

CRANFIELD UNIVERSITY

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THE EFFECTS OF A THERMAL CONDITIONING TREATMENT FOR
WEED CONTROL UPON SOIL BIOLOGICAL PROPERTIES

SCHOOL OF APPLIED SCIENCES
LAND MANAGEMENT

MSc THESIS

Academic year: 2008-2009

Supervisors: Professor Karl Ritz and Dr Mark Pawlett

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Degree of Master of Science

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Abstract

Weeds, and their associated control, are often significant in limiting production within organic farming due to restrictions on herbicide use within such systems. Organic farmers rely on alternative weed control methods, including soil thermal treatments. Preliminary research has shown soil steaming to be a potentially effective weed control method, but procedures have yet to be fully explored and implemented. One issue is the effect steam treatment has upon the non-targeted components of the soil system.

This study considered the magnitude and persistence of the effects that soil steaming had on biological aspects of soil systems within the organic production of *Daucus carota, sativus* (L) (carrots). A field-based study was conducted whereby soil treated with steam was sampled at intervals of 1 hour, and 14 and 42 days following treatment. Impacts upon the soil system were then assessed by measuring a range of chemical and biological properties related to carbon and nitrogen cycling.

Immediately following steaming, actual nitrification was inhibited with an associated accumulation of ammonium-N, displaying an initial low resistance to the thermal treatment. However, recovery of this process was apparent at approximately 14 days post-treatment with a significant rise in both nitrate-N and potential nitrification, indicating a degree of resilience of the nitrification process.

Overall, other measured components of the soil system, including microbial activity and organic carbon, also demonstrated signs of resilience, indicating that the system still had the ability to function and provide its regulatory and provisioning services within the short-term following soil steaming treatment.

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Key Terms and Abbreviations

Ammonium-N: $\text{NH}_4^+\text{-N}$

Basal respiration: The respiration rate at rest when there is no additional substrate to encourage activity.

Field DOC: Dissolved organic carbon extracted from fresh, field-moist soil samples.

Flush DOC: The difference in the amount of dissolved organic carbon extracted from fumigated and non-fumigated samples, indicating the amount of biomass carbon.

Microbial biomass carbon: The concentration of microbes in the soil.

Mineral N: Total oxidised nitrogen (TON: $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$) and $\text{NH}_4^+\text{-N}$.

Nitrate-N: $\text{NO}_3\text{-N}$

Nitrification: The oxidation process converting $\text{NH}_4^+\text{-N}$ into $\text{NO}_2\text{-N}$, and further oxidation into $\text{NO}_3\text{-N}$.

Nitrifying bacteria: The bacteria involved in the process of nitrification.

Nitrite-N: $\text{NO}_2\text{-N}$

Nitrogen Mineralisation: The conversion of organic nitrogen into inorganic, plant accessible forms ($\text{NO}_3\text{-N}$), encompassing the process of nitrification.

Resilience: The rate and extent of return to a defined norm of a prescribed function or property following a perturbation or stress event.

Resistance: The degree to which a prescribed function is altered from an initial state (the ‘norm’) following a perturbation or stress to the soil.

Soil health (agricultural context): The capability of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity (Kibblewhite *et al.*, 2008).

Substrate induced respiration (SIR): The initial respiration rate after the addition of an available substrate, conventionally glucose. It is directly proportional to the amount of microbial carbon (Paul 2007).

CHAPTER 1: Introduction

1.1 Aim

To determine the magnitude and persistence of the effects that a soil thermal treatment has upon biological aspects of a soil system within the organic production of *Daucus carota, sativus* L. (carrots).

1.2 Background and rationale

Weeds, and their associated control, are often significant in limiting production within organic farming (Wszelaki *et al.*, 2007). For organic production to advance, it is vital that research into weed control measures continue and develop, in order to increase effectiveness and minimise yield losses (U.K Register of Organic Food Standards cited by Turner *et al.*, 2001).

Thermally treating the soil to prevent weeds on a commercial scale was first patented in the 1940's (Egli *et al.*, 2008; Lague *et al.*, 1997), but interest was minimal due to the availability of cheap herbicides. However, due to recent developments, including a growing awareness and concern over environmental impacts of such biocides, there is now renewed interest into the potential of soil thermal conditioning as a weed control strategy (Wszelaki *et al.*, 2007).

