + B_{ETN} + S_{AN}$	47.3	24.4	50.6	72.6
N_{PB} (kg/ha)	**-9.5**		**-6.2**	**+15.8**

G_t – Grain yield (t/ha), G_k – Grain yield (kg/ha), G_{TN} - Total N in grain (kg/ha), S_{AN} – Soil Available N ($NH_4^+ + NO_3^-$ kg/ha), B_{ETN} – Estimated total nitrogen in stubble and roots, N_{PB} (Nitrogen partial balance) = $G_{TN} + B_{ETN} + S_{AN} - BR_{AN} - S_{AN}$ (of control soil), BR_{AN} = 50 kg/ha (calculated value of available nitrogen from applied bio-resources and inorganic fertiliser). † soil tests conducted six weeks after harvest.

The results confirm the variation in nitrogen release between ADB and LAB shown in previous results (biomass at Z13 and Z71), with an apparent 25.3 kg/ha more available N when lime is added to biosolids. They also show that of the calculated nitrogen for ADB and L+F, 9.5 kg/ha and 6.2 kg/ha were unaccountable at harvest. Leaching would be an unlikely loss pathway at this time of year due to minimal rainfall between harvest and sampling. End of year soil testing showed that ADB and L+F had more total nitrogen (0.18% and 0.17% respectively) than LAB (0.13), and although the differences were not significant, it provides some evidence of the cycling of the 'lost' nitrogen back into organic form.

4.4.7 General discussion

The general objective of this research was to compare the impact of lime amended biosolids (LAB), anaerobically digested biosolids (ADB), poppy mulch (PM) and poppy seed waste (PSW) with inorganic fertiliser on biological, chemical and physical properties of the surface layer of two texture contrast soils.

Soil Chemical Attributes

Analysis of the soil post harvest for years 1 and 2 showed significant differences between treatments for pH, EC, and Soluble NO_3^- for both years at Cambridge, and pH for both years at Cressy. There were significant differences between treatments for Colwell P after the first year at Cressy and after the second year at Cambridge. Pritchard *et al.* (2004) suggested that P should be considered as well as N in calculating biosolids application rates in case of excess P applied to satisfy N crop requirements. This research showed that LAB applied at the current guideline N rate at Cambridge, resulted in a similar Colwell P after the first year (125 mg/kg) to the pre-trial soil test (126 mg/kg), suggesting that P was supplied to satisfy plant requirements. However, at the Cressy site Colwell P for LAB was higher (85 mg/kg) than the pre-trial soil test (69 mg/kg) after the first year, but lower after the second (60 mg/kg). Although the increase after the second year for LAB (142 mg/kg) with no extra P applied at the Cambridge site validates comments by Pritchard *et al.* (2004), the result from the Cressy site demonstrates site variability (i.e. leaching rainfall events) even with similar soil types.

The $EC_{1:5}$ results indicated that although there were significant differences between treatments at the Cressy site after the first year and at the Cambridge site after both years, only the value for LAB was considered to be within the medium salinity rating as defined by Maas and Hoffman (1977). The ESP results indicated that the addition of LAB and PM may help to ameliorate the deleterious effects of sodicity by reducing any likelihood of dispersion. Using gypsum has been the most practical way to replace Na^+ with Ca^{2+} in sodic soils (Suarez, 2001), although access to, and price of this product has been prohibitive in Tasmania. However, it would appear that LAB (Ca^{2+} added as CaO) and PM (Ca^{2+} added in the lime extraction process) may provide an effective alternative for acidic surface soils displaying sodic properties. Furthermore the neutral salt formed

with the Na^+ ion can be leached through the soil profile to reduce salinity, although this could increase subsoil sodicity of Sodosols.

The research also demonstrated that applying LAB at guideline calculated rates increased pH (1:5 0.01M $CaCl^2$) of the surface layer of texture contrast soils by 0.9 units within 6 months of application and a further 0.3 units within 18 months. Aoyama *et al.* (2006) also found significant increases in soil pH after repeated yearly additions of composted lime treated sludge. However, pH (1:5 H_2O) of the composts averaged 7.85, which is much less than the pH (1:5 H_2O) of LAB used for this study (pH ~ 12). Similarly, the PM treatment increased soil pH (1:5 0.01M $CaCl^2$) by 0.6 units within 6 months. The significant soil pH increases for both LAB and PM could be attributed to the O^{2-} (from the CaO in LAB) and CO_3^{2-} (from the $CaCO_3$ in PM) lime reacting with the free H+ ions, also resulting in an accumulation of exchangeable Ca^{2+} in the soil.

Microbial Biomass (MB) and Soil Carbon (SC)

This research found that nine months after amendment application at the Cressy site, L+F and PM were significantly greater than Control and ADB with respect to bacterial biomass, whilst ADB, LAB, PM and L+F were significantly greater than Control with respect to fungal biomass. This contrasts with studies by Peacock *et.al.* (2001) and Bittman *et. al.* (2005), who found that bacterial biomass decreased in the first year after application of inorganic fertilisers to no-till cropping and pastures respectively as compared with control and organic amendments, and Barbarick *et al.* (2004) who found an 11% increase in microbial biomass after application of biosolids. Aoyama *et. al.* (2006) reported that water soluble Ca^{2+} associated with limed biosolids may decrease fungal biomass, however, the evidence presented here from the Cressy site shows no significant difference between limed (LAB) and un-limed (ADB) biosolids.

There were no significant differences in microbial biomass between treatments at the Cambridge site, however, the trend of LAB < L+F < Control < ADB supports the findings reported by Aoyama *et. al.* (2006). Although more frequent testing may clarify the flux in microbial activity soon after amendment application, the level of change (i.e. the rates of organic amendments) may not be enough to invoke a microbial response, which was the conclusion drawn by Ghosh *et al.* (2008) after applying manure, compost and vermicompost to a Vertosol. Monitoring over the longer term may be more

appropriate to assess the effect of any management change on the microbial community, particularly at relatively low rates of organic material amendments. However, Brendecke *et al.* (1993) found that after four years of continuous sludge application to semi-arid soils growing cotton, there was no significant affect on MB activity. Barbarick *et al.* (2004) on the other hand found an increase in MB six years after application of biosolids to grassland. Soil MB is dynamic and helps to drive the turnover of soil organic matter and the release of plant available nutrients (Hao *et al.*, 2008). However, limitations associated with soil test procedures such as handling, moisture content and storage make assessment of MB analysis difficult to interpret (Carter *et al.*, 1999). This may explain the variation of results and conclusions between this and other studies reported, suggesting that MB on its own may not be appropriate for assessing effects of bio-resources.

There were no significant differences between treatments for soil organic carbon and other soil physical properties after the first season. However, research has shown that under longer term applications of biosolids, SOC stocks can increase (Tian *et al.*, 2009; Wallace *et al.*, 2009); providing evidence of a suitable management system for those suggesting soil carbon sequestration to mitigate climate change (Lal *et al.*, 2007). Hardie and Cotching (2009) also noted the carbon sequestration potential of poppy mulch, although application rates were in excess of current industry rates used (200 m^3/ha compared with ~ 65 m^3/ha).

Soil Physical Properties

Results from this study suggest that significant changes to soil physical properties measured with bulk density, aggregate stability and penetration resistance may take longer to appear than just one year and may not be observed in such a system that uses tillage practices that significantly disturb the soil. Studies by Tester (1990), Giusquiani *et al.* (1995) and Mohammad *et al.* (2007) found changes to soil physical properties from applying composted wastes including sewage sludge to soil, over five, four and three year periods respectively, with a decrease in penetration resistance and bulk density. Furthermore, Armstrong (2007a) found a significant improvement in aggregate stability of texture contrast soils over a two year period after applying composted bedding litter.

Crop response to applied bio-resources

In the first year following application of amendments there were significant differences between treatments with respect to yield at both sites and growth parameters such as height and biomass at the Cressy site only. The LAB and L+F treatments at the Cambridge site yielded significantly more than the Control, suggesting that nitrogen supply was similar from both treatments. All treatments at the Cressy site yielded significantly more than the Control. However, in contrast to the volumes of the other bio-resources applied, PSW was applied to the soil at much lower rates than those for all other organic materials. The similar yield to LAB, ADB, L+F and PM for Year 1 may have been due to PSW being more homogenous and having a more balanced nutrient status than the other products.

No significant difference between treatments for crop yield at both sites in the second year indicates that nutrient supply from the added products was not sufficient for the two cropping seasons. Armstrong *et al.* (2007b) also found declining crop yields in subsequent years following the application of pig litter, contrasting with a study by Cooper (2005) who found yield increases from biosolids beyond the initial application year.

Crop Nutrient Analysis and Nitrogen Balance

The results suggest that organic materials may be used as an alternative to inorganic fertiliser with respect to supplying plant nutrients, with similar findings reported by Kidd *et al.* (2007) and Mohammad *et al.* (2007) in their respective studies of sewage sludge and composted waste products. However, results also confirmed comments by Cabrera *et al.* (2005) and Bünemann *et al.* (2006) that the inherent characteristics of organic materials make it difficult to match nutrient supply with plant demand. These characteristics include logistics such as availability of material and appropriate spreading conditions, and variable material composition. Inorganic fertilisers have known nutrients that are readily solubilised and incorporated into soil solution and therefore rapidly available to plants, whereas organic materials available for application to agricultural land contain variable quantities of nutrients with unknown or variable release rates. Unless immediately soluble, nutrients contained in incorporated bio-resources are made available by microbial activity that decomposes the organic material

to humus and soluble nutrients. However microbial activity can be enhanced (Barbarick *et al.*, 2004) or limited (Haynes *et al.*, 2009) by added organic material, which in turn can affect the turnover rate and availability of soluble nutrients. Australian EPA guidelines for biosolids application rates are based on an estimated N release of approximately 20% of total N within the first year. Results from the first year of the trials at Cambridge showed that 10 kg/ha and 9.7 kg/ha of the 50 kg/ha of nitrogen from ADB and L+F treatments respectively was unaccountable by growth stage Z71, decreasing to 9.5 kg/ha and 6.2 kg/ha respectively following harvest. Results also showed that 43.9 kg/ha of nitrogen additional to the calculated 50 kg/ha applied in LAB was introduced into the system by growth stage Z71, still retaining an additional 15.8 kg/ha of N in the system after harvest. Although some of the 28.1 kg/ha nitrogen lost from the system between Z71 and post harvest may be attributed to volatilisation or denitrification, there is considerable potential for leaching due to rainfall throughout December of 2007 (refer to Figure 4.8) and the irrigation event just after flowering (early December 2007).

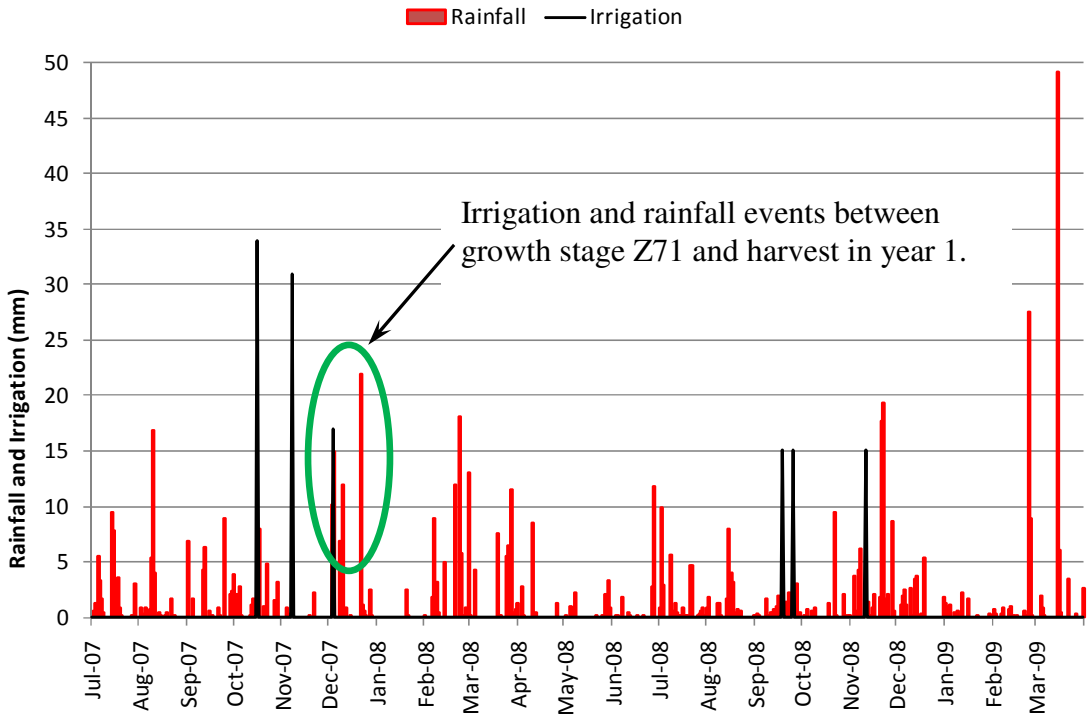

Figure 4.8 Rainfall recorded at the Cambridge Airport (http://www.dnr.qld.gov.au/silo) and irrigation recorded at the Cambridge trial site.

4.5 Conclusion

Bio-resources are applied to soil because of their potential to replace lost nutrients and soil organic matter. This research has identified that:-

- LAB applied to the surface layer of texture contrast soils at 1NLBAR and PM applied at 17.5 t/ha and incorporated may raise soil pH by up to 0.9 units and 0.6 units respectively within nine months of application.

- $EC_{(1:5)}$ of bio-resources (and soils) needs to monitored, particularly if applying on saline soils. Application prior to leaching winter rains may help wash salts through the upper layers of texture contrast soils and prevent accumulation.

- The ESP results indicated that the addition of LAB and PM may help to ameliorate the deleterious effects of sodicity by reducing any likelihood of dispersion. Furthermore the neutral salt formed with the Na^+ ion can be leached through the soil profile to reduce salinity, although this could increase subsoil sodicity of Sodosols.

- LAB applied at 1NLBAR and PM applied at 17.5 t/ha does not result in a reduction in soil Colwell P within the first year of application after growing a cereal crop. However, after the second year of growing a cereal crop, elevated soil Colwell P was found in the LAB treatment at one site whilst a reduction in soil Colwell P for both LAB and PM was found at another site. This suggests that soil Colwell P requires yearly monitoring after applying organic wastes due to site response variability. This variability could be environmental (rainfall) and/or management (cultivation, irrigation).

- Within the first twelve months after application, bacterial biomass may be increased after applying PM and L+F, whilst fungal biomass may be increased after applying PM, LAB, ADB and L+F. However, monitoring of microbial biomass to assess the effect of any management change on **soil health** may be more appropriate over the longer term, particularly at relatively low rates of organic material amendments.

- A longer time frame of monitoring may be required to demonstrate any improvement in soil health attributes such as aggregate stability and penetration resistance and soil organic carbon from the application of bio-resources.

- The application and incorporation of LAB, ADB, PM and PSW can result in cereal crop yield equivalent to inorganic fertiliser in the first year after application.

- The addition of lime, in the form of CaO, to biosolids appears to increase the nitrogen release of the product when incorporated in the 0-10 cm depth of texture contrast soils. Consequently there is a disparity between calculated (from guidelines) nitrogen release from LAB and ADB and the actual release within the first twelve months after application. Excess nitrogen from LAB is a potential point source of nutrient leaching into ground water and waterways.

Inorganic fertiliser can be applied to crops to meet nitrogen demand, however, due to logistic limitations, applications of bio-resources are restricted to times of the year that do not necessarily match crop demand (i.e. when soil moisture conditions do not result in soil compaction). This research has identified that decomposition of bio-resources and the release and availability of component nutrients requires clarification of nitrogen release rates and further understanding of nitrogen processes when incorporated into soil.

5 Agronomic and soil response over two years from different application rates of lime amended biosolids to texture contrast soils

5.1 Introduction

The application rate of biosolids in Tasmania is determined from the nitrogen limiting biosolids application rate (NLBAR) and contaminant limiting biosolids application rate (CLBAR) calculations defined in Dettrick and McPhee (1999). However, recent research by Eldridge *et al.*(2008) and Rigby *et al.* (2010) has shown that current guideline assumptions in Australia for nitrogen release may not reflect actual nitrogen release, whilst Rigby and Smith (2008), Cogger *et al.*(2011) and Rouch *et al.* (2011) have demonstrated the variability in nitrogen release from different biosolids treatment processes and/or soil moisture. The EPA guidelines in Australia also suggest an application frequency based upon the potential nutrient loadings, and an application regime that includes immediate incorporation after application of biosolids (Brown *et al.*, 2009; DEP *et al.*, 2002; Dettrick and McPhee, 1999; NSW-EPA, 1997; VIC_EPA, 2004). In order to test the validity of the guidelines with respect to nitrogen release, this chapter will present findings from a field experiment conducted at Cambridge in Tasmania in 2007 and 2008, in which soil and crop responses to different application rates of lime amended biosolids to texture contrast soils were studied.

5.1.1 Research objectives

The general objective of this research was to compare the impact of different application rates of lime amended biosolids (LAB) with lime and inorganic fertiliser on biological and chemical properties of the surface layer of a texture contrast soil. A treatment of single application of LAB at 1NLBAR not incorporated in the first year was included in the trial because many farmers growing cereals on the texture contrast soils of Tasmania use minimum and no-tillage in an effort to reduce the impact of cropping on this soil type.

Specific objectives were to:-

- Quantify soil residual chemistry from different application rates of LAB and lime and fertiliser after two years of growing cereals on texture contrast soils.
- Determine short term influences on microbial biomass and soil organic carbon from different application rates of LAB to texture contrast soils.
- Determine the impact of different application rates of LAB on pH and electrical conductivity of the surface layer of texture contrast soils.
- Determine the plant nutrient uptake and yield potential associated with the different application rates of LAB to texture contrast soils in Tasmania.
- Determine the impact that spreading but not incorporating LAB at guideline rates may have on soil pH, EC, yield and plant nutrient uptake of texture contrast soils.

5.2 Materials and Methods

5.2.1 Trial sites

One field trial was established in Tasmania at Cambridge for cropping seasons 2007 and 2008. A full description of paddock preparation, planting, irrigation, and sampling and analysis methods adopted during the course of the trial, including treatment and pre-trial soil analysis are detailed in Section 3.

5.2.2 Treatments

The experimental design at the site was a randomised block with three replications. Individual plot size was 4 m x 9 m with 1 m buffers between plots. Treatments applied in the first year of the trial are shown in Table 5.1. Additional plots of the LAB and L+F treatment were included in the trial design, with a repeat of the same treatments applied to these plots in year 2 (Table 5.2). All treatments except LAB-NIC were incorporated in the first year. In the first year The LAB-NIC treatment was not incorporated, nor were the re-application treatments of LAB and L+F incorporated in the second year.

Table 5.1 Treatments applied to the field trials at Cambridge in Year 1

Treatment	**Description**	**Application Rate**	**Available Nutrients**	**Nutrient Analysis**
L+F	Lime + Fertiliser	125 kg/ha DAP + 1330 kg/ha Lime + 60 kg/ha Urea	50 kg N 25 kg P 513 kg Ca	
LAB	LAB at 1 NLBAR	23 wet tonnes/ha (5.8 dry tonnes/ha)	50 kg N # 513 kg Ca ¥	Total N – 3.7 % Total P – 15000 mg/kg Total Ca – 161000 mg/kg
LAB2	LAB at 2 NLBAR	46 wet tonnes/ha (11.6 dry tonnes/ha)	100 kg N # 1026 kg Ca ¥	Total N – 3.7 % Total P – 15000 mg/kg Total Ca – 161000 mg/kg
LAB5	LAB at 5 NLBAR	115 wet tonnes/ha (29 dry tonnes/ha)	250 kg N # 2565 kg Ca ¥	Total N – 3.7 % Total P – 15000 mg/kg Total Ca – 161000 mg/kg
LAB-NIC	LAB at 1 NLBAR	23 wet tonnes/ha (5.8 dry tonnes/ha)	50 kg N # 513 kg Ca ¥	Total N – 3.7 % Total P – 15000 mg/kg Total Ca – 161000 mg/kg

Application rates for Biosolids treatments were calculated in accordance with the Tasmanian Biosolids Re-Use Guidelines (Dettrick and McPhee, 1999), based on the nitrogen requirements for wheat and barley.
¥ denotes Ca^{2+} applied to biosolids as quicklime at 4% by wet volume – does not include exchangeable Ca^{2+} in base product.

Table 5.2 Treatments applied to the field trials at Cambridge in Year 2

Treatment	Description	Application Rate	Available Nutrients	Nutrient Analysis
Control	Untreated	N/A		
L+F	Lime + Fertiliser	125 kg/ha DAP + 1330 kg/ha Lime + 60 kg/ha Urea	50 kg N 25 kg P 513 kg Ca	
LAB	LAB at 1 NLBAR	30 wet tonnes/ha (8.9 dry tonnes/ha)	50 kg N # 660 kg Ca ¥	Total N – 3.0 % Total P – 18000 mg/kg Total Ca – 248000 mg/kg

Application rates for Biosolids treatments were calculated in accordance with the Tasmanian Biosolids Re-Use Guidelines (Dettrick and McPhee, 1999), based on the nitrogen requirements for wheat and barley.
¥ denotes Ca^{2+} applied to biosolids as quicklime at 4% by wet volume – does not include exchangeable Ca^{2+} in base product.

The contaminant (heavy metals) and nitrogen loading of each biosolids product and their potential plant availability were estimated using equations for the contaminant limiting biosolids application rate (CLBAR) and the nitrogen limiting biosolids application rate (NLBAR). With respect to CLBAR, the biosolids were classed as grade B due to the concentrations of Cu and Zn in LAB being in the range of 100 - 1000 mg/kg and 200 - 2500 mg/kg respectively (Dettrick and McPhee, 1999). Using the following calculation from the guidelines:- CLBAR = ((MASCC – ASCC) x SM)/BACC

where:-

MASCC	=	Maximum Allowable Soil Contaminant Concentration (mg/kg)
ASCC	=	Actual Soil Contaminant Concentration (mg/kg) from soil test
BACC	=	Biosolids Adjusted Contaminant Concentration (mg/kg)
SM	=	Incorporated Soil Mass (dry tonnes/ha)

CLBAR (Cu)	=	((42 – 0.88) x 1000)/ 623	=	66 dry tonnes/ha
CLBAR (Zn)	=	((140 – 2.21) x 1000)/ 214	=	644 dry tonnes/ha

These results show that CLBAR was not the limiting factor for application rate of biosolids. Hence the biosolids application rate was determined by NLBAR. The

NLBAR calculations for the biosolids treatments were based on minimum crop nitrogen requirements for cereals, as follows:

Available Nitrogen (AN) = ammonia N + 0.15 (Total N – ammonia N)

Followed by:

NLBAR (of product) = Crop Requirement (kg/ha) / AN (kg/t)

For example:

Available Nitrogen = 3.6 kg / t + 0.15 x (37 kg / t – 3.6 kg / t)

= 8.61 kg / tonne

NLBAR (dry tonnes) = 50 kg / ha ÷ 8.61 kg / t

= 5.81 t / ha

Moisture content 75.1 % (solids 24.9%)

NLBAR (wet tonnes) = 5.81 x (100 / 24.9)

= 23.3 t / ha

The L + F application rate was calculated based on biosolids available N equivalent and the lime contained in LAB. All treatments were incorporated with a rotary cultivator four days after application and three days prior to planting. Control and LAB-NIC plots were also cultivated to ensure uniform soil disturbance. In addition, Urea at a rate of 60 kg/ha was applied to L + F plots at Zadoks stage 13.

It must be noted that the NLBAR estimation for calculating the application rate of biosolids and the inorganic fertiliser products applied (i.e. no additional trace elements) were used to satisfy the primary objective, which was to compare and contrast changes to soil and crop within a framework of traditional farming practice for the two regions of study. No additional K was applied due to the pre-trial Colwell K level (234 mg/kg) showing adequate K for crop production on a sandy loam soil. There is often a disparity between field results from scientific research and field results from practical application (Carberry *et al.*, 2009), which may be due to uni-dimensional and/or limited multi-dimensional analysis used by scientists. It was hoped that by emulating traditional practice, the research would better reflect the whole system response in that context, and subsequently facilitate practical application of results.

5.3 Results and discussion

5.3.1 Soil chemical attributes – years 1 and 2

There were significant differences between treatment means for post harvest soil chemical attributes for both years 1 and 2 at Cambridge (Refer to Table 5.3). The key attributes with significant differences between treatments after each year of growing cereals were pH, soluble NO_3^-, Colwell P and exchangeable Ca^{2+}.

Table 5.3 Post harvest soil chemical analysis for seasons 2007 and 2008 at Cambridge after application of lime amended biosolids and inorganic fertiliser to texture contrast soil

Analyte	Year	L+F	L+F x2Y	LAB	LAB x2Y	LAB2	LAB5	LAB-NIC	LSD (P≤0.05)	Pre-trial*
pH $^{1:5}$ ($CaCl_2$)	2007	5.97^{a}	6.03^{a}	6.83^{b}	7.00^{bc}	7.33^{c}	7.33^{c}	6.20^{a}	0.39	5.40
	2008	6.60^{ab}	6.10^{a}	7.07^{bc}	7.23^{c}	7.23^{c}	7.37^{c}	6.80^{bc}	0.57	
EC $^{1:5}$ (dS/m)	2007	0.13^{a}	0.14^{a}	0.20^{b}	0.24^{bc}	0.27^{c}	0.37^{d}	0.14^{a}	0.05	0.12
	2008	0.19	0.14	0.20	0.26	0.23	0.23	0.19	ns	
Soluble NO_3^- (mg/kg)	2007	15.7^{a}	24.3^{a}	39.0^{ab}	34.3^{ab}	63.7^{b}	119.7^{c}	24.0^{a}	30.4	7
	2008	15.0^{a}	21.0^{a}	24.7^{ab}	34.7^{bc}	23.0^{ab}	37.7^{c}	23.0^{ab}	12.0	
Soluble NH_4^+ (mg/kg)	2007	2.33	3.00	3.33	6.00	4.00	6.67	2.33	ns	2
	2008	2.00	2.33	1.67	2.33	2.00	2.33	2.00	ns	
Total N (%)	2007	0.17	0.16	0.13	0.12	0.17	0.17	0.11	ns	Nr
	2008	0.14	0.14	0.14	0.16	0.15	0.17	0.14	ns	
Colwell P (mg/kg)	2007	110^{a}	112^{a}	125^{a}	153^{ab}	207^{b}	296^{c}	103^{a}	63	126
	2008	94^{a}	122^{ab}	142^{ab}	191^{b}	161^{ab}	291^{c}	136^{ab}	77	
Colwell K (mg/kg)	2007	175	177	164	212	212	228	183	ns	234
	2008	202	174	198	241	210	265	191	ns	
Ext SO_4^{2-} (mg/kg)	2007	10.3^{a}	11.6^{a}	13.2^{ab}	13.6^{ab}	16.0^{b}	23.4^{c}	10.1^{a}	3.8	8.2
	2008	11.7	11.6	12.8	14.5	13.6	15.1	13.8	ns	
Exc Ca^{2+} (c mol/kg)	2007	7.3^{a}	7.5^{a}	9.2^{ab}	11.3^{bc}	12.6^{c}	14.1^{c}	6.8^{a}	3.3	6.0
	2008	8.1^{ab}	7.6^{a}	9.6^{abc}	12.6^{cd}	11.2^{bcd}	12.9^{d}	9.1^{ab}	3.4	
Exc K^+ (c mol/kg)	2007	0.38	0.43	0.38	0.45	0.46	0.50	0.40	ns	0.60
	2008	0.47	0.39	0.47	0.57	0.51	0.61	0.42	ns	
Exc Mg^{2+} (c mol/kg)	2007	2.76	3.25	2.78	3.63	3.59	2.80	2.74	ns	2.70
	2008	2.90	3.07	2.80	3.76	2.96	2.67	2.84	ns	
Exc Na^+ (c mol/kg)	2007	0.33	0.36	0.33	0.41	0.34	0.28	0.32	ns	0.50
	2008	0.51	0.52	0.45	0.56	0.54	0.50	0.49	ns	

Note: different letters indicate significant differences between treatment means, ns – no significant differences, nr – no result, * denotes pre-trial soil test of whole site and not individual plots.

After one year of growing cereals at Cambridge with no extra P applied, the significant differences between treatments for Colwell P concentration in order of greater significance were LAB5 > LAB2 > LAB ≈ L+F ≈ LAB-NIC. After the second year of growing cereals and re-applying LAB and L+F (LAB x2Y and L+F x2Y respectively) the significant differences between treatments for Colwell P concentration in order of greater significance were LAB5 > LAB x2Y > L+F. Treatments LAB2, LAB, L+F x2Y and LAB-NIC were not significantly different to either LAB x2Y or L+F. Using the pre-trial soil test for comparison (126 mg/kg), it would appear that there was significant drawdown of P reserves in the L+F control soil after each of the two years, but an increase in LAB after the second year. LAB-NIC also increased beyond the pre-trial soil test after the second year suggesting that the P is not bound up in the product indefinitely when the LAB is left on the surface and **not** incorporated, but has the potential to increase soil P reserves over time. The high Colwell P value for LAB5 after each of the two years (296 and 291 mg/kg respectively) confirms comments by Pritchard *et al.* (2004), who suggested that P should be considered as well as N in calculating biosolids application rates because in satisfying N crop requirements excess P can be applied.. The re-application treatments of LAB x2Y and L+F x2Y, although slightly higher in Colwell P, were not significantly different to the single application treatments (LAB and L+F) after the second year. This indicates that more study is required to validate the existing three year time frame between applications advocated by existing guidelines (Dettrick and McPhee, 1999), particularly with respect to P.

Soil pH (1:5 0.01M $CaCl_2$) for LAB (6.83) was significantly higher than LAB-NIC (6.20) and L+F (5.97) after the first year. The lime application rate for L+F was calculated as equivalent to that supplied by LAB, but interactions between the soils buffering capacity, the amendment application regime and the liming material may have contributed to the differences after the first year. After the second year, soil pH for LAB (7.07) was not significantly higher than LAB-NIC (6.80) or L+F (6.67). This suggests that there may be a slower response time for pH from lime applied as $CaCO_3$ in L+F compared to lime applied as CaO in biosolids, or when biosolids is applied and not incorporated. Although the pH for LAB2 and LAB5 was significantly higher than LAB after the first year, there was no significant difference between any of the LAB treatments after the second year. This suggests that the higher LAB treatments had achieved a new equilibrium of soil alkalinity. However, high rates of biosolids applied

in order to add more organic matter may be counterproductive, as Chan and Heenan (1999) have shown that lime can induce aggregate stability changes which in turn can reduce soil organic C.

The results for exchangeable Ca^{2+} showed significant differences between the higher rates of LAB (LAB2 and LAB5) and the remaining treatments, which demonstrates that the reactions between the CaO and the free H^+ ions not only change pH but also provide additional calcium in solution for plant uptake.

The $EC_{(1:5)}$ for LAB5 (0.37) and LAB2 (0.27) was significantly higher than for LAB (0.20) and within the medium salinity rating described by Maas and Hoffman (Maas and Hoffman, 1977), which suggests that higher rates to satisfy high N requirement crops may not be appropriate on soils with an $EC_{(1:5)}$ above 0.12 dS/m. However, providing that LAB is applied prior to leaching winter rains, salinity build up from the higher application rates (LAB2 and LAB5) may be prevented.

The results showed that the exchangeable sodium percentage (ESP) decreased with increasing rates of LAB in the first year after application (Figure 5.1). The ESP for L+F, was significantly higher than the LAB2 and LAB5 in the first year, whilst the ESP for L+F and L+F x2Y was significantly higher than all the LAB treatments except LAB-NIC in the second year. The low ESP results for increasing rates of LAB, combined with higher Ca^{2+} in solution for the same treatments, may have potential to ameliorate the effects of sodicity. Using gypsum has been the most practical way to replace Na^+ with Ca^{2+} in sodic soils (Suarez, 2001), although access to, and price of this product has been prohibitive in Tasmania. However, it would appear that increasing rates of LAB (Ca^{2+} added as CaO) may provide an effective alternative for acidic surface soils displaying sodic properties. Furthermore the neutral salt formed with the Na^+ ion can be leached through the soil profile to reduce salinity, although this could increase subsoil sodicity of Sodosols.

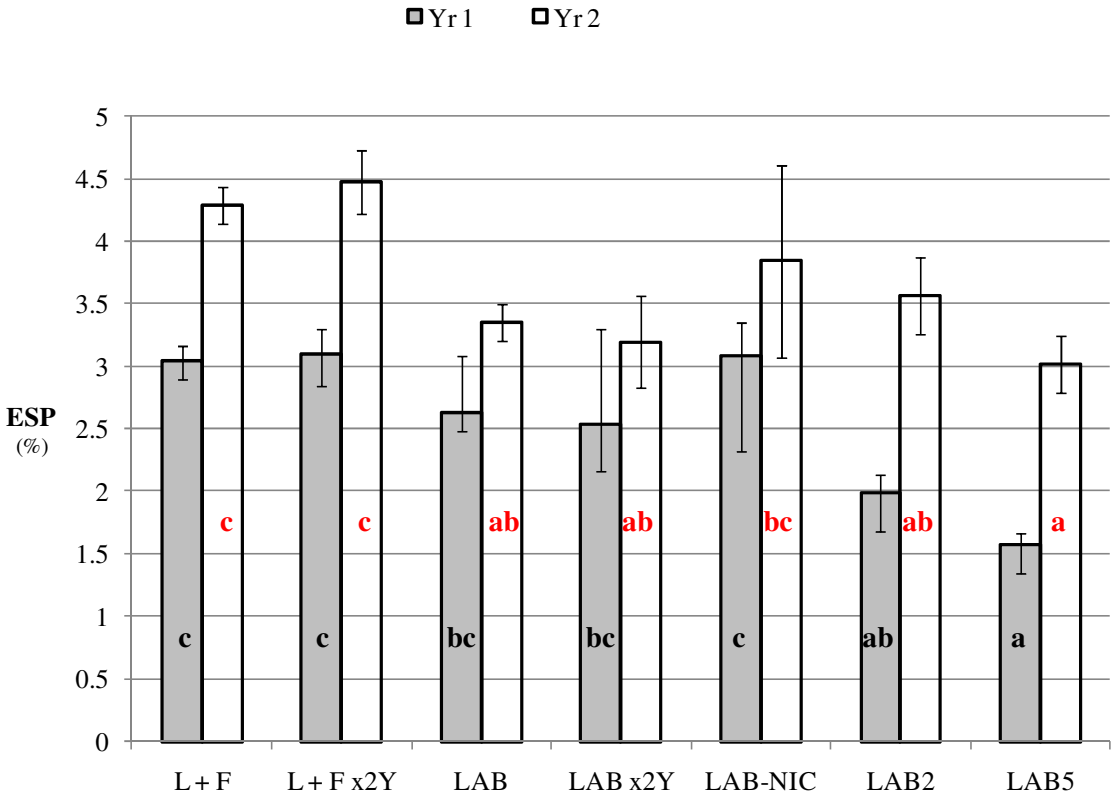

Figure 5.1 Post harvest soil exchangeable sodium percentage (ESP) at Cambridge for years 1 and 2

Note: different coloured letters indicate significant differences between treatments means for each year, Year 1 LSD ($P \leq 0.05$) = 0.65, Year 2 LSD ($P \leq 0.05$) = 0.69), error bars are standard deviation of the means.

Results for soluble NO_3^- after one year of growing a cereal crop showed that the significant differences between treatments in order of greater significance were LAB5 > LAB2 > L+F ≈ LAB-NIC. LAB was not significantly different to LAB2 or L+F after the first year. This result is consistent with expectations that the higher N rate applications would have higher residual nitrogen. The concern is that after the second year, although there were still significant differences between treatments, the magnitude of the differences was much less. This suggests that much of the soluble nitrogen applied in the LAB2 and LAB5 treatments exited the system between years via loss pathways such as leaching, volatilisation and denitrification.

5.3.2 Microbial biomass and soil carbon – year 1

Microbial biomass from soil samples taken at growth stage Z71 on the 27th September, 2007 for treatments in response to different application rates and not incorporated LAB are shown in Table 5.4.

Table 5.4 Soil bacterial and fungal biomass at growth stage Z13 in September 2007 for treatments at Cambridge in response to different application regimes of biosolids applied to texture contrast soil

	L+F	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	LSD (P<0.05)
Bacterial Biomass (µg/g)	8.98 (0.95)	6.71 (1.45)	7.90 (4.05)	9.31 (4.64)	6.34 (1.16)	ns
Fungal Biomass (µg/g)	6.11[a]	4.55[a]	6.23[a]	10.42[b]	5.98[a]	3.41
Soil Moisture (%)	10.63[ab]	10.27[a]	10.75[ab]	14.01[bc]	16.38[c]	3.43

Note: different letters indicate significant differences between treatment means, numbers in brackets are standard deviation from the means.

Three months after application of treatments, the results show that LAB2 contained significantly more fungal biomass than all other treatments, specifically the lowest and highest rates of lime amended biosolids (LAB and LAB5 respectively). Bacterial biomass showed a similar trend but was not significant (i.e. high variation in results). The results also show that soil moisture for LAB2 and LAB5 was also higher than LAB.

Further analysis of soil microbial biomass as well as soil organic carbon was conducted after harvest in March 2008 with results shown in Table 5.5. These results indicated that fungal biomass for LAB2 continued to be significantly higher than all other treatments six months after the first analysis, specifically LAB5. Initial application and incorporation of LAB5 was difficult due to the volume and consistency of the product, which resulted in areas of the plots where a high concentration of biosolids remained on the surface. This would have reduced the potential beneficial effects of adding organic matter to the remaining areas of the plots. Although sampling of all treatments was random, the areas of product concentration in the LAB5 plots were avoided.

Subsequently, the fungal biomass (and bacterial biomass) of LAB5 was not dissimilar to the L+F and lower rate LAB treatments. Incorporation of the LAB2 was more uniform, which is reflected in the lower standard deviation of the means. Aoyama *et. al.* (2006) reported that water soluble Ca^{2+} associated with limed biosolids may decrease fungal biomass, however, the evidence presented here suggests that there was either no effect or an increase.

Table 5.5 Bacterial and fungal biomass and total C of soil (and fractions) sampled in March 2008 for treatments at Cambridge in response to different application regimes of biosolids applied to texture contrast soil

	L+F	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	LSD (P<0.05)
Bacterial Biomass (µg/g)	10.30[ab] (0.95)	8.04[a] (0.95)	8.04[a] (2.07)	11.96[b] (1.49)	7.53* (3.45)	3.02
Fungal Biomass (µg/g)	9.17[a] (1.52)	8.04[a] (2.30)	8.42[a] (2.07)	13.69[b] (1.43)	8.41[a] (2.08)	3.85
Soil Moisture (%)	11.84	12.83	13.63	14.45	13.39	ns
Total C Whole Soil	2.52 (0.35)	2.57 (0.41)	2.58 (0.44)	2.78 (0.36)	3.15 (0.17)	ns
Total C Silt and Clay	1.43 (0.26)	1.31 (0.23)	1.36 (0.07)	1.49 (0.14)	1.49 (0.27)	ns
Total C Sand	1.09 (0.14)	1.26 (0.54)	1.23 (0.37)	1.30 (0.24)	1.66 (0.34)	ns

Note: different letters indicate significant differences between treatment means, numbers in brackets are standard deviation from the means. * results for this treatment and analyte not included in analysis because of high standard deviation compared to other treatments.

The bacterial biomass for LAB2 was significantly higher than the other LAB treatments but not L+F. This contrasts with studies by Peacock *et.al.* (2001) and Bittman *et. al.* (2005), who found that bacterial biomass decreased in the first year after application of inorganic fertilisers to no-till cropping and pastures respectively as compared with organic amendments. This may have affected the microbial population, as Fen *et al.*

(2003) observed changes in microbial community composition from tillage practices that were more pronounced in fallow.

Ghosh *et al.* (2008) concluded that lower rates of organic amendments may not be enough to affect the microbial biomass after applying manure, compost and vermicompost to a Vertosol. However, increasing the application rate of biosolids in this study by a factor of two from the recommended NLBAR was shown to be enough to invoke a microbial response.

There were no significant differences between treatments with respect to soil moisture, although the higher soil moisture for LAB2, LAB5 and LAB-NIC suggests a moisture buffering potential of added organic material within and on the soil surface. This buffering may have been enhanced by the presence of polyacrylamide (water attracting polymer) in the product. There were also no significant differences between treatments for total C or fractions thereof. However, the trend of LAB5 > LAB2 > LAB > LAB-NIC > L+F suggests that increasing application rates of organic amendments may increase soil carbon. Research has shown that under longer term applications of biosolids, SOC stocks can increase (Tian *et al.*, 2009; Wallace *et al.*, 2009); providing evidence of a suitable management system for those suggesting soil carbon sequestration to mitigate climate change (Lal *et al.*, 2007).

5.3.3 Crop growth and harvest assessments

Crop growth parameters were measured in year 1 and harvest assessments undertaken for years 1 and 2 at Cambridge. Wheat was grown in year 1 and barley in year 2. There were no significant differences in emergence or height and biomass at growth stage Z31 and Z71 year 1 (Table 5.6), despite the aerial photograph taken at growth stage Z71 showing colour differences between treatments (Plate 5.1). However, the low resolution of the photo does not pick up the variation between plots of the same treatment as shown in the standard deviation of the means in Table 5.6.

The low emergence rate and the high standard deviation for biomass at Z71 for the LAB5 treatment may be a reflection of the variability in distribution of the product when applied at high rates.

Table 5.6 Wheat crop growth parameters at Cambridge for year 1 in response to different application regimes of LAB and L+F to texture contrast soil

	L + F	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** (P≤0.05)
Emergence (no/m^2)	46 (2)	46 (16)	55 (15)	50 (8)	33 (18)	ns
Height Z31 (cm)	57.3 (16.7)	64.0 (8.5)	63.3 (9.9)	64.0 (1.0)	55.0 (5.0)	ns
Biomass Z31 (t/ha)	1.75 (0.47)	3.21 (0.61)	2.97 (1.23)	4.01 (1.18)	3.47 (1.09)	ns
Height Z71 (cm)	76.7 (11.7)	74.0 (6.9)	81.7 (9.6)	79.3 (3.8)	73.7 (7.1)	ns
Biomass Z71 (t/ha)	3.94 (0.88)	6.13 (1.01)	5.82 (1.45)	6.19 (0.38)	8.24 (3.11)	ns

Note: numbers in brackets indicate standard deviation of the means

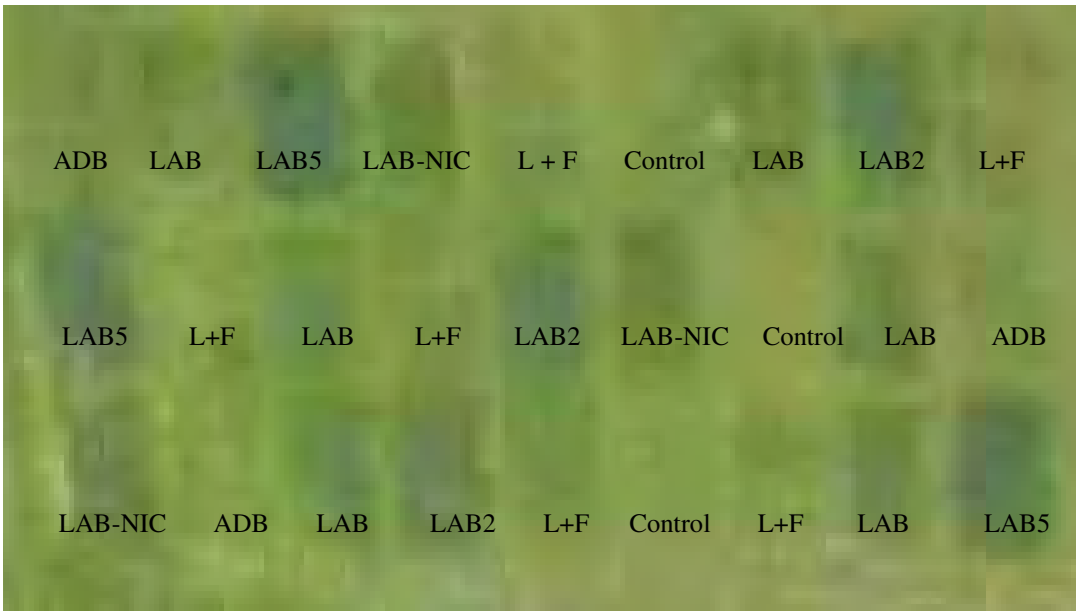

Plate 5.1 Aerial photograph of Cambridge in November 2007 at growth stage Z71 (treatments Control and ADB not included in this analysis)

Specific plant growth parameters measured from the 200 mm diameter core samples taken at growth stage Z71 showed that LAB2 and LAB5 had significantly longer seed heads and significantly more tillers than LAB, LAB-NIC and L+F (Table 5.7). Both of these parameters are indicative of high nitrogen accumulation particularly under moisture restricted conditions, as Nakagami *et al.* (2004) found that under these conditions, root development was also much more enhanced. This study found that the root biomass for LAB5 was higher than all other treatments but with no level of significance (due to the high standard deviation for LAB5, LAB-NIC and LAB).

Table 5.7 Wheat crop growth parameters at growth stage Z71 at Cambridge for year 1 in response to different application regimes of LAB and L+F to texture contrast soil

	L + F	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** ($P \leq 0.05$)
Seed Head Diameter (mm)	10.9	11.0	11.8	10.8	11.3	ns
Seed Head Length (mm)	73.3[a]	79.2[a]	78.8[a]	96.0[b]	101.2[b]	13.7
Root Biomass (g/m^2)	143 (47)	242 (134)	352 (163)	231 (16)	447 (154)	ns
Shoot/ Root Ratio	5.7	5.3	3.2	8.7	5.9	ns
Tiller Number (no)	11[a]	13[a]	11[a]	21[b]	24[b]	7
Leaf Number (no)	4.5	5.1	4.9	5.3	6.1	ns

Note: different letters indicate significant differences between treatment means, numbers in brackets are standard deviation of the means.

There was no significant difference between the yields of LAB, LAB-NIC and L+F treatments in the first year after application (Table 5.8). However, LAB, LAB-NIC and L+F yielded significantly more than LAB2 and LAB5, which is in contrast to other trials showing an increase in yield with increasing biosolids rate (Cooper, 2005). The inverse relationship between yield and application rate may be due to a higher nitrogen accumulation (particularly from LAB5) at flowering, which has been shown to prolong vegetative growth and delay leaf senescence in water limiting conditions (Nakagami *et*

al., 2004). This is also reflected in the harvest index of LAB5 being significantly lower than all other treatments except LAB2. The high percentage of shattered heads, possibly induced by high nitrogen and low soil water, may also have impacted on the yield result. Weeds may also have impacted on the yield result. However, there was no correlation between weeds and yield, which is highlighted by significant yield differences between LAB-NIC (2.22 t/ha) and LAB2 (1.56 t/ha), but no significant difference in weeds (34.6% for both).

Table 5.8 Wheat harvest parameters at Cambridge for year 1 in response to different application regimes of LAB and L+F to texture contrast soil

	L + F	**L + F (x2Y) ***	**LAB**	**LAB (x2Y) ***	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** (P≤0.05)
Harvest Index (%)	52.9^{bc}	53.1^{bc}	48.3^{b}	50.8^{b}	51.7^{b}	40.4^{ab}	34.9^{a}	11.8
Weeds (%)	23.5^{ab}	20.9^{ab}	10.6^{a}	19.6^{a}	34.6^{b}	34.6^{b}	22.4^{ab}	14.2
Heads per metre row (no)	41	45	55	50	40	42	52	ns
Shattered Heads (%)	7.7	0.3	5.8	12.1	6.0	28.0	27.1	ns (P=0.055)
Yield (t/ha)	2.01^{bc}	1.98^{bc}	2.20^{c}	2.05^{bc}	2.22^{c}	1.56^{ab}	1.18^{a}	0.55

Note: different letters indicate significant differences between treatment means, harvest index is grain weight as a percentage of whole plant, * treatments received a single application in year 1 and a second application in year 2

In the second year at Cambridge there were no significant differences between treatments for harvest index, weeds or seed heads per metre row (Table 5.9). However in contrast to the low yield for the wheat crop grown in year 1, LAB5 treatment yielded significantly higher than all other treatments for the barley crop grown in year 2. The crop response from LAB5 in the second year may have been due to a more even distribution of the dried product from year 1 by the cultivating action of the disc drill whilst planting the barley crop. No other tillage was used between years.

Table 5.9 Barley harvest parameters at Cambridge for year 2 in response to different application regimes of LAB and L+F to texture contrast soil

	L + F	**L + F (x2Y) ***	**LAB**	**LAB (x2Y) ***	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** (P≤0.05)
Harvest Index (%)	52.9	56.8	53.0	56.5	55.1	53.3	54.4	ns
Weeds (%)	7.7	9.6	20.2	20.4	9.6	4.9	6.4	ns
Heads per metre row (no)	83	84	69	86	74	112	103	ns
Shattered Heads (%)	0	0	0	0	0	0	0	ns
Yield (t/ha)	2.04[a]	1.86[a]	2.05[a]	2.20[a]	1.99[a]	2.54[a]	3.63[b]	0.97

Note: different letters indicate significant differences between treatment means, harvest index is grain weight as a percentage of whole plant, * treatments received a single application in year 1 and a second application in year 2

5.3.4 Biomass and grain analysis in year 1

Wheat biomass was analysed at growth stages Z13, Z31 and Z71 at the Cambridge site in year 1 (Table 5.10). There were no significant differences between treatments for P at any of the growth stages. Comparing between treatments with the same calculated nitrogen application rate, LAB and LAB-NIC contained significantly more K, S, Mg and total N than the L+F treatment at growth stage Z13. LAB contained significantly more Ca than LAB-NIC and L+F at the same growth stage. By growth stage Z31, LAB contained more Ca, Mg and total N than either L+F or LAB-NIC, and by growth stage Z71, LAB contained more total N than L+F and LAB-NIC. LAB2 and LAB5 contained significantly more K, S, Ca and Mg in the biomass than all other treatments at growth stage Z71, but not in the order of magnitude equivalent to application rates. Similarly at growth stages Z13 and Z31, the significant difference between the single rate treatments and LAB2 and LAB5 was not in the order of magnitude equivalent to application rates.

Table 5.10 Wheat biomass nutrient concentrations at Cambridge for growth stages Z13 (26/09/07), Z31 (25/10/07) and Z71 (26/11/07) in year 1 in response to different application regimes of biosolids and inorganic fertiliser to texture contrast soil

Analyte	Date	L+F	LAB	LAB-NIC	LAB2	LAB5	LSD (P≤0.05)
P (%)	26/09/07	0.47	0.44	0.47	0.49	0.47	Ns
	25/10/07	0.38	0.33	0.35	0.34	0.33	Ns
	26/11/07	0.24	0.20	0.23	0.19	0.17	Ns
K (%)	26/09/07	4.24^{a}	4.82^{b}	5.07^{b}	5.26^{b}	5.02^{b}	0.48
	25/10/07	2.86^{a}	3.52^{ab}	3.39^{a}	4.29^{bc}	4.58^{c}	0.82
	26/11/07	1.05^{a}	1.35^{a}	1.29^{a}	1.92^{b}	2.01^{b}	0.56
S (%)	26/09/07	0.29^{a}	0.33^{b}	0.33^{b}	0.37^{c}	0.35^{bc}	0.03
	25/10/07	0.17^{a}	0.21^{a}	0.19^{a}	0.26^{b}	0.26^{b}	0.05
	26/11/07	0.12^{a}	0.13^{a}	0.12^{a}	0.17^{b}	0.17^{b}	0.04
Ca (%)	26/09/07	0.31^{a}	0.40^{b}	0.37^{ab}	0.47^{c}	0.50^{c}	0.07
	25/10/07	0.21^{a}	0.33^{bc}	0.27^{ab}	0.39^{cd}	0.42^{d}	0.09
	26/11/07	0.12^{a}	0.17^{a}	0.14^{a}	0.23^{b}	0.24^{b}	0.05
Mg (%)	26/09/07	0.20^{a}	0.24^{bc}	0.23^{b}	0.27^{d}	0.25^{c}	0.02
	25/10/07	0.17^{a}	0.23^{bc}	0.19^{ab}	0.26^{c}	0.25^{c}	0.05
	26/11/07	0.13^{a}	0.14^{a}	0.14^{a}	0.19^{b}	0.18^{b}	0.02
Total N (%)	26/09/07	3.8^{a}	4.9^{b}	4.7^{b}	5.5^{c}	5.5^{c}	0.5
	25/10/07	2.0^{a}	2.5^{b}	2.3^{ab}	3.4^{c}	3.8^{c}	0.5
	26/11/07	1.0^{a}	1.4^{bc}	1.2^{ab}	1.6^{cd}	1.7^{d}	0.3
NO_3^- (mg/kg)	26/09/07	60^{a}	540^{a}	571^{a}	2274^{b}	2763^{b}	1116
	25/10/07	47^{a}	491^{a}	194^{a}	2368^{b}	4600^{c}	1254
	26/11/07	39^{a}	46^{a}	40^{a}	345^{ab}	785^{b}	491

Note: different letters indicate significant differences between treatment means.

However at growth stage Z13, the LAB2 treatment contained four times the NO_3^- in the biomass compared to either LAB or LAB-NIC (LAB2 was calculated as only two times available N compared to LAB), whilst LAB5 treatment contained five times the NO_3^- in the biomass compared to either LAB or LAB-NIC. By growth stage Z31, the LAB2 treatment still contained four times the NO_3^- in the biomass compared to LAB, and twelve times compared to LAB-NIC. At the same growth stage the LAB5 treatment contained nine times and twenty four times the NO_3^- in the biomass compared to LAB and LAB-NIC respectively. At growth stage Z71, the LAB2 and LAB5 treatments

contained eight times and seventeen times respectively more NO_3^- in the biomass compared to LAB, LAB-NIC and L+F. Although there were significant differences between the higher rate treatments and the single rate treatments with respect to K, S, Ca, Mg and total N, the absolute values were within the range suggested by Reuter and Robinson (Reuter and Robinson, 1997). However, the magnitude of difference between the higher rates of LAB and the single rate treatments with respect to NO_3^- in the biomass indicates that guideline calculations do not adequately reflect **a)** the variation in nitrogen release with respect to higher application rates, and **b)** the influence of application timing (i.e. time of year, temperature and soil moisture) on the rate of N release from applied biosolds.

Translocation of the nutrients to the grain showed no significant differences between treatments for P, K, Ca, Mg and NO_3^-, but significant differences with respect to S and total N (Table 5.11).

Table 5.11 Wheat grain nutrient concentrations at Cambridge from year 1 in response to different application regimes of biosolids and inorganic fertiliser to texture contrast soil

Analyte	**L+F**	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** (P≤0.05)
P (%)	0.37	0.35	0.36	0.33	0.33	ns
K (%)	0.39	0.41	0.38	0.39	0.41	ns
S (%)	0.116[a]	0.127[ab]	0.120[a]	0.138[b]	0.154[c]	0.014
Ca (%)	0.04	0.03	0.04	0.04	0.05	ns
Mg (%)	0.13	0.13	0.13	0.13	0.13	ns
NO_3^- (mg/kg)	39	37	40	43	40	ns
Total N (%)	1.41[a]	1.74[b]	1.56[ab]	2.04[c]	2.56[d]	0.26
Protein (%)†	8.8	10.8	9.70	12.7	15.9	ns

Note: different letters indicate significant differences between treatment means.
† calculated from total N multiplied by a conversion factor of 6.22 (Dean, 2008).

The optimum nutrient concentrations for wheat grain to be used for stock feed have been suggested as P at 0.44%, K at 0.40%, S at 0.14%, Ca at 0.05% and Mg at 0.13% (Lardy and Bauer, 1999). LAB5 grain contained the same or slightly higher levels of K, S, Ca and Mg, but lower P. All other treatments contained adequate Mg but lower P, K, S and Ca. Sayre (Sayre, 2002) described a range of between 9.27 and 11.15 for protein content in durum wheat used for bread production obtained from on-farm trials in Mexico (Table 5.12). The protein levels for LAB (10.8) and LAB-NIC (9.70) appear similar to results obtained from basal fertiliser of 75 and 225 kg/ha respectively (9.31 and 10.63). However, L+F protein (8.8) was much lower than no applied nitrogen (9.27), whilst LAB2 (12.7) and LAB5 (15.9) were much higher than the 300 kg/ha (+25 kg/ha) of applied nitrogen (11.15). These results suggest that calculating nitrogen availability from rates of LAB higher than 1NLBAR may not simply be a matter of using a multiplying factor (i.e. 2 and 5 times the calculated NLBAR for LAB2 and LAB5 respectively).

Table 5.12 Response of different fertiliser N rates and timings on protein and yield from sixteen on-farm trials with durum wheat cultivar Altar 84, Yaqui Valley, Sonora, Mexico

N applied in fertiliser		Protein Content of wheat grain	Yield of wheat grain
Basal (kg/ha)	Applied with 1st irrigation (kg/ha)	(%)	(t/ha)
0	0	9.27	4.5
75	25	9.31	5.4
150	25	10.27	5.8
225	25	10.63	6.1
300	25	11.15	6.5

Table adapted from Sayre (2002) using data courtesy of Dr Ivan Ortiz-Monasterio, CIMMYT wheat agronomist.

5.3.5 Soil and crop nitrogen balance for year 1

Table 5.13 shows the total nitrogen of the biomass at growth stages Z13, Z31 and Z71, together with soil nitrogen analysis undertaken at the same time in year 1. Soil NO_3^- for LAB5 was significantly higher than LAB, LAB-NIC and L+F at all measured growth stages. There were no significant differences in soil NO_3^- between LAB5 and LAB2 at stages Z13 and Z31, although LAB5 was significantly higher than LAB2 at Z71.

Table 5.13 Wheat biomass nitrogen and soil NO_3^- and NH_4^+ at Cambridge for growth stages Z13 (26/09/07), Z31 (25/10/07) and Z71 (26/11/07) in year 1 in response to application of bio-resources to texture contrast soil

Analyte	Date	L+F	LAB	LAB-NIC	LAB2	LAB5	LSD (P≤0.05)
Biomass Total N (%)	26/09/07	3.8^{a}	4.9^{b}	4.7^{b}	5.5^{c}	5.5^{c}	0.5
	25/10/07	2.0^{a}	2.5^{b}	2.3^{ab}	3.4^{c}	3.8^{c}	0.5
	26/11/07	1.0^{a}	1.4^{bc}	1.2^{ab}	1.6^{cd}	1.7^{d}	0.3
Soil NO_3^- (mg/kg)	26/09/07	10.7^{a}	12.7^{a}	14.2^{a}	74.7^{ab}	110.9^{b}	66.1
	25/10/07	3.6^{a}	5.6^{a}	3.7^{a}	13.1^{ab}	17.7^{b}	9.6
	26/11/07	5.0^{a}	12.6^{ab}	8.2^{a}	19.3^{b}	39.0^{c}	9.6
Soil NH_4^+ (mg/kg)	26/09/07	2.3	0.4	1.2	0.5	0.1	Ns
	25/10/07	5.5	3.8	2.8	5.4	4.7	Ns
	26/11/07	0.6	0.4	0.9	1.1	1.0	Ns

Note: different letters indicate significant differences between treatment means.

A partial nitrogen balance is shown inTable 5.14, using biomass (t/ha) from Table 5.8 and nitrogen analysis of soil and biomass from Table 5.13.

Table 5.14 Partial nitrogen balance relative to calculated nitrogen inputs from applied bio-resources and inorganic fertilizer at Cambridge for growth stages Z31 (25/10/07) and Z71 (26/11/07) in year 1

	Date	**Control †**	**L + F**	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**
B_t	25/10/07		1.75	3.21	2.97	4.01	3.47
	26/11/07		3.94	6.13	5.82	6.19	8.24
B_k	25/10/07		1750	3210	2970	4010	3470
	26/11/07		3940	6130	5820	6190	8240
B_{TN}	25/10/07		35.0	80.3	68.3	136.3	131.9
	26/11/07		39.6	85.8	69.8	99.0	140.1
S_{AN}	25/10/07	**4.8 †**	9.1	9.4	6.5	18.5	22.4
	26/11/07	**4.9 †**	5.6	13.0	9.1	20.4	40.0
$B_{TN} + S_{AN}$	25/10/07		44.1	89.7	74.8	154.8	154.3
	26/11/07		45.2	98.8	78.9	119.4	180.1
N_{PB} (kg/ha)	25/10/07		**-10.7**	**+34.9**	**+20.0**	**+50.0**	**-100.5**
	26/11/07		**-9.7**	**+43.9**	**+24.0**	**+14.5**	**-74.8**

B_t - Biomass (t/ha), B_k - Biomass (kg/ha), B_{TN} - Total N in Biomass (kg/ha), S_{AN} – Soil Available N ($NH_4^+ + NO_3^-$ kg/ha), N_{PB} (Nitrogen partial balance) = $B_{TN} + S_{AN} - BR_{AN} - S_{AN}$ (of control soil), BR_{AN} = 50 kg/ha, 100 kg/ha and 250 kg/ha for LAB, LAB2 and LAB5 respectively (calculated value of available nitrogen from applied lime amended biosolids and inorganic fertiliser), † Control soil is an unamended control treatment that has not been included in any analysis, but is used here to provide background nitrogen.

These calculations demonstrate that by the flowering stage (Z71 – 26/11/07), 9.7 kg/ha of nitrogen was unaccounted for from the 50 kg/ha of available nitrogen applied from the L+F treatment and 74.8 kg/ha of nitrogen unaccounted from the 250 kg/ha of calculated nitrogen from the LAB5 treatment. Furthermore, the LAB, LAB-NIC and LAB2 treatments showed **93.9 kg/ha**, **74.0 kg/ha** and **114.5 kg/ha** respectively of available nitrogen in the system, which is higher than the 50 kg/ha for LAB and LAB-NIC and 100 kg/ha for LAB2 calculated from the current Tasmanian guidelines

(Dettrick and McPhee, 1999). This variation in observed nitrogen availability demonstrates the complexity of estimating nitrogen release from different rates of lime amended biosolids (LAB, LAB2 and LAB5) and single rates both incorporated (LAB) and not incorporated (LAB-NIC). A plot of calculated nitrogen availability (i.e. LAB to LAB5 inclusive) against the observed available nitrogen values for LAB and LAB5 is shown in Figure 5.2.

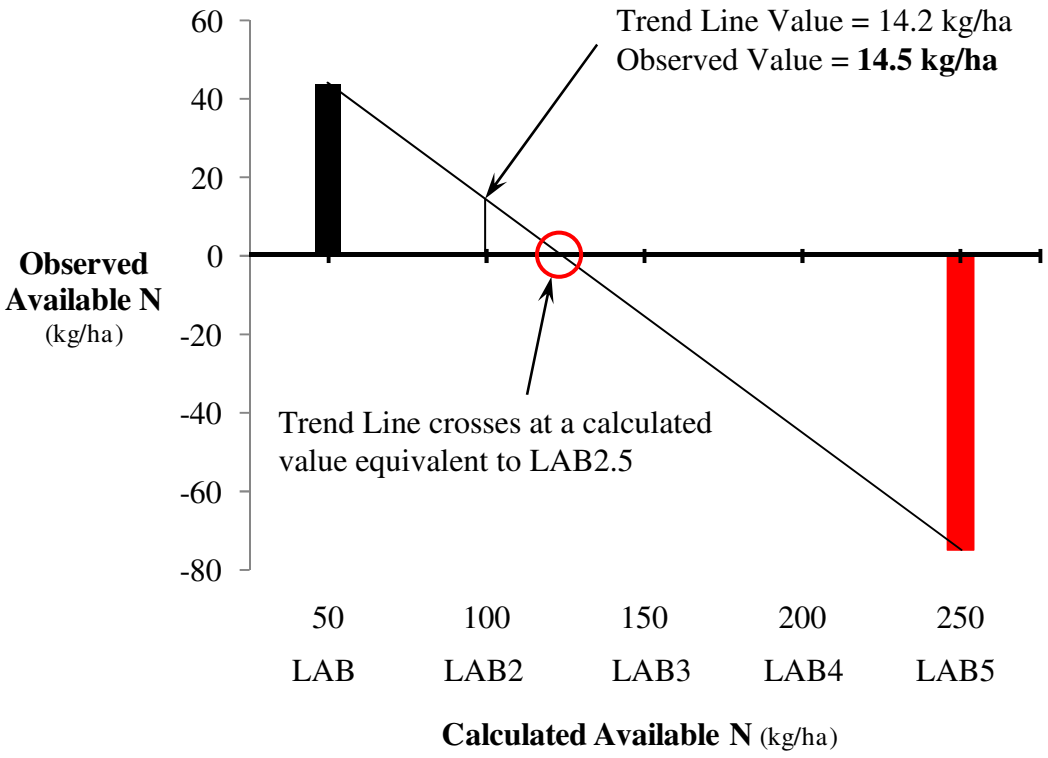

Figure 5.2 Plot of calculated nitrogen release against observed nitrogen release at growth stage Z71 from application of different rate of lime amended biosolids

Assuming a linear trend line between LAB and LAB5, the LAB2 value would be 14.2 kg/ha more than the calculated value of 100 kg/ha. The observed value was found to be **14.5 kg/ha**. Although there is not enough data to validate this correlation between calculated and observed available N, it shows that the present guidelines may be underestimating and overestimating the release of nitrogen from LAB applied at rates lower and higher respectively than LAB2.5 (i.e. 2.5 NLBAR). Underestimating N release may be due to the volume of LAB and LAB2 being low enough for a high soil to product contact, and faster breakdown and mineralisation of the product by microbial

activity. Whereas, overestimating N release from LAB5 may be due to the high volume of product having less overall direct soil contact, and slower breakdown and mineralisation by microbial activity. This variation in calculated and observed nitrogen release from the different rates of lime amended biosolids also raises concerns about the potential for nitrogen exiting the system through leaching or volatilisation.

Table 4.21 shows that grain for the LAB treatment contained significantly more total nitrogen than L+F, but not LAB-NIC.

Table 5.15 Wheat grain nitrogen and soil NO_3^- and NH_4^+ at Cambridge for year 1 in response to different application regimes of lime amended biosolids and inorganic fertiliser to texture contrast soil

Analyte	**L + F**	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**	**LSD** (P≤0.05)
Grain Total N (%)	1.41[a]	1.74[b]	1.56[ab]	2.04[c]	2.56[d]	0.26
Grain NO_3 (mg/kg)	39	37	40	43	40	Ns
Soil NO_3^- * (mg/kg)	9.1[a]	16.3[a]	14.1[a]	28.7[a]	51.3[b]	22.4
Soil NH_4^+ * (mg/kg)	0	0	0.4	0	0	Ns

* soil tests conducted six weeks after harvest

A partial nitrogen balance relative to calculated nitrogen inputs from different application rates of lime amended biosolids, non-incorporated lime amended biosolids and inorganic fertilizer at Cambridge following harvest in year 1 is shown in Table 5.16. The caveat in the calculations is that soil tests were conducted six weeks after harvest. Whole plant nitrogen analysis was not undertaken, therefore, based on results obtained by Austin *et al.* (1977) using 47 genotypes of wheat, 68% of the total nitrogen in the whole plant was assumed to be contained in the grain. The remaining 32% is shown in the table as B_{ETN} .

Table 5.16 Partial nitrogen balance relative to calculated nitrogen inputs from applied bio-resources and inorganic fertilizer at Cambridge following harvest in year 1

	Control †	**L + F**	**LAB**	**LAB-NIC**	**LAB2**	**LAB5**
G_t		2.01	2.20	2.22	1.56	1.18
G_k		2010	2200	2220	1560	1180
G_{TN}		28.2	38.3	34.6	31.8	30.2
B_{ETN}		13.3	18.0	16.3	14.9	14.2
S_{AN} *	**6.8 †**	9.1	16.3	14.5	28.7	51.3
G_{TN} + B_{ETN} S_{AN}		50.6	72.6	65.4	75.4	95.7
N_{PB} (kg/ha)		**-6.2**	**+15.8**	**+8.6**	**-31.4**	**-161.1**

G_t – Grain yield (t/ha), G_k – Grain yield (kg/ha), G_{TN} - Total N in grain (kg/ha), S_{AN} – Soil Available N (NH_4^+ + NO_3^- kg/ha), B_{ETN} – Estimated total nitrogen in stubble and roots, N_{PB} (Nitrogen partial balance) = G_{TN} + B_{ETN} + S_{AN} -BR_{AN} - S_{AN} (of control soil), BR_{AN} = 50 kg/ha, 100 kg/ha and 250 kg/ha for LAB, LAB2 and LAB5 respectively (calculated value of available nitrogen from applied lime amended biosolids and inorganic fertiliser), * soil tests conducted six weeks after harvest, † Control soil is an unamended control treatment that has not been included in any analysis, but is used here to provide background nitrogen.

These results show that LAB still retained 15.8 kg/ha more available nitrogen in the system than the calculated 50 kg/ha at harvest. LAB2 and LAB5 also showed that 31.4 kg/ha and 161.1 kg/ha of available nitrogen was unaccounted from the 100 kg/ha and 250 kg/ha calculated available nitrogen at harvest. A plot of calculated nitrogen availability (i.e. LAB to LAB5 inclusive) against the observed available nitrogen values for LAB and LAB5 is shown in Figure 5.3.

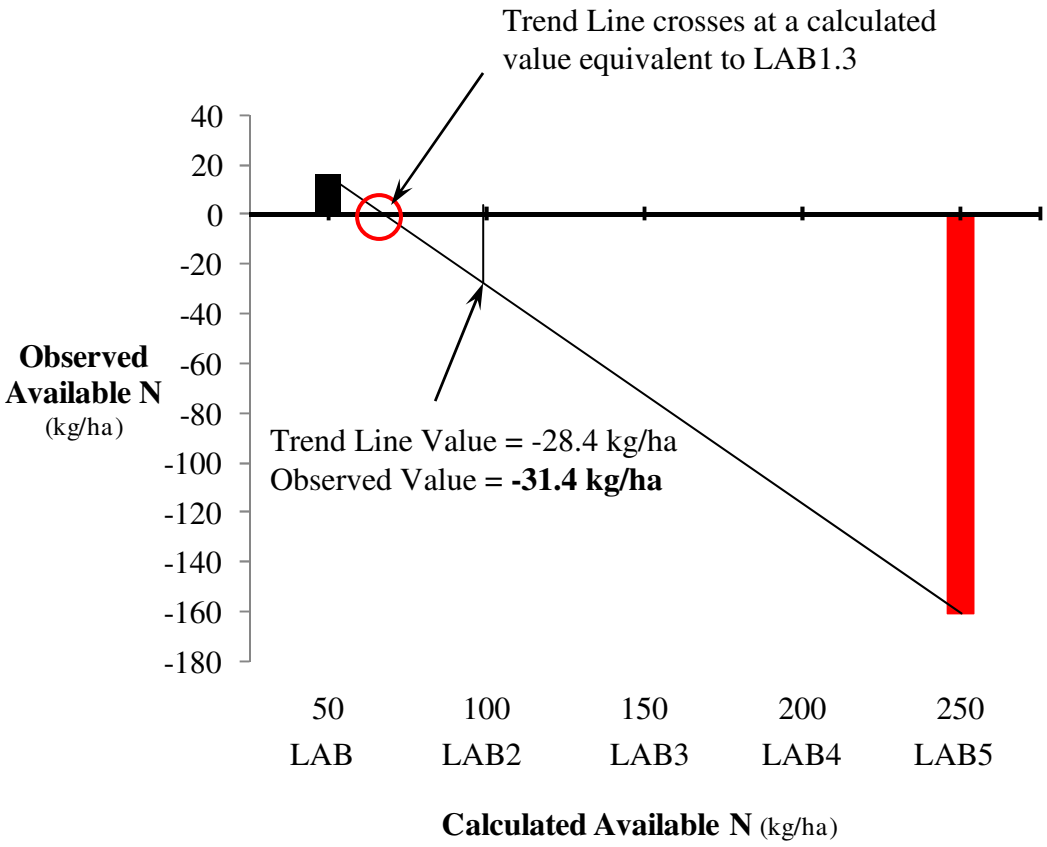

Figure 5.3 Plot of calculated nitrogen release against observed nitrogen release at harvest from application of different rates of lime amended biosolids

Assuming a linear trend line between LAB and LAB5, the LAB2 value would be 28.4 kg/ha less than the calculated value of 100 kg/ha. The observed value was found to be **31.4 kg/ha** less than the calculated value.

These results further reinforce the inconsistency found with the analysis at growth stage Z71, between guideline calculated available nitrogen (Dettrick and McPhee, 1999) and observed available nitrogen, particularly with increasing application rates of lime amended biosolids. The concern is that between growth stage Z71 and harvest, LAB2 and LAB5 lost 45.9 kg/ha and 86.3 kg/ha respectively of available nitrogen from the system. Some of the loss could be accounted by denitrification, as total soil nitrogen for LAB2 and LAB5 at the end of year 1 was 0.17% compared to LAB at 0.13% (although the difference was not significant). However, some of the nitrogen may have been lost

through leaching due to rainfall throughout December of 2007 (refer to Figure 4.8) and the irrigation event just after flowering (early December 2007).

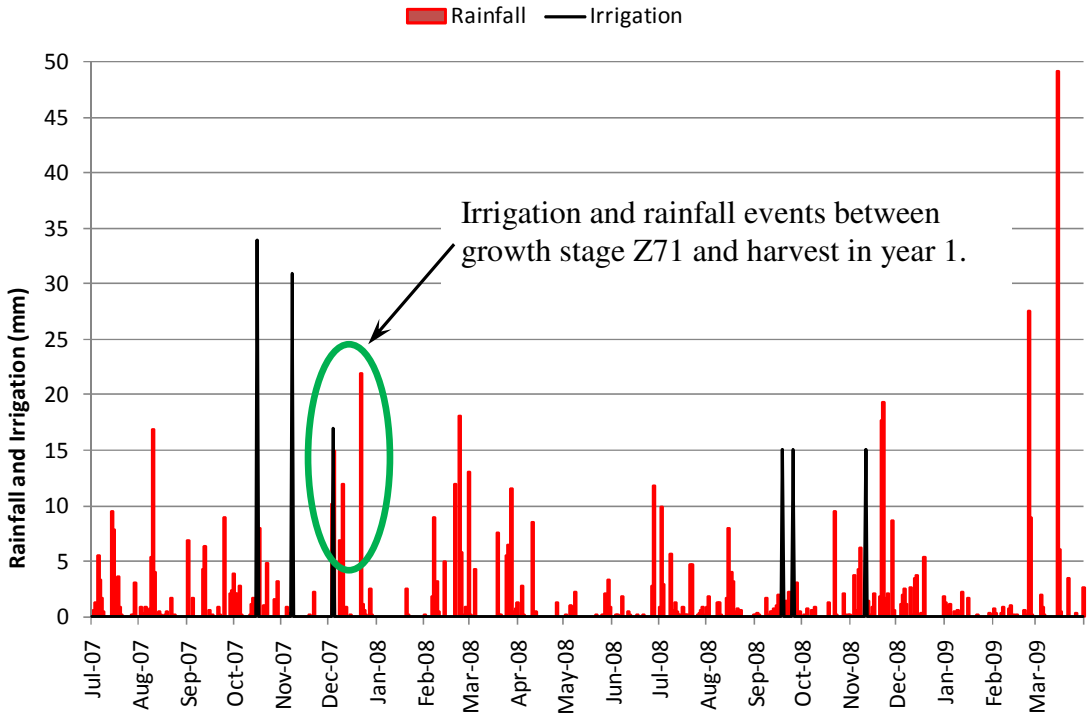

Figure 5.4 Rainfall recorded at the Cambridge Airport (http://www.dnr.qld.gov.au/silo) and irrigation recorded at the Cambridge trial site.

5.4 General discussion

The general objective of this research was to compare the impact of different rates of lime amended biosolids (LAB) with lime and inorganic fertiliser on biological and chemical properties of the surface layer of a texture contrast soil.

Soil Chemical Attributes

Analysis of the soil post harvest for years 1 and 2 showed significant differences between treatments for $EC_{(1:5)}$ and extractable SO_4^{2-} after the first year and pH, Colwell P, soluble NO_3^- and exchangeable Ca^{2+} after each year. Results from the single rate treatments applied in the first year showed that LAB applied at the current guideline N rate contained a similar Colwell P after the first year (125 mg/kg) to the pre-trial soil test (126 mg/kg), but a higher value (142 mg/kg) after the second year. This suggests that in the first year sufficient P was supplied to satisfy plant requirements, but that

further P was released from LAB in the second year. The LAB-NIC treatment however, showed a drawdown of P reserves after the first year (down to 103 mg/kg), but an increase after the second (up to 136 mg/kg). The LAB2 and LAB5 treatments contained significantly higher soil Colwell P than LAB after the first year (207 and 296 mg/kg respectively) and, although remaining high after the second year, only LAB5 contained significantly higher P than LAB. The trial area had been under pasture for at least three years before the trial was established, so the pre-trial Colwell P was already at a level considered high when assessing the Colwell P critical soil test value to achieve 95% maximum pasture yield (Gourley *et al.*, 2007). Gourley (2007) suggested the following equation:-

Colwell P critical soil test value = $19.6 + 1.1 \times PBI^{(0.55)}$ (Pre-trial PBI = 66.5)

= 30.66 mg/kg

Although this equation is for pasture, it suggests that excessive P applied to low PBI soils has potential for extreme losses. PBI is an index to provide the phosphorus buffering capacity of a soil (Burkitt *et al.*, 2002). This is in agreement with Alleoni *et al.*(2008), who found excessive P leaching from Spodosols (a poorly P sorbed coarse sandy textured soil) in Florida after application of biosolids. These results further demonstrate that P should be considered as well as N when applying biosolids to satisfy N requirements (Pritchard *et al.*, 2004; Schroder *et al.*, 2008), particularly with respect to pre-test Colwell P and PBI.

The $EC_{1:5}$ results indicated that increasing rates of LAB concomitantly increased the soil $EC_{1:5}$ post harvest year 1 to a level rated as medium salinity (Maas and Hoffman, 1977). Although the LAB2 and LAB5 levels decreased after the second year, they were still considerably higher than the pre-trial value. The LAB-NIC and the L+F did not increase significantly after the first year, but increased considerably after the second year. This suggests that application of higher rates of LAB or not incorporating LAB should occur prior to a leaching rain event to ensure that excess salts from the applied products are leached through the soil profile and not allowed to accumulate. This application timing has implications for grain consumption from sites with either LAB or L+F applied to soil, as a rise in EC has been correlated with increased uptake of heavy metals in vegetable crops (McLaughlin *et al.*, 1993).

Lime is applied to soil to increase soil pH of an acid soil. Studies have also shown that application of lime amended biosolids can also improve pH of acid soils (Moody *et al.*, 1998; Sloan and Basta, 1995). Although the pH of the soil in this trial prior to establishment was in the neutral range, the LAB and L+F (lime as CaO and $CaCO_3$ respectively) treatments were applied to assess the pH changing potential of applying increasing rates of LAB, either incorporating or not incorporating LAB and re-applying LAB over a two year period. The results showed that within the first twelve months LAB applied at guideline rates to a neutral soil could increase pH (1:5 0.01M $CaCl^2$) by 0.8 units more than L+F. LAB2 increased soil pH (1:5 0.01M $CaCl^2$) by 1.3 units more than L+F in the same year. The LAB5 result was the same as LAB2 after the first year, which may reflect the uneven product distribution rather than be a direct treatment effect. The re-applied LAB treatment showed a further 0.2 unit increase in pH (1:5 0.01M $CaCl^2$) after the second year indicating some soil buffering of pH at these slightly alkaline pH's. The significant soil pH increases with increasing LAB application rate and incorporated LAB after the first year could be attributed to the O^{2-} (from the CaO in LAB) from the lime reacting with the free H+ ions. The increase in pH was paralleled by increases in exchangeable Ca^{2+} for the same treatments. The benefit of increasing soil pH is the reduction in heavy metal availability for plant uptake, however P availability can be limited and solubility of As increased (US_EPA, 2007). However, the results for Colwell P indicate that high pH may not be limiting P availability, possibly due to the low PBI of the soil.

Microbial Biomass (MB) and Soil Carbon (SC)

This research found nine months after amendment application, that LAB2 contained significantly more fungal and bacterial biomass than LAB or LAB-NIC. However, the L+F treatment was not significantly different to LAB or LAB2 with respect to bacterial biomass. This contrasts with studies by Peacock *et.al.* (2001) and Bittman *et. al.* (2005), who found that bacterial biomass decreased in the first year after application of inorganic fertilisers to no-till cropped soil and pastures respectively as compared with control and organic amendments, but is in agreement with Barbarick *et al.* (2004) who found an 11% increase in microbial biomass after application of biosolids. Aoyama *et. al.* (2006) also reported that water soluble Ca^{2+} associated with limed biosolids may

decrease fungal biomass, however, the evidence presented here suggests there was either no effect or an increase.

There were no significant differences between treatments for soil organic carbon after the first season, which may be a reflection of the period of treatment rather than the treatments per say. For example, Cotching *et al.* (2001) found a significant correlation between microbial biomass and soil organic carbon, but under management regimes that were in place over many years. Research has also shown that under longer term applications of biosolids and increased rates of organic amendments, SOC stocks can increase (Hardie and Cotching, 2009; Tian *et al.*, 2009; Wallace *et al.*, 2009).

Crop response to applied lime amended biosolids

Increasing LAB rates did not show an increase in yield as found by Cooper (2005), which may be due to a higher nitrogen accumulation (particularly from LAB5) at flowering but also a high percentage of shattered heads for LAB2 and LAB5. The nitrogen accumulation has been shown to prolong vegetative growth (Nakagami *et al.*, 2004), whilst seed shattering has been linked to high nitrogen inputs in water limiting conditions. Although there was a high weed presence, there was no correlation with yield.

In the second year, only the LAB5 treatment yielded significantly more than all other treatments. This was presumably as a result of the nutrients from concentrated areas of biosolids being more uniformly distributed by cultivation action of the direct seeding disc planter used in the second year. No significant difference between the other treatments suggests that a higher initial rate of biosolids is required (ensuring water is not a limiting factor) to satisfy crop nutrient requirements over the longer term when growing cereals. However, this may also supply some nutrients in excess (i.e. P), with subsequent environmental issues.

Crop Nutrient Analysis and Nitrogen Balance

Results from the first year of the trials showed a lineal increasing difference between calculated and observed available nitrogen with increasing LAB application rates. By growth stage Z71, LAB showed an additional 43.9 kg/ha available nitrogen in the system than the calculated available nitrogen (50 kg/ha), whilst LAB5 showed that 74.8

kg/ha of the 250 kg/ha of calculated nitrogen was unaccountable. By harvest, LAB only showed an additional 15.8 kg/ha of available nitrogen in the system, whereas LAB showed an unaccountable 161.1 kg/ha of the 250 kg/ha of calculated nitrogen. Not incorporating a single rate of LAB also showed that by growth 71, there was an additional 24 kg/ha available nitrogen in the system, which reduced to 8.6 kg/ha available nitrogen by harvest. The disparity between calculated and observed available nitrogen has implications for application timing of lime amended biosolids to texture contrast soils, with potential for nitrogen loss in extreme rainfall events if available nitrogen is out of sync with plant demand.

Australian EPA guidelines for biosolids application rates are based on an estimated N release of approximately 20% of organic nitrogen within the first year. However, Eldridge *et al.* (2008) found that 50% of organic nitrogen from granulated biosolids was available in the first two months after application, whilst Rigby *et al.* (2010) found 65.1% of organic nitrogen was available from lime amended biosolids in the first season after application. However, these results suggest that increasing the rate of biosolids does not necessarily mean an increase in nitrogen availability.

5.5 Conclusion

Lime amended biosolids are applied to soil because of their potential to replace lost nutrients and soil organic matter and increase soil pH. This research has identified that:-

- LAB at 1NLBAR for cereals can increase soil pH by 0.8 units more than L+F within nine months of application. Increasing the application rate of LAB from 1NLBAR to 2NLBAR can increase the surface soil pH of texture contrast soils by a further 0.5 units in the same period. However further pH increases from higher rates of LAB (i.e. 5NLBAR) may be restricted by pH buffering from the slightly alkaline soils. Soil pH response from LAB applied and not incorporated may be slower than the response to LAB applied and incorporated, but may be equivalent after eighteen months.

- $EC_{(1:5)}$ of LAB (and soils) needs to monitored if applying higher rates of LAB to satisfy plant nitrogen requirements on saline soils. Application prior to a leaching rainfall event may prevent accumulation of salts from the product in the

surface layer of texture contrast soils. However, this may have implications with concomitant losses of any soluble P or N.

- The low ESP results for increasing rates of LAB, combined with higher Ca^{2+} in solution for the same treatments, may have potential to ameliorate the effects of sodicity in the surface layer of acidic soils. However, the neutral salt formed with the Na^{+} ion that can be leached through the soil profile to reduce salinity, may increase subsoil sodicity of Sodosols, a texture contrast soil with a sodic upper B horizon.

- LAB applied at 1NLBAR for a cereal crop does not result in a significant change in soil Colwell P within the first year. However, results show that initial soil test P and PBI need to be considered prior to any application of LAB at higher rates, to prevent significant leaching and overland flow losses of soluble P.

- Increasing the application rate of LAB to LAB2 may increase both fungal and bacterial biomass. However, applying rates equivalent to LAB5 for a cereal crop may not provide any microbial response due to the volume of material and the difficulty in obtaining a uniform distribution. There was no significant increase in soil organic carbon with increasing LAB application rate; however, the upward trend observed across the three rates suggests a potential increase in SOC over the longer term.

- There is a disparity between calculated (from guidelines) nitrogen availability and observed nitrogen availability within the first twelve months with respect to applying different rates of LAB (LAB, LAB2 and LAB5), and not incorporating LAB at 1NLBAR. There appeared to be a lineal relationship between calculated and observed available nitrogen, which may be due to differences in volume of material and incorporation uniformity. This has implications for applying higher rates of LAB, particularly for crops with high N requirements.

These results have demonstrated that lime amended biosolids at a rate of 1NLBAR (LAB) and 2NLBAR (LAB2) for a cereal crop, releases more nitrogen in the 0 – 10 cm depth of texture contrast soils within the first **five** months of application than the current

guideline calculations suggest for a **twelve** month period. Furthermore, the results show that the guideline calculations overestimate nitrogen release from higher application rates (LAB5). This disparity indicates that calculations for application rates need to consider the total and available nitrogen of the product in the context of the volume and consistency of material applied, particularly if applying LAB to satisfy the requirements of high N input crops.

This research has suggested that a linear relationship may exist between calculated nitrogen release (using current guideline calculations) and actual nitrogen release with increasing application rate of lime amended biosolids. Further research is required to confirm whether this linear relationship between product volume/consistency and nitrogen release can be used to better predict nitrogen release from different rates of lime amended biosolids. More work is also required to determine whether nitrogen release calculations for biosolids may be appropriate for other bio-resources used in agriculture.