Although thermally treating the soil has proved to be successful at lowering weed densities (Wszelaki *et al.*, 2007; Rahkonen and Jokela, 2003), procedures have yet to be fully explored and implemented. One issue is the effect it has on the non-target components of the soil system. This study investigates the effects of thermal treatment using steam upon a soil system to help further develop the method.

1.3 Objectives

The specific objectives were:

1. To assess the immediate response of non-target soil organisms, and associated biochemical processes, to field-based soil heat treatment.
2. To determine the nature and extent of changes in such properties following such heat treatment.
3. To establish the resistance and resilience of soil systems to heat treatment, with respect to its regulatory and provisioning functions, including carbon and nitrogen cycling.

1.4 Hypothesis

The soil system will demonstrate resilience and show signs of recovery following the perturbation induced by heat-treatment.

1.5 Outline of work

To achieve the aim of this study it was necessary to read available literature surrounding the subject area, gaining an in-depth understanding from both an industrial and academic perspective. An appropriate research design was then developed, whereby soil samples thermally treated with steam in the field prior to sowing were analysed by suitable laboratory-based assays. Analysis was conducted, assessing the effects quantitatively using a resistance and resilience conceptual approach (Ritz *et al.*, 2003; Orwin and Wardle, 2004), and interpreted in terms of the concept of soil health, adopting the definitions outlined in 'Key Terms'.

CHAPTER 2: Literature Review

2.1 Introduction

The pressure to develop non-chemical and environmentally benign methods in horticultural systems has increased over recent years due to several factors. To begin with, the number of agri-chemicals available has become progressively limited due to increasingly restrictive legislation. Secondly, increasing societal concern over the impact of agri-chemicals upon the environment, human health and food safety has further pushed the need for ecologically sound alternatives (Barberi *et al.*, 2009; Bonanomi *et al.*, 2008; Loenen *et al.*, 2003). Other drivers include an increasing number of herbicide-resistant weed species and alternative methods such as hand-weeding being economically unviable (Wszelaki *et al.*, 2007).

Restrictions on herbicide use are greater within organic farming systems compared with conventional ones. Several alternative weed control methods currently exist within organic farming systems, including soil thermal treatments. The possibility of using steam to sterilise the soil has yet to be fully explored, although preliminary research has shown it to be an effective method for controlling weed densities (Roux-Michollet *et al.*, 2008). One issue however is the effect it may have upon the non-targeted components of soil systems and soil health. An ideal weed control method should achieve complete elimination of the target organisms whilst not adversely affecting soil health (Egli *et al.*, 2006).

Here, previous studies on soil thermal treatments for weed control, particularly steam sterilisation, will be briefly reviewed and their influence upon soil systems considered.

2.2 Soil thermal treatments

There are several types of soil thermal treatment. Slash and burn is one of the oldest known forms and is still used today by subsistence farmers. Stubble burning, although now banned in the U.K., was the traditional thermal treatment in modern agriculture (Bond, 2002). The current most popular certified method of thermal weed control within U.K organic farming is flaming, which was first developed in the 1940's (Egli *et al.*, 2006; Lague *et al.*, 1997; Organic Food Federation, 2008).

Flaming uses liquefied petroleum gas burners and kills weeds by heating to a critical temperature, disrupting cell membranes and consequently dehydrating the plants (Bond, 2002; Rahkonen and Jokela, 2003; Wszelaki *et al.*, 2007). The temperature required to cause dehydration depends upon the exposure time (65 – 130 seconds is recommended) and the species (Wszelaki *et al.*, 2007). Flaming is a popular method as it has a non-residual effect on the soil, and does not physically disrupt the soil surface. For this reason, it causes minimum soil erosion and prevents buried weed seeds emerging at the surface (Barberi *et al.*, 2009; Bond 2002; Wszelaki *et al.*, 2007). The long-term effectiveness of this method largely depends on how resilient the weeds are (Bond, 2002). Certain management approaches can be adopted to increase the effectiveness, such as ensuring the correct timing of application. Turner *et al.* (2001) found that treatment 3 – 5 weeks after 50% crop emergence was the most effective time frame to reduce weed density without significantly harming the crop.