6 Determination of soil residual nitrogen from applied bio-resources

6.1 Introduction

A field trial was conducted in the northern Midlands during the 2008-09 growing season using lime amended biosolids (LAB), anaerobically digested biosolids (ADB), poppy mulch (PM) and poppy seed waste (PSW), lime and fertiliser (L+F), and control (unamended) treatments applied to soil, to determine soil residual nitrogen during the growth of a cereal crop in a temperate region. Organic soil amendments in general have often been labelled 'slow release fertilisers' due to most nutrients being present in organic form (www.natureneem.com). However, Kara (2000) has suggested that the quality of introduced organic material can affect the nitrogen dynamics and SOM decomposition rate, with incorrect assumptions potentially leading to excess nitrate after plant harvest being lost by leaching and denitrification. In Tasmania, biosolids, along with other organic materials, are applied in autumn when paddocks are prepared for spring sown cropping. This trial was conducted in late autumn/early winter with the following objectives.

- To quantify the N mineralised from soil applied LAB, ADB, PM and PSW as compared with L+F whilst growing a cereal crop on texture contrast soils in a temperate region.
- To determine the peak N mineralisation periods of LAB, ADB, PM and PSW after application in late autumn/winter for comparison with crop N requirements.
- To assess the mobility of N in the top 20 cm of texture contrast soils after application of LAB, ADB, PM and PSW as compared to L+F.

6.2 Methods and materials

A field trial was established on the 17th June, 2008 at Cressy. The whole site was cultivated with an S-tine cultivator three times in different directions. The LAB, ADB, L+F, PM and PSW treatments were applied on the 20th June and then incorporated on the 23rd June to a depth of 10cm using a hand fork. The experimental design was a randomised complete block with three replications. Plot size was 1 m^2 (1 x 1 m) with a

0.5 m buffer between each plot. A machine was not used due to plot size, and also the delay between application and incorporation was to simulate traditional farmer practice. However, it is noted that some volatilisation of ammonia from the applied products may have occurred particular for the LAB and ADB treatments. Sub-samples of individual products were taken prior to application from a composite of five grab samples. The composite sample for each product was mixed to ensure uniformity of composition. Ten soil cores to a depth of 10 cm were collected at random from the trial site with a 20 mm diameter tube sampler prior to applying treatments, bulked together, and sub-sampled. Samples of all amendments including site soil were then stored at 4° C until 3rd July, when they were transferred to Analytical Services Tasmania (AST) for analysis.

Biosolids application rates were based on Biosolids Re-use Guidelines (Dettrick and McPhee, 1999) to apply 50 kg/ha nitrogen for crop nutrient requirements, while rates for poppy mulch and poppy seed waste were based on current farmer practice. The lime and fertiliser rates were calculated to match the nitrogen and calcium applied with LAB. All rates are presented in Table 6.1.

Table 6.1 Application rates for treatments applied at Cressy on 23rd June 2008

Treatment	**Description**	**Application Rate**
Control	Untreated	N/A
L+F	Lime + Fertiliser	125 kg/ha DAP + 1330 kg/ha Lime + 60 kg/ha Urea
ADB	Anaerobically Digested Biosolids at 1 NLBAR	27.5 wet t/ha
LAB	Lime Amended Biosolids at 1 NLBAR	31.4 wet t/ha
PM	Poppy Mulch	17.5 t/ha
PSW	Poppy Seed Waste	1 t/ha

Analysis of the bio-resources used in the trial, together with soil analysis of the trial site are shown in Table 3.3

On the 24th June, 2008, a disc planter was used to plant 'Brennan' wheat at a rate of 120 kg/ha. The whole site was then rolled with a Cambridge roller to ensure consistent soil-seed contact.

Table 6.2 Nutrient analysis for bio-resources applied at Cressy

	Units (DMB)	LAB	ADB	PM	PSW	Soil
Moisture	% (w/w)	70.1	80.3	55.1	10.8	13.9
pH (H_20) ‡		13	6.6	7.3	5.5	7.3
Electrical conductivity‡	µS/cm	8 820	6 590	7 690	4 460	281
Organic C	% (w/w)	15.0	13.6	26.1	34.6	2
NH_4^+ - N	mg/kg	1300	4300	8.6	46	<1
NO_3^- - N	mg/kg	1.7	1.2	<1.0	20	7.9
NO_2^- - N	mg/kg	1.2	<1.0	1.6	6	<1
Total N	mg/kg	30 000	46 000	16 000	51 000	1 500
Total Ca	mg/kg	248 000	20 700	89 400	23 600	7 790

‡pH and electrical conductivity (EC) results from 1:5 soil:water suspension

Environmental data collection

On the 30 July 2008, three data logging temperature sensors were buried at a depth of 10 cm randomly across the site in order to collect data for the whole season.

Sampling protocol

Soil sampling for this trial was compromised by the environmental conditions that prevailed for 8 weeks following planting. Within a week of planting, consistent rain followed by minimum air temperatures below 0 °C meant that the soil was either too wet to collect in the tube sampler or impenetrable because it was frozen. When soil conditions improved, weekly sampling was commenced and continued for 12 weeks. However, it is recognised that the delay in sampling may have missed key mineralisation kinetics in the soil. Sampling was conducted using a 100 mm square grid

sampling frame elevated 250 mm above the ground to prevent plant damage. At each sampling, five soil samples to a depth of 10 cm were collected from each plot with a 20 mm diameter tube sampler. Samples from individual plots were mixed thoroughly and sub-sampled for mineral N, microbial biomass N (MBN) and gravimetric moisture content (GMC) analysis. The five sampling locations on the grid were randomly allocated for each week of the 12 week period. However, sample location on the grid was the same for each plot at each weekly sampling. Refer to Plate 6.1.

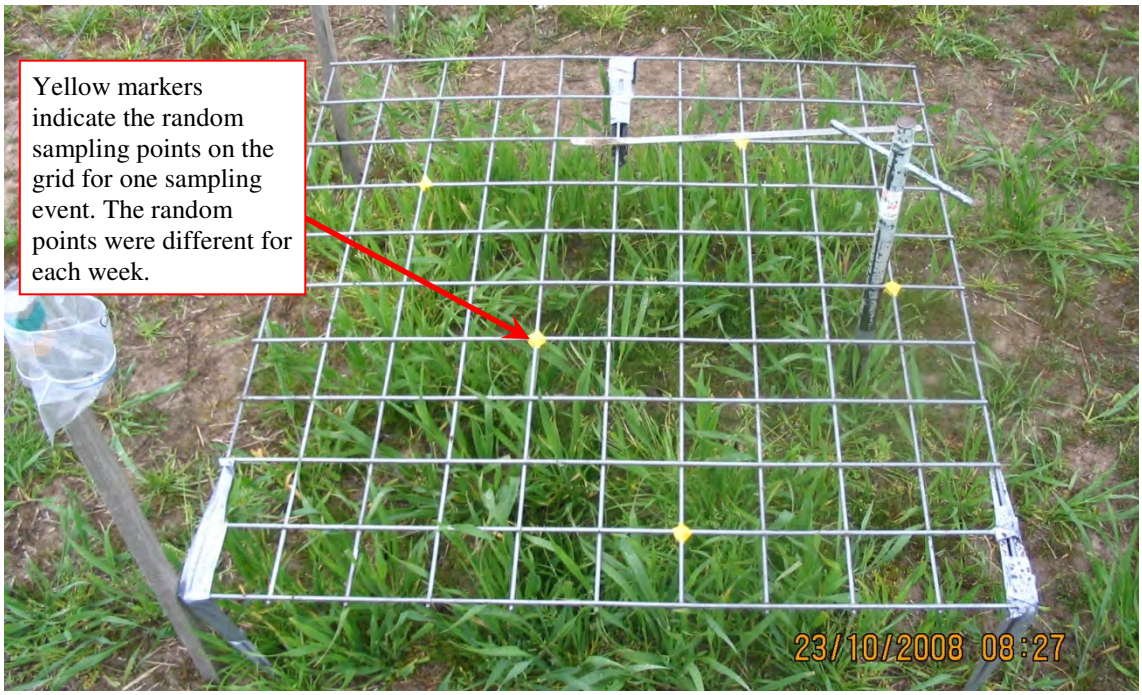

Plate 6.1 Sampling grid used for weekly soil sampling**.**

The samples for mineral N were frozen at -19° C until the end of the trial and analysed in one batch. The GMC and MBN samples were stored for a maximum of 14 days at 4° C before analysis. Concomitant with other sampling, deeper cores (10 – 20 cm depth) were taken to monitor mineral-N mobility and frozen until analysed. Upon thawing for analysis, all soil samples were sieved to < 4 mm.

GMC analysis

A measured amount of field moist soil (approximately 15 g) was oven dried at 105° C for 24 hours and reweighed for GMC.

Mineral N determination

Concentrations of mineral N (NH_4^+-N, NO_3^--N and NO_2^--N) at 0-10 cm soil depth and mobile N (NO_3^--N and NO_2^--N) at 10-20 cm soil depth were determined using a 2M KCl extraction. Five g fresh weight soil was mixed 1:10 w/v with the extractant and mixed for 30 minutes on a flat bed horizontal rotator. The extract was then filtered through Whatman #42 filter paper and analysed using a flow injection automated colour method (Maynard *et al.*, 2008) by CSBP Plant and Soil Laboratory. Final results were corrected for moisture.

Microbial biomass N determination

A chloroform fumigation, direct extraction method was used based on Voroney *et al.* (2008). Microbial biomass N was calculated from the difference between the amount of total N extracted from fresh soil fumigated with $CHCl_3$ and the amount extracted from un-fumigated soil. A total of 60 ml of 0.5 *M* K_2SO_4 solution was added to 15 – 20 g of fresh soil (between 1:2 and 1:5 w/v ratio) in a 125 ml container, capped and then mixed on a horizontal rotating shaker for 30 minutes. Then 1 ml of $CHCl_3$ was added to a duplicate sample, capped and also mixed for 30 minutes. After shaking, the $CHCl_3$ was expelled by bubbling CO_2 free air through the suspension for 1 – 2 minutes. Both soil suspensions were then filtered through Whatman #42 filter paper and frozen until time of analysis. Organic N in the soil extracts was then determined using the alkaline persulphate oxidation method outlined by Cabrera and Beare (1993).

A 15 ml aliquot of filtered extract was mixed 1:1 with 15 ml of an oxidizing reagent in a 50 ml glass tube and immediately sealed with screw caps containing Teflon liners. The tubes were weighed and placed in an autoclave for 30 minutes at 120° C with the caps loosely fitted. The reagent was prepared by dissolving 25 g of $K_2S_2O_8$ and 15 g of H_3BO_4 in 50 ml of 3.75 *M* NaOH, and the volume made up to 500 ml with distilled water. After autoclaving, the tubes were reweighed, with any moisture loss accounted for in final nitrate calculations. Nitrate was then determined by CSBP Plant and Soil Laboratory using the flow injection automated colour method (Maynard *et al.*, 2008).

All nitrogen extract concentrations provided by the laboratory in mg/L were subsequently converted to mg/kg using the following coefficients and formula:

CA = Concentration of analyte, CE = Concentration in extract, EV = Extract volume, SDW = Sample dry weight,

$$\text{CA (mg/kg)} = \frac{\text{CE (mg/L) x EV (L)}}{\text{SDW (kg)}}$$

Agronomic Assessments

Total yield and biomass were determined at harvest, after which the grain was analysed for total N, using nitric acid digestion and elemental analysis by ICPAES. Analysis was undertaken by CSBP Plant and Soil Laboratory.

6.3 Results and discussion

Agronomic assessments did not reveal any significant differences between treatments for biomass or yield (Figure 6.1 and Figure 6.2 respectively). However, the trends indicate that ADB and LAB were higher than the Control and PSW. The standard error shows the variation in results, which may have been due in part to poor plant establishment (refer to Plate 6.2 later in the text) as well as high sampling intensity. A total of 60, 30 mm diameter soil cores were removed from each plot leaving a minimum of 70 mm between holes for plant growth. Damage to adjacent plant roots was unavoidable.

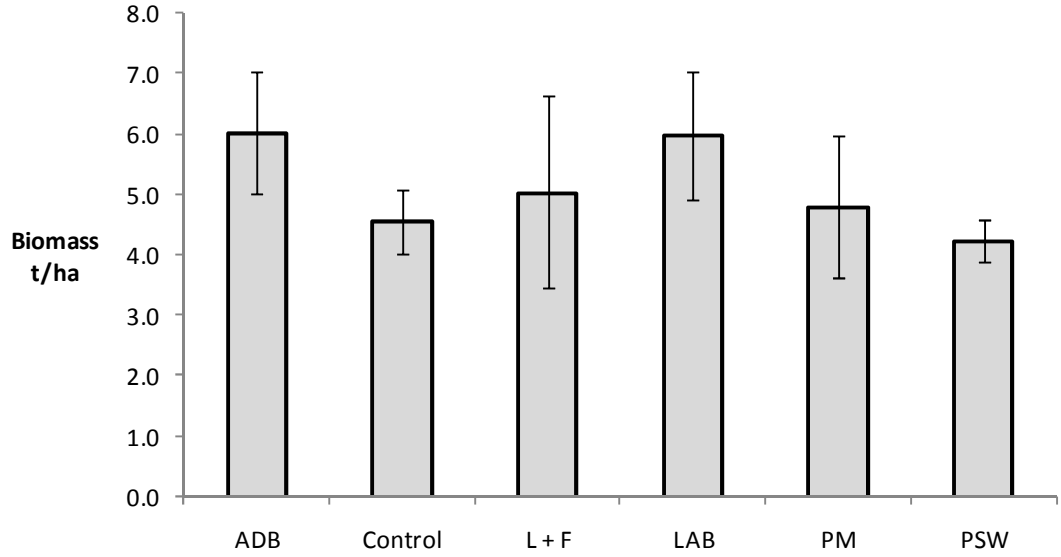

Figure 6.1 Wheat biomass at harvest, December 2008 from Cressy trial site

Note: error bars are standard error from the means.

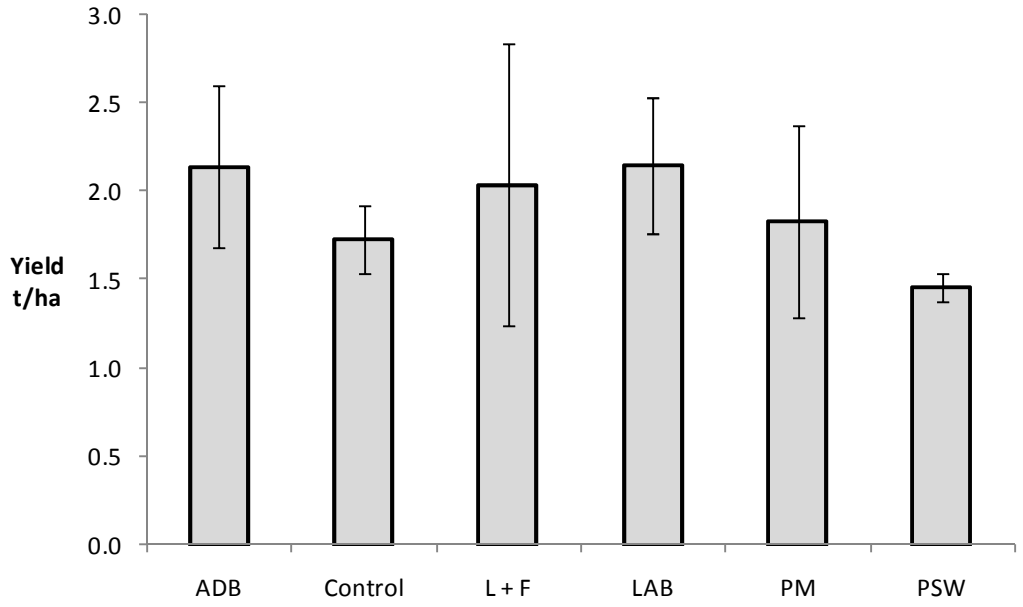

Figure 6.2 Wheat harvest yield, December 2008 from Cressy trial site

Note: error bars are standard error from the means.

The rainfall and minimum air and soil temperatures for the last seven months of 2008 are shown in Figure 6.3. Note the rain just after planting followed by minimum soil temperatures below 10º C until 5th October 2008 (meteorological data from http://www.bom.gov.au/silo/ for Cressy Research Station).

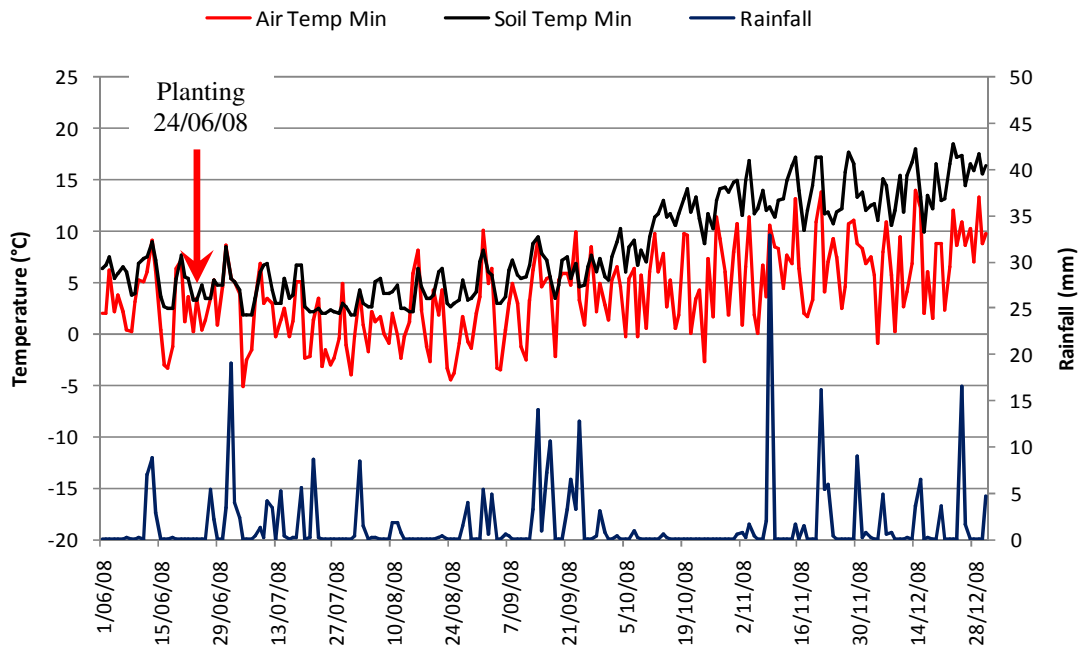

Figure 6.3 Rainfall and temperature data for Cressy, June to December 2008

The climatic conditions experienced early in the trial may have contributed to poor germination and poor plant vigour. Strong and Mason (1999) suggest that in continuously saturated soil the addition of organic materials provides a carbon food source for denitrifying microbes, thereby converting soil nitrate to gases (N_2 and N_20) which are then lost to the atmosphere. However, with saturated soil in a cool temperate region any PAN not taken up by plants would more likely be immobilised or leached through the soil profile. Plate 6.2 shows the sampling eight weeks after planting. Note that the plants are difficult to see at Zadoks growth stage 13 (3 leaves).

Plate 6.2 Soil core sampling for 0 – 10 cm and 10 – 20 cm depth at Cressy using sampling grid.

When comparing the rainfall data with gravimetric moisture content in Figure 6.4, note the increase in soil GMC after the rain event in November. The decrease prior to this time through September and October 2008 is indicative of crop uptake.

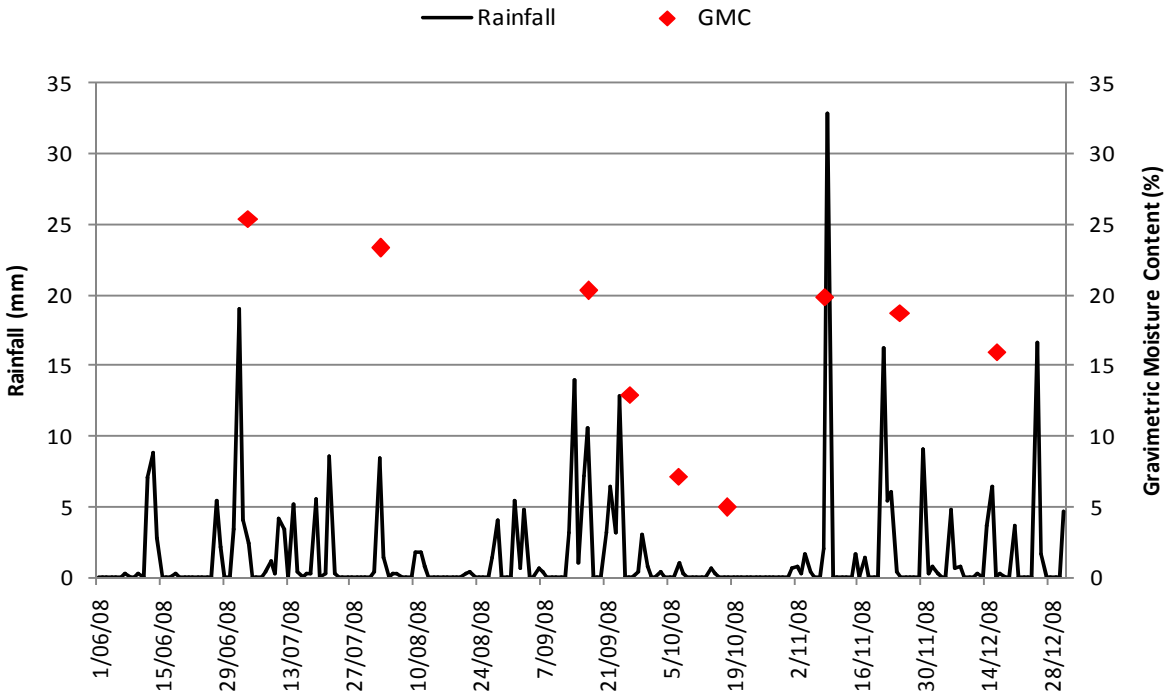

Figure 6.4 Rainfall data from http://www.bom.gov.au/silo/ overlayed with average gravimetric moisture content at 0 – 10cm soil depth at Cressy

Acknowledging that the eight week delay after planting in sampling may have missed the key periods of nitrogen release from the applied bio-resources, there were still significant differences between treatments. Results for NO_3^- recovered from the 0 – 10 cm are shown in Figure 6.5 and Table 6.3, whilst NO_3^- recovered from the 10 – 20 cm depth are shown in Figure 6.6 and Table 6.4. Applying biosolids at guideline recommended rates and applying poppy mulch at supplier recommendations showed that LAB contained significantly more NO_3^- than all other treatments in the 0 – 10 cm depth on the 22nd August 2008. However by 16th October 2008, soil NO_3^- in the same depth for both PM and LAB was significantly higher than for all other treatments. On both the 23rd and 30th October 2008, soil NO_3^- in the same depth for PM was significantly higher than all other treatments. At the 10 – 20 cm depth, soil NO_3^- for LAB was significantly higher than all other treatments (except ADB) on the 22nd August 2008, significantly higher than all other treatments on the 10th September 2008, but only significantly higher than PM, PSW and Control on the 16th October 2008. By the 30th October soil NO_3^- in the same depth for PM was significantly higher than all other treatments.

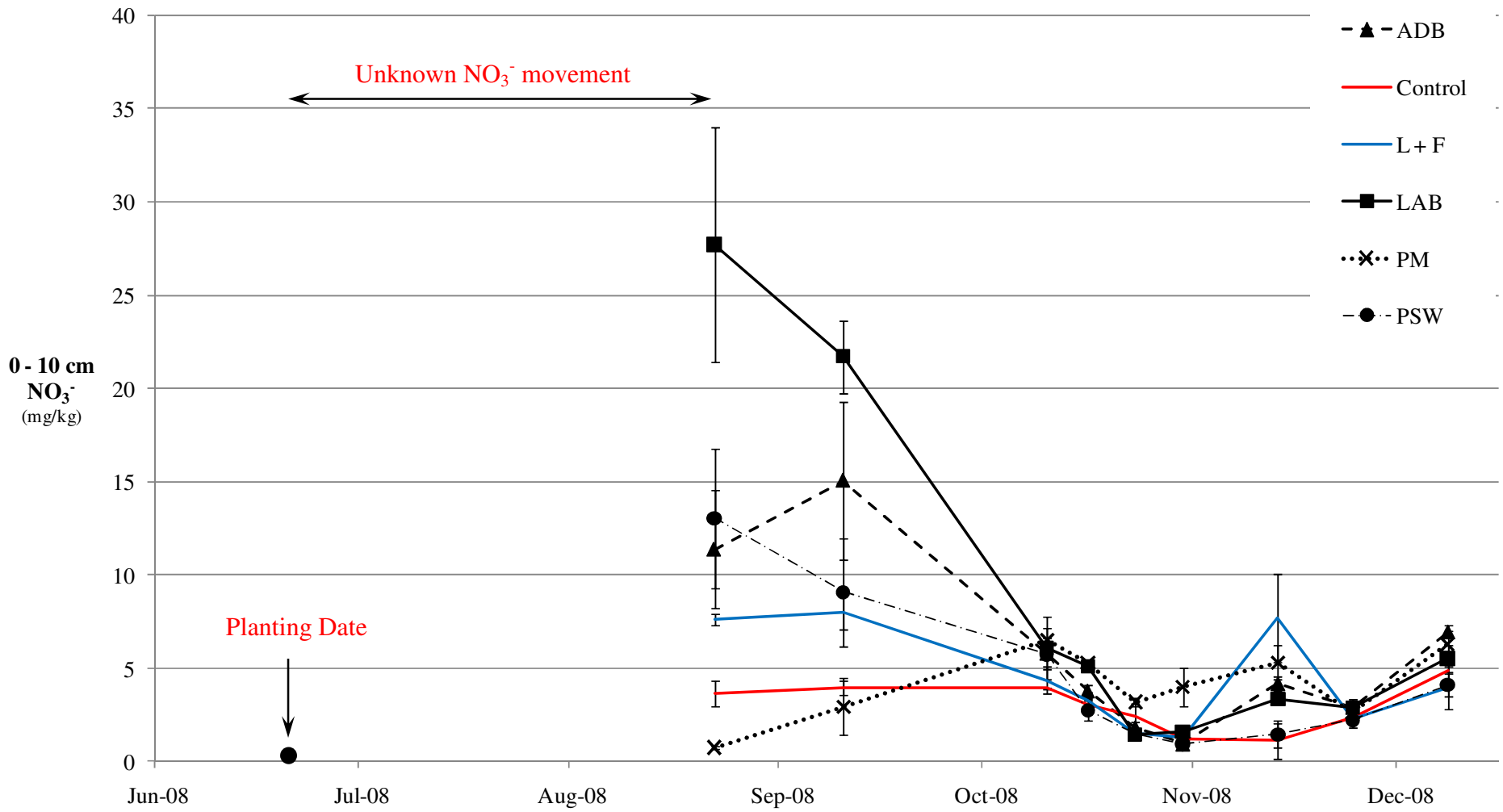

Figure 6.5 Soil NO_3^- nitrogen analysis results from samples taken at the 0 – 10 cm depth (Error bars are standard error of the means)

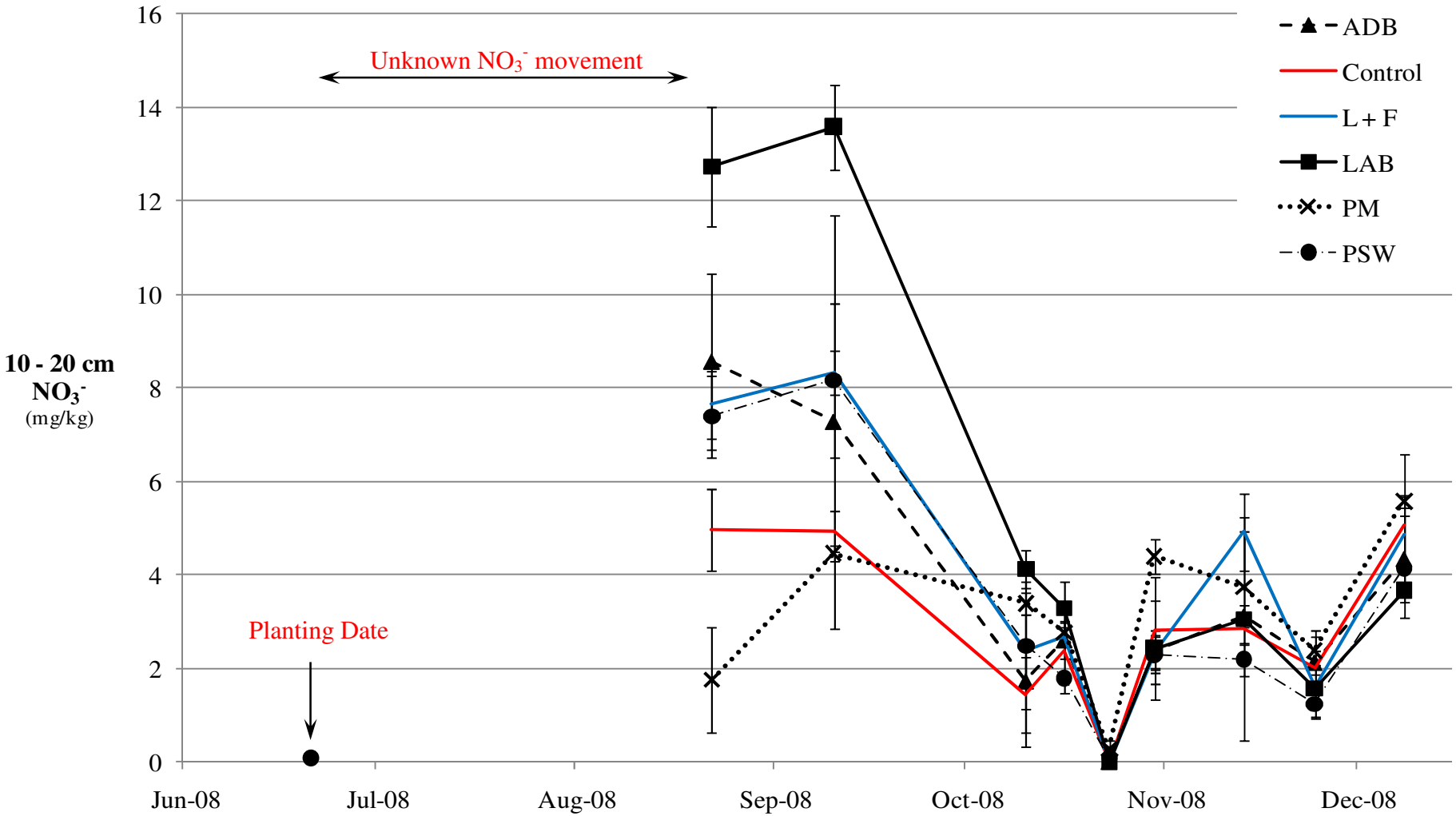

Figure 6.6 Soil NO_3^- nitrogen analysis results from samples taken at the 10 – 20 cm depth (Error bars are standard error of the means)

Table 6.3 Soil NO_3^- nitrogen from 0 – 10 cm depth

	ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
22/08/08	11.4^{b}	1.7^{a}	7.6^{ab}	33.7^{c}	0.8^{a}	13.0^{b}	8.7
10/09/08	15.1^{bc}	4.0^{a}	8.0^{ab}	21.7^{c}	2.9^{a}	9.1^{ab}	8.0
10/10/08	5.8	3.4	4.4	6.1	6.5	5.2	ns
16/10/08	3.80^{a}	3.08^{a}	3.25^{a}	5.11^{b}	5.28^{b}	2.75^{a}	1.11
23/10/08	1.84^{a}	2.40^{ab}	1.55^{a}	1.44^{a}	3.19^{b}	1.46^{a}	1.16
30/10/08	0.96^{a}	1.21^{a}	1.29^{a}	1.57^{a}	3.97^{b}	0.94^{a}	1.58
13/11/08	4.18^{abc}	1.12^{a}	7.73^{c}	3.35^{ab}	5.30^{bc}	1.47^{ab}	4.07
24/11/08	2.92	2.32	2.29	2.90	2.64	2.21	ns
08/12/08	6.64	4.90	3.97	5.53	6.26	4.10	ns

Note: different letters indicate significant difference between treatment means.

Table 6.4 Soil NO_3^- nitrogen from 10 – 20 cm depth

	ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
22/08/08	8.57^{cd}	4.77^{ab}	7.65^{bc}	12.01^{d}	1.76^{a}	7.39^{bc}	3.57
10/09/08	7.28^{a}	4.93^{a}	8.31^{a}	13.58^{b}	4.46^{a}	8.16^{a}	4.48
10/10/08	1.73	2.29	2.40	4.14	3.39	2.49	ns
16/10/08	2.61^{bc}	2.38^{ab}	2.70^{bc}	3.28^{c}	2.77^{bc}	1.60^{a}	0.86
23/10/08	0.01	0	0	0.01	0.29	0.09	ns
30/10/08	2.40^{a}	2.80^{a}	2.35^{a}	2.06^{a}	4.40^{b}	2.30^{a}	1.40
13/11/08	2.96	2.85	4.92	3.06	3.75	2.19	ns
24/11/08	2.13	2.00	1.60	1.58	2.38	1.24	ns
08/12/08	4.01	5.06	4.88	3.67	5.57	4.14	ns

Note: different letters indicate significant difference between treatment means.

Results for NH_4^+ recovered from the 0 – 10 cm are shown in Figure 6.7 and Table 6.5, whilst NH_4^+ recovered from the 10 – 20 cm depth are shown in Figure 6.8 and Table 6.6. Similar to soil NO_3^-, NH_4^+ for LAB was significantly higher than all treatments in the 0 – 10 cm depth at the commencement of sampling on the 22nd August 2008.

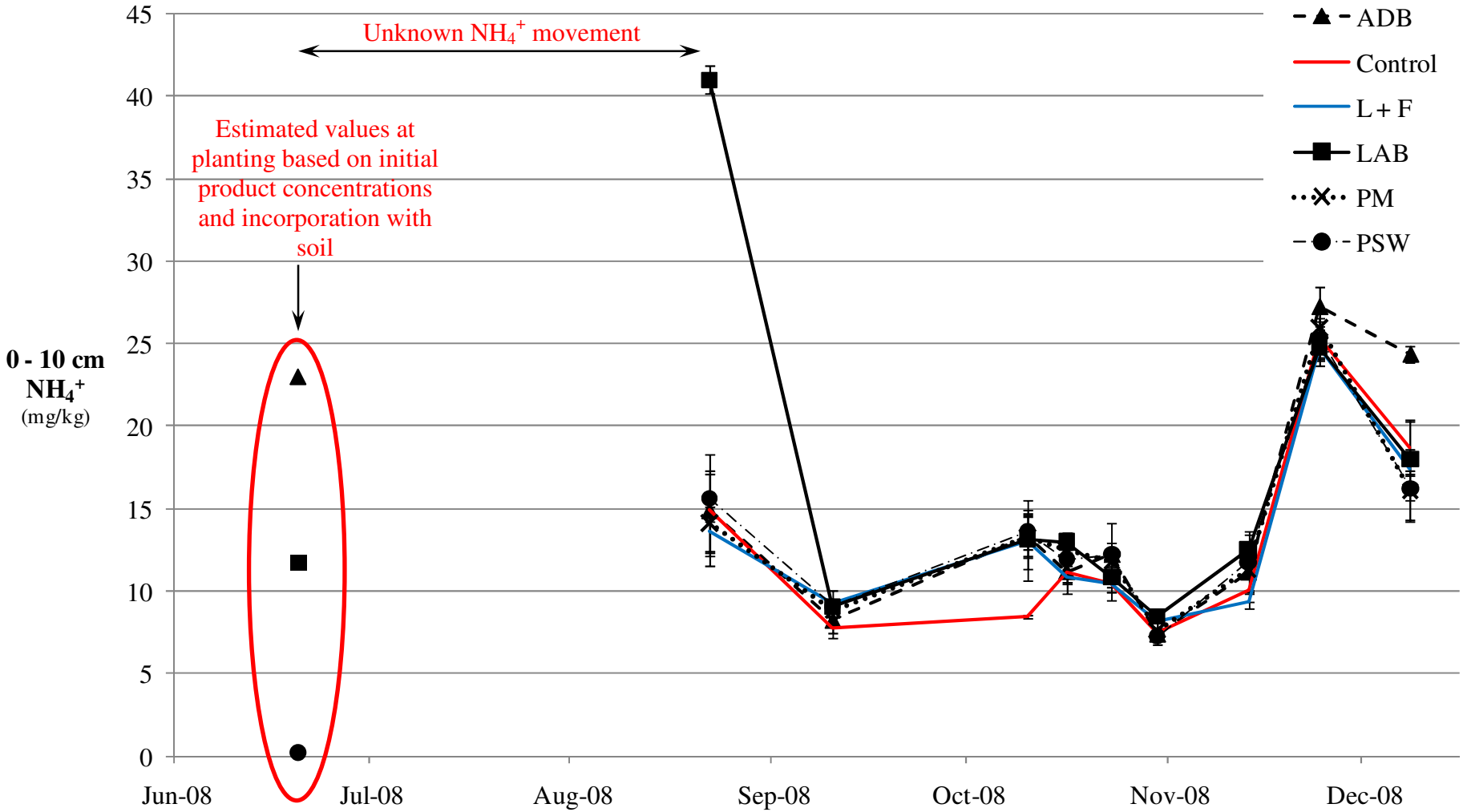

Figure 6.7 Soil NH_4^+ nitrogen analysis results from samples taken at the 0 – 10 cm depth (Error bars are standard errors of the means)

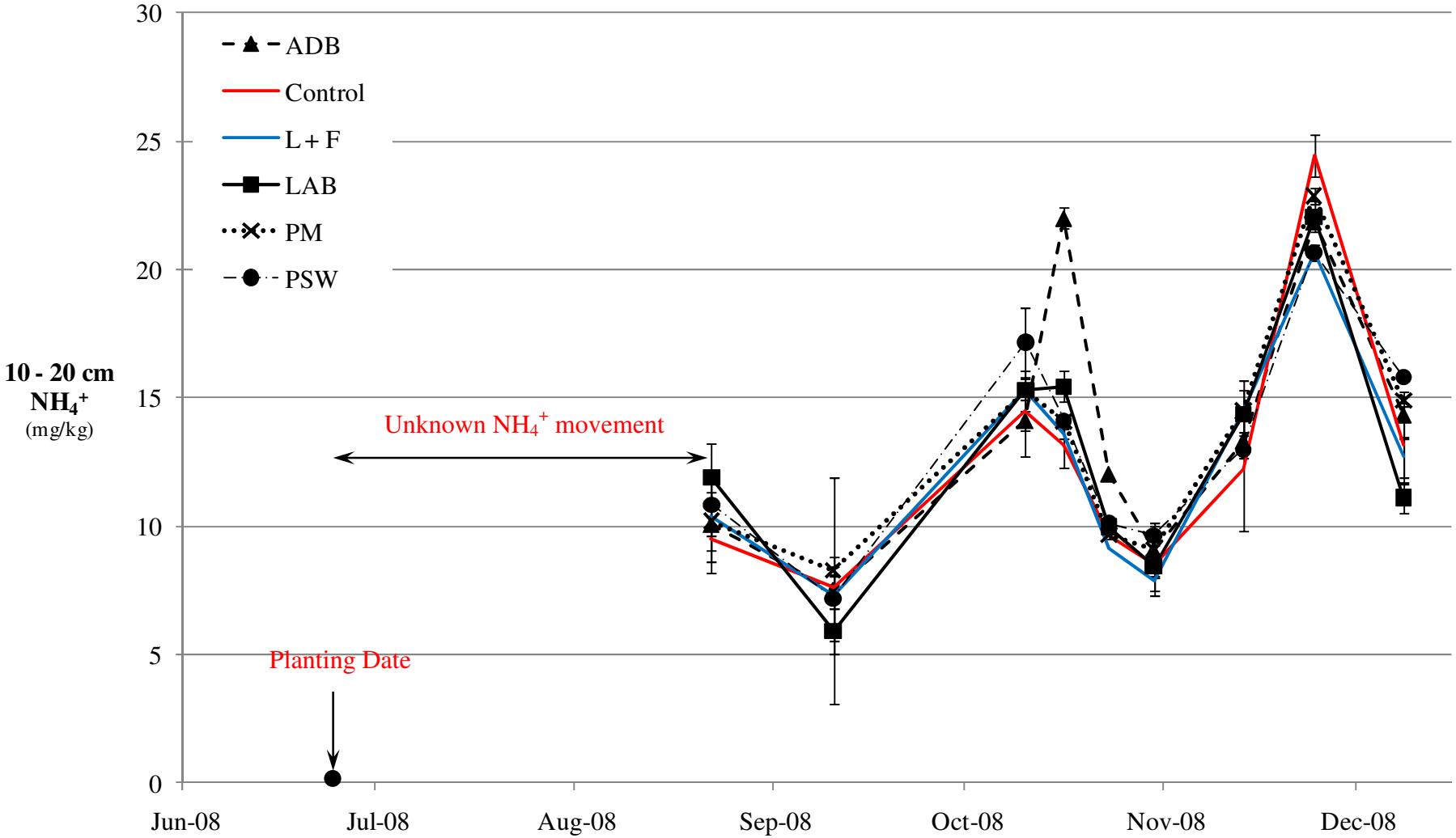

Figure 6.8 Soil NH_4^+ nitrogen analysis results from samples taken at the 10 – 20 cm depth (Error bars are standard errors of the means)

Table 6.5 Soil NH_4^+ nitrogen from 0 – 10 cm depth

	ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
22/08/08	10.1^{ab}	8.8^{a}	10.4^{ab}	12.6^{c}	10.2^{ab}	10.8^{bc}	2.1
10/09/08	7.5^{bc}	7.7^{bc}	7.3^{bc}	5.9^{a}	8.3^{c}	7.2^{b}	1.1
10/10/08	14.1	15.3	15.3	15.3	15.3	14.4	ns
16/10/08	22.0	13.2	13.6	15.4	14.1	14.1	ns (P=0.054)
23/10/08	12.0^{c}	9.7^{ab}	9.1^{a}	9.9^{ab}	9.7^{ab}	10.1^{b}	0.91
30/10/08	9.1	8.5	7.9	8.2	9.1	9.6	ns
13/11/08	12.4	12.2	14.5	14.4	14.5	13.0	ns
24/11/08	21.9	24.5	20.7	22.1	22.9	20.7	ns
08/12/08	14.5	13.2	12.7	11.1	14.9	15.8	ns

Note: different letters indicate significant difference between treatment means.

Table 6.6 Soil NH_4^+ nitrogen from 10 – 20 cm depth

	ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
22/08/08	14.9^{a}	13.0^{a}	13.6^{a}	41.2^{b}	14.2^{a}	15.6^{a}	3.1
10/09/08	8.3	7.7	9.2	9.1	8.9	9.1	ns
10/10/08	13.3^{b}	7.4^{a}	13.1^{b}	13.1^{b}	13.3^{b}	11.6^{b}	3.8
16/10/08	11.2	11.2	10.8	13.0	12.5	11.9	ns
23/10/08	12.2	10.5	10.5	10.9	11.8	12.2	ns
30/10/08	7.4	7.5	8.2	8.5	7.6	7.3	ns
13/11/08	11.7	10.1	9.4	12.5	11.3	11.8	ns
24/11/08	27.2	25.3	24.7	24.8	26.0	25.3	ns
08/12/08	23.5	18.7	17.4	18.0	16.1	16.2	ns*

Note: different letters indicate significant difference between treatment means,
* P=0.052).