Alternative weed flammers use infra-red radiation to heat the soil surface. Burners heat ceramic or metal panels which radiate heat onto the weeds, using less fuel than standard flammers (Litterick *et al.*, 1999; Rahkonen and Jokela, 2003). However, the ceramic or metal panels take time to heat up, are sensitive to mechanical damage and do not generate temperatures as high as conventional flammers (Bond and Lennartsson, 1999).

Soil solarisation is widely used in the Mediterranean and other areas with dry, warm climates (Hasing *et al.*, 2004). Radiant heat is trapped under a polyethylene sheet placed over the soil surface. The thickness and colour of the polythene sheet influences

the temperature reached (Kassaby, 1985). The efficiency of the method to control weeds is highly contested. Hasing *et al.* (2004) suggests that weed populations are significantly lowered whereas Bonanomi *et al.* (2008) found the method to be only partially effective.

2.3 Soil steaming

At present, steaming is only allowed in green-houses, and is not certified for use within the field under current U.K organic guidelines (Bond, 2002). Soil steaming can be applied in a number of ways. In sheet steaming, the soil is covered with a thermo-resistant sheet sealed at the edges. Steam is then injected under the sheet, penetrating the soil (Dabbene *et al.*, 2003). Soil steaming can also be applied by more mechanical means. For example, Roux-Michollet *et al.* (2008) describe a purpose-built machine, picks up the soil within worked ridges, or rows, injects it with pressurised steam and then deposit it back onto the ground within its original formation. The steam raises the soil temperature, killing most weed seeds within the targeted area (Bond, 2002).

The required duration of steaming has been greatly debated. Triolo and D'Errico (2002) cited by Baberi *et al.* (2009), and Pullman *et al.* (1981), suggest that steaming at 70°C for 30 minutes is sufficient to control targeted species in a single treatment. However, Loenen *et al.* (2003) propose that 3 minutes is adequate.

The maximum soil temperature reached during treatment can be increased by using activating compounds which create an exothermic reaction. Barberi *et al.* (2009) tested the activating compounds potassium hydroxide (KOH) and calcium oxide (CaO) which prolonged the duration of the maximum soil temperature reached. However, it was noted that in order to lower seed viability the maximum temperature reached was more important than the temperature duration.

Steaming consumes a great deal of energy and is therefore expensive. Before steaming can be widely used it needs to become more fuel and energy efficient. Otherwise it will

only be suitable for high-value horticultural crops (Dabbene *et al.*, 2003; Litterick *et al.*, 1999; Loenen *et al.*, 2003; Norberg and Dolling, 2003).

2.4 Effects of soil thermal treatments upon weeds

Studies demonstrating the effect of soil thermal treatments upon weeds have produced varying results. The success depends upon a number of factors, the most important being the species targeted and weed abundance. This is because weeds are not uniform in their germination behaviour or in their responses to perturbations (Grundy and Bond, 1998). The type of thermal treatment applied also influences the efficiency. For example, whilst streaming has been shown to be successful at controlling grass (Norberg and Dolling, 2003), flaming has displayed little effectiveness but is efficient at controlling annual broad leaved weeds (Litterick *et al.*, 1999; Wszelaki *et al.*, 2007). Plant size is also influential upon the sensitivity of the plant; the smaller the plant, the more sensitive (Ascard, 1994 cited by Wszelaki *et al.*, 2007). Due to the species-specific responses, soil thermal treatments will need to be adjusted accordingly (Barberi *et al.*, 2009; Grundy and Bond, 1998).

2.5 Effects of soil thermal treatments upon soil systems

2.5.1 Soil microorganisms

Several studies have indicated that soil thermal treatments disturb the soil systems equilibrium, affecting both the targeted and potentially beneficial, non-target soil microorganisms (Barberi *et al.*, 2009). The effect of high temperatures upon soil microorganisms is largely dependent upon the species as heat tolerances and optimum temperature ranges vary between species. The microbial community composition also changes on a seasonal basis, as well as varying on a very small spatial scale, both of which are consequently reflected in the soil systems response to any perturbation (Theis and Grossman, 2006).