Combined NO3- and NH4+ for both depths are shown in Figure 6.9 and Table 6.7 as PAN (plant available nitrogen). The results show that PAN for LAB was significantly higher than all other treatments on the 22nd August 2008 and significantly higher than all other treatments (except ADB) on the 9th September 2008. There were no significant differences between treatments on any of the other sampling dates.

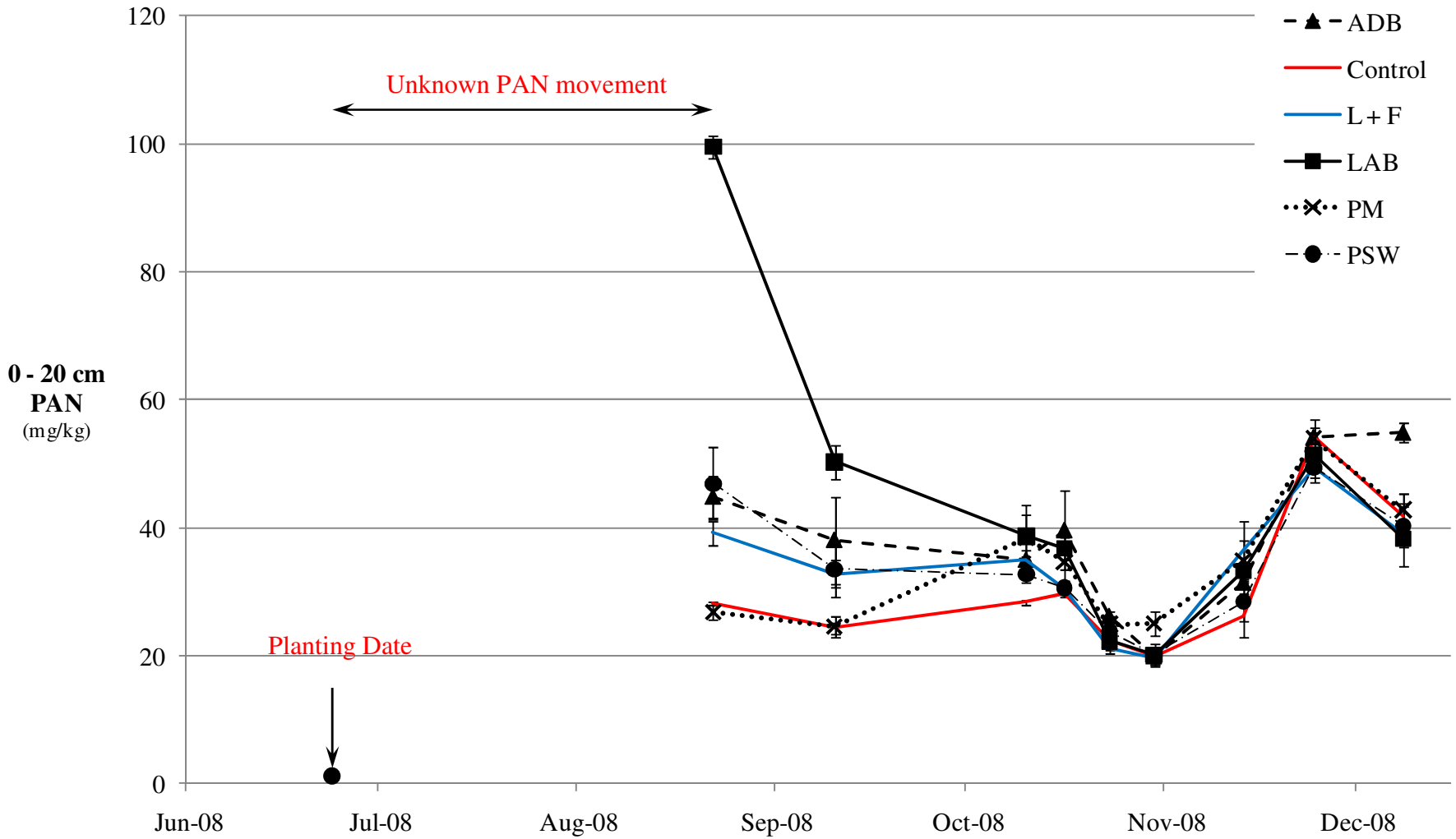

Figure 6.9 Sum of NO_3^- and NH_4^+ (PAN) analysis results from soil depth 0 – 20 cm (Error bars are standard errors of the means)

Table 6.7 Soil calculated PAN from 0 – 20 cm depth

	ADB	Control	L+F	LAB	PM	PSW	LSD (P≤0.05)
22/08/08	44.9^{c}	28.2^{ab}	39.2^{bc}	99.5^{d}	26.8^{a}	46.9^{c}	11.4
10/09/08	38.1^{bc}	24.3^{a}	32.8^{ab}	50.3^{c}	24.6^{a}	33.5^{ab}	12.4
10/10/08	35.0	28.1	35.1	38.7	38.5	32.4	ns
16/10/08	39.6	29.8	30.4	36.8	34.6	30.6	ns
23/10/08	26.1	22.5	21.2	22.3	24.9	23.9	ns
30/10/08	19.8	19.9	19.7	20.3	25.1	20.2	ns
13/11/08	31.3	26.3	36.5	33.3	34.8	28.4	ns
24/11/08	54.2	54.1	49.3	51.3	53.9	49.4	ns
08/12/08	48.5	41.8	38.9	38.3	42.8	40.3	ns

Note: different letters indicate significant difference between treatment means.

Key points from individual available nitrogen pools (NO_3^- and NH_4^+) and the combined pool (PAN) were that:-

- A top dressing of 60 kg/ha urea in mid-November 2008 coincided with a peak in NO_3^- pool for the L+F treatment for both soil depths. However it also shows that the application may have missed the timing required for plant uptake.
- The inverse flux of the NO_3^- and NH_4^+ pools shows the conversion of nitrogen between pools. However, plant uptake has not been accounted for.
- Leaching losses have not been considered due to the shallow surface soil depth (190 mm) in the texture contrast soils. Another loss pathway could have been volatilisation, however, Fenn and Escarzarga (1977) found that ammonium was liable to move down through the soil profile with recurring wetting of the soil surface, rather than be volatilised. Furthermore, Lui *et al.* (2007) concluded that ammonium volatilisation increased with **low** water contents rather than with **high** water contents experienced at this site. This leaves immobilisation by other microorganisms as the most likely reason for declining ammonium.

- The sudden decline for NO_3^- in the 10 – 20 cm depth on the 23rd October 2008 not emulated in the 0 – 10 cm depth results, indicate a significant plant uptake period.

All the treatments (except for LAB and ADB) are unrelated but selected for this trial because of current commercial use. In order to better compare the treatments the results for the first sampling date of 22nd August were normalised with respect to total N contents in the original bio-resource. The measured PAN results for NH_4^+ and NO_3^- for the total sampling depth 0 – 20 cm for the first sampling date of 22 August 2008 for each treatment are shown in Table 6.8. Also included is the PAN as a percentage of total N applied in the bio-resources accounting for background control PAN.

Table 6.8 Measured PAN as a percentage of total N applied in bio-resource for sampling date 22 August 2008

	ADB	L+F	LAB	PM	PSW	LSD (P≤0.05)
$BioR_{DW}$ (kg/ha)	5487	23*	9389	7858	892	N/A
$BioR_{TN}$ (mg/kg)	46000	1000000	30000	16000	51000	N/A
$BioS_{TN}$ (mg/kg)	249	23	282	126	45	N/A
$BioS_{PAN}$ (mg/kg)	16.5	10.8	70.0	-1.6	18.5	N/A
$BioS_{PAN}$/ $BioS_{TN}$ (%)†	6.6^{ab}	46.9^{c}	25.2^{bc}	-1.3^{a}	40.6^{c}	26.1

$BioR_{DW}$ – Dry weight application rate of bio-resource, $BioR_{TN}$ – Total N in bio-resource, $BioS_{TN}$ – Calculated Total N in soil to a depth of 10cm after incorporating bio-resource assuming a bulk density of 1 g cm^{-3}, $BioS_{PAN}$ – measured PAN recovered from a soil depth of 20cm corrected for background PAN of Control treatment, * N applied in planting fertiliser, a further 27 kg/ha N was applied in mid-November as Urea (60 kg/ha).

Eight weeks after application of bio-resources and inorganic fertiliser 25.2 % of the total N applied in LAB and only 6.6 % of the total N applied in ADB were recovered from the 0 – 20 cm depth of the texture contrast soil. Despite no quantification of nitrogen release prior to this date, the results show that current biosolids guidelines for Tasmania

may not reflect the actual release of N, specifically for biosolids with added lime. The L+F results shows an almost 50 % recovery of applied N, with PSW showing 40.6 % recovered N from the total N supplied with the product. Furthermore, PSW applied at only 0.9 dry t/ha provided slightly more PAN than ADB applied at 6 times the rate (5.5 dry t/ha) of PSW. The C:N ratios are similar between products, which suggests that other composition factors may be influencing the decomposition of the two products.

Due to limited resources, microbial biomass nitrogen (MBN) was only determined in the warmer period from October to December 2008 (Figure 6.10).

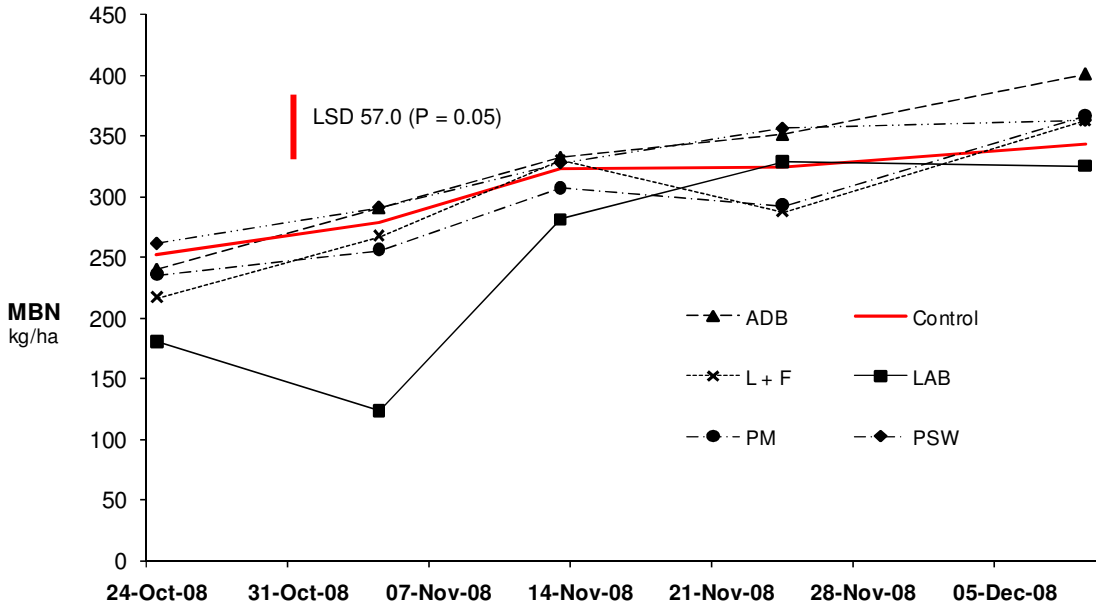

Figure 6.10 Microbial biomass nitrogen at 0 – 10 cm soil depth

Soil microbial biomass is the 'labile' fraction of soil organic matter (Billore *et al.*, 1995) and 'the eye of the needle through which all the natural organic material that enters the soil must pass' (Jenkinson, 1978). The microbial biomass is also both a source and sink of potential PAN (Singh *et al.*, 1991). The application of organic amendments has been shown to affect microbial activity both negatively and positively, depending on site factors such as soil type and cultivation (Brady and Weil, 1999). The steady increase in MBN over time for all treatments except LAB is indicative of temperature driven mineralisation of organic nitrogen and accumulation of PAN by the microbial biomass. However, the significant decrease in MBN for LAB, at least initially, may have been due to a liming affect on the microbial biomass. Onwonga *et al.* (2010) found that lime

additions to acid soils inhibited microbial biomass (but did not reduce MBN), however adding lime with manure and inorganic fertiliser enhanced MBN. Aoyama *et al.* (2006) studied the effect of adding lime stabilised sludge compost to an alkaline soil, and found that the microbial biomass was adversely affected. They suggested that it was due to the high electrolyte concentration associated with the amount of water soluble Ca^{2+} from the product (Aoyama *et al.*, 2006).

The lime in the L+F treatment did not produce the same result possibly because it was the slower reactive calcium carbonate and not the more reactive calcium oxide (present in LAB). The reason for the subsequent recovery of MBN for LAB is not clear, however rainfall in November may have been enough to flush the water soluble Ca^{2+} in LAB further down the soil profile and away from the centre of microbial activity. The biosolids without lime (ADB) did not display the same initial decrease as for the LAB treatment. The high carbon/nitrogen ratio (16:1) of the PM treatment may have lead to immobilisation of N as Qiu *et al.* (2008) found decreasing soil water N with increasing C:N ratios.

6.4 General Discussion

The main objectives of this field experiment were:

- To quantify the N mineralised from soil applied LAB, ADB, PM and PSW as compared with L+F whilst growing a cereal crop on texture contrast soils in a temperate region.

- To determine the peak N mineralisation periods of LAB, ADB, PM and PSW after application in late autumn/winter for comparison with crop N requirements.

- To assess the mobility of N in the top 20 cm of texture contrast soils after application of LAB, ADB, PM and PSW as compared to L+F.

Unfortunately, environmental conditions prevented any sampling between 20th June 2008 (the time of treatment application) and the 22nd August 2008. However, despite this, the results showed that soil treated with LAB contained more plant available nitrogen than all other treatments eight weeks after an autumn amendment application and incorporation. This represents almost 25 % of organic N applied in the product,

which is more than guideline assumptions over a twelve month period. Eldridge *et al.* (2008) found that up to 50 % of total N in land applied granulated biosolids was mineralised in the first two months after application, whilst Rigby *et al.* (2010) found 65.1% of organic nitrogen was available from lime amended biosolids in the first season after application. These latter studies were conducted in New South Wales and Western Australia respectively, where temperatures are generally higher than in Tasmania, which may reflect the differences in mineralisation.

The two biosolids treatments (ADB and LAB) undergo the same treatment process until just before exiting the treatment system when lime (as CaO) is added to LAB and incorporated by the action of a spiral conveyor (worm). ADB contained only 6.6 % of total nitrogen applied by the first sampling, which is considerably less than LAB. The difference in nitrogen release rates may be due to the calcium from LAB invoking an earlier microbial response in texture contrast soils and hence earlier and higher release of N, as Maroney *et al.* (1987) found that in a treatment process calcium added to sludge aggregated the microbial biomass sooner than when not added to the process. However, PM did not result in a similar trend to LAB, even though the total calcium in PM product prior to application (89400 mg/kg) was 4 times the level in ADB (20700 mg/kg). The high C:N ratio of PM (16:1) may have been the limiting factor for decomposition, rather than the higher calcium influencing nitrogen release. However, a delay in decomposition for the PM treatment may provide a better opportunity to synchronise with plant nitrogen requirements.

Due to the delayed sampling, it is unclear whether or not the NO_3^- in the 0 – 10 cm soil depth for LAB on the 22nd August 2008 (33.7 mg/kg) was a peak value or part of the downward trend. However, the increase in NO_3^- in the 10 – 20 cm soil depth for LAB between 22nd August 2008 (12.01 mg/kg) and the 10th September 2008 (13.58 mg/kg) may have due to downward movement of soluble nitrogen through the profile. This indicates that the first sampling date may have been close to the peak value. The NO_3^- for ADB showed an increase from 22nd August 2008 (11.4 mg/kg) until 10th September 2008 (15.1 mg/kg) in the 0 – 10cm depth, but this wasn't followed by an increase in the NO_3^- for the 10 – 20 cm depth as occurred with the LAB.

6.5 Conclusion

The results presented the variation in decomposition rates of bio-resources used in texture contrast soils in Tasmanian agriculture. The main outcomes were:-

- There is a disparity between LAB and ADB with respect to the release of PAN within eight weeks of application to texture contrast soils in late autumn/winter, with a higher PAN from LAB than guideline assumptions. The high calcium in LAB may be a contributing factor.
- The percentage of PAN released of the total N from PSW (40.6 %) after eight weeks was 6 times higher than from ADB (6.6 %), even though ADB application rate was 6 times higher (5.5 dry t/ha) than PSW (0.9 dry t/ha) and C:N ratio of both products was similar.
- There was a significant drawdown of nitrogen reserves from the application of PM within eight weeks of application to texture contrast soils. However, results suggest that over the growing season the slower nitrogen release may better synchronise with plant nitrogen requirements.

Research is needed to provide further evidence of the release rates from LAB, ADB, PM and PSW, particularly for the first eight weeks following incorporation. The influence of calcium on the release of N from LAB also requires further work, as does investigating the variation in N release from products with similar C:N ratios but different application rates.

7 Nitrogen release from poppy waste and biosolids at field temperature

7.1 Introduction

The Tasmanian biosolids re-use guidelines suggest that only about 20% of total nitrogen in biosolids is mineralised in the first twelve months (Dettrick and McPhee, 1999) following land application, an assumption not dissimilar to the NSW guidelines (NSW-EPA, 1997). However, Bell *et al.* (2004) and, more recently, Eldridge *et al.* (2008) found these assumptions to be inadequate for broader interpretation. In cool temperate climates such as Tasmania, soil preparation for crop production or pasture renovation traditionally occurs in autumn or spring when soil temperatures are relatively low, at which time soil amendments are also applied and incorporated. This chapter reports on an incubation study that was undertaken to determine nitrogen mineralisation of poppy mulch (PM), poppy seed waste (PSW), lime-amended biosolids (LAB) and anaerobically digested biosolids (ADB) at a temperature associated with autumn and spring periods in Tasmania.

Incubation experiments have been conducted by Flavel and Murphy (2006), Burgos *et al.* (2006) and Hseu and Huang (2005) to investigate N mineralisation of various soil-applied organic amendments. Incubation temperatures (and times) used for the amended soils were 15° C (142 days), 28° C (280 days) and 30° C (336 days) respectively. Although these studies were conducted for periods between 20 and 48 weeks, most changes occurred within the first 4 weeks following incorporation. N mineralisation studies conducted specifically on biosolids-amended soil by Smith *et al.* (1998) concluded that biosolids type, soil temperature and time from incorporation were dominant factors in determining release rate and nitrate formation. The incubation temperature in that experiment was 25° C, with subsequent biosolids studies by Smith and Durham (2002) and Rouch *et al.* (2009) using 25° C and 20° C respectively. Aside from the study by Flavel and Murphy (2006) the temperatures in the other studies mentioned ranged between 20 and 30° C, temperatures most favourable for the nitrification process (Brady and Weil, 1999).

Using the Q10 concept, each 10° C increase in temperature would lead to a determinant increase in mineralisation rate (Silvia and Machado, 2005). Some researchers have

suggested a Q10 value of around 2 (Stanford *et al.*, 1973), although the affect of climate and soil type has shown higher and lower values (Campbell *et al.*, 1984). This has been explained by Agren and Bosatta (2002) in that the soil organic matter (SOM) in cold climate soils mineralises faster when exposed to warmer temperatures than warm climate soils where the SOM is much more resistant to change. However, adding organic material to the soil may affect the response of SOM to temperature, and thus affect the nitrogen release from SOM and the introduced material. Therefore, the objectives of this study were:-

- To quantify the rate of N release from PM. PSW, LAB and ADB when mixed with a sandy loam soil at a temperature typical of the Tasmanian climate in autumn and spring.

- To determine the peak mineralisation periods of the different products, that may be used to influence application timing to match crop demand.

- To determine the effect of the slow reactive $CaCO_3$ on N release to compare with N release from LAB.

7.2 Methods and materials

An incubation study was undertaken in a growth chamber over 56 days at 12.5° C. This temperature was selected based on a calculated average of data obtained from http://www.bom.gov.au/climate/averages/ for five Midland sites around Tasmania (Cressy, Cambridge, Campbell Town, Ross and Palmerston) for autumn and spring seasonal periods. A randomised complete block design with three replicates was used. Treatments included control (unamended), LAB, ADB, PM and PSW. Two other controls of $NaNO_3$ and NH_4Cl at 1% w/w soil were included for observing denitrification and mineralisation respectively (Rouch *et al*., 2009). A further control soil plus lime treatment ($CaCO_3$ at 4% of LAB wet rate) was used to determine the effect (if any) of calcium on the release of nitrogen in the absence of the biosolids treatment (i.e. LAB). Each replicate included seven samples for removal and analysis at days 0, 3, 7, 14, 28, 42 & 56. Overall, there were eight treatments, replicated three times for seven sampling events.

Treatment preparation was derived from Smith *et al.* (1998) with application rates based on treatments being incorporated in the soil to a depth of 10 cm at a wet weight equivalent rate of 7.5 dry solid (DS) t/ha, assuming a bulk density of 1 Mg m^{-3}. Although measured bulk density for this soil *in situ* was 1.4 Mg m^{-3}, the lesser value was used to reflect the state of soil immediately following cultivation. Soil to a depth of 10 cm was collected from an agricultural site near Cressy, Tasmania, sieved to < 4 mm and stored at 4° C. The soil had been previously classified as a Brown Sodosol (Cotching *et al.*, 2001). The gravimetric moisture content (GMC) of the soil at field capacity (FC) was determined using 'Haines' apparatus (Haines, 1930) and calculated as 33%. One and a half kilogram sub-samples of field moist soil (20% GMC ≈ 61% FC) were spread loosely at an even thickness on a 35 cm x 40 cm stainless steel tray.

Each amendment was then evenly distributed over the soil samples at the required DS rate and mixed by hand using a broad spatula turning the soil in a uniform motion. Both biosolids products were mixed into a slurry with 40 ml of distilled water before incorporating in the soil. A 40 ml aliquot of distilled water was added to all other treatments (including control) to maintain a minimum of 70% field capacity. Seven, 50g samples for each replicate were weighed out in 125 ml plastic bottles (per sample) with loose fitted lids (for gaseous exchange) and incubated in the dark at an average of 12.5° C. The treated and untreated soils were tamped down in the bottles (7 light taps on a bench) to achieve a similar bulk density (i.e. similar height in container). No additional water was added to the samples over the incubation period due to minimal moisture loss.

On each sampling day (i.e. 3, 7, 14, 28, 42 & 56) a sample bottle from each treatment was removed, the soil placed in individual plastic bags and frozen at -19 °C until analysis (Plate 7.1). Samples for day 0 were bagged and frozen straight after mixing.

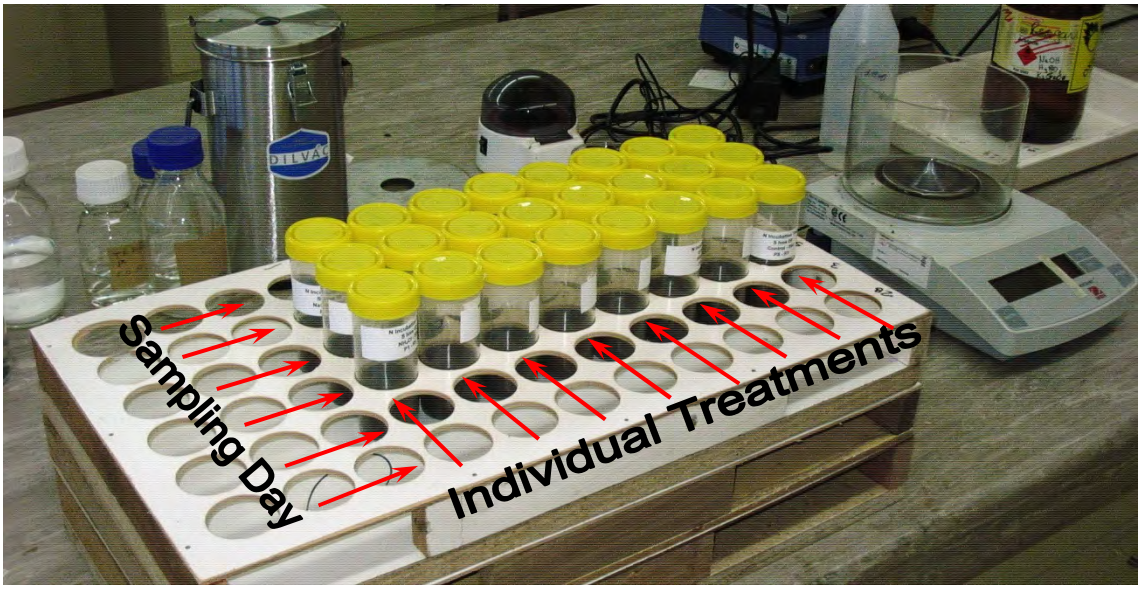

Plate 7.1 N mineralisation experiment incubation tray for treatments mixed with soil (8 treatments x 6 sampling days).

Frozen samples were thawed to room temperature before weighing (10 – 15 g), drying at 105 °C for 24 hours, and reweighing to determine GMC. 5 g of each moist sample was also weighed into a 125 ml PPE screw top container and mixed with 2M KCl solution at a 1:10 ratio (w/v) for 1 hour. Extracts were then filtered through Whatman No. 42 filter paper (Plate 7.2), analysed colorimetrically by CSBP Laboratories for NH_4^+ and NO_3^-, with results corrected for moisture using GMC.

Plate 7.2 Filtering 2M KCl extracts for N analysis

The total inorganic N content was calculated as the sum of NH_4^+ and NO_3^- extracted from each sample throughout the incubation and the net mineralised N from the applied products was calculated as the difference between inorganic N in each treatment and the control soil (Burgos *et al*., 2006). Extract concentrations in mg/L were converted to mg/kg using the following coefficients and formula:

CA = Concentration of analyte, CE = Concentration in extract, EV = Extract volume, SDW = Sample dry weight.

$$\text{CA (mg/kg)} = \frac{\text{CE (mg/L) x EV (L)}}{\text{SDW (kg)}}$$

Chemical composition of LAB, ADB, PM and PSW, together with the base soil used in the trial are shown inTable 7.1.

Table 7.1 Chemical characteristics of bio-resources and soil

	Units	LAB	ADB	PM	PSW	Soil
Moisture	% (w/w)	70.1	80.3	55.1	10.8	20.0
pH (1:5 H_20)		13	6.6	7.3	5.5	7.3
Organic C	% (w/w)	15.0	13.6	26.1	34.6	2.0
Soluble NH_4^+	mg/kg	1 300	4 300	8.6	46	<1.0
Soluble NO_3^-	mg/kg	1.7	1.2	<1.0	20	7.9
Soluble NO_2^-	mg/kg	1.2	<1.0	1.6	6	<1.0
Total N	% (w/w)	3	4.6	1.6	5.1	0.15
Total N_{DS}*	kg/ha	225	345	120	383	1 500
Total P	mg/kg	18 000	11 000	9 300	15 000	340
Ca	mg/kg	248 000	20 700	89 400	23 600	7 790
C:N Ratio†		5:1	3:1	16:1	7:1	13:1

Total N_{DS}* - Total N in 7.5 dry solid tonnes / ha of organic amendment, C:N Ratio† - assumes total C ≈ organic C.

7.3 Results and discussion

The results for NO3- and NH4+ concentration of treated soils after incubation at 12.5° C for 56 days are shown in Table 7.2 and Note: different letters indicate significant differences between treatment means.

Table 7.3 respectively.

Table 7.2 NO_3^- concentration of treated soils (dry weight) after incubation at 12.5° C for 56 days

	ADB (mg/kg)	Control (mg/kg)	LAB (mg/kg)	Lime (mg/kg)	PM (mg/kg)	PSW (mg/kg)	LSD (P≤0.05)
Day 0	9.75	8.47	9.37	9.49	9.57	9.79	ns
Day 3	14.43^{c}	12.04^{c}	11.60^{c}	13.97^{c}	5.68^{b}	0.79^{a}	3.86
Day 7	19.57^{b}	14.59^{b}	21.20^{b}	17.69^{b}	0.18^{a}	1.10^{a}	9.37
Day 14	73.79^{d}	19.21^{b}	73.66^{d}	25.48^{bc}	3.84^{a}	33.97^{c}	9.31
Day 28	132.99^{c}	31.48^{b}	129.93^{c}	33.44^{b}	5.62^{a}	167.55^{d}	24.10
Day 42	134.80^{c}	37.31^{b}	167.12^{d}	41.52^{b}	14.04^{a}	230.76^{e}	11.56
Day 56	168.89^{b}	48.30^{a}	187.30^{b}	48.17^{a}	28.99^{a}	234.89^{c}	22.80

Note: different letters indicate significant differences between treatment means.

Table 7.3 NH_4^+ concentration of treated soils (dry weight) after incubation at 12.5° C for 56 days

	ADB (mg/kg)	Control (mg/kg)	LAB (mg/kg)	Lime (mg/kg)	PM (mg/kg)	PSW (mg/kg)	LSD (P≤0.05)
Day 0	65.16^{c}	20.03^{a}	34.96^{b}	23.20^{a}	22.65^{a}	22.45^{a}	3.63
Day 3	69.99^{b}	22.46^{a}	80.73^{b}	22.03^{a}	22.99^{a}	29.53^{a}	12.61
Day 7	80.66^{c}	22.63^{a}	97.97^{d}	25.13^{a}	23.43^{a}	50.87^{b}	11.72
Day 14	23.23^{b}	8.21^{a}	47.44^{c}	10.41^{a}	14.18^{a}	109.59^{d}	8.34
Day 28	10.02^{a}	8.33^{a}	11.42^{a}	8.80^{a}	19.47^{a}	34.48^{b}	11.48
Day 42	13.06	7.01	11.19	7.53	17.51	11.54	ns
Day 56	8.47	6.79	8.65	8.72	9.69	8.68	ns

Note: different letters indicate significant differences between treatment means.

There was a reduction in soil NO_3^- for PSW after 3 days before recovering to be significantly more than all other treatments by day 56. There was also a reduction in soil NO_3^- for PM, which lasted for 7 days before recovering. The loss of NO_3^- by these two treatments could have been due to denitrification or a priming effect often associated with introduction of organic residues to soil (Brady and Weil, 1999). Qian and Schoenau (2002) found limited release of nitrogen over 67 days from cattle manure with a C:N ratio of between 13 and 15, which is close to the C:N ratio for PM (16:1). Furthermore, they suggested that if the C:N ratio exceeds 25:1, the microbes would source nitrogen from soil reserves, stimulating a priming effect. However, the same inference cannot be made with respect to the PSW treatment, which had a pre-application C:N ratio of 7:1. The lime treatment ($CaCO_3$) was not dissimilar to Control for both NO_3^- and NH_4^+, which suggests that either the calcium released as part of the reaction between the CO_3 (from the lime) and the H^+ ions in solution did not impact on nitrogen release in the short term, or that not enough calcium was available to induce a change.

A peak in NH_4^+ concentration for PSW (109.59 mg/kg) occurred 7 days after the peak in NH_4^+ concentration for ADB (80.66 mg/kg) and LAB (97.97 mg/kg). Nitrification of the NH_4^+ to NO_3^- was then evident in the days following the peak in NH_4^+ for all three treatments. The same dry weight application rate was used for all bio-resources in the incubation in an effort to maintain similar soil to product contact, regardless of total N in the product. The C:N ratio was also not used as the constant because it has been found not to be a reliable indicator of mineralisation rates (Griffin and Hutchinson, 2007). However, in order to compare between mineralisation rates of ADB, LAB, PM and LAB, the data was normalised relative to the total N contained in each product after mixing with soil. Results as a percentage of total N of the product are shown in Table 7.4, Table 7.5 and Table 7.6 for NO_3^-, NH_4^+ and PAN ($NO_3^- + NH_4^+$) concentrations respectively. The data was also corrected for background N from the control soil. Corresponding graphs with error bars are shown in Figure 7.1, Figure 7.2 and Figure 7.3 for NO_3^-, NH_4^+ and PAN respectively.

Table 7.4 NO_3^- concentration of treated soils (dry weight) as percentage of total N of product after incubation at 12.5° C for 56 days

	ADB	LAB	PM	PSW	LSD (P≤0.05)
Day 0	0.37	0.40	0.92	0.35	ns
Day 3	0.69[b]	-0.19[b]	-5.29[a]	-2.94[a]	2.47
Day 7	1.44[c]	2.91[c]	-12.18[a]	-3.52[b]	4.22
Day 14	15.82[c]	24.27[d]	-12.81[a]	3.86[b]	4.83
Day 28	30.52[b]	43.75[b]	-22.14[a]	35.53[b]	16.58
Day 42	27.30[b]	57.69[c]	-19.39[a]	50.51[c]	7.21
Day 56	34.96[b]	61.78[c]	-16.08[a]	48.72[c]	13.32

Note: different letters indicate significant differences between treatment means.

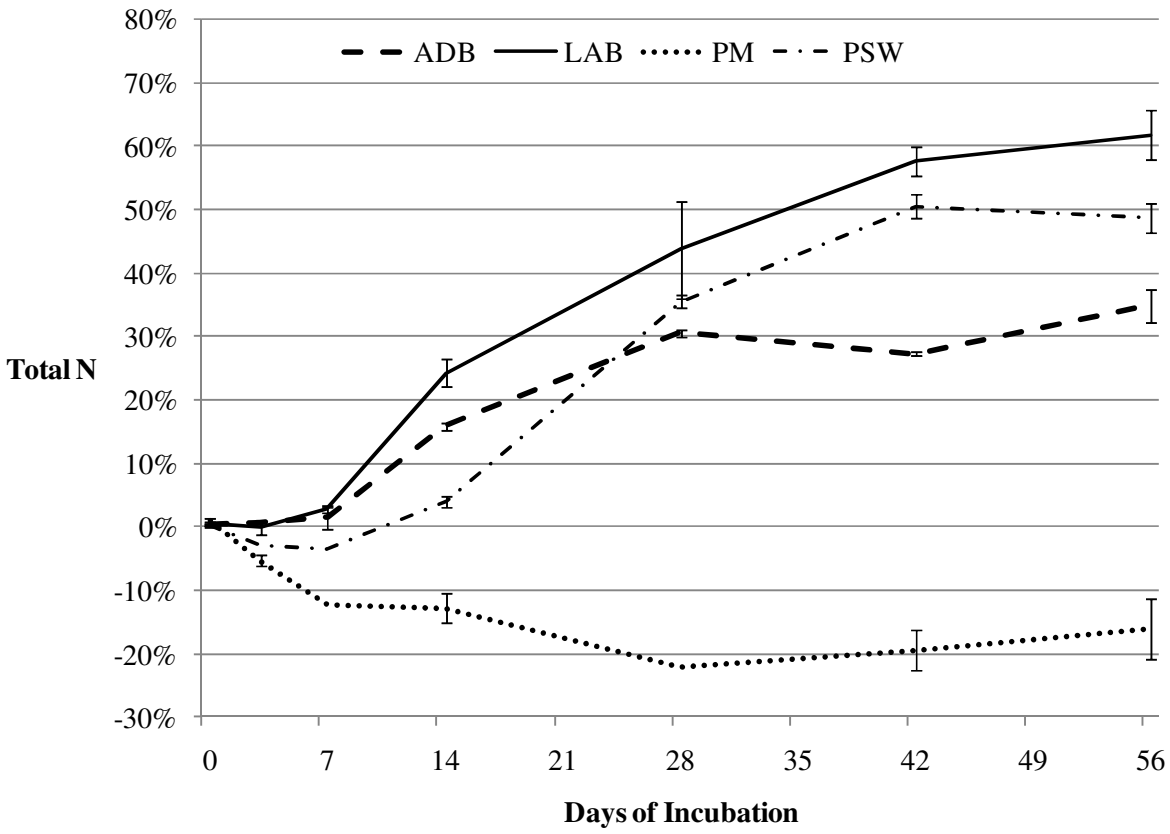

Figure 7.1 NO_3^- concentration of treated soils (dry weight) as percentage of total N of product (error bars are standard error of the means)

Table 7.5 NH_4^+ concentration of treated soils (dry weight) as percentage of total N of product after incubation at 12.5° C for 56 days

	ADB (mg/kg)	LAB (mg/kg)	PM (mg/kg)	PSW (mg/kg)	LSD (P≤0.05)
Day 0	13.08[d]	6.64[c]	2.18[b]	0.63[a]	1.43
Day 3	13.78[b]	25.90[c]	0.45[a]	1.85[a]	7.31
Day 7	16.82[c]	33.48[d]	0.67[a]	7.37[b]	6.56
Day 14	4.09[a]	16.65[b]	4.23[a]	25.98[c]	6.64
Day 28	0.70	1.17	9.29	6.83	ns
Day 42	1.75	1.86	8.76	1.18	ns
Day 56	0.49	0.83	2.41	0.49	ns

Note: different letters indicate significant differences between treatment means.

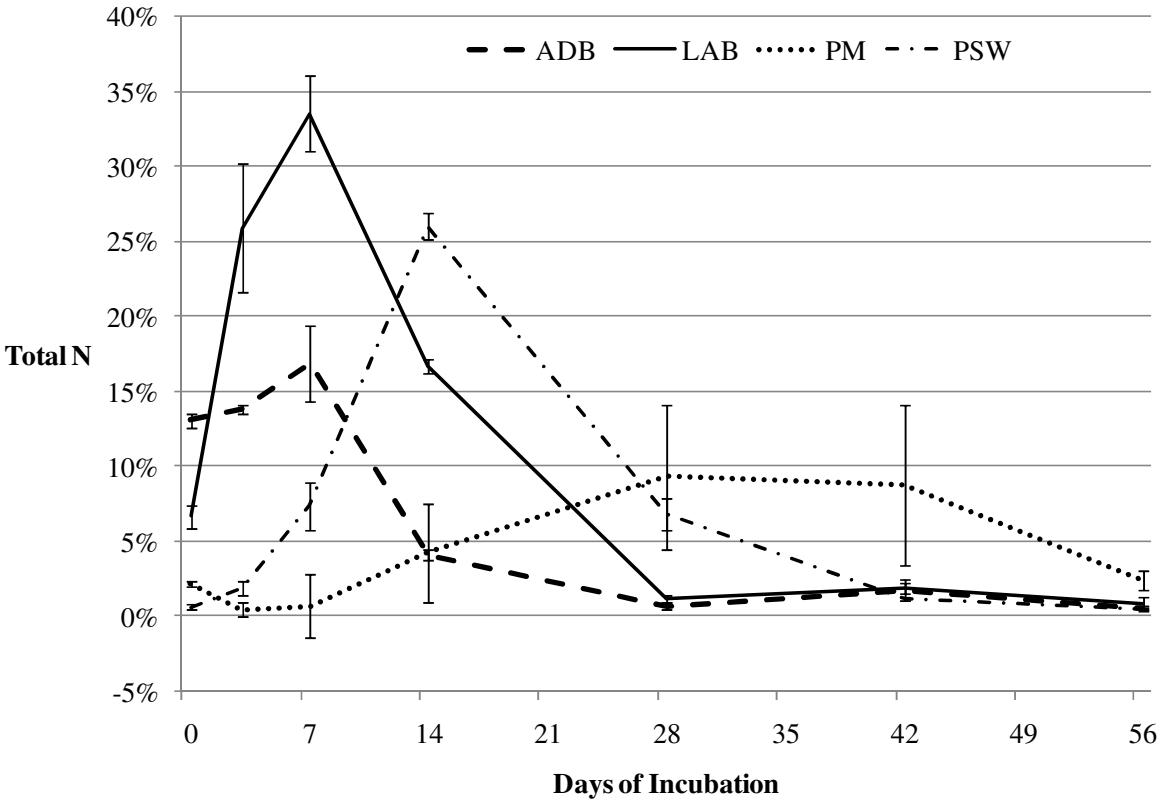

Figure 7.2 NH_4^+ concentration of treated soils (dry weight) as percentage of total N of product (error bars are standard error of the means)

Table 7.6 PAN (NO_3^- + NH_4^+) of treated soils (dry weight) as percentage of total N of product after incubation at 12.5° C for 56 days

	ADB (mg/kg)	LAB (mg/kg)	PM (mg/kg)	PSW (mg/kg)	LSD (P≤0.05)
Day 0	13.45^{d}	7.04^{c}	3.10^{b}	0.98^{a}	1.92
Day 3	14.47^{b}	25.71^{c}	-4.85^{a}	-1.09^{a}	8.77
Day 7	18.26^{c}	36.81^{d}	-14.49^{a}	3.85^{b}	4.13
Day 14	19.92^{b}	40.92^{d}	-8.58^{a}	29.83^{c}	5.98
Day 28	28.94^{b}	53.24^{c}	-14.10^{a}	42.35^{bc}	18.48
Day 42	28.30^{b}	59.55^{c}	-10.63^{a}	51.69^{c}	15.40
Day 56	35.44^{b}	62.61^{d}	-18.76^{a}	49.21^{a}	12.66

Note: different letters indicate significant differences between treatment means.

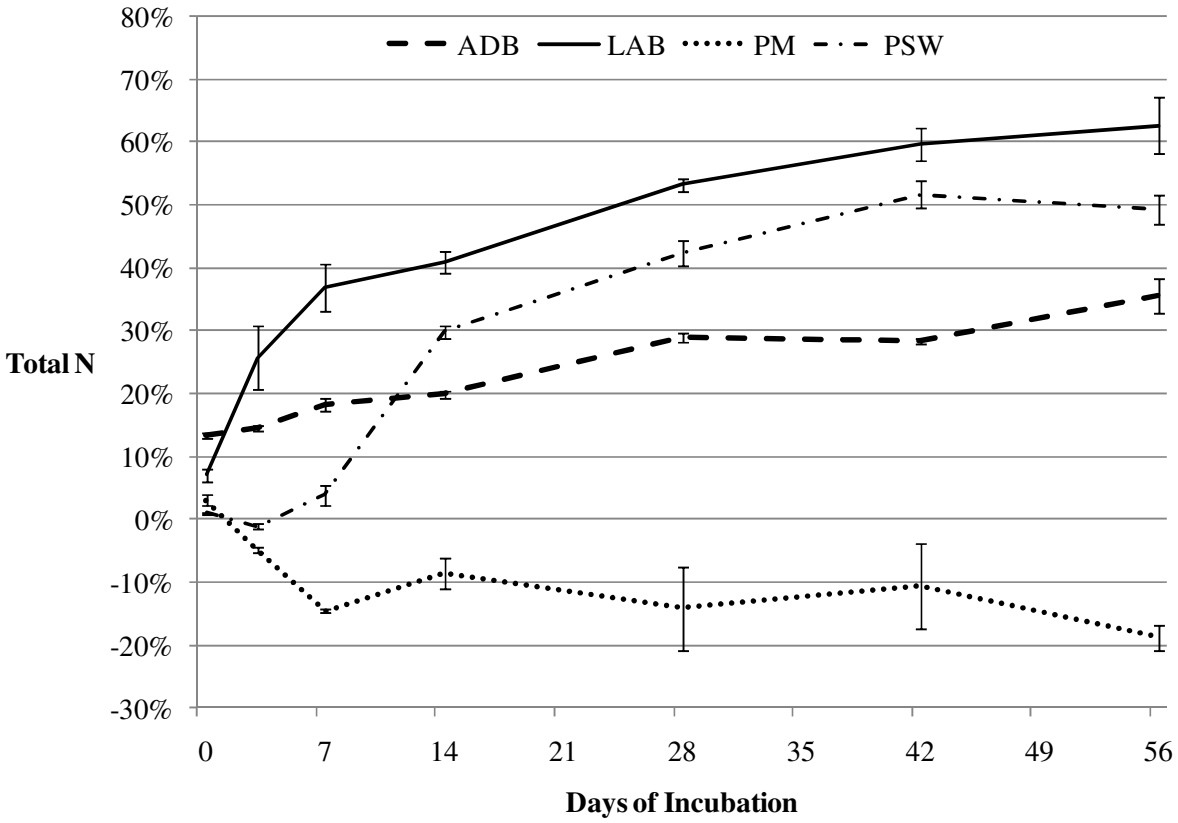

Figure 7.3 PAN (NO_3^- + NH_4^+) of treated soils (dry weight) as percentage of total N of product (error bars are standard error of the means)

The percentage NO_3^- and NH_4^+ of total N followed similar trends to dry weight concentrations of NO_3^- and NH_4^+ in the soil, when products were applied at the same dry weight rate, regardless of total N. There was a 7 day lag time in NO_3^- release for ADB and LAB with an estimated 10 day lag time in NO_3^- release from PSW. There was a steady decline in NO_3^- for the PM treatment until day 28, before a slight recovery to day 56. However, values were still below 0, indicating that NO_3^- was either denitrified or taken up by microbial biomass. NH_4^+ concentration for LAB (33.5%) was significantly higher than ADB (16.8%) at their respective peaks after 7 days incubation. The peak for NH_4^+ as a percentage of total N for the PSW treatment did not occur until day 14, whilst for PM the peak, or plateau, occurred at day 28, but was not significantly different to any of the other treatments at that time.