High temperatures disturb soil microorganism's functions, consequently inducing chemical and physiological changes within the soil system (Roux-Michollet *et al.*, 2008; Tanaka *et al.*, 2003). Roux-Michollet *et al.* (2008) found post-steaming activity of soil microorganisms to be higher in steamed soil compared to the control due to weak competition of resources in the altered soil environment. One month after the steaming, the number of cultivable heterotrophic and denitrifying bacteria was higher in steamed soil compared to the control due to the initial increase in activity. The genetic structure also remained altered, demonstrating a lack of resilience (Roux-Michollet *et al.*, 2008).

Although a large proportion of the bacterial community has been shown to be affected by heat perturbations, the degree of alteration and recovery varies. Under the treatment of steaming, Roux-Michollet *et al.* (2008) reported more alterations in nitrifying bacteria compared to denitrifying or heterotrophic bacteria. This is thought to be caused by the activity of ammonia and nitrite oxidising bacteria reducing resulting in a suppression of nitrification (Tanaka *et al.*, 2003; Roux-Michollet *et al.*, 2008). Tanaka *et al.* (2003) also found nitrite oxidising bacteria to recover faster than ammonia oxidising bacteria.

Fungi are also affected by soil thermal treatments. In one study, the abundance of cultivable fungi decreased immediately after soil steaming, but recovered to the level of the control plots 12 days post steaming (Tanaka *et al.*, 2003). Pullman *et al.* (1981) suggest that the heat inactivation of soil organisms is caused by enzyme inactivation.

2.5.2 Nitrogen cycling

Temperatures during thermal treatments can have a series of impacts upon the soil N-cycle. Previous experiments investigating soil thermal treatments have shown the availability of soil mineral nitrogen to be strongly affected due to reduced mineralisation rates. Nitrification has shown to be more greatly affected than ammonification, leading to a reduction in the level of nitrate (Roux-Michollet *et al.*, 2008; Tanaka *et al.*, 2003). An accumulation in ammonium is also likely (Barberi *et al.*, 2009; Loenen *et al.*, 2003; Tanaka *et al.*, 2003).

2.5.3. Carbon cycling

Egli *et al.* (2006) found a decrease in soil organic carbon whilst Roux-Michollet *et al.* (2008) reported a decrease in microbial biomass carbon as a result of heat treatment. This is possibly due to the heat disturbance encouraging the decomposition or leaching of organic matter out of the soil system (Egli *et al.*, 2006). For this effect to be significant, a high soil organic concentration is needed prior to the thermal treatment (Egli *et al.*, 2006).

2.5.4 Short and long-term effects of soil thermal treatments (resistance and resilience)

It is possible for the effects of soil thermal treatments to only occur in the short-term having no long-term damage. This is because the soil biota is very adaptive to changes within its environment (Kibblewhite *et al.*, 2008). This adaptability is manifested as the resistance and resilience of the system, which influences the capability to continue functioning under changing conditions (Orwin and Wardle, 2004). The resilience of a soil system increases with diversity which depends upon the biotic relationships that overlap, creating a highly integrated system (Kibblewhite *et al.* 2008).

In the study by Roux-Michollet *et al.* (2008) it is suggested that alterations to the microbial community and associated properties, are likely to achieve a full recovery having no long term damage. This potentially demonstrates the concept that soil is a self-organising system, having the ability to repair itself to within normal functioning ranges (Kibblewhite *et al.*, 2008). As the soil system is highly integrated, a perturbation which disturbs one function will alter the dynamics of another. The opposite is true also; as one function recovers from stress, other functions that it interacts with will also recover (Kibblewhite *et al.*, 2008).

2.6 Concluding remarks

Preliminary research has shown steaming to be an effective soil thermal treatment against weeds (Wszelaki *et al.*, 2007; Rahkonen and Jokela, 2003), although it remains uncertified under U.K organic guidelines due to high energy costs and the unknown effects it has long-term on the soil system (Bond, 2002).