The results in Table 7.6 and Figure 7.3 show that 62%, 49% and 35% of total N applied in LAB, PSW and ADB respectively was released as PAN by day 56, with the PM treatment showing a significant drawdown from soil reserves for the whole period. The results for LAB are in agreement with Rigby *et al*. (2010) who also found up to 65% of PAN was released from total N in the first season after application of lime amended biosolids to sandy soils in Western Australia. However, the results of this incubation experiment contrast with the Tasmanian Biosolids Re-use guidelines that suggest only about 20% of total nitrogen in the product is released in the first twelve months following application (Dettrick and McPhee, 1999). Furthermore, the results indicated that applying biosolids at guideline rates in autumn and spring may produce mineralised nitrogen in excess of plant requirements and increase the potential for leaching. Based on a previous biosolids study, Eldridge *et al.* (2008) also questioned the adequacy of their current state biosolids guidelines (NSW-EPA, 1997) for calculating application rates.

Brady and Weil (1999) suggested that the lower the C:N ratio of residues added to soil, the higher the microbial activity and subsequent mineralisation. Based on this assumption the mineralisation extent and rates of the incubated treatments should follow the sequence ADB > LAB > PSW > PM, with C:N ratios of 3:1, 5:1, 7:1 and 16:1 respectively. However, the results showed the extent and rate sequence of the organic amendments to be in the order of PSW > LAB > ADB > PM.

7.4 Conclusion

The results of this study confirms that N mineralisation from organic amendments is far from uniform, and that predictions of mineralisation extent and rates may not be reliably based on the C:N ratio of the applied product, particularly when applying to sandy loam soils. Results also showed that nitrogen mineralisation for PSW, LAB and ADB continued to occur at a lower than optimum mineralisation temperature. This suggests that application timing is essential in ensuring that mineralisation of nitrogen from the applied products coincides with plant nutrient requirements and is not exposed to loss pathways (e.g. leaching). The results also demonstrated that further work is required to understand the relationship between N mineralisation, composition of bio-resources and interaction of bio-resources with different soil types.

8 Simulation Modelling

8.1 Introduction

Process based farming systems models have been developed to simulate and predict the potential cycling of nutrients and complex interactions within the plant, soil and environment continuum in response to variable management, climate and soil characteristics. This chapter reports on the use of such a model with experimental validation data from Chapters 4 and 5, to explore key soil processes and plant responses from applying organic materials as soil amendments.

Effective simulation of soil carbon and nutrient dynamics in a farming system requires the use of modelling tools that capture the key interactions between processes and biological, plant, management and environmental factors. In this study the APSIM (Agricultural Production Systems Simulator) model was used for the following reasons. Firstly, APSIM has been used for similar studies simulating N release from organic materials in India (Dimes and Revanuru, 2004), Kenya (Micheni *et al.*, 2004) and Zimbabwe (Chivenge *et al.*, 2004). Secondly, APSIM has been calibrated with local Australian data sets to suit the range of soil types, crops and climates occurring across the country. The biophysical modules within APSIM have been developed from various models including CERES (Jones and Kiniry, 1986) for soil organic matter decomposition and soil water balance, EPIC (Williams and Renard, 1985) for soil temperature, and PERFECT (Littleboy *et al.*, 1992) for soil water balance, and can be configured to simulate biophysical and physical processes in farming systems (Keating *et al.*, 2003). Broad applications of process based farming systems models include:-

- Identifying knowledge gaps in soil processes and model assumptions (can be fed back into model) for long term process analysis.
- Extrapolating measured data to other environments (i.e. soil type, temperature, rainfall and crops).
- Developing ‘what if’ analysis accounting for different management scenarios (i.e. irrigation, different organic soil amendments and timing of application).
- Using the model to form the basis of decision support tools, to inform soil amendment application guidelines, to educate end users of the model and to

show potential impacts of changes in management or environment in lieu of long term observations (i.e. climate change).

However, there are a number of caveats associated with the use of APSIM. As with all models, APSIM is a representation of reality and captures the current knowledge of farm system processes. Underlying processes within farm systems are not yet fully understood, and although simple relationships used in models may be adequate for single season predictions, long term simulations may result in substantial differences between predicted outcomes (Matthews, 2002). APSIM in particular predicts potential yield outcomes without accounting for crop growth limitations such as weed competition, insect and disease damage, water logging, lodging and extreme weather events like frost.

Specific objectives of this study were to use the APSIM model to:

- Compare the simulated crop growth, development and yield, and key soil nutrient (N and C) responses to soil-applied organic materials against field results in a different set of environments.
- Assist the interpretation of results by demonstrating the potential application of Systems Models in bio-resource application to agricultural land.
- Assess the risk of off-site nitrogen losses when bio-resources are applied to texture contrast soils.

8.2 Materials and methods

8.2.1 Field trial details

Replicated field trials were conducted at Cambridge and Cressy. A full description of the trial design, methodologies and soil details can be found in Chapter 3, 4 and 5. Key trial management and product details are summarised in Table 8.1 (Cambridge) and Table 8.2 (Cressy). Soil treatments applied in the first year at the Cambridge site were lime and fertiliser (L+F), lime amended biosolids x 3 rates (LAB, LAB2 and LAB5), anaerobically digested biosolids (ADB), lime amended biosolids not incorporated (LAB-NIC) and a control. Extra replicated plots included for repeat applications in the second year were L+F 2Y and LAB 2Y (2Y indicating 2 applications of the single rate over two years, rather than double the rate in the first year). All treatments except for

LAB2, LAB5 and LAB-NIC were also applied at the Cressy site in the first year. However, poppy seed waste (PSW) and poppy mulch (PM) were also included at the Cressy site in the first year along with PSW 2Y and PM 2Y for repeat applications in the second year. Cereal plant growth and development were monitored regularly throughout the first season at both sites including sequential harvests for biomass determination. Grain yield and quality determinations were made at final harvest for each year. The soil at each site was fully characterised prior to the commencement of each trial. Additional measurements were made over the course of the trial of key soil chemical, physical and biological properties.

Table 8.1 Management details for Cambridge

Year	2007							
Crop	Wheat							
Cultivar	Brennan							
Rate	176 plants/m^2							
Sowing date	July 9, 2007							
Pre-sow tillage	July 1 (100% incorporation surface residue)							
Treatment	L+F	L+F 2Y	LAB	LAB 2Y	LAB-NIC	LAB2	LAB5	ADB
Rate (kg DM/ha)	23 kg/ha NH_4^+-N sowing + 60kg/ha urea on Sep 19		5800		5800	11600	29000	5060
C:N	N/A		5.7		5.7	5.7	5.7	8.5
Organic C fraction	N/A		0.21		0.21	0.21	0.21	0.35
NO_3 (ppm)	Nil		10		10	10	10	10
NH_4 (ppm)	N/A		3590		3590	3590	3590	4390
Application date	July 2		July 2		July 12	July 2	July 2	July 2
Incorporation date	July 5		July 5		N/A	July 5	July 5	July 5
Incorporation depth & fraction	10cm / 0.5		10cm / 0.5		N/A	10cm / 0.5	10cm / 0.5	10cm / 0.5
Year	2008							
Crop	Barley							
Cultivar	Gairdner							
Rate	200 plants/m^2							
Sowing date	September 12, 2008							
Harvest Residues	December 16, 2007 (75% removal of above ground residues)							
Herbicide Appln.	June 17, 2008							
Pre-sow Pdk Prep	July 9 (90% burning of surface residue and stubble)							
Treatment	L+F	L+F 2Y	LAB	LAB 2Y	LAB-NIC	LAB2	LAB5	ADB
Rate (kg DM/ha)	Nil	As per 2007	Nil	5800	Nil	Nil	Nil	Nil
C:N	N/A	N/A	N/A	5.0	N/A	N/A	N/A	N/A
Organic C fraction	N/A	N/A	N/A	0.13	N/A	N/A	N/A	N/A
NO_3 (ppm)	Nil	Nil	N/A	10	N/A	N/A	N/A	N/A
NH_4 (ppm)	N/A	N/A	N/A	1290	N/A	N/A	N/A	N/A
Application date	N/A	Aug 31	N/A	Aug 31	N/A	N/A	N/A	N/A

Table 8.2 Management details for Cressy

Year	2007								
Crop	Barley								
Cultivar	Gairdner								
Rate	204 plants/m^2								
Sowing date	September 18, 2007								
Pre-sow tillage	September 12, 2007 (100% incorporation surface residue)								
Treatment	L+F	L+F 2Y	LAB	LAB 2Y	PM	PM 2Y	PSW	PSW 2Y	ADB
Rate (kg DM/ha)	23 kg/ha NH4-N sowing + 60kg/ha urea on Nov 5		5800		7860		892		5060
C:N	N/A		5.7		16.3		6.8		8.5
Organic C fraction	N/A		0.21		0.26		0.35		0.35
NO_3 (ppm)	Nil		10		2		26		10
NH_4 (ppm)	N/A		3590		9		46		4390
Application date	Sep 13		Sep 13		Sep 13		Oct 11		Sep 13
Incorporation date	Sep 15		Sep 15		Sep 15		N/A		Sep 15
Incorporation depth & fraction	10cm / 0.5		10cm / 0.5		10cm / 0.5		N/A		10cm / 0.5
Year	2008								
Crop	Wheat								
Cultivar	Brennan								
Rate	175 plants/m^2								
Sowing date	June 23, 2008								
Harvest Residues	January 7, 2008 (75% removal of above ground residues)								
Pre-sow tillage	June 16, 2008 (50% incorporation surface residue)								
Treatment	L+F	L+F 2Y	LAB	LAB 2Y	PM	PM 2Y	PSW	PSW 2Y	ADB
Rate (kg DM/ha)	Nil	As per 2007	Nil	5800	Nil	7860	Nil	892	Nil
C:N	N/A	N/A	N/A	5.0	N/A	16.3	N/A	6.8	N/A
Organic C fraction	N/A	N/A	N/A	0.13	N/A	0.26	N/A	0.35	N/A
NO_3 (ppm)	Nil	Nil	N/A	10	N/A	2	N/A	26	N/A
NH_4 (ppm)	N/A	N/A	N/A	1290	N/A	9	N/A	46	N/A
Application date	N/A	Jun 18	N/A	Jun 18	N/A	Jun 18	N/A	Jun 18	N/A
Incorporation date	June 22, 2008								
Incorporation depth & fraction	10cm / 0.5								

8.2.2 APSIM parameterisation and configuration

The modelling study was performed using the APSIM - Agricultural Production Systems Simulator modelling tool (Keating *et al.*, 2003). APSIM simulates agricultural production systems by combining modules describing the specific processes within the system under investigation. In this study, the soil water module SOILWAT2 (Probert ME *et al.*, 1997), the soil nitrogen module SOILN2 (Probert ME *et al.*, 1997), and the surface residue module SurfaceOM (Probert ME *et al.*, 1997) were linked with the WHEAT and BARLEY crop modules. All management details are specified via the MANAGER module. The chemical/nutrient characteristics of each of the product types were configured into the SurfaceOM module. Details are shown in Table 2.1 in Chapter 2. The simulations were based on daily temperature, radiation and rainfall data for Cambridge airport (42.8ºS, 147.5ºE) and the Cressy Research Station (41.7ºS, 147.1ºE), and sourced from the SILO database (www.bom.gov.au/silo). Trial sites were within 10 km of the weather stations nominated. However, actual data from the Cressy site may differ slightly from the recorded data at the research station because of its proximity to a mountain range. Site-specific soil chemical and physical properties were sourced from the soil characterisation performed at each site (National Committee on Soil and Terrain 2009). Site specific details including management settings used in the model, soil details and results of field trials used to validate the model are shown in Chapters 3, 4 and 5. Specific details of each module can be found at www.apsim.info.

The SOILN2 module describes the dynamics of both carbon and nitrogen in soil. Four main pools of C and N are simulated: fresh organic matter (FOM) which includes root or recently incorporated surface residues; soil organic matter which is divided into a 'biom' pool (representing the more labile, soil microbial biomass and microbial products) and 'hum' which comprises the rest of the soil organic matter; and mineral N. The flows between the different pools are calculated in terms of carbon with corresponding nitrogen flows dependent on the C:N ratio of the receiving pool. The rate of decomposition of FOM, biom and hum pools are determined by fixed rate constants modified by factors involving soil temperature, moisture and, in the case of FOM, C:N ratio. To simulate the reduction in susceptibility to decomposition with increasing soil depth, the user can specify the fraction of biom that is subject to decomposition in each layer. Mineralisation or immobilisation of mineral-N is determined as the balance

between the release of nitrogen during decomposition and immobilisation during microbial synthesis and humification. An inadequate supply of mineral-N to satisfy the immobilisation demand results in a slowing of the decomposition. Both ammonium- and nitrate-N are available for immobilisation, though ammonium-N is used preferentially. Decomposition of any organic matter pool results in evolution of carbon dioxide to the atmosphere and transfer of carbon to the biom and hum pools.

The rate of nitrification (ammonium to nitrate conversion) is set by a fixed rate, modified by temperature, water and pH factors. Similarly, the rate of denitrification is a fixed rate modified by temperature and water factors together with the concentration of carbon in the FOM and biom pools. The loss of nitrate via leaching beyond the root zone is simulated by the SOILWAT2 module in conjunction with saturated and unsaturated water flow. Nitrate uptake by the crop is captured within the plant modules.

The SurfaceOM module describes the fate of surface residues. Residue can be burnt, removed without burning, incorporated into the soil via tillage operations, or decomposed. The fraction of residue burnt, removed or incorporated can be set by the operator, as can the depth of incorporation. All above ground residues are considered as a single pool which is defined in terms of its mass, its C:N ratio, and its specific area. Tillage results in a transfer of some surface residue into the soil FOM pool. The rate of decomposition is initially set to a fixed rate and then modified by temperature, C:N ratio, water and contact factors. Decomposition results in loss of some carbon as CO_2 and transfer of carbon and nitrogen to the biom and hum soil pools. Decomposition of residues with a high C:N ratio creates an immobilisation demand, which is satisfied from mineral-N in the uppermost soil layers; in extreme situations, inadequate mineral-N in soil restricts decomposition of residues. The specific area of residue is used to calculate cover due to residue and is used by water balance modules to modify runoff and evaporation.

The SOILWAT2 module simulates the key component processes of the soil water balance; surface runoff and evaporation, saturated and unsaturated flow between layers based on soil-specific water holding characteristics and deep drainage. Water uptake by each crop is simulated by the plant modules.

The WHEAT and BARLEY plant modules simulate the growth and development processes of each crop. These are driven by daily climate inputs (temperature, rainfall and radiation) and influenced by soil nutrient and water status (via interaction with other modules). Also driving the model are management practices such as pre-plant paddock preparation and irrigation.

The model was run on a daily time step basis (1440 minutes) from 01 June 2007 until 01 June 2009. Summary files of the model runs for LAB are provided in Appendix 11.1 for Cambridge and Appendix 11.2 for Cressy.

8.3 Results and discussion

8.3.1 Climate

Seasonal rainfall distribution for the Cressy and Cambridge sites is shown in Figure 8.1and Figure 8.2 respectively. The red lines indicate additional irrigation events.

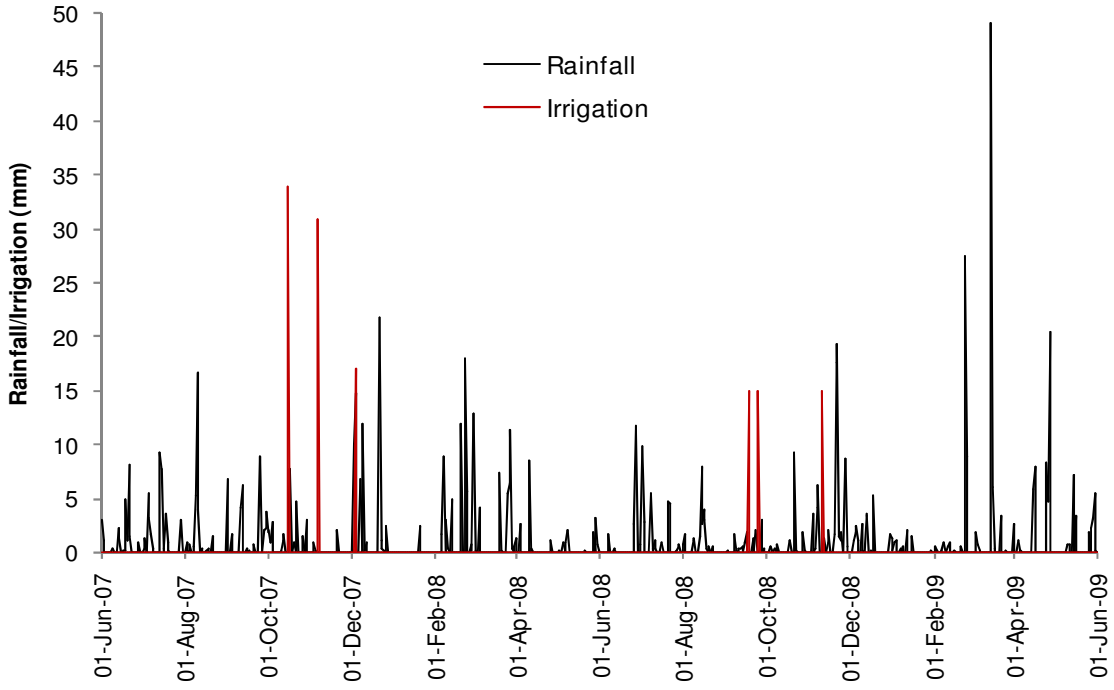

Figure 8.1 Seasonal rainfall distribution and irrigation at the Cambridge trial site for the period of June 2007 until June 2009

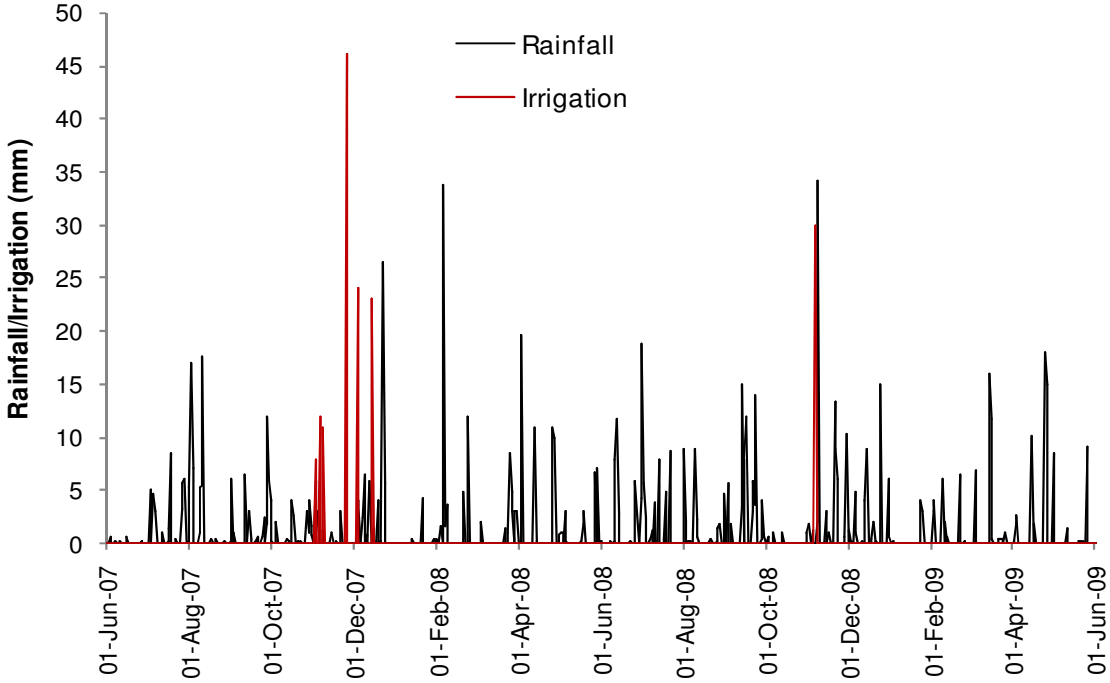

Figure 8.2 Seasonal rainfall distribution and irrigation at the Cressy trial site for the period of June 2007 until June 2009

8.3.2 Surface organic matter (SurfaceOM)

At the Cambridge and Cressy sites, the surface organic matter biomass followed similar seasonal trends for both growing seasons after the single application of biosolids (ADB and LAB) and poppy waste treatments (PM and PSW) in the first year (Figure 8.3). An initial increase of surface organic matter biomass after application was followed by a sharp decrease (~50% of applied organic material) once incorporated, thereafter declining to virtual depletion by the first season harvest due to microbial degradation. The non-incorporated treatment (LAB-NIC) at the Cambridge site displayed the same initial increase, but showed a more gradual decrease than the incorporated treatments (Refer to Figure 8.4). All sites then received a boost from first season harvest residues before declining once more to depletion by the second season harvest. The cultivation event prior to sowing of Year 1 at both sites removed or depleted any existing SurfaceOM for the control and L+F treatments at both sites. Plate 8.1 shows the LAB2 treatment with the depleted existing surface organic matter after cultivation.

Plate 8.1 Cultivation of site following LAB2 treatment application at Cambridge

The PSW treatment at Cressy was similar to the Control and L+F, with the small addition to surface organic matter biomass from the material itself assumed to be depleted by irrigation shortly after application.

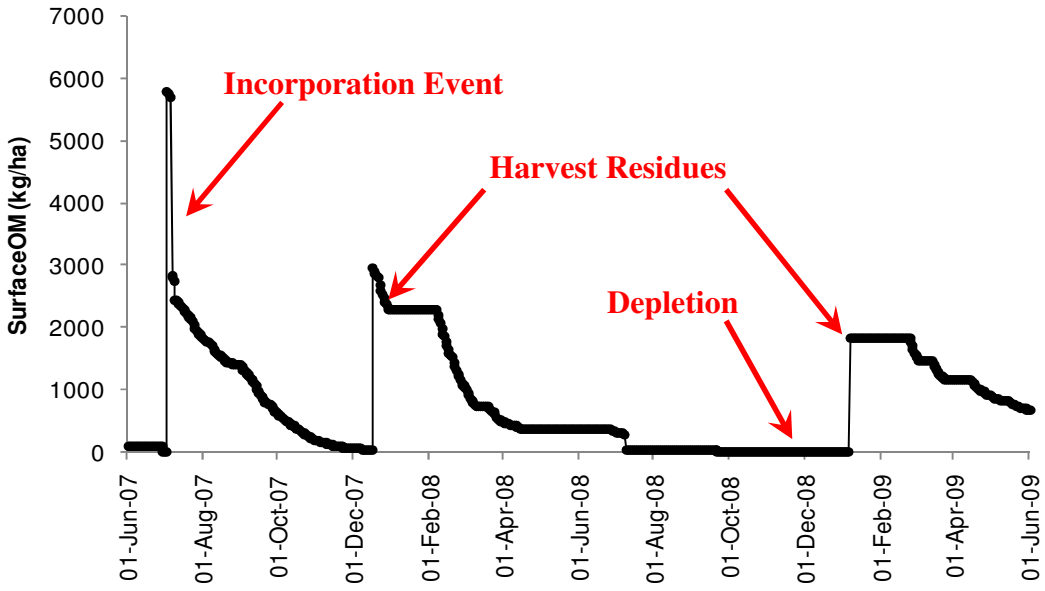

Figure 8.3 Simulated surface organic matter time series – LAB treatment, Cambridge

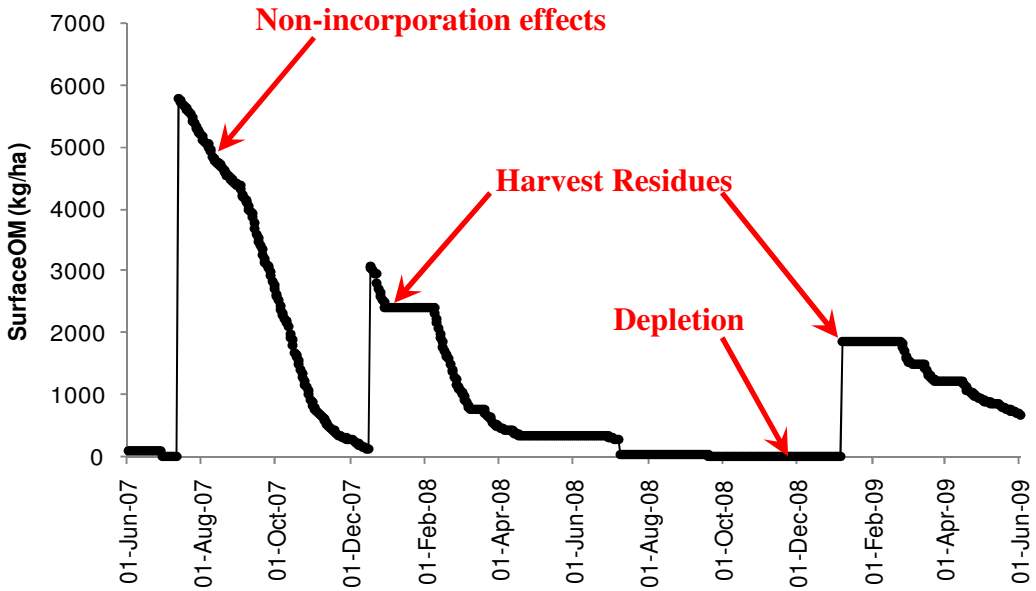

Figure 8.4 Simulated surface organic matter degradation – LAB-NIC, Cambridge

8.3.3 Soil organic matter

Figure 8.5 shows the simulated seasonal trend in soil organic matter nitrogen content for the LAB treatment at the Cambridge site as an example of all organic treatments at both sites (except for PSW at the Cressy site). Upon incorporation, the surface organic matter enters the soil fresh organic matter (FOM) pool, with the majority of the pool converted over time into labile organic matter (BIOM) by microbial activity. The difference between the nitrogen contents of the FOM and BIOM is shown as the nitrogen mineralised over the trial period. The increase in BIOM-N equates to nitrogen that is potentially plant available but bound (i.e. not in mineral form). The corresponding seasonal trends for the inorganic fertiliser treatment (Figure 8.6) at the same site show a slight drawdown of nitrogen from the BIOM pool for both seasons 1 and 2. This may be due to an unfavourable C:N ratio, where nitrogen is redrawn from the BIOM pool by the microbes. Note that both organic and inorganic treatments displayed an increase in BIOM-N between seasons due to decomposing harvest residues and remaining plant material.

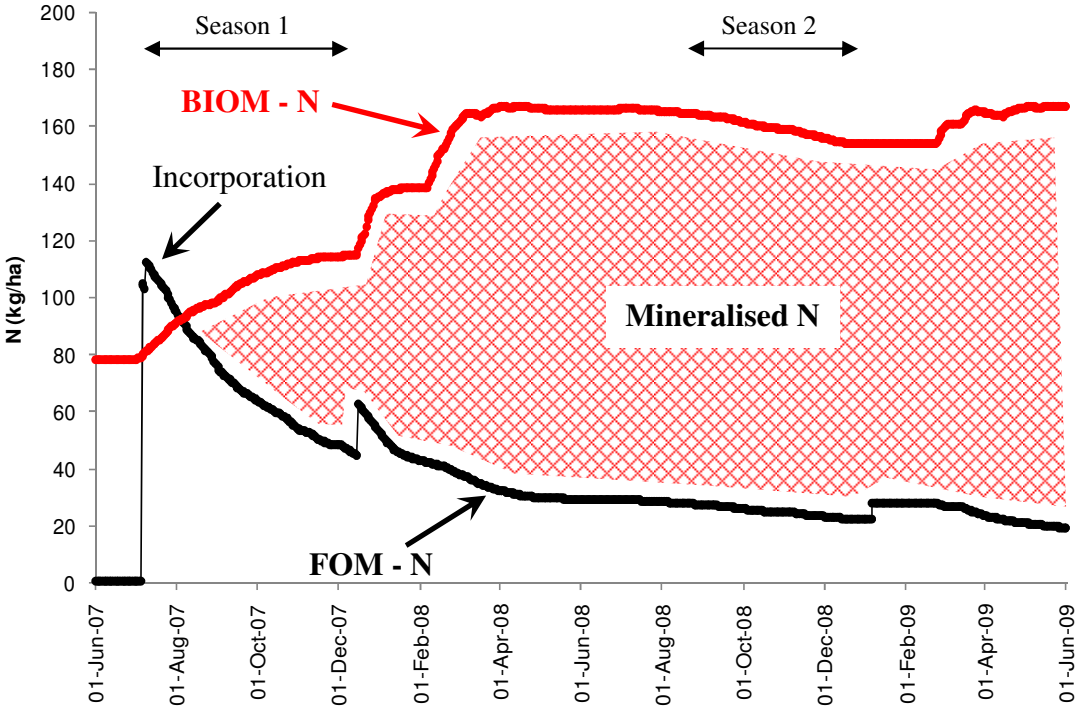

Figure 8.5 Simulated soil FOM and BIOM - N for LAB treatment, Cambridge.

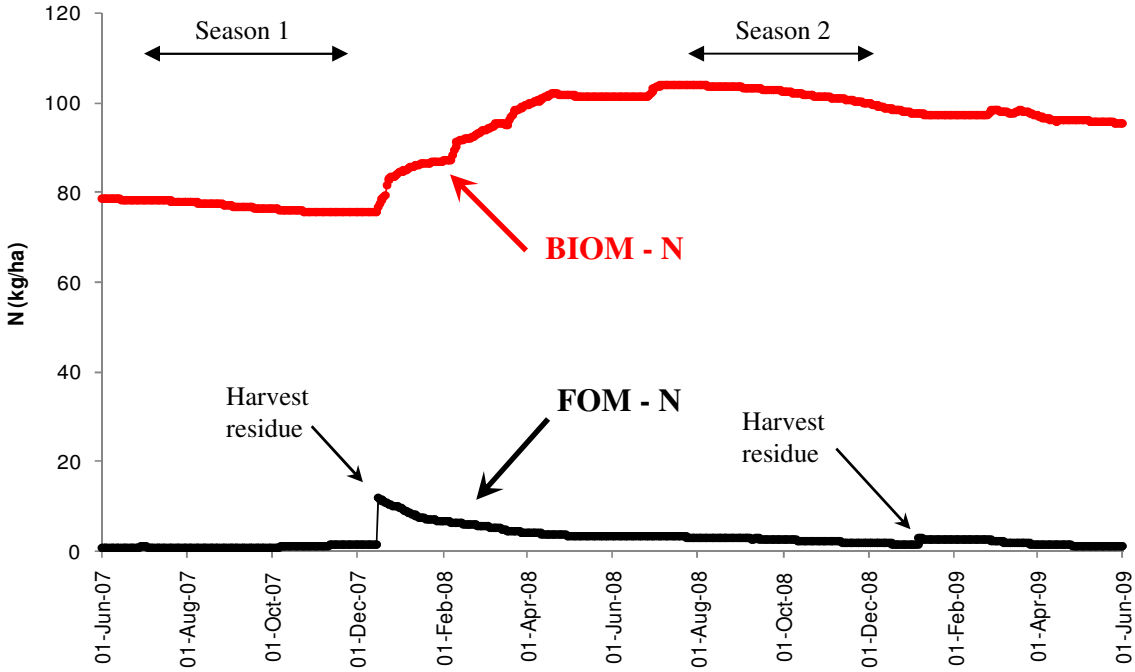

Figure 8.6 Simulated soil FOM and BIOM - N for L+F treatment, Cambridge

The simulated seasonal trend for the PSW treatment at the Cressy site showed that although there was a small increase in FOM-N from the surface applied amendment, there was no mineral nitrogen accumulation in the BIOM pool until after the crop was removed (Figure 8.7). This may be due to immediate plant uptake of the available nitrogen from microbial degradation of the FOM.

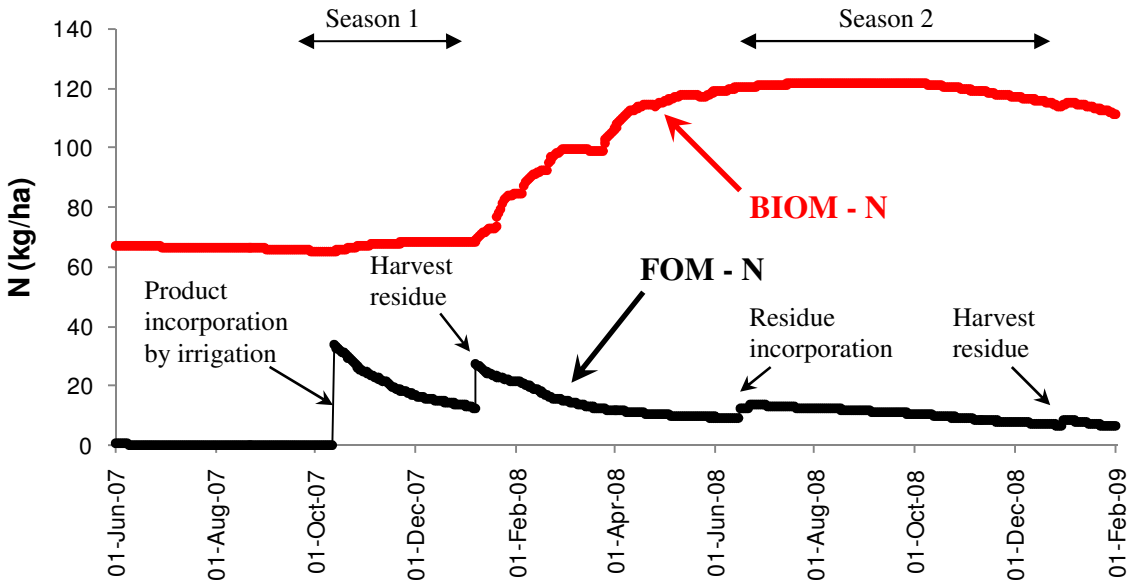

Figure 8.7 Simulated soil FOM and BIOM - N for PSW treatment, Cressy

8.3.4 Soil Mineral Nitrogen

8.3.4.1 *Cambridge*

Figure 8.8, Figure 8.9, Figure 8.11, Figure 8.13, Figure 8.15, Figure 8.16 and Figure 8.17 show the seasonal trends in total mineral nitrogen in the top 10 cm of the soil profile for each of the seven treatments at the Cambridge site. The simulated results aligned closely to the observed results for the first growing season for all treatments except for LAB5 and LAB-NIC (Figure 8.16 and Figure 8.17 respectively). After incorporation, all organic treatments displayed a sharp increase in soil mineral N. Initially, this increase would be from the mineral N contained in the product, thereafter, from mineralization of organic nitrogen within the product. An increase in crop demand decreases soil stocks of soil mineral N, leading to eventual crop N stress that slows growth. This results in a decrease in crop demand and subsequent onset of later growth

stages of crop phenological development. After soil mineral N reaches pre-sowing levels at or near harvest, soil stocks are gradually replenished due to mineralisation between cropping seasons until crop demand once again decreases soil stocks in the second season. Note that the observed results for all organic treatments for the second year appear to vary from simulated results by approximately five orders of magnitude. This may be because the model was not set up to allow for additional soil biomass between seasons from weed growth and plant regrowth. Furthermore, uncertainties in initial settings such as pre-crop soil nitrate and soil moisture may have contributed to substantial errors over the two year term. Another reason why simulated results varied from the observed results in the second year may be because some processes used within the model are not yet fully understood (i.e. decomposition of, and nutrient release from, organic materials).

Crop demand decreased soil mineral N for the 1NLBAR biosolids treatments, ADB and LAB, through September 2007 (shown in Figure 8.8 and Figure 8.9 respectively).

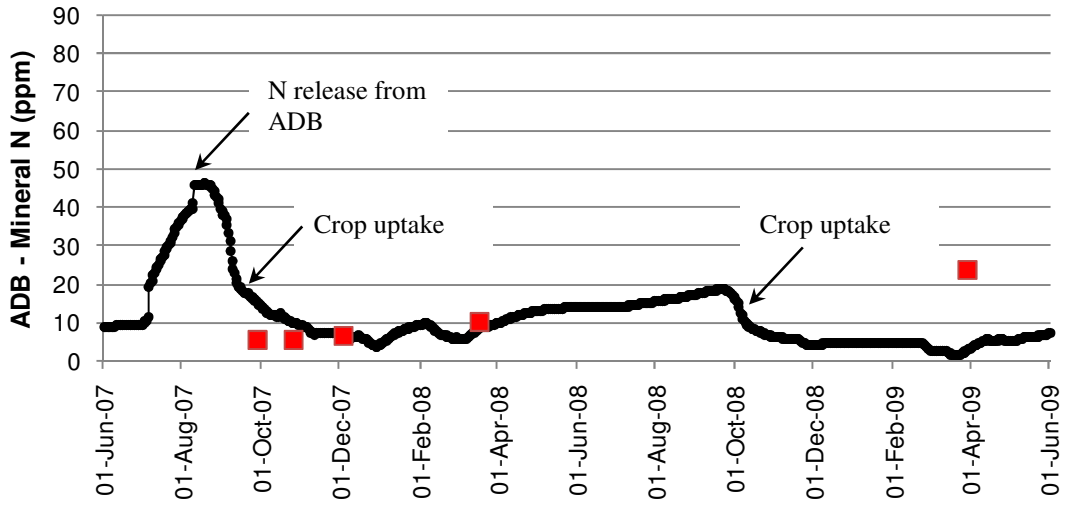

Figure 8.8 Simulated (line) and observed (red points) mineral N (0-10cm) for the ADB treatment at the Cambridge site.

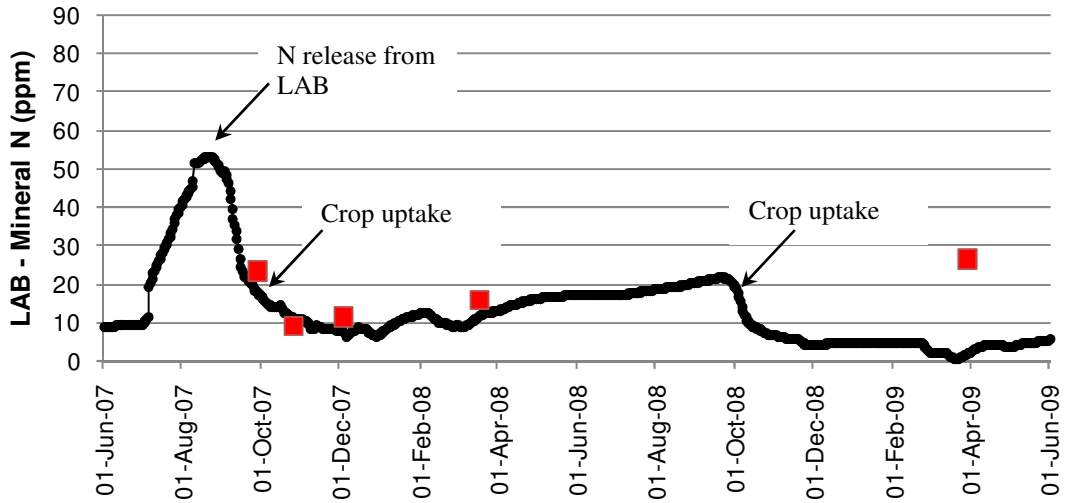

Figure 8.9 Simulated (line) and observed (red points) mineral N (0-10cm) for the LAB treatment at the Cambridge site.

The model indicated crop N stress through October 2007 (Figure 8.10), which was followed by a period of crop water stress until early December 2007. Crop water stress is shown as SW Stress, which indicates the crop stress related to soil water (SW). This shows that water supply from irrigation and rainfall did not meet crop requirements for the same period. Trends were similar in 2008 for N stress, although irrigation and rainfall in November and December 2008 reduced water stress. Leaf expansion is shown as it is considered a more sensitive indicator of stress (Angus, 1977).

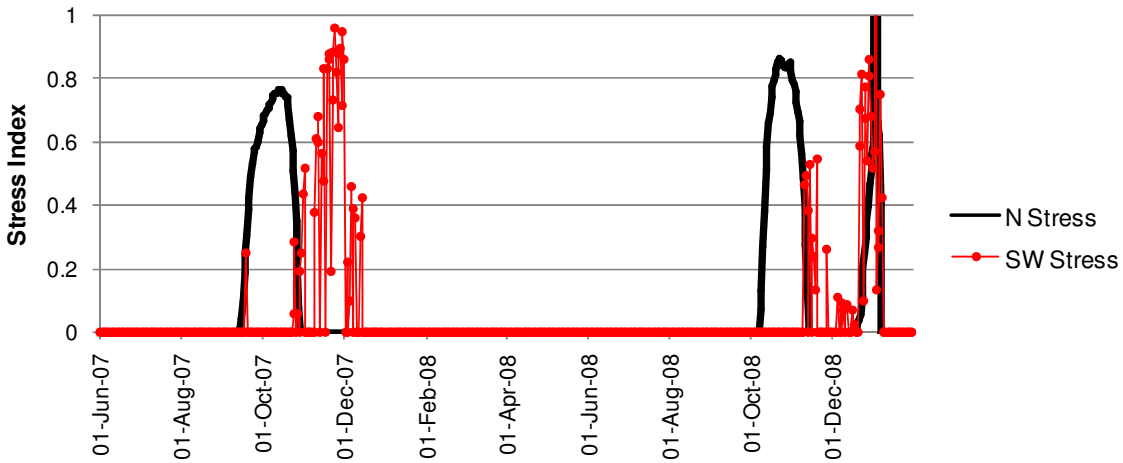

Figure 8.10 Simulated crop nitrogen and water stress for leaf expansion – LAB (similar to ADB) at the Cambridge site.

Note: stress index scale ranges from 0 (no stress) to 1 (maximum stress)

However, the magnitude of simulated plant available soil mineral N in the early stages of crop growth in the first season (between July and October, 2007) for the LAB2 treatment (Figure 8.11) reduced subsequent crop nitrogen stress but increased the magnitude and intensity of crop water stress soon after (Figure 8.12). That is, the extra nitrogen supply early in the season resulted in a larger canopy and above ground biomass. This in turn resulted in a larger demand for water later in the season and higher crop water stress index values.

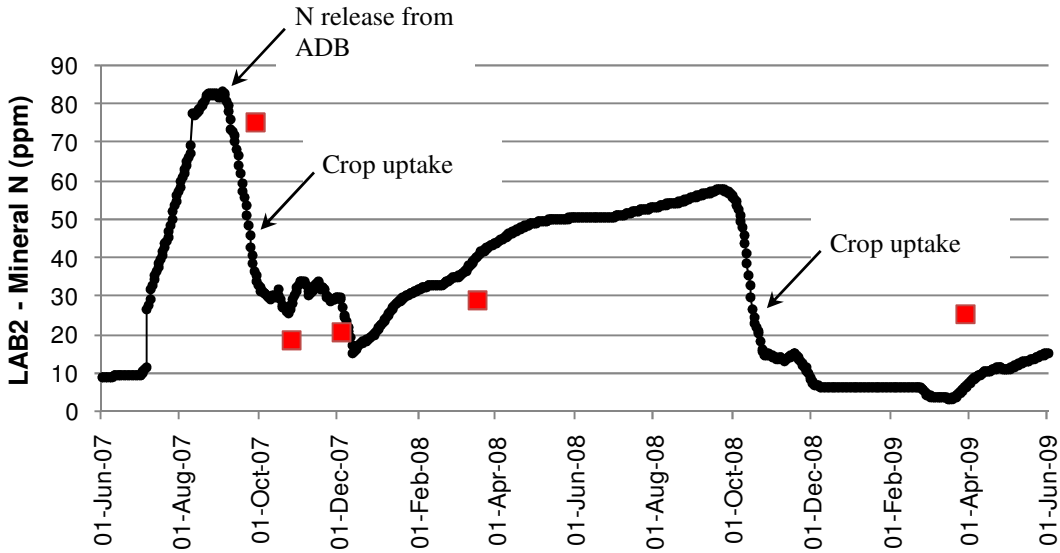

Figure 8.11 Simulated (line) and observed (red points) mineral N (0-10cm) for the LAB2 treatment at the Cambridge site.

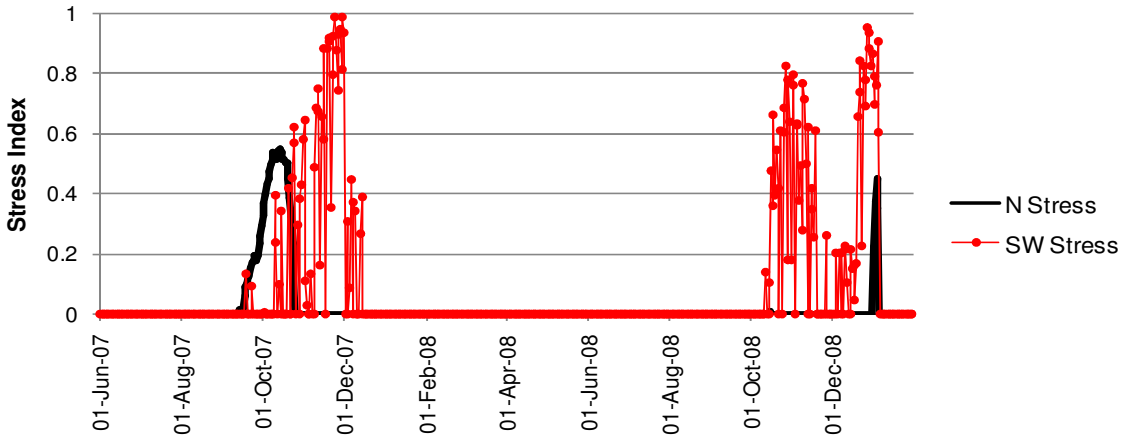

Figure 8.12 Simulated crop nitrogen and water stress for leaf expansion – LAB2 at the Cambridge site.

Note: stress index scale ranges from 0 (no stress) to 1 (maximum stress)

The sharp soil mineral N increases in July and September of 2007 for the L+F treatment are due to pre-plant incorporated fertiliser (DAP) and top dressed fertiliser (Urea) events (Figure 8.13). However, this was followed by depletion in soil mineral N to such an extent that crop nitrogen stress occurred earlier and with more severity than the organic amendments, while crop water stress was still evident in November and December of 2007 (Figure 8.14).

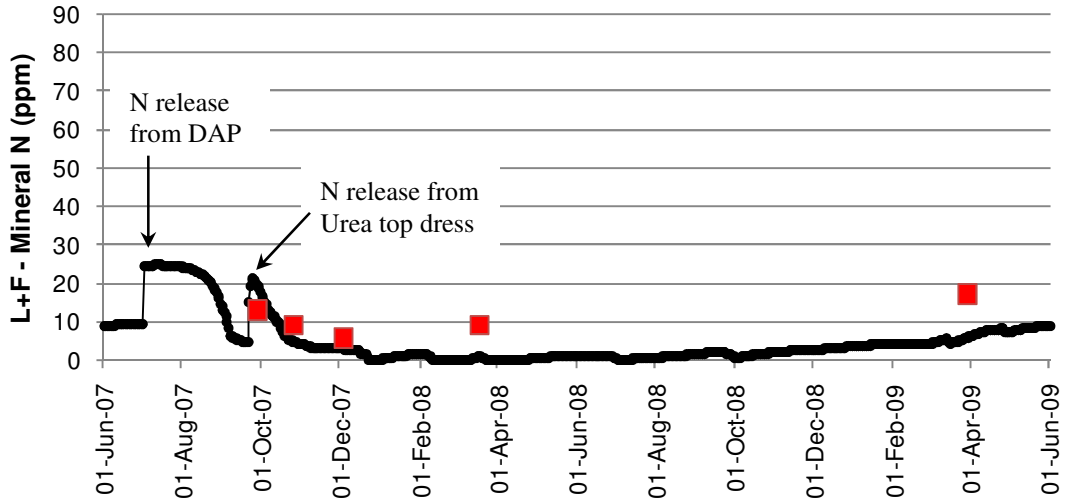

Figure 8.13 Simulated (line) and observed (red points) mineral N (0-10cm) for the L+F treatment at the Cambridge site.

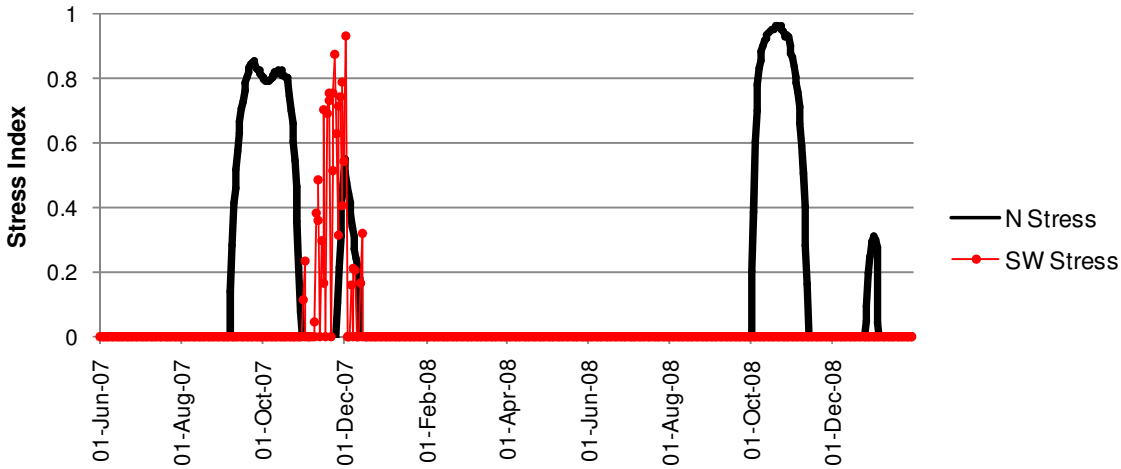

Figure 8.14 Simulated crop nitrogen and water Stress for leaf expansion – L+F at the Cambridge site.

Note: stress index scale ranges from 0 (no stress) to 1 (maximum stress)

Unlike all other treatments, the control treatment showed that soil stocks of mineral N were completely exhausted by plant demand in September 2007 (Figure 8.15). In contrast to the biosolids treatments the limited nitrogen supply early in the season for the control treatment resulted in a smaller canopy and above ground biomass, which in turn reduced water demand and subsequent nitrogen demand later in the season.

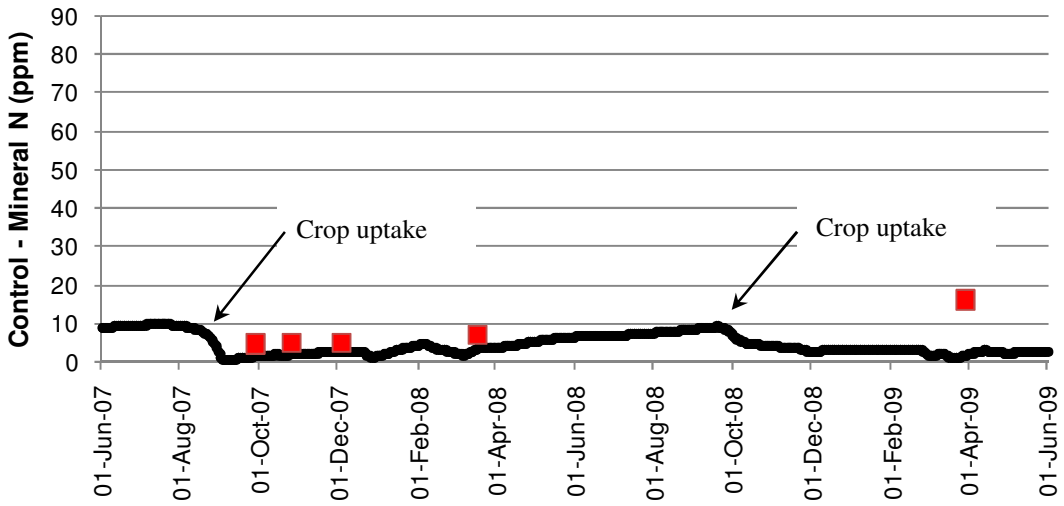

Figure 8.15 Simulated (line) and observed (red points) mineral N (0-10cm) for the Control treatment at the Cambridge site.

Simulated seasonal trends for the LAB5 treatment shown in Figure 8.16, follow a similar observed trend but only for the first three results. The remaining observed results are considerably lower than simulated results. Calculations in the model are based on even distribution of product through incorporation and uniform soil contact whether fully, partially or not incorporated. This assumption may have lead to an overestimation of mineral N, because the consistency (similar to scone dough) and water content (75%) of the product applied at five times the guideline rate meant that distribution was not uniform in the field trials.

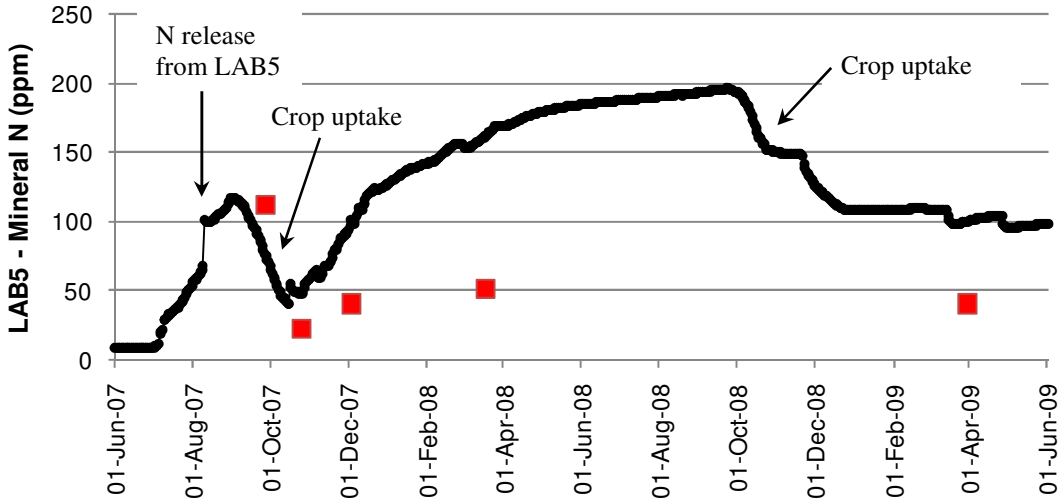

Figure 8.16 Simulated (line) and observed (red points) mineral N (0-10cm) for the LAB5 treatment at the Cambridge site.

LAB-NIC in Figure 8.17 shows that the model overestimated mineral N at the beginning of the first season but underestimated mineral N at the end of the second season, for reasons given above for LAB5.

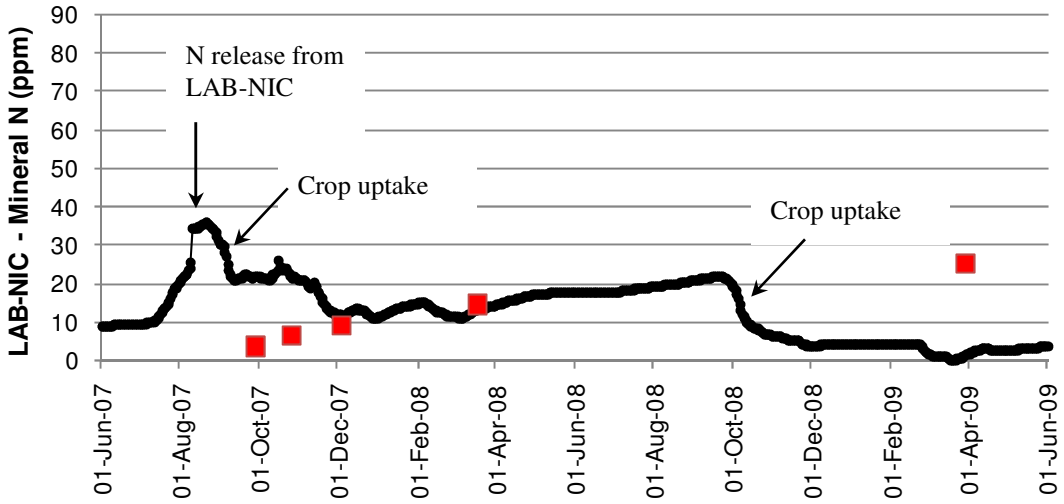

Figure 8.17 Simulated (line) and observed (red points) mineral N (0-10cm) for the LAB-NIC treatment at the Cambridge site.

8.3.4.2 ***Cressy***

Unfortunately, observed soil mineral N results at the Cressy site were only obtained late in the first season and during the second season. However, the simulated soil mineral N did appear to follow the general trend of observed results for both biosolids treatments until September 2008, where the decrease was estimated to be more than observed (Figure 8.18). This disparity was addressed in section 8.3.4.1.

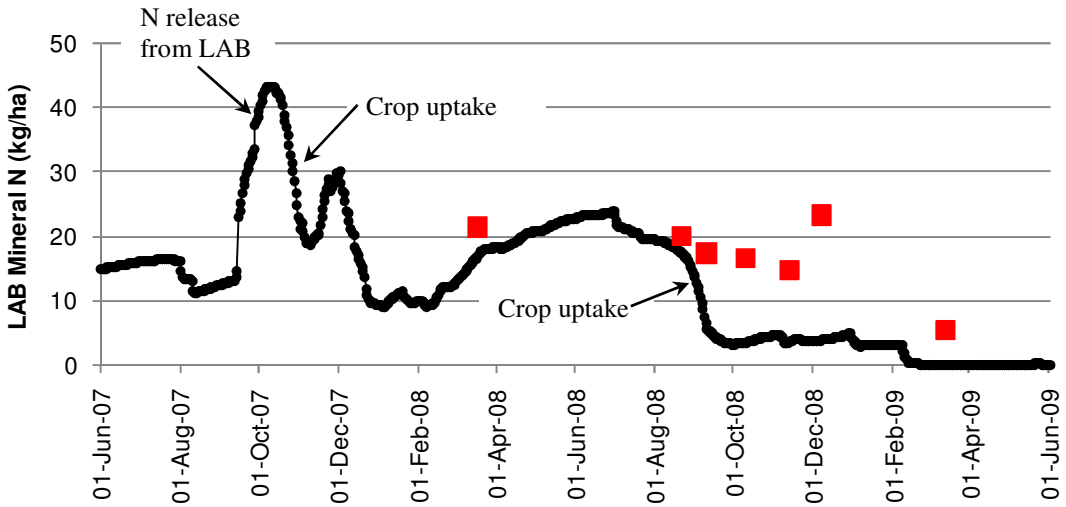

Figure 8.18 Simulated (line) and observed (red points) mineral N (0-10cm) for the LAB treatment at the Cressy site (ADB treatment similar).

The simulated soil mineral N and obvious variation to observed results shown for the PSW treatment at the Cressy site (Figure 8.19) is similar for treatments PM, Control and L+F at the same site.

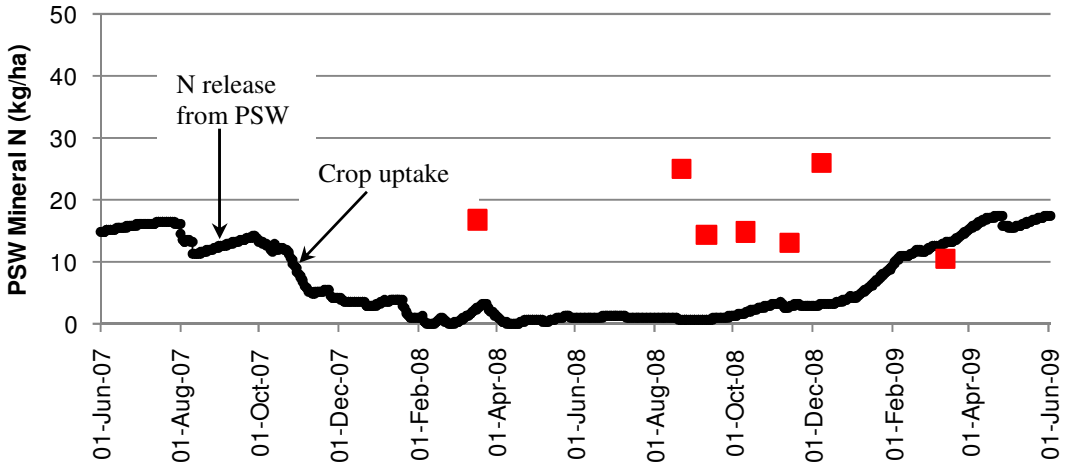

Figure 8.19 Simulated (line) and observed (red points) mineral N (0-10cm) for the PSW treatment at the Cressy site.

The simulated crop nitrogen stress and water stress for the PSW (Figure 8.20) at the Cressy site was less than ADB and LAB at the Cambridge site (Figure 8.10). This may be due to less N availability at trial commencement, leading to lower crop biomass and less water demand. However the lower stress values may also be due to rainfall and irrigation at the Cressy site being more uniformly distributed than the Cambridge site.

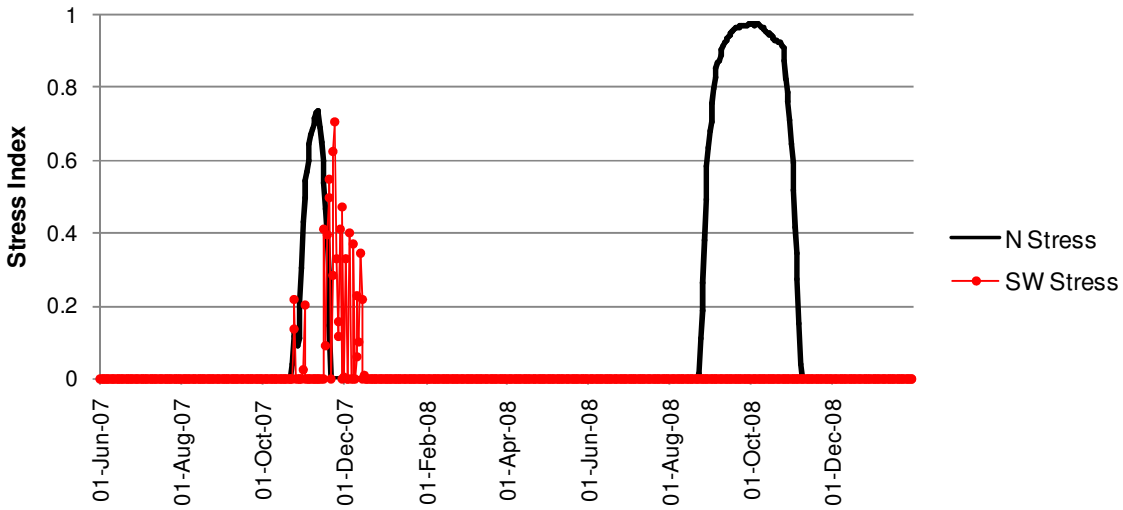

Figure 8.20 Simulated crop nitrogen and water stress – PSW at the Cressy site.

Note: Stress index scale ranges from 0 (no stress) to 1 (maximum stress)

8.3.5 Biomass and yield

8.3.5.1 *Cambridge biomass*

The simulated crop biomass trend for all of the organic treatments at the Cambridge site followed the observed biomass results until flowering in late November 2007, but then overestimated the biomass at harvest of the same year by a factor of approximately two (Figure 8.21).

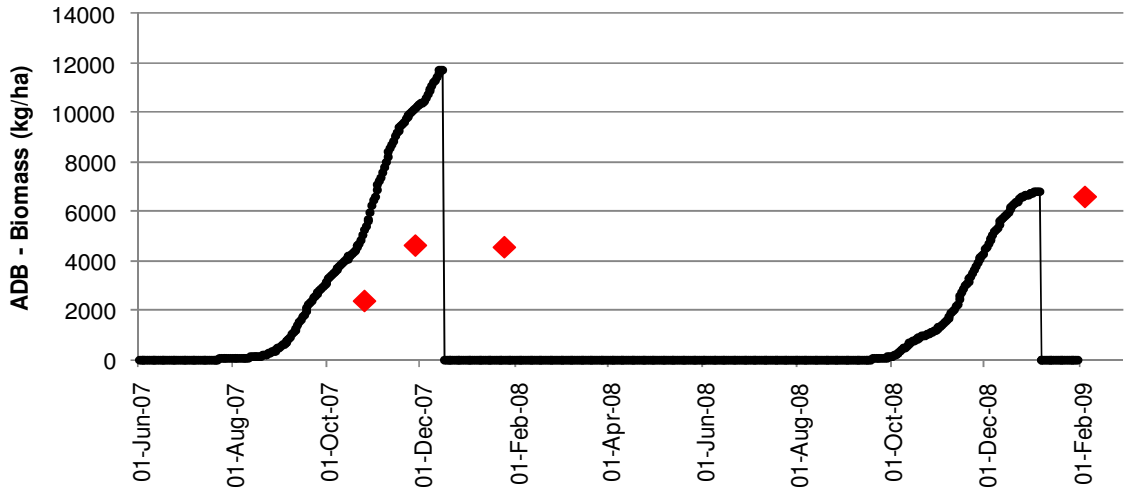

Figure 8.21 Simulated (line) and observed (red points) crop biomass for the ADB treatment at the Cambridge site (as typical for all organic treatments).

A possible cause for this over-predication was the presence of weeds throughout the growing season and seed shedding prior to harvest. Table 8.3 shows the magnitude of weed pressure and shattered heads (table also shown in Chapters 4 and 5). Percentage of weeds is based on total plant biomass per square metre and percentage of shattered heads is based on total head count per square metre. The weeds would have increased competition for nutrient and water resources thereby reducing observed results, whilst the shattered heads may have been the result of nutrient supply not being met by adequate water supply (as shown for LAB2 in Figure 8.12).

Without the weed pressure in the following year, simulated biomass at harvest was very close to the observed result. Note that simulated crop maturity is approximately 30 days before observed results because simulated crop maturity is taken at physiological

maturity (seed formation - when contents are considered milky) and not at dry maturity (seed moisture content below 11%).

Table 8.3 Agronomic results of all treatments at Cambridge in year 1

	ADB	**Control**	**L+F**	**LAB**	**LAB2**	**LAB5**	**LAB-NIC**	**LSD** (P≤0.05)
Height Z71 (cm)	61.2 ^{ab}	57.5 ^{a}	64.9 ^{abc}	63.8 ^{ab}	76.3 ^{d}	75.5 ^{cd}	69.5 ^{bcd}	10.8
Biomass Z71 (t/ha)	4.6 ^{ab}	3.9 ^{a}	4.7 ^{ab}	7.4 ^{bc}	7.4 ^{bc}	9.9 ^{c}	7.0 ^{abc}	3.2
1000 Grain Wt (g)	46.4 ^{c}	44.9 ^{bc}	46.8 ^{c}	45.6 ^{bc}	44.2 ^{ab}	42.6 ^{a}	46.5 ^{c}	2.2
Weeds (%)	20.9 ^{ab}	12.3 ^{a}	23.5 ^{ab}	10.6 ^{a}	34.6 ^{b}	22.4 ^{ab}	34.6 ^{b}	16.0
Shattered Heads (%)	4.4 ^{a}	0.0 ^{a}	7.7 ^{a}	5.8 ^{a}	28.0 ^{b}	27.1 ^{b}	6.0 ^{a}	18.6
Yield (t/ha)	1.7 ^{abc}	1.4 ^{ab}	2.0 ^{bc}	2.2 ^{c}	1.6 ^{abc}	1.2 ^{a}	2.2 ^{c}	0.8

The simulated crop biomass trend for the control treatment at the Cambridge site followed to the observed results more closely (Figure 8.22). This may be due to little or no weed pressure and seed shedding observed for this treatment. Also, reduced nitrogen availability, reduces general crop growth and subsequent water requirement.

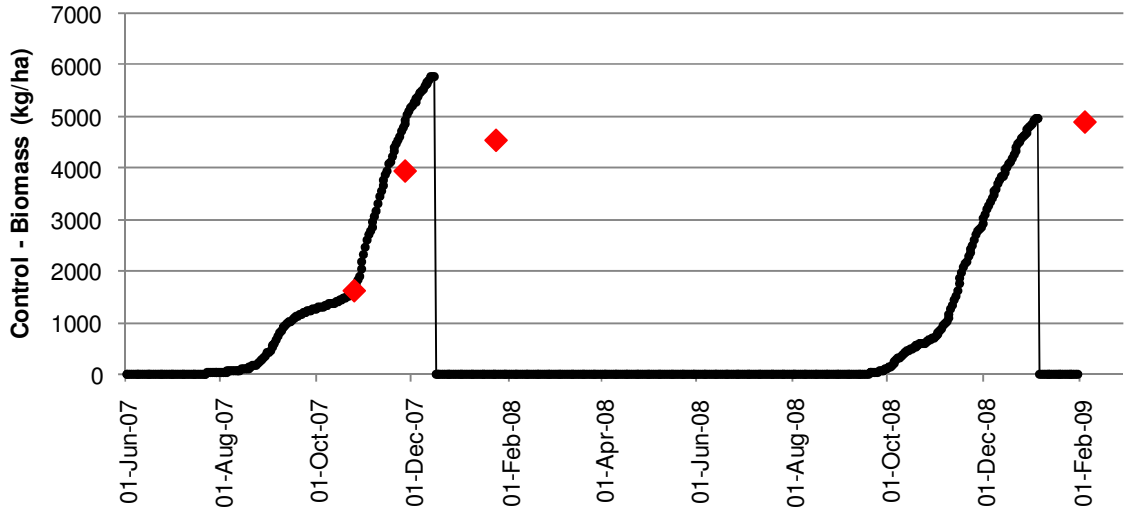

Figure 8.22 Simulated (line) and observed (red points) crop biomass for the Control treatment at the Cambridge site.

8.3.5.2 *Cressy biomass*

The simulated crop biomass trend for both biosolids treatments at the Cressy site followed the observed biomass results for the first season, albeit with an earlier maturity, although biomass in the second season was overestimated (Figure 8.23).

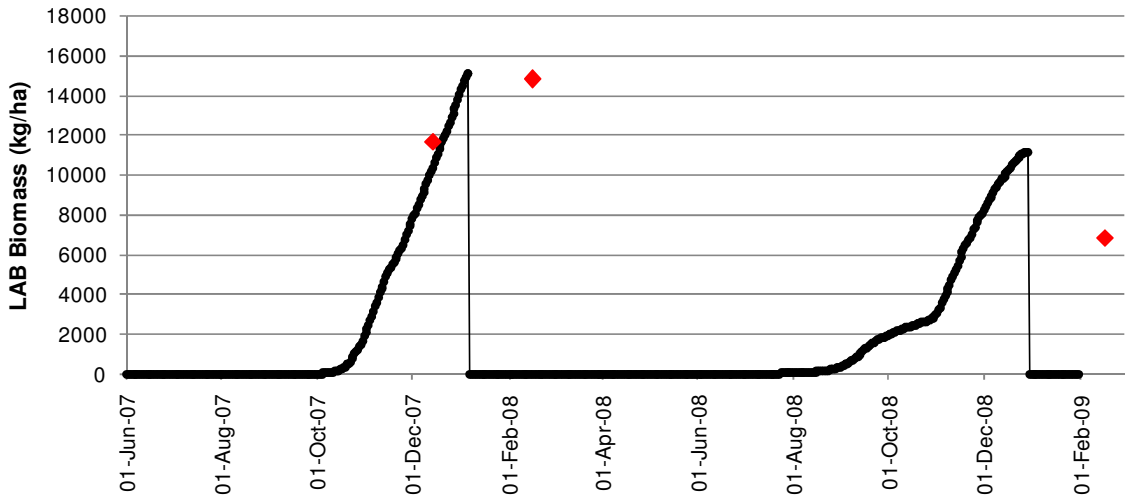

Figure 8.23 Simulated (line) and observed (red points) crop biomass for the LAB treatment at the Cressy site (similar to ADB).

This may have been due to poor crop establishment and growth in the second year because of unfavourable climatic conditions resulting in waterlogging. The simulated crop biomass trends for the control and L+F treatments were also similarly close to

observed results as per the biosolids treatments in the first year (Figure 8.24). However, the simulated biomass in the second season was well below the observed result.

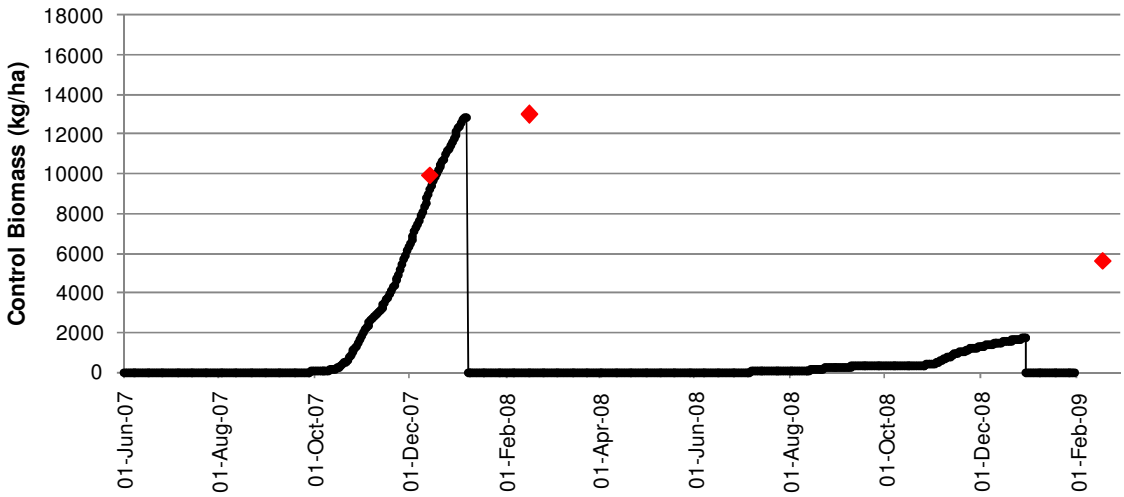

Figure 8.24 Simulated (line) and observed (red points) crop biomass for the Control treatment at the Cressy site (similar to L+F).

This may have been because the model did not account for soil biomass accumulation from weeds and crop regrowth between seasons and subsequent nutrient supply in the second season. As a further contrast, the simulated crop biomass trends for both poppy waste treatments (PM and PSW) were close to the observed results for both years (Figure 8.25). This may be due to both products being relatively dry (PM - 55.1%, PSW – 10.8% moisture respectively) resulting in more uniform spreading and incorporation. Therefore the model was able to better predict outcomes.

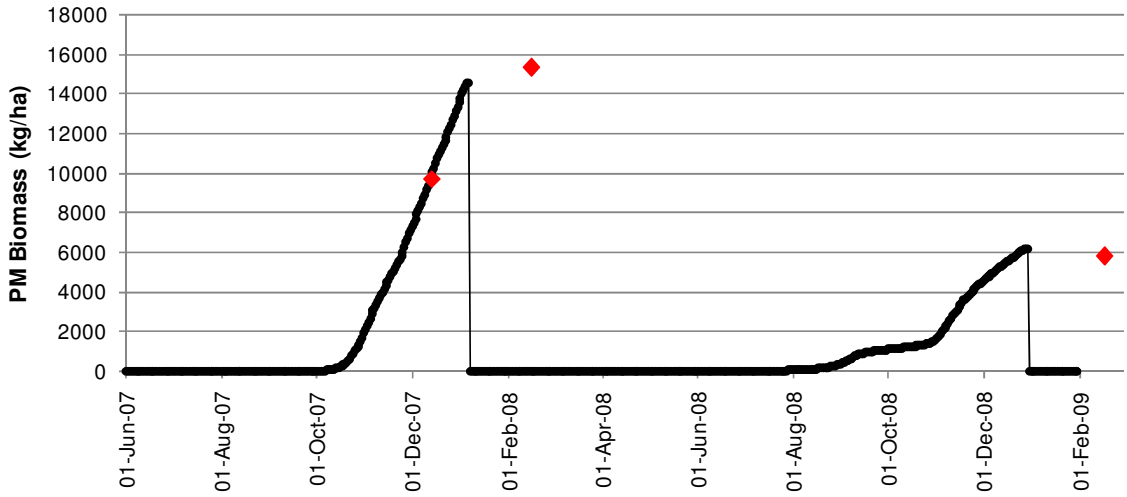

Figure 8.25 Simulated (line) and observed (red points) crop biomass for the PM treatment at the Cressy site (similar to PSW).

8.3.5.3 ***Cambridge yield***

The simulated wheat yield trends at the Cambridge site (Figure 8.26 and Figure 8.27) were similar to the simulated biomass trends at the same site. In 2008, the yields at Cambridge were overestimated for all treatments except for the control (Figure 8.26). This may be due in part to model assumptions that organic products were uniformly incorporated, and to the effects of weed competition and seed shedding referred to earlier. However, there is also an apparent inverse trend between simulated and observed results with the increased application rates of LAB. This may have been caused by higher nitrogen inputs, with limited water, reducing grain size and final yield. Ultimately, the model is predicting the potential yield of these treatments given the absence of the constraints listed.

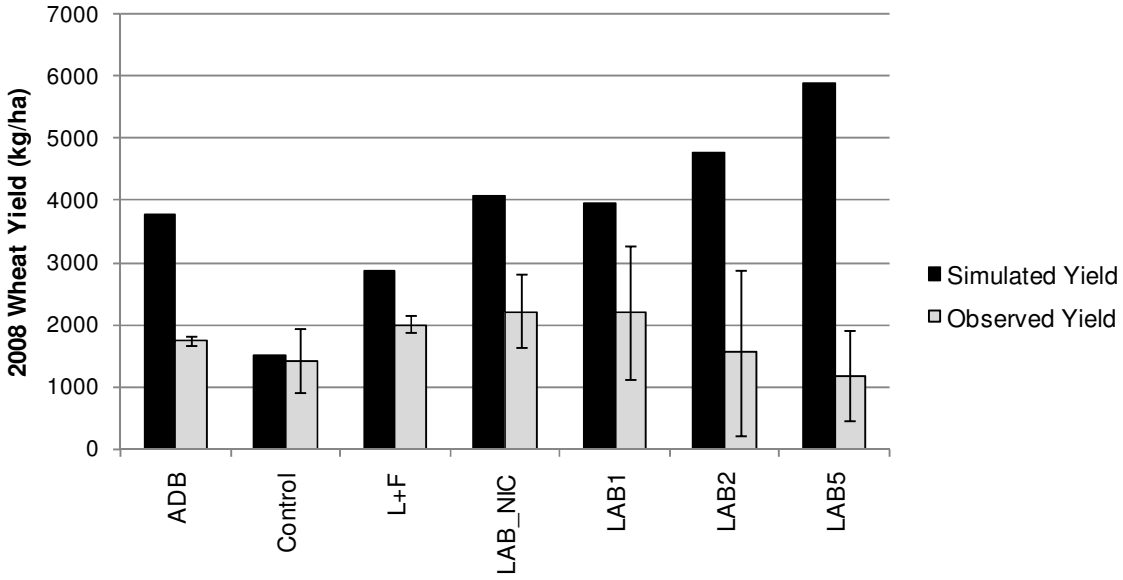

Figure 8.26 2008 season simulated and observed wheat yield for the Cambridge site.

Note: error bars are standard deviation of the mean.

Figure 8.27 shows that the difference between observed and simulated results was much less in the second year. This may have been because weed competition was less and there was no seed shedding. Importantly, the model is picking up the trend in yield.

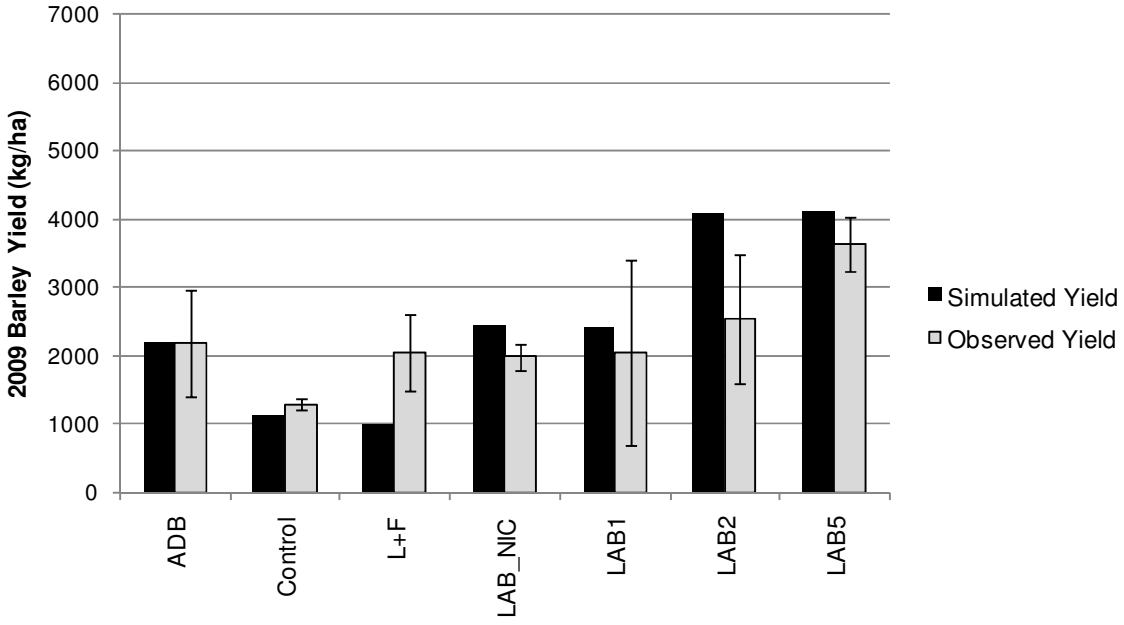

Figure 8.27 2009 season simulated and observed barley yield for the Cambridge site.

Note: error bars are standard deviation of the mean.

8.3.5.4 ***Cressy yield***

The Cressy site shown in Figure 8.28 contrasted with the Cambridge site in that simulated results in the first year matched closely with the observed yield results, despite the variability in results for LAB and ADB. Better alignment may have been achieved because there was no weed pressure at the Cressy site due to barley being a much more competitive plant than wheat. Also, this site was not exposed to deficit irrigation and subsequently water was not limiting the uptake of available nutrients.

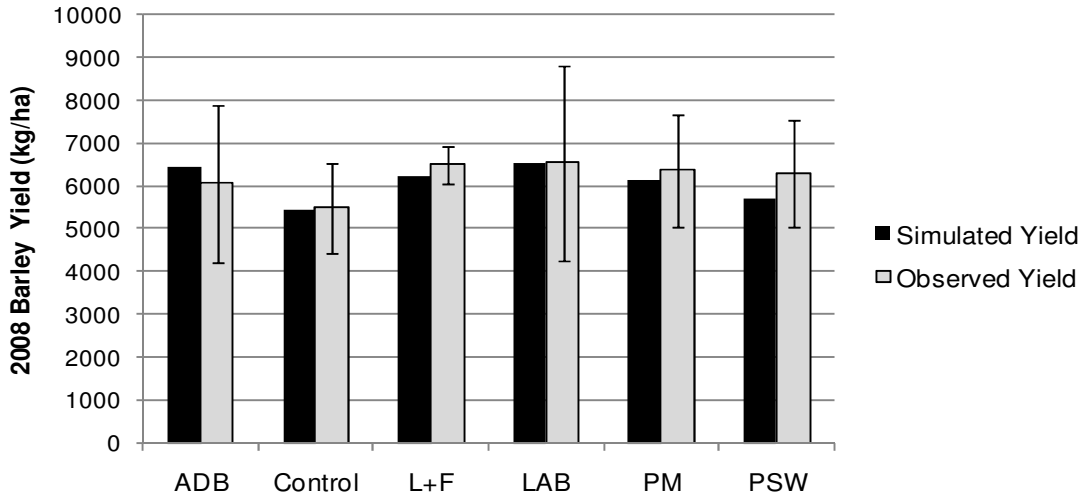

Figure 8.28 2008 season simulated and observed barley yield for the Cressy site.

Note: error bars are standard deviation of the mean.

The second year simulated yield for Cressy shown in Figure 8.29 was relatively close to observed results for ADB, LAB and PM, but not as close for Control, L+F and PSW. The under-prediction of yield for these latter treatments was also evident for mineral N (Figure 8.19), suggesting that factors such as initial soil nitrate, carbon to nitrogen ratio and organic matter in general may not have been correctly parameterised.

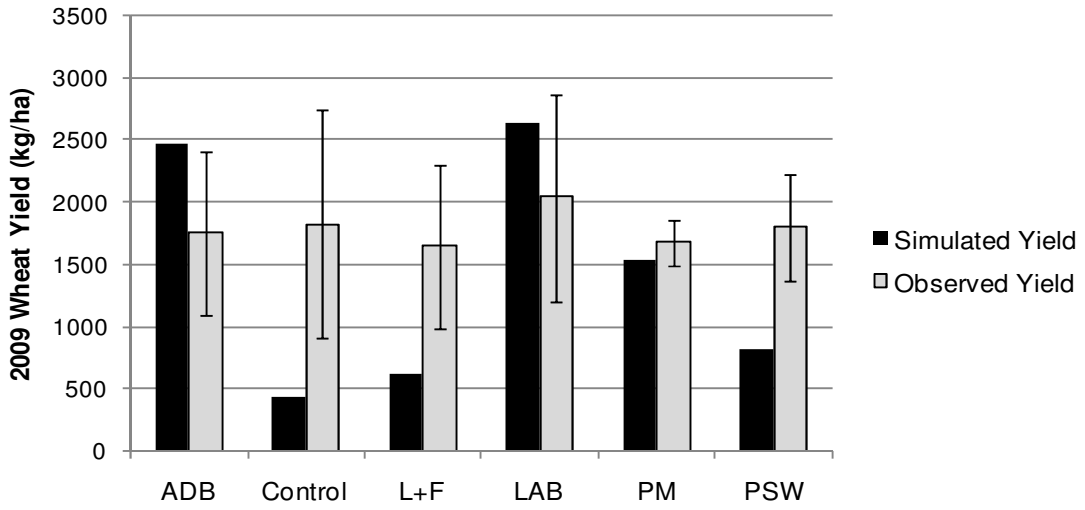

Figure 8.29 2009 season simulated and observed wheat yield for the Cressy site.