Soil thermal treatments in general have demonstrated to have a modest influence upon soil microorganisms, which in turn cause chemical and physiological changes in the soil environment (Roux-Michollet *et al.*, 2008; Tanaka *et al.*, 2003). The resistance and resilience of these microorganisms vary between species. Both ammonia and nitrite oxidising bacteria have been found to decrease in activity causing a suppression of nitrification (Tanaka *et al.*, 2003; Roux-Michollet *et al.*, 2008). Decreases in soil organic carbon and microbial biomass carbon have also been reported (Egli *et al.*, 2006; Roux-Michollet *et al.*, 2008). The effects caused by heat disturbance are thought mainly to be short term only, although the recovery of the system (resistance and resilience) depends upon numerous factors.

CHAPTER 3: Research Design and Methodology

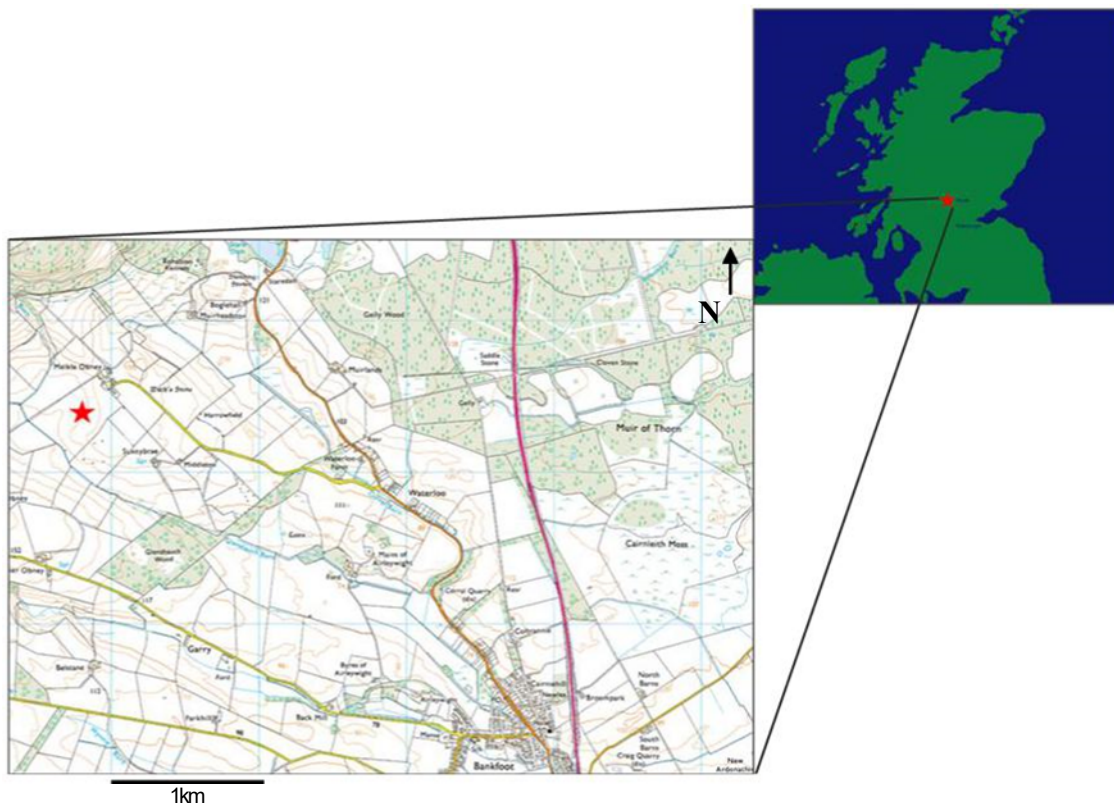
3.1 Study area

3.1.1 Location

Research was conducted at Meikle Farm near the village of Waterloo in Perthshire, Scotland (OS Grid Ref NO 03626 37440) during June and July, 2009 (Figure 3.1). The average maximum temperature for June and July is 19 – 20 °C, with mean temperatures of 13 – 14 °C. Average monthly rainfall is between 40 – 60 mm for both months (averages based on readings between 1971 and 2000, U.K Meteorological Office, 2009).

The site lies in a vale within the flood plain of the River Tay. The soil within the area is formed from alluvial deposits out washed from the surrounding Grampian Mountains during the last glacial period. The soil therefore is sandy.

Figure 3.1 OS map of study area; Meikle Farm, Waterloo, Perthshire, Scotland. Source:



Digimap, altered using ArcGIS.1:25000 : location of site.