Note: error bars are standard deviation of the mean.

8.3.6 Nitrate Leaching

The model indicated very little nitrate accumulation with depth at each site over both years for all but one treatment. The model showed an accumulation of nitrate N for LAB5 but only in the 15 – 30 cm soil depth (Figure 8.30). This increase in nitrate N between growing seasons may be attributed to temperature driven microbial activity, although there was no corresponding increase in the soil layer above. This suggests that the accumulation may be a result of leaching from the upper soil layer as evidenced by the spike in nitrate in association with substantial rainfall events in December 2007 and March 2008 (Figure 8.31).

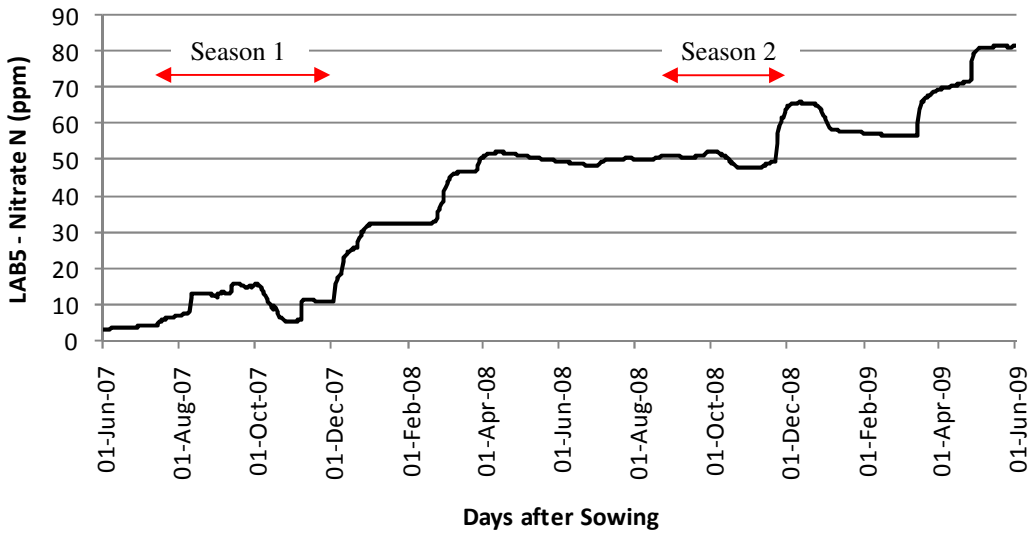

Figure 8.30 Simulated soil nitrate in the 15 – 30 cm depth at the Cambridge site for LAB5 treatment.

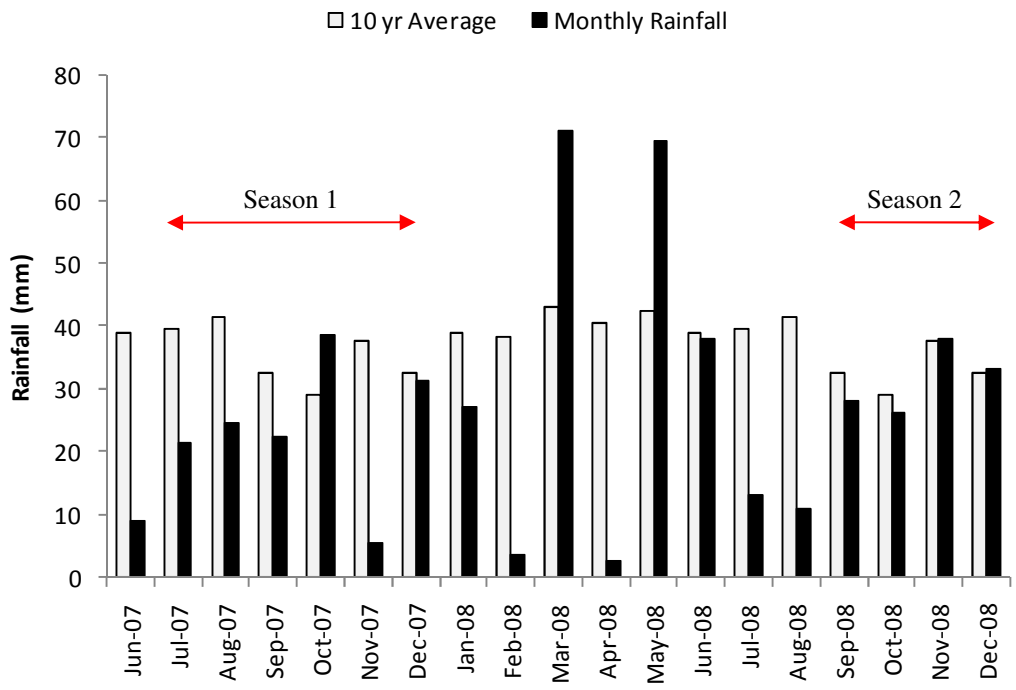

Figure 8.31 Monthly rainfall for the Cambridge site
(sourced from SILO database, www.bom.gov.au/silo)

Nitrate leaching is normally associated with a combination of excess loading and high rainfall/irrigation. However, leaching is also a complex response to soil physical properties, crop and evaporative losses and rooting depth. Therefore, including wetter years in future long-term modelling studies may assist in determining the maximum loading from these organic amendments.

8.3.7 Soil Carbon

The simulated seasonal trend for soil carbon was similar for all organic amendment treatments at both sites for both years (Figure 8.32 and Figure 8.33), aside from the different site treatment prior to commencing season two (burning residues as against incorporation). Initial soil carbon increased after incorporation of the organic treatments in the first season. As the soil organic matter is degraded via microbial activity, CO_2 is released, leading to a decline in soil carbon. However, as introduced organic material and other surface residues (indicated as SurfaceOM) are broken down through the season, soil carbon gradually accumulates. The harvest event each year introduces new organic material, which then undergoes degradation as previously described.

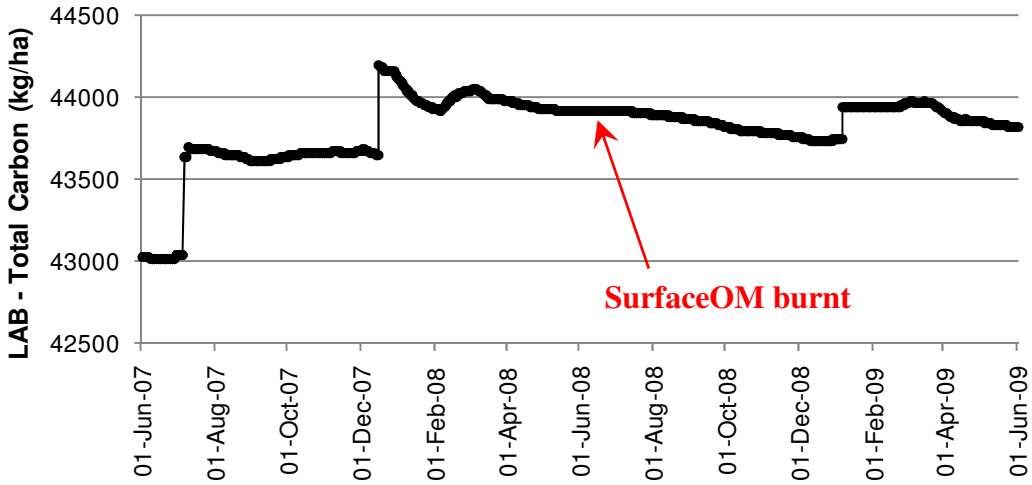

Figure 8.32 Simulated seasonal trends of total carbon for the LAB treatment at the Cambridge site.

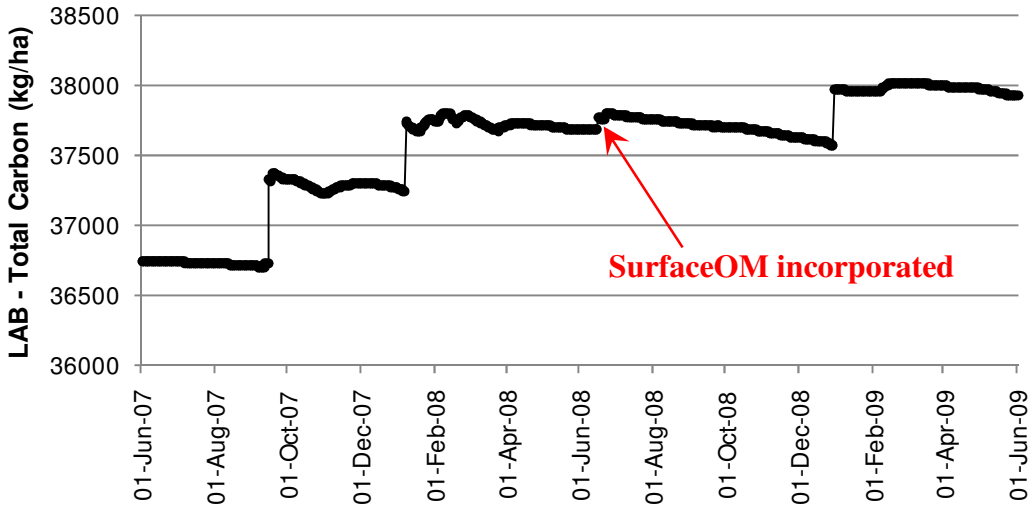

Figure 8.33 Simulated seasonal trends of total soil carbon for the LAB treatment at the Cressy site.

8.4 General Discussion

The main objective of undertaking the modelling was to compare the simulated crop growth, development and yield, and key soil nutrient (N and C) responses to soil-

applied organic materials against field results in a different set of environments. The model was also used to improve component process understanding related to applying bio-resources to soil, with a view to using the output from the model to assist in the interpretation of results from two field trials conducted at Cambridge and Cressy in Tasmania. Furthermore, the model was used to identify any off-site risks of nitrogen loss particularly with higher application rates of biosolids.

The caveat with using any model is that all models are wrong but some models are useful (Derry, 1999), suggesting that models are oversimplifications requiring omissions and assumptions. For example in response to application of different bio-resources, the APSIM model does not consider the impact that microbial population dynamics may have on the potential change in nitrification rate over time (http://www.apsim.info/Wiki/SoilN.ashx). This has implications for bio-resources that cannot be uniformly distributed through the soil matrix, such as higher rates of LAB.

It must also be noted that environmental data used in the model from the SILO database (www.bom.gov.au/silo) for both the Cambridge and Cressy sites was collected up to 10 km away from the trial sites. This may explain some of the variation between observed results and simulations.

Major findings from the simulation were that:

- All surface organic matter remaining after product incorporation in the first season was fully degraded within 5 – 6 months of the application date, although the rate was slower in the winter months.
- The application of organic materials was shown by the simulations to potentially increase soil carbon. It also reinforced the premise that retaining and/or incorporating residues, although initially decreasing soil carbon, may contribute more to long term carbon storage than burning or removing residues.
- There were substantial net gains in labile organic matter N over the cropping seasons from the microbial degradation of fresh organic matter from LAB, ADB and PM, representing a significant store of potential plant available nitrogen for subsequent crops and needing to be accommodated in future crop N rates.
- All mineral N from the L+F treatment was released upon incorporation, whereas mineral N was released over a longer time frame for all of the organic

treatments. Therefore, the expected risk of nitrate leaching from these latter products may be reduced (relative to the inorganic products) in environments or seasons where conditions promote leaching.

- Except for organic matter N reserves from harvest residues after each season, the L+F treatment had little N buffering capacity once soil mineral N reserves were depleted.
- The model reliably simulated mineral N in the top 10 cm of the soil profile for all treatments at Cambridge except for LAB5 and LAB-NIC. The model assumed uniform incorporation of treatments, which was not able to be achieved in practice for the LAB5 and LAB-NIC treatments. However, the model is reportedly less reliable when predicting the fate of high rate organic amendments (Akponikpè *et al.*, 2009).
- Early crop N stress was experienced by low N input treatments, leading to lower crop biomass and low crop water stress, whereas high N inputs led to higher crop biomass and higher crop water stress.
- The seed shedding and weed competition for the higher N input treatments confounded model comparisons for yield and biomass at the Cambridge site in the first year. Second year Cambridge and first year Cressy observed yield and biomass results provided acceptable agreement with the model. Site affects may have contributed to the disparity in second year results at the Cressy site.
- The simulated trends for all treatments except for LAB5 showed little or no nitrate leaching beyond 15 cm soil depth. However, due to the simulation being validated by data taken in two years of average or below average rainfall, greater losses may be expected in wetter years.
- The model also highlighted the complex response of soil mineral nitrogen to a range of management and environmental factors such as soil water, crop N demand, temperature, amendment composition and C:N ratio of soil organic matter.

8.4.1 Potential modelling outcomes

The key findings resulting from specific field trial experimental data helped to identify areas for future modelling applications or areas in which the model may be improved. These include:-

- Investigating the simulated response to different soil types and a broad spectrum of cropping scenarios from applying organic amendments.
- Exploring long term trends in N and C accumulation from continued application of organic products and implications on future cropping season N management.
- Exploring seasonal climate variability by including wetter seasons in future long-term modelling studies. This may assist in determining residual nutrients for subsequent crops and the maximum N loading from the organic amendments to avoid nitrate leaching losses.
- Investigating the decomposition of different organic materials, relative to initial surface distribution, intensity, level of incorporation and soil contact, to better inform and improve the existing manure module.
- Developing a decision support tool for farmers and farm advisory consultants to inform soil amendment application guidelines, to educate end users of the model and to show potential impacts of changes in management or environment in lieu of long term observations (i.e. climate change).

8.5 Conclusions

The simulations conducted and presented using APSIM have confirmed the potential of process-based farming systems models for exploring the complex interactions between soil, plant, environment, management and organic amendments. The study also identified that the model may benefit from improved process understanding with regard to nitrogen release from soil applied organic materials. Quantifying decomposition rates and pools of nitrogen within the organic materials would help with initial parameterisation and setup of the SurfaceOM and SoilN2 modules. This in turn may reduce the magnitude of error in long term simulations and build confidence in predicted results.

9 General Discussion

9.1 Bio-resources and texture contrast soils

The general objective of the research was to investigate agronomic and soil characteristic changes from organic materials applied to texture contrast soils in a temperate environment. The impetus for the research was the loss of soil organic matter (SOM) as a consequence of increased cropping and irrigation on these soils, and the availability of local organic materials that provide a source of plant available nutrients and to replace lost SOM. A series of field and incubation experiments were conducted using lime amended biosolids (LAB), anaerobically digested biosolids (ADB), poppy mulch (PM) and poppy seed waste (PSW). A further modelling component was undertaken using the field results to explore key soil processes and plant responses from applying organic materials as soil amendments.

Based upon the general objective, there were three key areas that required further understanding from outcomes of this research.

- The potential for bio-resources to replace soil organic matter and improve the health of texture contrast soils under current management regimes.
- Bio-resources as a substitute for inorganic fertiliser.
- Mineral nitrogen management from applied bio-resources

9.2 Changes in soil physical properties and soil health

The health of a soil is based on its capacity to function as a vital living system within ecosystem and land use boundaries (Doran and Zeiss, 2000). Soil health has been suggested as primarily an ecological characteristic measured by a resilience response to change (van Bruggen and Semenov, 2000), indicated by microbial biomass dynamics (Pankhurst *et al.*, 2002), aggregate stability and penetration resistance. Wardle (1998) found no difference in temporal variability in microbial biomass between differing systems (till, no till, forest, grassland), suggesting that microbial biomass is not destabilised by increasing disturbance. Destabilisation and subsequent increase in

turnover is initiated by stress (Wardle, 1998), which may be brought about by a sudden change in soil composition such as the addition of bio-resources.

One of the objectives of the research reported herein was to determine short term influences on microbial biomass from the application and incorporation of bio-resources. Although the sampling frequency was not enough to determine the flux of activity associated with adding organic material to soil, the results still showed that the addition of PM, LAB and ADB can increase fungal biomass within 3 and 6 months of application. Increasing fungal biomass has been associated with an increase in potential C sequestration (Bailey *et al.*, 2002), which suggests that over time organic carbon may increase with the addition of these amendments. Fungal biomass retains more of the C they metabolise than does bacterial biomass (Adu and Oades, 1978), and, although the single rate trials did not show a significant increase in soil carbon in response to applied bio-resources within 6 months, the rate trials for LAB showed an upward trend of soil organic carbon concomitant with an increase in fungal biomass.

There were no significant changes in soil structural parameters of aggregate stability, or penetration resistance over the short monitoring period as a result of applying bio-resources to texture contrast soils in Tasmania. However, stabilising aggregates requires the build up of soil humic material over time (Haynes and Swift, 1990), which may follow on from the increase in fungal biomass. This suggests that the application of biosolids (LAB and ADB) at 1NLBAR for cereals and PM (at current industry rates) over a longer time frame may improve aggregate stability of non-sodic surface soil of texture contrast soil. The structure of the soil may also be stabilised by the application of LAB and PM in the longer term because it has been found that the Ca^{2+} can inhibit CO_2 release and stablise soil structure (Oades, 1988).

Soil pH is an indicator of soil nutrient availability, which can also be a measure of soil quality and health. The availability of the macro nutrients (N, K, S, Ca and Mg) and Mo increases as soils become more alkaline, whilst the availability of micro nutrients (Fe, Mn, Zn, Cu and Co) increases as soil becomes more acidic. The ideal pH for plant growth is on the range of 6 to 8 units. The pre-trial soil test showed that the soils used in this study were within this range (Cambridge 6.3_{H_2O}, and Cressy 6.9_{H_2O}), so lime would not ordinarily be applied to such soils due to the potential for limiting P availability with

increasing pH. Furthermore, sandy soils require less lime than clay soils to increase soil pH. However, decomposition of organic matter releases CO_2, which when combined with rainwater can form weak organic acids (Golabi *et al.*, 2007) and reduce soil pH. Thus, applying organic materials that contain lime to soils may prevent this pH reduction. The research conducted herein showed that applying LAB at 1NLBAR and PM at 17.5 wet t/ha and incorporating in the top 10cm of a texture contrast soil raised the pH of the surface layer by 0.9 units and 0.6 units respectively within 9 months of application. Furthermore, increasing the rate of LAB from 1NLBAR to 2NLBAR increased the pH by a further 0.5 units in the same period. Although the pH's for the LAB treatments and PM treatment were slightly higher and lower respectively after the second year, they were not significantly different between years. The PM product had a higher initial C:N ratio (16:1) than LAB (5:1), which when incorporated in the soil may have taken longer to decompose, delaying the release of organic acids (beyond the lime effect on the pH) and thereby reducing the pH after the second year.

Soil salinity and sodicity can negatively affect the physical function of a soil. Alan *et al.* (2008*)* showed that applying composts can alleviate problems associated with salinity and sodicity, whilst Aoyama *et al.* (2006) showed that electrical conductivity (a measure of soil salinity) may be increased with the application of lime treated sludge. This research showed that at the end of the first growing season after applying bio-resources at the Cressy site, the $EC_{1:5}$ was significantly higher for LAB (0.16 dS/m) than for L+F (0.09 dS/m). Results were similar at the Cambridge site although the difference was not significant (P=0.06). The absolute values for the single rate LAB are considered to be in a low to moderate range however, increasing the rate of LAB increased the $EC_{1:5}$ significantly with LAB2 at 0.27 dS/m and LAB5 at 0.37 dS/m. Although these absolute values are significantly higher, accumulation of salts in the surface layer of texture contrast soils may be reduced by applying higher rates of LAB prior to leaching winter rains. However, applying higher rates of LAB may have implications for subsoil sodicity of Sodosols with an accumulation of the neutral salts formed with the Na^+ ions.

9.3 Substitution of inorganic fertiliser

Bio-resources are often applied to soil in lieu of inorganic fertiliser to supply essential plant nutrients (Kidd *et al.*, 2007; Mohammad *et al.*, 2007). However, the decomposition rate of alternative materials can vary considerably depending on a range of factors including management, soil characteristics, temperature, moisture and composition of the products (Cabrera *et al.*, 2005). The primary objective of this research programme with respect to nutrient substitution was to follow traditional practice and compare the use of inorganic fertiliser with treatments applied at industry (poppy waste) and EPA guideline (biosolids) application rates. Although this created an inherent problem in the field trials because of no constant with which to compare (eg. total N), it provided an opportunity to identify specific priorities for targeted research.

9.3.1 Bio-resource management

Cultivation has been shown to degrade the surface layer of a texture contrast soil when potatoes are included in the rotation (Cotching *et al.*, 2001). As an alternative to cultivation, direct drilling and stubble retention has been shown to significantly increase aggregate stability of texture contrast soils (Carter and Steed, 1992). This management practice has been advocated by Southern Farming Systems to improve soil structure and reduce degradation (http://www.sfs.org.au). However, the use of biosolids in such managed systems may be problematic as Australian EPA biosolids application guidelines suggest that biosolids be incorporated soon after application to avoid off-site removal of nutrients and contaminants from overland flow after rainfall (Brown *et al.*, 2009; DEP *et al.*, 2002; Dettrick and McPhee, 1999; NSW-EPA, 1997; VIC_EPA, 2004).

Paschold *et al.* (2008) found that incorporating swine slurry reduced the mineralised N from 70% to 40% of total N applied and mineralised P from 100% to 60% of total P applied in the year of application compared to not incorporating. However this research found that there was no significant difference in soil Colwell P or soluble N (or macro nutrients) between incorporating and not incorporating LAB applied at 1NLBAR after each season of growing cereals, compared to inorganic fertiliser. Furthermore, there were no differences in plant response with regard to yield for both years and nutrient

uptake in the biomass and grain (results only obtained in first year). There was also no difference in post harvest soil soluble nutrients or yield for both years between LAB2 (2NLBAR) applied and incorporated in the first year, and LAB applied and incorporated in the first year with a repeat application (LABx2Y) in the second year (but not incorporated). However, the repeat application LAB (LAB x2Y) contained more soluble nitrate and exchangeable Ca^{2+} in the soil than the repeat application of L+F (L+F x2Y) after the second year.

Hardie *et al.* (2011) have shown that initial soil moisture can affect the flow of water through texture contrast soils, whilst some soils can form surface seals from flocculation of soil particles assisted by organic particles adsorbed on the clay (Quirk and Murray, 1991). These soil conditions may have limited translocation of nutrients through the soil from applied inorganic fertiliser spread on top of dry soil and not incorporated even with irrigation or rainfall. In contrast, LAB contained > 70% moisture that may have pre-wetted the soil surface in the clumps of product, enhancing the downward movement of soluble nutrients with rainfall and/or irrigation.

9.3.2 Soil characteristics and incorporation of bio-resources

Three different processes were adopted within the research programme to incorporate the inorganic fertiliser and bio-resources in the soil. Each of the products varied in their consistency and moisture content, which may have impacted on distribution uniformity in the soil fabric. Both LAB and ADB, although dewatered, had a consistency of thick custard (Shammas and Wang, 2007), PM was a fibrous material consisting of processed poppy stem and capsule, whilst PSW was a granular product that flowed similarly to inorganic fertiliser. All bio-resources for the two year field trials were incorporated to a depth of 10 cm using walk-behind rotary cultivator. All bio-resources for the one year nitrogen field trial were manually incorporated with a fork to a depth of 10 cm. In the incubation study, biosolids were mixed into a slurry before being mixed in with the soil, whilst PM and PSW were mixed through the soil without adding a mixing agent. This last process enabled near-homogeneous mixes between soil and bio-resource.

In the field, mixtures between bio-resources and soil are more likely to be heterogeneous (Pathan *et al.*, 2003), which suggests that non-uniformity is normal. Therefore, the more heterogeneous the soil/bio-resource mixture, the slower the

mineralisation of elements such as C (Oades, 1988). However, soils with a high sand content, such as those used in this research (Cressy 71%, Cambridge 75%), are prone to rapid decomposition. This has implications for N release, which will be referred to in a later section.

9.3.3 Soil and plant growth response to applied bio-resources

In the field trials at Cressy, there was no significant difference between LAB, PM and L+F for post harvest soil Colwell P in year 1 (86, 77 and 74 mg/kg respectively). There was also no significant difference in grain P or yield in the same year. However, PM contained significantly higher biomass P than the other treatments at growth stage Z71, which suggests that the release of P from PM was more aligned with plant demand than from the applications of L+F or LAB. At the Cambridge site post harvest Colwell P for the LAB treatment increased after each year despite no additional P supplied. Weggler-Beaton (2003) reported similar findings with P supply from biosolids not meeting plant P demand. Shober and Sims (2003) reported on a national survey conducted in the US in 2002, to establish P limits from applied biosolids. They found that P availability varied depending on the biosolids type and the waste water treatment process, and that contradictory research meant that one rule was not adequate to manage P from biosolids (Shober and Sims, 2003). This contradiction was evident in this research with Colwell P at the Cressy for ADB being significantly lower than LAB after the first year, whilst at Cambridge there were no significant differences between biosolids types after either year. The significant increase in soil Colwell P with increasing LAB rates confirms that P management is of paramount importance if applying biosolids to meet plant N demand to limit overland and leaching losses (Pritchard, 2006). Although lime is often added to acid soils to increase phosphate availability, research has found that phosphate availability can be decreased with precipitation of insoluble calcium phosphates at high pH (Haynes, 1982).

9.4 Mineral nitrogen management

Inorganic fertilisers are sold based on available nutrients as a percentage of total weight of the product and typically labelled N:P:K:Mg:S. Bergstrom and Brink (1986) emphasised the importance of application rate and timing of inorganic fertilisers being

calculated to meet crop demand, with new techniques used to slow down the release of elemental N (Adegbidi *et al.*, 2003; Diez *et al.*, 2000), and stewardship programmes recommended to prevent soluble nutrient losses through leaching or overland flow from agriculture (Kay *et al.*, 2009). Texture contrast soils have specific issues with regard to application timing of inorganic fertilisers with potential soluble N losses through denitrification and leaching from both waterlogged (Bronson and Fillery, 1998) and irrigated dry soil (Hardie *et al.*, 2011). Therefore, the same concerns need to be addressed when determining rates and timing of bio-resource applications on texture contrast soils.

9.4.1 Application rates and timing

The Tasmanian biosolids re-use guidelines suggest that only about 20 % of the organic nitrogen contained in dewatered biosolids is mineralised in the first twelve months following application (Dettrick and McPhee, 1999), whilst in NSW and SA, guidelines suggest 10%, 15% and 25% for composted, anaerobic and aerobically digested biosolids respectively (Brown *et al.*, 2009; NSW-EPA, 1997). In the US, suggested rates are 10%, 20% and 30% respectively with the onus on individual states to provide further application rate advice (US-EPA, 1994). Decomposition of added organic matter in bio-resources depends on soil properties, soil water content and temperature, and is driven by microbial growth (Neill and Gignoux, 2006; Singh and Kashyap, 2007). Rowel *et al.* (2001) also suggested that decomposition and nitrogen mineralisation from introduced organic materials is also related to the initial chemistry of the materials. The C:N ratio has been used to predict short term N availability from solid manure amendments (Qian and Schoenau, 2002), however Griffin and Hutchinson (2007) found that the C:N ratio was poorly correlated with the rate and extent of mineralisation from soil applied organic materials.

This research found that the amount of nitrogen released from both LAB and ADB in the first twelve months after application was not in agreement with EPA guidelines. Furthermore, application of PM at industry recommended rates resulted in a drawdown of nitrogen from soil reserves within the first twelve months, and N mineralisation for PSW was found to be similar to inorganic fertiliser.

In the two year field trials, a partial nitrogen budget at harvest in the first season after application showed that actual mineralised N from LAB was > 30% higher than calculated mineral N from EPA guidelines, whilst actual mineralised N from ADB was 19% lower than calculated mineral N. Despite the sampling issues with the one year field trial, results confirmed the disparity found in two year field trials with 25.2% and 6.6% of total N mineralised from LAB and ADB respectively eight weeks after application. The result for ADB was contrary to Pu *et al.* (2008), who found that guideline calculated rates for anaerobically digested biosolids exceeded crop requirement for N, and that only 0.5 NLBAR was sufficient to meet crop demand. Total C and N for anaerobically digested biosolids used in the Pu *et al.* (2008) study were 33% and 6.11% respectively (C:N ratio of 5.4:1) compared to total C and N for ADB used in the one year trial which were 13.6% and 4.6% respectively (C:N ratio of 3:1).

The incubation study was undertaken to clarify mineral N movement in the first eight weeks after application and found that 62% and 35% of total N was mineralised from LAB and ADB respectively in that period. The caveat in this study in attempting to compare to the field trials is that the soil/product mixtures in the incubation study were more homogeneous than in the field trials, which may have increased absolute values. However, similar results were found by Rigby *et al.* (2010) in a field trial with lime amended biosolids and dewatered biosolids cake mineralising 65.1% and 39.4% respectively of the organic N within the first twelve months after application to an acidic sandy soil. The two year field trials also identified that increasing the rate of LAB on texture contrast soils did not result in an accumulation of mineralised N in the 0 – 10 cm soil depth in the first twelve months after application, which contradicts published research (Pu *et al.*, 2008).

The two main issues arising from the biosolids research aside from the disparity between calculated (from EPA guidelines) and actual release of N from biosolids are that:-

a) There is a major difference in mineral N release from LAB compared to that of ADB.
b) An increase in mineralised N does not follow from increasing the application rate of LAB beyond current EPA guideline rates.

Both ADB and LAB used in the research programme underwent similar anaerobic and dewatering treatment processes, with the lime added to LAB after dewatering and prior to the end product being discharged into distribution containers. Therefore the difference in release of N is more likely to be within the soil matrix, with water soluble Ca^{2+} from LAB potentially stimulating microbial aggregation soon after incorporation subsequently accelerating decomposition and mineralisation of N. Mahoney *et al.* (1987) found similar microbial aggregation when lime was added to an anaerobic sludge digester. However, the sampling frequency for microbial biomass used in the field trials was insufficient to detect any flux in microbial activity soon after incorporation. Although Barbarick *et al.* (2004) found an 11% increase in microbial biomass six years after application of biosolids, more research is required to determine short term differences in microbial activity in response to limed and un-limed biosolids.

Increasing the application rate of LAB was found to have an inverse relationship with the accumulation of N in the 0 – 10cm depth of the texture contrast soil (Figure 5.3). Although the inference to the relationship is only based on three points on a graph, the trend lines for both growth stage Z71 and harvest were similar (despite absolute values being different). Further work is required to confirm the relationship, which would need to include more application rates on different soil types and under different environmental conditions.

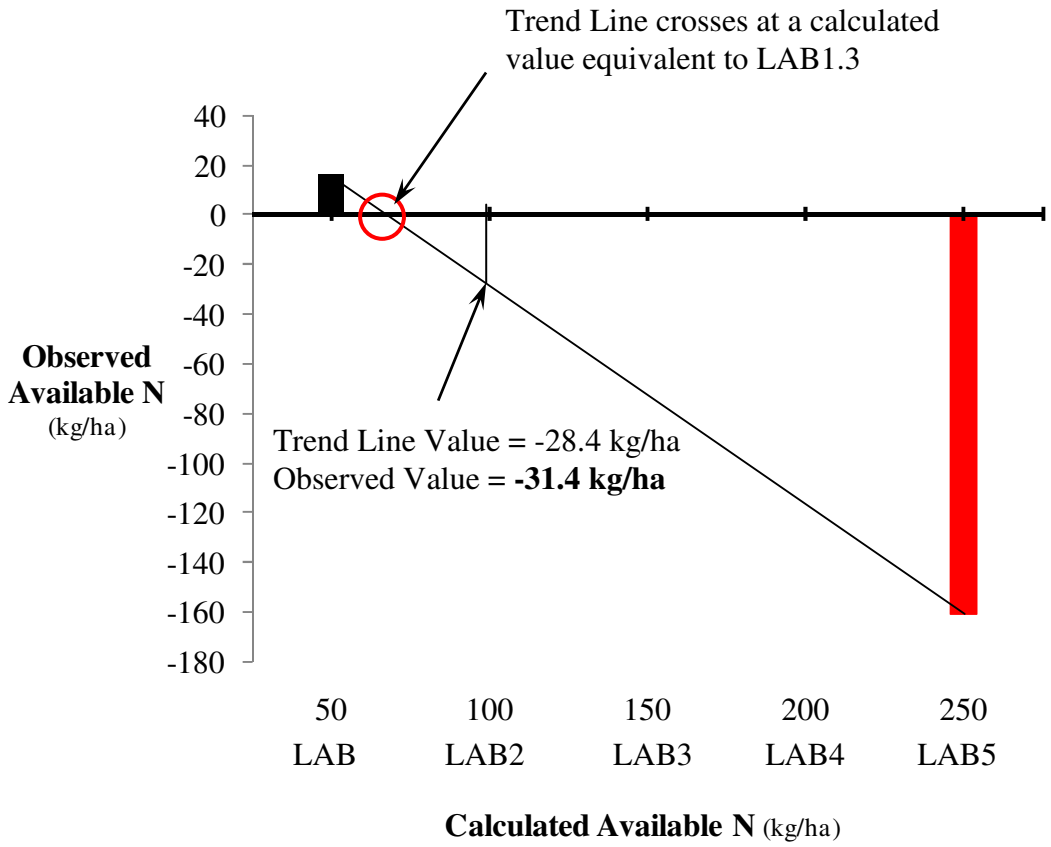

Figure 9.1 Plot of calculated nitrogen release against observed nitrogen release at harvest from application of different rates of lime amended biosolids

Pu *et al.* (2008) found that increasing rates of anaerobically digested biosolids increased the accumulation of mineral N, which is contrary to findings reported herein. The increased heterogeneity of the mixture of soil and LAB with increasing LAB application rate may have limited soil to product contact subsequently decreasing the potential for decomposition.

The application of PM has been found to negatively affect plant growth soon after application (Hardie and Cotching, 2009), which has been explained as being a result of 'salts' in the product (Aitken, 2007). However, the field trials and incubation study showed that the application of PM resulted in a drawdown of soil mineral N within eight weeks of application, which may explain the negative plant growth experienced by Hardie and Cotching (2009). The drawdown was most likely caused by the high C:N

ratio of the product, in which more N was required for microbial activity than was supplied by the product. It would appear that the application of PM would benefit from the addition of a nitrogen source to reduce the impact on natural soil nitrogen reserves. Moran *et al.* (2005) found that adding mineral N to crop residues not only assisted in decomposition but also had a positive impact on transforming residue C into stable soil organic matter.

The research showed that almost half of the total organic N in PSW was mineralised within eight weeks of incorporation, which was six times higher than ADB, despite the application rate of ADB being six times higher than PSW and total N values of initial products being 4.1% and 4.2% respectively. The C:N ratios were also different between products with ADB at 3:1 and PSW at 7:1. This demonstrates that the C:N ratio may not be a reliable predictor of nitrogen release from different bio-resources, a conclusion also drawn by Griffin and Hutchinson (2007). However, it shows that all a compositional factor may be useful in helping to determine nitrogen release in a field sitation.

9.4.2 Agricultural systems models

The simulations using the results of the two year field trials showed a reasonable fit with observed results in the first season for LAB, L+F and Control treatments. However, simulations for the higher rate LAB treatments (LAB2 and LAB5) over-estimated the release of mineral N, which confers with the inverse relationship between application rate and mineral N referred to earlier. This shows that the mineralisation kinetic equations used in the APSIM model may not adequately reflect the compositional differences between different bio-resources. This confirms comments by Morvan and Nicolardot (2009) who warned of the difficulties in parameterising organic wastes because of no relevant relationships between model parameters and composition of wastes.

Although Cabrera *et al.* (2005) has suggested that more complex models be developed to include processes and organisms involved in the nitrogen cycling from incorporated bio-resources, the models will remain limited in simulating field conditions. Therefore, introduction of a constant into kinetic equations used in simulation models that represents the heterogeneity of the mixture between the bio-resource and the soil may

strengthen the predictions and allow models such as APSIM to be used more effectively in simulating the release of nitrogen from bio-resources.

9.5 Conclusions

There are a number of key findings from this research that have implications for the re-use of urban and industry waste on texture contrast soils.

Soil health attributes – The application of LAB and ADB at 1NLBAR for cereals and PM at current industry rates over a longer time frame may improve aggregate stability of non-sodic surface soil of texture contrast soil. Although significant changes in soil organic carbon were not shown, trends from increasing rates of LAB suggested that organic carbon may be increased over time.

pH and EC – LAB and PM can increase soil pH significantly more than conventional lime six months after application. Consequently, LAB and PM can be used as a lime substitute in agriculture. However, the magnitude of soil pH increases may limit the number of repeat applications on texture contrast soils, due to limiting P availability. Soil salinity and sodicity can negatively affect the physical function of a soil. Applying LAB prior to winter rains may prevent accumulation of salts in the surface layer of texture contrast soils, however, subsoil accumulation of neutral salts formed with the Na^+ ions may have implications for Sodosols.

Nutrient Substitution – LAB and ADB can yield the same as inorganic fertiliser suggesting that plant available nutrients within organic amendments can be sufficient to meet plant demand. There was also no significant difference in yield between incorporating and not incorporating LAB. PM and PSW applied at industry recommended rates were also shown to yield the same as inorganic fertiliser. Consequently, LAB, ADB, PM and PSW can all be used as fertiliser substitutes to supply plant available nutrients in a twelve month period.

Bio-resource management – There is a disparity between guideline calculation and actual nitrogen release from LAB and ADB, with significantly more nitrogen mineralised from LAB than ADB. Higher application rates if LAB may not result in accumulation of soluble nitrogen in texture contrast soils. Applying PM at industry

recommended rates may require additional nitrogen to reduce crop nitrogen deficiency in the first year after application. PSW may need to be applied at higher agronomic rates to satisfy plant nutrient requirements, recognising that almost half of the total N may be available in the first eight weeks after application.

Modelling – Introduction of a constant into kinetic equations used in simulation models that represents the heterogeneity of the mixture between the bio-resource and the soil may strengthen the predictions and allow models such as APSIM to be used more effectively in simulating the release of nitrogen from bio-resources.

In conclusion, this research has demonstrated that the use of bio-resources currently available for agriculture in Tasmania may provide a substitute for inorganic fertilisers within a twelve month period and improve soil health over the longer term. However, management of bio-resources such as biosolids and poppy waste needs to consider the rate of nitrogen release under various environmental conditions to take advantage of available nutrients but limit potential leaching losses.

9.6 Future Research

This research has shown that application of bio-resources to texture contrast soils requires further investigation including:-

- A study of mineral N release from ADB compared to LAB using multiple application rates and conditions (i.e. incorporated vs not incorporated), in order to validate the linear relationship found in this research between product volume/consistency and nitrogen release.
- Assessment and analysis of microbial response to applied bio-resources within the first eight weeks following application at a range of temperatures from temperate to sub-tropical, on soils endemic to specific temperature zones.
- Improved parameterisation of a broad range of organic amendments to strengthen simulation models, using a variety of constants representing the heterogeneity of the mix between bio-resources and soil across a range of soils types.