3.1.2 Site history

The site is subject to organic production and has not recently been used in conventional farming and neither is it situated near any conventional farming systems so there is no, or very little, cross-contamination with chemical pesticides. All previous production has been within organic farming systems. Couch grass (*Elymus repens* L.) was a major problem at the site, dominating several areas of the field (Figure 3.2). Prior to treatment and sampling, all soil beds had 3 applications of flaming, whereby a naked flame was applied to the soil, destroying any weeds present at the surface.



Figure 3.2 Study site following flaming and bed formation, prior to thermal treatment and sowing, showing the extent of Couch grass (*Elymus repens* (L)) infestation, visible as green patches. Location: Meikle Farm, Waterloo.

3.2 The soil thermal treatment machine

The soil thermal treatment machine picked up soil from a predefined row within the bed, treated it with pressurised steam with a target temperature of 70°C, and then replaced it onto the bed within the predefined rows (Figure 3.3). This increased efficiency as only the area of soil to be drilled was heated, cutting down fuel use and costs.

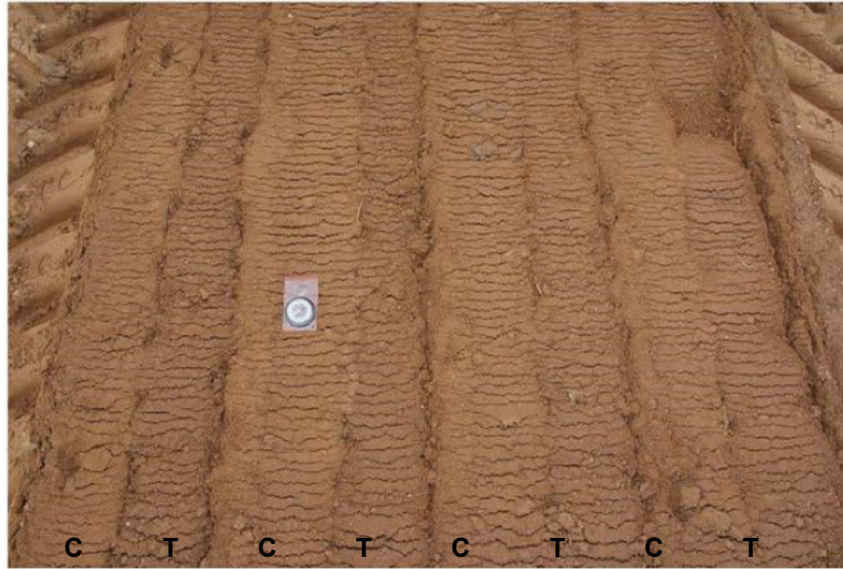


Figure 3.3 Bed following treatment showing both treated and control rows. T = treated rows, C = control row. Width of compass = 5 cm.

3.3 Research design

3.3.1 Sampling plan

The thermal treatment was applied along beds approximately 2 m wide including 20 cm on either side for wheelings (Figure 3.3 and 3.4). Within each bed, four rows of *Daucus carota, sativus* (L) (carrots) were drilled. Within each of these four rows, there were 3 rows of drilled carrots (Figure 3.4). The planting density was greater for the outside two rows compared to the middle two, which is convention for such systems since outer rows are subject to more direct sunlight.