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11 APSIM model runs for LAB

11.1 Cambridge

```
The Agricultural Production Systems Simulator
          Copyright(c) APSRU

Version             = 6.0
Title               = LAB1
Component     "clock" = c:\program files\apsim6\apsim\clock\lib\clock.dll
Component       "met" = c:\program files\apsim6\apsim\input\lib\input.dll
Paddock:
Component "Outputfile" = c:\program files\apsim6\apsim\report\lib\report.dll
Component     "accum" = c:\program files\apsim6\apsim\accum\lib\accum.dll
Component "Fertiliser" = c:\program files\apsim6\apsim\fertiliz\lib\fertiliz.dll
Component "Irrigation" = c:\program files\apsim6\apsim\irrigate\lib\irrigate.dll
Component "Irrigate on fixed date" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(1)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(2)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(1-2008)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(2-2008)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(3-2008)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Reset water, nitrogen and surfaceOM on fixed date" = c:\program
files\apsim6\apsim\manager\lib\manager.dll
Component     "Logic" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Loam Water" = c:\program files\apsim6\apsim\soilwat2\lib\soilwat2.dll
Component  "SurfaceOM" = c:\program files\apsim6\apsim\surfaceom\lib\surfaceom.dll
Component "Loam Nitrogen" = c:\program files\apsim6\apsim\soiln2\lib\soiln2.dll
Component     "wheat" = c:\program files\apsim6\apsim\plant\lib\plant.dll
Component    "barley" = c:\program files\apsim6\apsim\plant\lib\plant.dll

------- clock Initialisation ----------------------------------------------------
    Sequencer phases:
      prepare
      process
      post
    Simulation start date =  1/06/2007
    Simulation end date   =  1/06/2009
    Time step =          = 1440 (mins)

------- met Initialisation ------------------------------------------------------
    Sparse data is not allowed
    INPUT File name: C:\Documents and Settings\sives\My
Documents\PhD\APSWORK\cambridge\cambridge.met

------- Outputfile Initialisation -----------------------------------------------
    Output frequency:
      post
    Output variables:
      year
      day
      das
      yield
      biomass
      flowering_date
      floral_initiation_date
      grain_protein
      grain_no
```

```
      grain_oil_conc
      lai
      n_stress_expan
      n_stress_grain
      n_stress_photo
      n_stress_pheno
      sw_stress_expan
      sw_stress_pheno
      sw_stress_photo
      surfaceom_wt
      no3ppm
      nh4ppm
      fom_c
      fom_n
      hum_c
      hum_n
      biom_c
      biom_n
      carbon_tot
      dnit
      esw
      rain
      irrig_tot
      flow_no3
      es
      ep
      maxt

    Output file = LAB1.out
    Format = normal

------- accum Initialisation -----------------------------------------------
    Initialising

------- Fertiliser Initialisation ------------------------------------------
     Initialising

      - Reading Parameters


              Fertiliser Schedule (kg/ha)
        ------------------------------------------------
         No fertiliser schedule is used
        ------------------------------------------------

------- Irrigation Initialisation ------------------------------------------
     Initialising

      - Reading Parameters


              Irrigation parameters
        ------------------------------------------------
         Irrigation Schedule (Disabled)
         Automatic Irrigation Application (Disabled)
         critical fraction of available soil water =  0.50
         depth for calculating available soil water =      600.00
```

```
          Irrigation Allocation Budget (Disabled)
         ----------------------------------------------

------- Irrigate on fixed date Initialisation ---------------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('16-oct-2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 34 (mm)
    endif
    END of rules
------- Irrigate on fixed date(1) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('7-nov-2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 31 (mm)
    endif
    END of rules


------- Irrigate on fixed date(2) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('4-dec-2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 17 (mm)
    endif
    END of rules


------- Irrigate on fixed date(1-2008) Initialisation -------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('18-sep-2008')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 15 (mm)
    endif
    END of rules


------- Irrigate on fixed date(2-2008) Initialisation -------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('25-sep-2008')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 15 (mm)
    endif
    END of rules


------- Irrigate on fixed date(3-2008) Initialisation -------------------------
    Manager rules:
```

```
    SECTION:- start_of_day
    if (today = date('11-nov-2008')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 15 (mm)
    endif
    END of rules


------- Reset water, nitrogen and surfaceOM on fixed date Initialisation ------
    Manager rules:

    SECTION:- start_of_day
            if (today = date('9-jul-2008')) then
    resetwater = 'yes'
    resetnitrogen  = 'no'
    resetsurfaceom = 'no'
    if (resetwater = 'yes') then
       'loam water' reset
    endif
    if (resetnitrogen = 'yes') then
       'loam nitrogen' reset
    endif
    if (resetsurfaceom = 'yes') then
       'surfaceom' reset
    endif
    act_mods reseting
            endif
    END of rules


------- Logic Initialisation ----------------------------------------------------
    Manager rules:

    SECTION:- init
     irrigation_effective = 0

    SECTION:- start_of_day
    if day =  180 and year = 2007 then
      surfaceom tillage type = decomp
    endif
    if day = 183 and year = 2007 then
      surfaceom add_surfaceom name=manure, type=lab07, mass=5800, cnr =5.7, cpr=14
    endif
    if day =  187 and year = 2007 then
        surfaceom tillage type = chisel
    endif
    if day =  190 and year = 2007 then
       wheat sow cultivar = tas, plants = 152, sowing_depth = 40
       surfaceom tillage type = planter ()
    endif
    if wheat.stage_name = 'maturity' or wheat.plant_status = 'dead' then
      wheat harvest_crop
      wheat end_crop
    endif
    if day = 350 and year = 2007 then
       surfaceom tillage type = graze, f_incorp = 0.75 (), tillage_depth = 0.0 ()
           endif
    if day = 190 and year = 2008 then
       surfaceom tillage type = burn_90, f_incorp = 0.9 (), tillage depth = 0.0 ()
```

```
    endif
    if day =  255 and year = 2008 then
       barley sow cultivar = gairdner, plants = 200, sowing_depth = 40
       surfaceom tillage type = planter ()
    endif
    if day = 261 and year = 2008 then
    endif
    if day = 268 and year = 2008 then
    endif
    if day = 315 and year = 2008 then
    endif
    if barley.stage_name = 'maturity' or barley.plant_status = 'dead' then
      barley harvest_crop
      barley end_crop
    endif
    if day = 6 and year = 2009 then
       surfaceom tillage type = graze, f_incorp = 0.75 (), tillage_depth = 0.0 ()
          endif

    SECTION:- end_of_day
    END of rules

    Manager creating a new local real variable : irrigation_effective =     0.00000000000000

------- Loam Water Initialisation --------------------------------------------

       - Reading constants

       - Reading Soil Property Parameters

       - Reading Soil Profile Parameters
    Initial soilwater distributed using "sw" parameter.

                Soil Profile Properties
      ------------------------------------------------------------------------
          Depth  Air_Dry  LL15   Dul    Sat     Sw     BD   Runoff  SWCON
            mm     mm/mm  mm/mm  mm/mm  mm/mm  mm/mm  mm/mm  g/cc    wf
      ------------------------------------------------------------------------
        0.-  150.  0.150  0.290  0.540  0.590  0.400  1.020  0.762  0.300
      150.-  300.  0.260  0.290  0.530  0.580  0.400  1.030  0.190  0.300
      300.-  600.  0.290  0.290  0.540  0.590  0.400  1.020  0.048  0.300
      600.-  900.  0.290  0.290  0.540  0.580  0.290  1.020  0.000  0.300
      900.- 1200.  0.300  0.300  0.520  0.570  0.300  1.060  0.000  0.300
     1200.- 1500.  0.310  0.310  0.500  0.550  0.310  1.110  0.000  0.300
      ------------------------------------------------------------------------

            Soil Water Holding Capacity
       ------------------------------------------------------------
          Depth    Unavailable Available  Max Avail.  Drainable
                   (LL15)   (SW-LL15)  (DUL-LL15)  (SAT-DUL)
                     mm         mm          mm          mm
       ------------------------------------------------------------
        0.-  150.      43.50      16.50      37.50       7.50
      150.-  300.      43.50      16.50      36.00       7.50
      300.-  600.      87.00      33.00      75.00      15.00
      600.-  900.      87.00       0.00      75.00      12.00
      900.- 1200.      90.00       0.00      66.00      15.00
     1200.- 1500.      93.00       0.00      57.00      15.00
       ------------------------------------------------------------
```

```
      Totals     444.00      66.00     346.50      72.00
 ------------------------------------------------------------

        Initial Soil Parameters
 ------------------------------------------------------------
      Insoil        Salb     Dif_Con   Dif_Slope
 ------------------------------------------------------------
        0.00        0.13       40.00       16.00
 ------------------------------------------------------------
        Runoff is predicted using scs curve number:
      Cn2  Cn_Red  Cn_Cov   H_Eff_Depth
                             mm
 ------------------------------------------------------------
    73.00   20.00    0.80  450.00
 ------------------------------------------------------------
  Using Ritchie evaporation model
   Cuml evap (U):           6.00 (mm^0.5)
   CONA:                    3.50 ()
   Eo from priestly-taylor

------- SurfaceOM Initialisation -----------------------------------------------

        - Reading constants

        - Reading parameters


                Initial Surface Organic Matter Data
 ------------------------------------------------------------------------
   Name   Type        Dry matter   C        N        P    Cover  Standing_fr
                        (kg/ha)  (kg/ha)  (kg/ha)  (kg/ha) (0-1)     (0-1)
 ------------------------------------------------------------------------
  wheat_stubwheat          100.0    40.0     0.5     0.0   0.049     0.0
 ------------------------------------------------------------------------

              Effective Cover from Surface Materials =   0.0


------- Loam Nitrogen Initialisation -------------------------------------------

       - Reading Parameters

       - Reading Constants
     Using standard soil mineralisation for soil type Loam

        TAV and AMP supplied externally

              Soil Profile Properties
 -------------------------------------------------
  Layer    pH    OC      NO3      NH4     Urea
             (%)  (kg/ha)  (kg/ha)  (kg/ha)
 -------------------------------------------------
    1     6.30  2.81    10.71     3.06     0.00
    2     5.70  1.13     4.64     1.55     0.00
    3     6.70  0.68     6.12     3.06     0.00
    4     7.80  0.34     3.06     3.06     0.00
    5     8.00  0.24     3.18     9.54     0.00
    6     8.00  0.24     3.33     3.33     0.00
```

```
      ------------------------------------------------
      Totals              31.03   23.59    0.00
      ------------------------------------------------

           Initial Soil Organic Matter Status
      ------------------------------------------------------------
      Layer      Hum-C   Hum-N  Biom-C  Biom-N   FOM-C   FOM-N
             (kg/ha) (kg/ha) (kg/ha) (kg/ha) (kg/ha) (kg/ha)
      ------------------------------------------------------------
        1     42363.8  3389.1   629.2    78.6    31.2     0.8
        2     17321.6  1385.7   136.9    17.1    23.1     0.6
        3     20746.5  1659.7    61.5     7.7    12.7     0.3
        4     10393.7   831.5    10.3     1.3     7.0     0.2
        5      7628.2   610.3     3.8     0.5     3.8     0.1
        6      7988.0   639.0     4.0     0.5     2.1     0.1
      ------------------------------------------------------------
      Totals  106441.9  8515.3   845.6   105.7    80.0     2.0
      ------------------------------------------------------------

------- wheat Initialisation ----------------------------------------------------
    phenology model: Wheat

------- barley Initialisation ---------------------------------------------------
    phenology model: Wheat
------- Start of simulation  ----------------------------------------------------
29 June 2007(Day of year=180), Logic:
    Manager sending message :- surfaceom tillage  type = decomp
29 June 2007(Day of year=180), SurfaceOM:

       - Reading residue tillage info
    Residue removed using decomp
                                  Fraction Incorporated =     1.00
                                  Incorporated Depth    =   200.00
2 July 2007(Day of year=183), Logic:
    Manager sending message :- surfaceom add_surfaceom  name = manure, type = lab07, mass = 5800,
cnr = 5.7, cpr = 14
2 July 2007(Day of year=183):
    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
                  APSIM Warning Error
                  -------------------
    nh4ppm =     3590.000
          exceeds upper limit of    1000.000
    Component name: SurfaceOM
    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


6 July 2007(Day of year=187), Logic:
    Manager sending message :- surfaceom tillage  type = chisel
6 July 2007(Day of year=187), SurfaceOM:

       - Reading residue tillage info
    Residue removed using chisel
                                  Fraction Incorporated =     0.50
                                  Incorporated Depth    =   100.00
9 July 2007(Day of year=190), Logic:
    Manager sending message :- wheat sow  cultivar = tas, plants = 152, sowing_depth = 40
9 July 2007(Day of year=190), wheat:
    Crop Sow
       ------------------------------------------------
```

```
      cultivar                 = tas
      pesw germination         =      0.00 (0-1)
      vernalisation sensitivity  =     3.90 ()
      photoperiod sensitivity    =     5.00 ()
      phyllochron              =      30 ()
      tt start gf to maturity    =     530 (dd)
      grains_per_gram_stem         =     25.0 (/g)
      potential_grain_filling_rate  =   0.0031 (g/grain/day)
      potential_grain_growth_rate   =   0.0010 (g/grain/day)
      max_grain_size               =   0.0410 (g)
      ------------------------------------------------


                  Root Profile
      ------------------------------------------------
       Layer      Kl         Lower    Exploration
       Depth    Factor       Limit     Factor
       (mm)       ()       (mm/mm)     (0-1)
      ------------------------------------------------
      150.0     0.060         0.290      1.000
      150.0     0.060         0.290      1.000
      300.0     0.060         0.290      0.300
      300.0     0.060         0.290      0.000
      300.0     0.060         0.300      0.000
      300.0     0.060         0.310      0.000
      ------------------------------------------------
      Extractable SW:   346mm in  1500mm total depth ( 23%).
      Crop factor for bounding water use is set to   1.5 times eo.

                Crop Sowing Data
      ------------------------------------------------
      Sowing  Depth Plants Spacing Skip  Skip  Cultivar
      Day no   mm     m^2     mm   row   plant name
      ------------------------------------------------
        190   40.0  152.0  250.0   0.0   0.0 tas
      ------------------------------------------------

    Manager sending message :- surfaceom tillage  type = planter
9 July 2007(Day of year=190), SurfaceOM:

       - Reading residue tillage info
    Residue removed using planter
                                  Fraction Incorporated =     0.10
                                  Incorporated Depth    =    50.00
10 July 2007(Day of year=191), wheat:
     stage 2.0 germination
23 July 2007(Day of year=204), wheat:
     stage 3.0 emergence
                biomass =          0.70 (g/m^2)   lai         =   0.030 (m^2/m^2)
                stover N conc =     5.85 (%)    extractable sw =   28.42 (mm)
24 July 2007(Day of year=205), wheat:
     stage 4.0 end_of_juvenile
                biomass =          0.85 (g/m^2)   lai         =   0.033 (m^2/m^2)
                stover N conc =     5.84 (%)    extractable sw =   27.21 (mm)
16 October 2007(Day of year=289), Irrigate on fixed date:
    Manager sending message :- irrigation apply  amount = 34 (mm)
20 October 2007(Day of year=293), wheat:
     stage 5.0 floral_initiation
                biomass =        495.13 (g/m^2)   lai         =   6.506 (m^2/m^2)
```

```
                stover N conc =     2.24 (%)    extractable sw =   75.29 (mm)
5 November 2007(Day of year=309), wheat:
     stage 6.0 flowering
                biomass =         779.19 (g/m^2)   lai         =   5.755 (m^2/m^2)
                stover N conc =     1.58 (%)    extractable sw =   36.75 (mm)
7 November 2007(Day of year=311), Irrigate on fixed date(1):
    Manager sending message :- irrigation apply  amount = 31 (mm)
14 November 2007(Day of year=318), wheat:
     stage 7.0 start_grain_fill
                biomass =         942.58 (g/m^2)   lai         =   4.532 (m^2/m^2)
                stover N conc =     1.29 (%)    extractable sw =   39.81 (mm)
4 December 2007(Day of year=338), Irrigate on fixed date(2):
    Manager sending message :- irrigation apply  amount = 17 (mm)
13 December 2007(Day of year=347), wheat:
     stage 8.0 end_grain_fill
                biomass =        1197.90 (g/m^2)   lai         =   1.180 (m^2/m^2)
                stover N conc =     0.66 (%)    extractable sw =   37.84 (mm)
15 December 2007(Day of year=349), wheat:
     stage 9.0 maturity
                biomass =        1199.48 (g/m^2)   lai         =   1.142 (m^2/m^2)
                stover N conc =     0.66 (%)    extractable sw =   31.20 (mm)
16 December 2007(Day of year=350), Logic:
    Manager sending message :- wheat harvest_crop
    Manager sending message :- wheat end_crop
16 December 2007(Day of year=350), wheat:
    Crop ended. Yield (dw) =  3948.4  (kg/ha)
       Organic matter from crop:-      Tops to surface residue      Roots to soil FOM
                    DM (kg/ha) =              11994.8                  2352.9
                    N  (kg/ha) =              131.66                   33.16

    Manager sending message :- surfaceom tillage  type = graze, f_incorp = 0.75, tillage_depth = 0.0
16 December 2007(Day of year=350), SurfaceOM:
    Residue removed using graze
                                Fraction Incorporated =     0.75
                                Incorporated Depth    =     0.00
8 July 2008(Day of year=190), Logic:
    Manager sending message :- surfaceom tillage  type = burn_90, f_incorp = 0.9, tillagedepth = 0.0
8 July 2008(Day of year=190), SurfaceOM:

       - Reading residue tillage info
    Residue removed using burn_90
                                Fraction Incorporated =     0.90
                                Incorporated Depth    =     0.00
9 July 2008(Day of year=191), Reset water, nitrogen and surfaceOM on fixed date:
    Manager creating a new local string variable : resetwater = yes
    Manager creating a new local string variable : resetnitrogen = no
    Manager creating a new local string variable : resetsurfaceom = no
9 July 2008(Day of year=191), Loam Water:

       - Reading constants

       - Reading Soil Property Parameters

       - Reading Soil Profile Parameters
    Initial soilwater distributed using "sw" parameter.
11 September 2008(Day of year=255), Logic:
    Manager sending message :- barley sow  cultivar = gairdner, plants = 200, sowing_depth = 40
11 September 2008(Day of year=255), barley:
    Crop Sow
```

```
 ------------------------------------------------
 cultivar                 = gairdner
 pesw germination         =       0.00 (0-1)
 vernalisation sensitivity  =     1.00 ()
 photoperiod sensitivity    =     3.50 ()
 phyllochron              =       40 ()
 tt start gf to maturity    =     580 (dd)
 grains_per_gram_stem       =     25.0 (/g)
 potential_grain_filling_rate  =  0.0033 (g/grain/day)
 potential_grain_growth_rate   =  0.0010 (g/grain/day)
 max_grain_size             =     0.1000 (g)
 ------------------------------------------------


              Root Profile
 ------------------------------------------------
 Layer      Kl         Lower    Exploration
 Depth    Factor       Limit     Factor
 (mm)       ()       (mm/mm)     (0-1)
 ------------------------------------------------
 150.0    0.060        0.290     1.000
 150.0    0.060        0.290     1.000
 300.0    0.060        0.290     0.300
 300.0    0.060        0.290     1.000
 300.0    0.060        0.300     1.000
 300.0    0.060        0.310     1.000
 ------------------------------------------------
 Extractable SW:   346mm in  1500mm total depth ( 23%).
 Crop factor for bounding water use is set to   1.5 times eo.

            Crop Sowing Data
 ------------------------------------------------
 Sowing  Depth Plants Spacing Skip  Skip  Cultivar
 Day no   mm     m^2     mm   row   plant name
 ------------------------------------------------
   255   40.0  200.0  250.0   0.0   0.0 gairdner
 ------------------------------------------------

    Manager sending message :- surfaceom tillage  type = planter
11 September 2008(Day of year=255), SurfaceOM:

     - Reading residue tillage info
    Residue removed using planter
                                Fraction Incorporated =     0.10
                                Incorporated Depth    =    50.00
12 September 2008(Day of year=256), barley:
     stage 2.0 germination
18 September 2008(Day of year=262), Irrigate on fixed date(1-2008):
    Manager sending message :- irrigation apply  amount = 15 (mm)
19 September 2008(Day of year=263), barley:
     stage 3.0 emergence
               biomass =          0.92 (g/m^2)   lai         =   0.040 (m^2/m^2)
               stover N conc =     5.85 (%)    extractable sw =   16.05 (mm)
20 September 2008(Day of year=264), barley:
     stage 4.0 end_of_juvenile
               biomass =          1.24 (g/m^2)   lai         =   0.046 (m^2/m^2)
               stover N conc =     5.83 (%)    extractable sw =   15.62 (mm)
25 September 2008(Day of year=269), Irrigate on fixed date(2-2008):
    Manager sending message :- irrigation apply  amount = 15 (mm)
```

```
29 October 2008(Day of year=303), barley:
     stage 5.0 floral_initiation
                 biomass =        131.86 (g/m^2)   lai         =   2.146 (m^2/m^2)
                 stover N conc =     2.02 (%)    extractable sw =   40.93 (mm)
11 November 2008(Day of year=316), Irrigate on fixed date(3-2008):
    Manager sending message :- irrigation apply  amount = 15 (mm)
18 November 2008(Day of year=323), barley:
     stage 6.0 flowering
                 biomass =        320.58 (g/m^2)   lai         =   1.663 (m^2/m^2)
                 stover N conc =     0.96 (%)    extractable sw =   29.63 (mm)
27 November 2008(Day of year=332), barley:
     stage 7.0 start_grain_fill
                 biomass =        433.31 (g/m^2)   lai         =   1.425 (m^2/m^2)
                 stover N conc =     0.67 (%)    extractable sw =   50.82 (mm)
3 January 2009(Day of year=3), barley:
     stage 8.0 end_grain_fill
                 biomass =        728.31 (g/m^2)   lai         =   0.410 (m^2/m^2)
                 stover N conc =     0.31 (%)    extractable sw =    4.68 (mm)
5 January 2009(Day of year=5), barley:
     stage 9.0 maturity
                 biomass =        728.84 (g/m^2)   lai         =   0.371 (m^2/m^2)
                 stover N conc =     0.31 (%)    extractable sw =    4.15 (mm)
6 January 2009(Day of year=6), Logic:
    Manager sending message :- barley harvest_crop
    Manager sending message :- barley end_crop
6 January 2009(Day of year=6), barley:
    Crop ended. Yield (dw) =  2410.1  (kg/ha)
       Organic matter from crop:-      Tops to surface residue      Roots to soil FOM
                    DM (kg/ha) =              7288.4                  788.2
                    N  (kg/ha) =              38.48                  8.25

    Manager sending message :- surfaceom tillage  type = graze, f_incorp = 0.75, tillage_depth = 0.0
6 January 2009(Day of year=6), SurfaceOM:
    Residue removed using graze
                                  Fraction Incorporated =     0.75
                                  Incorporated Depth    =     0.00
1 June 2009(Day of year=152), clock:
    Simulation is terminating due to end criteria being met.
```

11.2 Cressy

```
The Agricultural Production Systems Simulator
          Copyright(c) APSRU

Version             = 6.0
Title               = LAB
Component      "clock" = c:\program files\apsim6\apsim\clock\lib\clock.dll
Component        "met" = c:\program files\apsim6\apsim\input\lib\input.dll
Paddock:
Component "Outputfile" = c:\program files\apsim6\apsim\report\lib\report.dll
Component      "accum" = c:\program files\apsim6\apsim\accum\lib\accum.dll
Component "Fertiliser" = c:\program files\apsim6\apsim\fertiliz\lib\fertiliz.dll
Component "Irrigation" = c:\program files\apsim6\apsim\irrigate\lib\irrigate.dll
Component "Irrigate on fixed date" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(1)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(2)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(3)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(4)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
```

Component "Irrigate on fixed date(5)" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Irrigate on fixed date(1)-2008" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Reset water, nitrogen and surfaceOM on fixed date" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Logic" = c:\program files\apsim6\apsim\manager\lib\manager.dll
Component "Loam Water" = c:\program files\apsim6\apsim\soilwat2\lib\soilwat2.dll
Component "SurfaceOM" = c:\program files\apsim6\apsim\surfaceom\lib\surfaceom.dll
Component "Loam Nitrogen" = c:\program files\apsim6\apsim\soiln2\lib\soiln2.dll
Component "barley" = c:\program files\apsim6\apsim\plant\lib\plant.dll
Component "wheat" = c:\program files\apsim6\apsim\plant\lib\plant.dll

------- clock Initialisation ----------
Sequencer phases:
prepare
process
post
Simulation start date = 1/06/2007
Simulation end date = 1/06/2009
Time step = = 1440 (mins)

------- met Initialisation ----------
Sparse data is not allowed
INPUT File name: C:\Documents and Settings\sives\My Documents\PhD\APSWORK\cressy\cressy.met

------- Outputfile Initialisation ----------
Output frequency:
post
Output variables:
year
day
yield
biomass
flowering_date
floral_initiation_date
grain_protein
grain_no
grain_oil_conc
lai
n_stress_expan
n_stress_grain
n_stress_photo
n_stress_pheno
sw_stress_expan
sw_stress_pheno
sw_stress_photo
surfaceom_wt
no3ppm
nh4ppm
fom_c
fom_n
hum_c
hum_n
biom_c
biom_n
carbon_tot
dnit
esw
rain

```
      irrig_tot
      flow_no3
      es
      ep
      maxt

   Output file = LAB.out
   Format = normal

------- accum Initialisation ----------------------------------------------
   Initialising

------- Fertiliser Initialisation -----------------------------------------
    Initialising

      - Reading Parameters



              Fertiliser Schedule (kg/ha)
        ------------------------------------------------
         No fertiliser schedule is used
        ------------------------------------------------

------- Irrigation Initialisation -----------------------------------------
    Initialising

      - Reading Parameters


              Irrigation parameters
        ------------------------------------------------
         Irrigation Schedule (Disabled)
         Automatic Irrigation Application (Disabled)
         critical fraction of available soil water =  0.50
         depth for calculating available soil water =     600.00
         Irrigation Allocation Budget (Disabled)
        ------------------------------------------------

------- Irrigate on fixed date Initialisation ----------------------------------
   Manager rules:

   SECTION:- start_of_day
   if (today = date('2/11/2007')) then
     'irrigation' set irrigation_efficiency = 1
     'irrigation' apply amount = 8 (mm)
   endif
   END of rules
------- Irrigate on fixed date(1) Initialisation ------------------------------
   Manager rules:

   SECTION:- start_of_day
   if (today = date('5/11/2007')) then
     'irrigation' set irrigation_efficiency = 1
     'irrigation' apply amount = 12 (mm)
   endif
   END of rules
```

```
------- Irrigate on fixed date(2) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('8/11/2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 11 (mm)
    endif
    END of rules


------- Irrigate on fixed date(3) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('25/11/2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 46 (mm)
    endif
    END of rules


------- Irrigate on fixed date(4) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('3/12/2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 24 (mm)
    endif
    END of rules


------- Irrigate on fixed date(5) Initialisation -----------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('14/12/2007')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 23 (mm)
    endif
    END of rules


------- Irrigate on fixed date(1)-2008 Initialisation -------------------------
    Manager rules:

    SECTION:- start_of_day
    if (today = date('6/11/2008')) then
      'irrigation' set irrigation_efficiency = 1
      'irrigation' apply amount = 30 (mm)
    endif
    END of rules


------- Reset water, nitrogen and surfaceOM on fixed date Initialisation ------
    Manager rules:

    SECTION:- start_of_day
```

```
        if (today = date('16-jun-2008')) then
    resetwater = 'no'
    resetnitrogen  = 'no'
    resetsurfaceom = 'no'
    if (resetwater = 'yes') then
       ' water' reset
    endif
    if (resetnitrogen = 'yes') then
       ' nitrogen' reset
    endif
    if (resetsurfaceom = 'yes') then
       'surfaceom' reset
    endif
    act_mods reseting
          endif
    END of rules


------- Logic Initialisation -----------------------------------------------
    Manager rules:

    SECTION:- init
     irrigation_effective = 0

    SECTION:- start_of_day
    if day =  255 and year = 2007 then
      surfaceom tillage type = decomp
    endif
    if day = 256 and year = 2007 then
      surfaceom add_surfaceom name=manure, type=lab07, mass=5800, cnr=5.7, cpr=14
    endif
    if day =  258 and year = 2007 then
       surfaceom tillage type = chisel
    endif
    if day =  261 and year = 2007 then
       barley sow cultivar = gairdner, plants = 155, sowing_depth = 40
       surfaceom tillage type = planter ()
    endif
    if day =  306 and year = 2007 then
    endif
    if day =  309 and year = 2007 then
    endif
    if day =  312 and year = 2007 then
    endif
    if day =  329 and year = 2007 then
    endif
    if day =  337 and year = 2007 then
    endif
    if day =  346 and year = 2007 then
    endif
    if barley.stage_name = 'maturity' or barley.plant_status = 'dead' then
      barley harvest_crop
      barley end_crop
    endif
    if day = 7 and year = 2008 then
       surfaceom tillage type = graze, f_incorp = 0.75 (), tillage_depth = 0.0 ()
          endif
    if day =  168 and year = 2008 then
      surfaceom tillage type = chisel
```

```
    endif
    if day =  174 and year = 2008 then
        surfaceom tillage type = chisel
    endif
    if day =  175 and year = 2008 then
       wheat sow cultivar = tas, plants = 175, sowing_depth = 40
       surfaceom tillage type = planter ()
    endif
    if day =  310 and year = 2008 then
    endif
    if wheat.stage_name = 'maturity' or wheat.plant_status = 'dead' then
      wheat harvest_crop
     wheat end_crop
    endif
    if day = 365 and year = 2008 then
       surfaceom tillage type = graze, f_incorp = 0.75 (), tillage_depth = 0.0 ()
           endif

    SECTION:- end_of_day
    END of rules

    Manager creating a new local real variable : irrigation_effective =     0.00000000000000

------- Loam Water Initialisation --------------------------------------------

       - Reading constants

       - Reading Soil Property Parameters

       - Reading Soil Profile Parameters
    Initial soilwater distributed using "sw" parameter.


                Soil Profile Properties
      ------------------------------------------------------------------------
          Depth  Air_Dry  LL15   Dul    Sat     Sw     BD   Runoff  SWCON
            mm     mm/mm  mm/mm  mm/mm  mm/mm  mm/mm  mm/mm  g/cc    wf
      ------------------------------------------------------------------------
        0.-  150.  0.150  0.290  0.540  0.590  0.540  1.020  0.762  0.300
      150.-  300.  0.260  0.290  0.530  0.580  0.530  1.030  0.190  0.300
      300.-  600.  0.290  0.290  0.540  0.590  0.540  1.020  0.048  0.300
      600.-  900.  0.290  0.290  0.540  0.580  0.540  1.020  0.000  0.300
      900.- 1200.  0.300  0.300  0.520  0.570  0.520  1.060  0.000  0.300
     1200.- 1500.  0.310  0.310  0.500  0.550  0.500  1.110  0.000  0.300
      ------------------------------------------------------------------------


            Soil Water Holding Capacity
      ------------------------------------------------------------
         Depth    Unavailable Available  Max Avail.  Drainable
                  (LL15)   (SW-LL15)  (DUL-LL15)  (SAT-DUL)
                    mm        mm          mm         mm
      ------------------------------------------------------------
        0.-  150.      43.50      37.50      37.50       7.50
      150.-  300.      43.50      36.00      36.00       7.50
      300.-  600.      87.00      75.00      75.00      15.00
      600.-  900.      87.00      75.00      75.00      12.00
```

```
 900.- 1200.      90.00      66.00      66.00      15.00
1200.- 1500.      93.00      57.00      57.00      15.00
------------------------------------------------------------
    Totals     444.00     346.50     346.50      72.00
------------------------------------------------------------

       Initial Soil Parameters
------------------------------------------------------------
      Insoil       Salb     Dif_Con   Dif_Slope
------------------------------------------------------------
        0.00       0.13       40.00       16.00
------------------------------------------------------------


       Runoff is predicted using scs curve number:
     Cn2  Cn_Red  Cn_Cov   H_Eff_Depth
                              mm
------------------------------------------------------------
   73.00   20.00    0.80  450.00
------------------------------------------------------------


 Using Ritchie evaporation model
  Cuml evap (U):           6.00 (mm^0.5)
  CONA:                    3.50 ()
  Eo from priestly-taylor

------- SurfaceOM Initialisation ----------------------------------------------

        - Reading constants

        - Reading parameters


                Initial Surface Organic Matter Data
       ------------------------------------------------------------------------
         Name   Type        Dry matter   C        N        P    Cover  Standing_fr
                          (kg/ha)  (kg/ha)  (kg/ha)  (kg/ha) (0-1)     (0-1)
       ------------------------------------------------------------------------
        wheat_stubwheat          100.0    40.0     0.5     0.0   0.049     0.0
       ------------------------------------------------------------------------

              Effective Cover from Surface Materials =   0.0


------- Loam Nitrogen Initialisation ------------------------------------------

       - Reading Parameters

       - Reading Constants
    Using standard soil mineralisation for soil type Loam


        TAV and AMP supplied externally


              Soil Profile Properties
       ------------------------------------------------
        Layer    pH    OC     NO3     NH4    Urea
```

```
                (%) (kg/ha) (kg/ha) (kg/ha)
      -------------------------------------------------
        1    6.70  2.40   12.24   10.71    0.00
        2    6.30  0.33    7.73    1.55    0.00
        3    6.70  0.17   61.20    9.18    0.00
        4    6.80  0.33   29.07    6.12    0.00
        5    8.00  0.24    3.18    9.54    0.00
        6    8.00  0.24    3.33    3.33    0.00
      -------------------------------------------------
       Totals             116.74   40.43    0.00
      -------------------------------------------------
           Initial Soil Organic Matter Status
      -----------------------------------------------------------
       Layer     Hum-C   Hum-N  Biom-C  Biom-N   FOM-C   FOM-N
             (kg/ha) (kg/ha) (kg/ha) (kg/ha) (kg/ha) (kg/ha)
      -----------------------------------------------------------
        1     36182.6  2894.6   537.4    67.2    31.2     0.8
        2      5058.5   404.7    40.0     5.0    23.1     0.6
        3      5186.6   414.9    15.4     1.9    12.7     0.3
        4     10088.0   807.0    10.0     1.2     7.0     0.2
        5      7628.2   610.3     3.8     0.5     3.8     0.1
        6      7988.0   639.0     4.0     0.5     2.1     0.1
      -----------------------------------------------------------
       Totals  72132.0  5770.6   610.5    76.3    80.0     2.0
      -----------------------------------------------------------

------- barley Initialisation ----------------------------------------------
    phenology model: Wheat

------- wheat Initialisation -----------------------------------------------
    phenology model: Wheat
------- Start of simulation  -----------------------------------------------
12 September 2007(Day of year=255), Logic:
    Manager sending message :- surfaceom tillage  type = decomp
12 September 2007(Day of year=255), SurfaceOM:

       - Reading residue tillage info
    Residue removed using decomp
                                  Fraction Incorporated =     1.00
                                  Incorporated Depth    =   200.00
13 September 2007(Day of year=256), Logic:
    Manager sending message :- surfaceom add_surfaceom  name = manure, type = lab07, mass = 5800,
cnr = 5.7, cpr = 14
13 September 2007(Day of year=256):
    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
                  APSIM Warning Error
                  -------------------
    nh4ppm =     3590.000
          exceeds upper limit of    1000.000
    Component name: SurfaceOM
    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

15 September 2007(Day of year=258), Logic:
    Manager sending message :- surfaceom tillage  type = chisel
15 September 2007(Day of year=258), SurfaceOM:

       - Reading residue tillage info
    Residue removed using chisel
                                  Fraction Incorporated =     0.50
```

```
                                Incorporated Depth    =   100.00
18 September 2007(Day of year=261), Logic:
    Manager sending message :- barley sow  cultivar = gairdner, plants = 155, sowing_depth = 40
18 September 2007(Day of year=261), barley:
    Crop Sow
      ------------------------------------------------
      cultivar                 = gairdner
      pesw germination         =      0.00 (0-1)
      vernalisation sensitivity  =      1.00 ()
      photoperiod sensitivity    =      3.50 ()
      phyllochron              =       40 ()
      tt start gf to maturity    =       580 (dd)
      grains_per_gram_stem         =      25.0 (/g)
      potential_grain_filling_rate   =    0.0033 (g/grain/day)
      potential_grain_growth_rate    =    0.0010 (g/grain/day)
      max_grain_size             =    0.1000 (g)
      ------------------------------------------------
                  Root Profile
      ------------------------------------------------
       Layer      Kl         Lower    Exploration
       Depth    Factor       Limit     Factor
       (mm)       ()       (mm/mm)     (0-1)
      ------------------------------------------------
      150.0     0.060         0.290      1.000
      150.0     0.060         0.290      1.000
      300.0     0.060         0.290      0.300
      300.0     0.060         0.290      1.000
      300.0     0.060         0.300      1.000
      300.0     0.060         0.310      1.000
      ------------------------------------------------
      Extractable SW:   346mm in  1500mm total depth ( 23%).
      Crop factor for bounding water use is set to   1.5 times eo.

                  Crop Sowing Data
      ------------------------------------------------
      Sowing  Depth Plants Spacing Skip  Skip  Cultivar
      Day no   mm     m^2     mm   row   plant name
      ------------------------------------------------
        261   40.0  155.0  250.0   0.0   0.0 gairdner
      ------------------------------------------------

    Manager sending message :- surfaceom tillage  type = planter
18 September 2007(Day of year=261), SurfaceOM:

       - Reading residue tillage info
    Residue removed using planter
                                Fraction Incorporated =     0.10
                                Incorporated Depth    =    50.00
19 September 2007(Day of year=262), barley:
     stage 2.0 germination
29 September 2007(Day of year=272), barley:
     stage 3.0 emergence
                biomass =          0.71 (g/m^2)   lai         =   0.031 (m^2/m^2)
                stover N conc =     5.85 (%)    extractable sw =   38.52 (mm)
30 September 2007(Day of year=273), barley:
     stage 4.0 end_of_juvenile
                biomass =          1.02 (g/m^2)   lai         =   0.036 (m^2/m^2)
                stover N conc =     5.83 (%)    extractable sw =   38.46 (mm)
2 November 2007(Day of year=306), Irrigate on fixed date:
```

```
   Manager sending message :- irrigation apply  amount = 8 (mm)
5 November 2007(Day of year=309), Irrigate on fixed date(1):
   Manager sending message :- irrigation apply  amount = 12 (mm)
8 November 2007(Day of year=312), Irrigate on fixed date(2):
   Manager sending message :- irrigation apply  amount = 11 (mm)
12 November 2007(Day of year=316), barley:
    stage 5.0 floral_initiation
              biomass =        441.70 (g/m^2)   lai         =   6.129 (m^2/m^2)
              stover N conc =     2.84 (%)    extractable sw =  104.30 (mm)
25 November 2007(Day of year=329), Irrigate on fixed date(3):
   Manager sending message :- irrigation apply  amount = 46 (mm)
28 November 2007(Day of year=332), barley:
    stage 6.0 flowering
              biomass =        720.15 (g/m^2)   lai         =   3.704 (m^2/m^2)
              stover N conc =     1.85 (%)    extractable sw =   84.09 (mm)
3 December 2007(Day of year=337), Irrigate on fixed date(4):
   Manager sending message :- irrigation apply  amount = 24 (mm)
5 December 2007(Day of year=339), barley:
    stage 7.0 start_grain_fill
              biomass =        854.27 (g/m^2)   lai         =   3.330 (m^2/m^2)
              stover N conc =     1.58 (%)    extractable sw =   83.90 (mm)
14 December 2007(Day of year=348), Irrigate on fixed date(5):
   Manager sending message :- irrigation apply  amount = 23 (mm)
5 January 2008(Day of year=5), barley:
    stage 8.0 end_grain_fill
              biomass =       1512.55 (g/m^2)   lai         =   1.670 (m^2/m^2)
              stover N conc =     1.18 (%)    extractable sw =  122.18 (mm)
6 January 2008(Day of year=6), barley:
    stage 9.0 maturity
              biomass =       1512.55 (g/m^2)   lai         =   1.521 (m^2/m^2)
              stover N conc =     1.19 (%)    extractable sw =  116.20 (mm)
7 January 2008(Day of year=7), Logic:
   Manager sending message :- barley harvest_crop
   Manager sending message :- barley end_crop
7 January 2008(Day of year=7), barley:
   Crop ended. Yield (dw) =  6544.7  (kg/ha)
     Organic matter from crop:-      Tops to surface residue      Roots to soil FOM
                 DM (kg/ha) =              15125.5                  1942.5
                 N  (kg/ha) =               210.72                  44.58

   Manager sending message :- surfaceom tillage  type = graze, f_incorp = 0.75, tillage_depth = 0.0
7 January 2008(Day of year=7), SurfaceOM:
   Residue removed using graze
                              Fraction Incorporated =     0.75
                              Incorporated Depth    =     0.00
16 June 2008(Day of year=168), Reset water, nitrogen and surfaceOM on fixed date:
   Manager creating a new local string variable : resetwater = no
   Manager creating a new local string variable : resetnitrogen = no
   Manager creating a new local string variable : resetsurfaceom = no
16 June 2008(Day of year=168), Logic:
   Manager sending message :- surfaceom tillage  type = chisel
16 June 2008(Day of year=168), SurfaceOM:

     - Reading residue tillage info
   Residue removed using chisel
                              Fraction Incorporated =     0.50
                              Incorporated Depth    =   100.00
22 June 2008(Day of year=174), Logic:
   Manager sending message :- surfaceom tillage  type = chisel
```

22 June 2008(Day of year=174), SurfaceOM:

- Reading residue tillage info
Residue removed using chisel
Fraction Incorporated = 0.50
Incorporated Depth = 100.00

23 June 2008(Day of year=175), Logic:
Manager sending message :- wheat sow cultivar = tas, plants = 175, sowing_depth = 40

23 June 2008(Day of year=175), wheat:
Crop Sow

cultivar	= tas
pesw germination	= 0.00 (0-1)
vernalisation sensitivity	= 3.90 ()
photoperiod sensitivity	= 5.00 ()
phyllochron	= 30 ()
tt start gf to maturity	= 530 (dd)
grains_per_gram_stem	= 25.0 (/g)
potential_grain_filling_rate	= 0.0031 (g/grain/day)
potential_grain_growth_rate	= 0.0010 (g/grain/day)
max_grain_size	= 0.0410 (g)

Root Profile

Layer Depth (mm)	Kl Factor ()	Lower Limit (mm/mm)	Exploration Factor (0-1)
150.0	0.060	0.290	1.000
150.0	0.060	0.290	1.000
300.0	0.060	0.290	0.300
300.0	0.060	0.290	0.000
300.0	0.060	0.300	0.000
300.0	0.060	0.310	0.000

Extractable SW: 346mm in 1500mm total depth (23%).
Crop factor for bounding water use is set to 1.5 times eo.

Crop Sowing Data

Sowing Day no	Depth mm	Plants m^2	Spacing mm	Skip row	Skip plant	Cultivar name
175	40.0	175.0	250.0	0.0	0.0	tas

Manager sending message :- surfaceom tillage type = planter

23 June 2008(Day of year=175), SurfaceOM:

- Reading residue tillage info
Residue removed using planter
Fraction Incorporated = 0.10
Incorporated Depth = 50.00

24 June 2008(Day of year=176), wheat:
stage 2.0 germination

7 July 2008(Day of year=189), wheat:
stage 3.0 emergence

```
                biomass =          0.80 (g/m^2)   lai         =   0.035 (m^2/m^2)
                stover N conc =     5.85 (%)    extractable sw =   32.66 (mm)
8 July 2008(Day of year=190), wheat:
     stage 4.0 end_of_juvenile
                biomass =          0.96 (g/m^2)   lai         =   0.037 (m^2/m^2)
                stover N conc =     5.84 (%)    extractable sw =   32.31 (mm)
26 October 2008(Day of year=300), wheat:
     stage 5.0 floral_initiation
                biomass =        266.53 (g/m^2)   lai         =   3.560 (m^2/m^2)
                stover N conc =     2.01 (%)    extractable sw =   84.40 (mm)
6 November 2008(Day of year=311), Irrigate on fixed date(1)-2008:
    Manager sending message :- irrigation apply  amount = 30 (mm)
12 November 2008(Day of year=317), wheat:
     stage 6.0 flowering
                biomass =        508.83 (g/m^2)   lai         =   2.867 (m^2/m^2)
                stover N conc =     1.09 (%)    extractable sw =  101.68 (mm)
21 November 2008(Day of year=326), wheat:
     stage 7.0 start_grain_fill
                biomass =        673.69 (g/m^2)   lai         =   2.236 (m^2/m^2)
                stover N conc =     0.72 (%)    extractable sw =   89.26 (mm)
27 December 2008(Day of year=362), wheat:
     stage 8.0 end_grain_fill
                biomass =       1116.03 (g/m^2)   lai         =   0.738 (m^2/m^2)
                stover N conc =     0.34 (%)    extractable sw =   32.19 (mm)
29 December 2008(Day of year=364), wheat:
     stage 9.0 maturity
                biomass =       1117.52 (g/m^2)   lai         =   0.685 (m^2/m^2)
                stover N conc =     0.34 (%)    extractable sw =   27.15 (mm)
30 December 2008(Day of year=365), Logic:
    Manager sending message :- wheat harvest_crop
    Manager sending message :- wheat end_crop
30 December 2008(Day of year=365), wheat:
    Crop ended. Yield (dw) =  2644.5  (kg/ha)
       Organic matter from crop:-      Tops to surface residue      Roots to soil FOM
                    DM (kg/ha) =              11175.2                  1460.6
                    N  (kg/ha) =              63.46                   14.46

    Manager sending message :- surfaceom tillage  type = graze, f_incorp = 0.75, tillage_depth = 0.0
30 December 2008(Day of year=365), SurfaceOM:
    Residue removed using graze
                                  Fraction Incorporated =     0.75
                                  Incorporated Depth    =     0.00
1 June 2009(Day of year=152), clock:
    Simulation is terminating due to end criteria being met.
```

12 List of publications arising from the thesis

- Ives, S.W. and Cotching, W.E., (2008). "Effects of biosolids, poppy mulch and poppy seed waste on sodosol properties", In Proceedings of the Australian Water Association Biosolids Specialty IV Conference, Adelaide, Australia.
- Ives, S.W. and Cotching, W.E., (2008). "The Effects of Reuse of Industry and Urban Waste on Sodosols", 2008. In Proceedings of the Joint conference of the Australia and New Zealand Societies of Soil Science, Palmerston North, New Zealand.
- Cotching, W. E., Ives, S. W., Lisson, S. N., Doyle, R. B., Sparrow, L. and Coad, J. (2008). Final project report titled "Boosting agricultural productivity with biosolids; urban waste for soil health". Australian Landcare Association, DAFF. Canberra, Australia.
- Ives, S.W., Cotching, W.E., Doyle, R.B., Lisson, S.N. and Sparrow, L.A., (2009). "The Effects of Organic Wastes on Sodosols in Tasmania, Australia", In Proceedings of the 24th International Conference on Solid Waste Technology and Management, Philadelphia, USA.
- Lisson, S.N., Ives, S.W. and Doyle, R.B., (2009). "Farm System Modelling of Organic Amendments in Tasmania, Australia". In Proceedings of the 24th International Conference on Solid Waste Technology and Management, Philadelphia, USA.
- Ives, S.W., Sparrow, L.A.,Cotching, W.E., Doyle, R.B. and Lisson, S.N., (2010). "Nitrogen Release from Poppy Waste and Biosolids at Low Temperature", Accepted as poster presentation at the International Soils Conference in Brisbane, Australia.
- Ives, S.W., Cotching, W.E.,Sparrow, L.A., Lisson, S.N. and Doyle, R.B. (2011) Plant growth and soil responses to soil applied organic materials in Tasmania, Australia. *Soil Research.* 49 (7) 572-581.