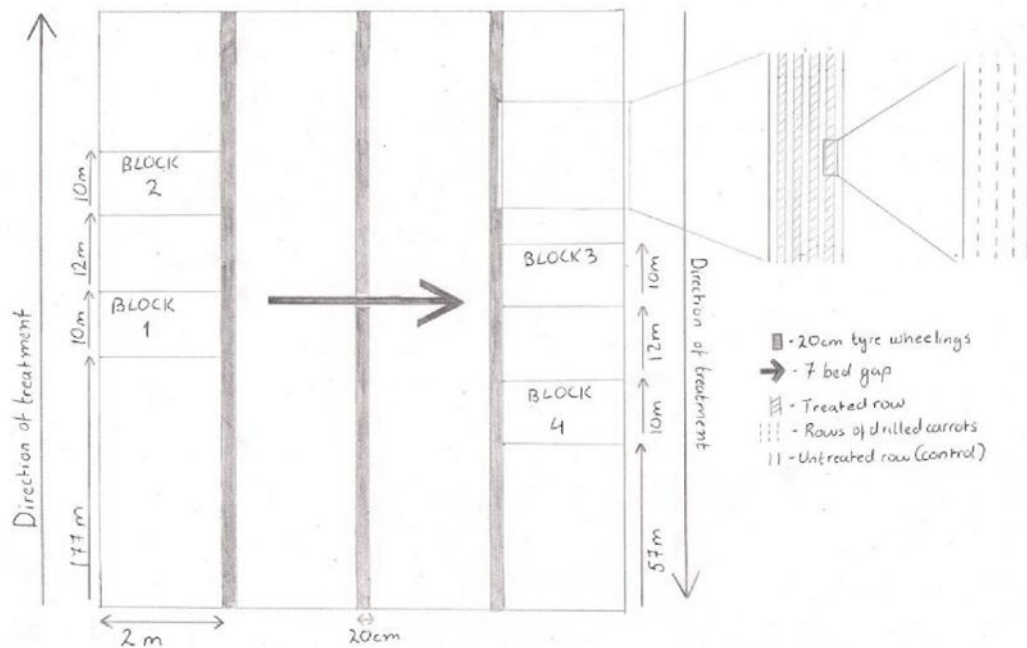


Figure 3.4 Sampling plan highlighting sampling blocks within the treated beds, and distances apart in metres.

Two beds were steam treated, both approximately 150 m in length with 7 untreated beds in-between. Within the treated beds, two 10 m long sampling blocks were marked. Soil samples were taken from 3 of the 4 treated rows within the block with the precise locations randomly, avoiding edge rows. Samples from 0 – 5 cm depth (Depth 1) and 5 – 10 cm (Depth 2) were taken. The same was conducted for the control rows, sampling from 3 of the 5 rows, again avoiding edges. The sub-samples were pooled together to provide 4 samples from each block (i.e treated and control, two depths each) in total. Sampling occurred at three intervals, 1 hour immediately following treatment (Day 0), and 14 and 42 days thereafter, using the same sampling approach each time, but with new random locations within each plot. This represents a repeated-measure fully factorial design, which provides a sound statistical basis for analysis of the data. The sowing of the crop occurred within the week following the treatment.

Since the soil was too unconsolidated to use traditional augers, soil samples were taken using a cylindrical steel sleeve, 11 cm in depth and 4 cm in diameter (Figure 3.5). Sampling from the outside rows was avoided due to potential edge effects. Soil to the prescribed depth was scooped out in two steps.



Figure 3.5 Soil sampling procedure (a) driving cylindrical steel sleeve into planting bed; (b) sleeve with upper layer of soil removed. Diameter of core = 4 cm.

3.3.2 Field measurements

Soil temperature

Temperature loggers were used to record the soil temperature as soon after steaming as practicable. The loggers were placed in the soil within a minute of the treatment, with 6 in treated rows and 6 in control rows. For both treated and control soil, 3 temperature loggers were placed at 5 cm depth, and 5 at 10 cm depth. They were left in the soil for approximately 2 hours and a further temperature logger was left out of the soil to record the ambient temperature.

3.3.3 Laboratory measurements

A range of soil chemical and biological properties were measured that relate to a range of key indicators of soil functions (Table 3.1).

Table 3.1 Laboratory tests.

Measurement	Indicator
<i>Physico-chemical:</i>	
pH	<i>General soil characteristic</i>
•	<i>Potential change in availability of nutrients</i>
•Dissolved organic carbon (DOC)	<i>Carbon cycling</i>
•Total carbon	<i>Carbon cycling</i>
•Total nitrogen	<i>Nitrogen cycling</i>
Mineral N (NH ₄ ⁺ -N and NO ₃ ⁻ -N)	<i>Nitrogen cycling</i>
<i>Biochemical:</i>	
• Microbial biomass	<i>Size of microbial community</i>
• Respiration	<i>Activity of microbial community</i>
• N mineralisation	<i>N supplying potential of soil</i>
◦ actual mineralisation	
◦ potential nitrification	

Soil preparation

Soils were sieved to 4 mm and were kept in a fridge at 0.5 - 1°C, prior to analysis.

pH

pH was only measured on soil samples from Day 0. Samples were air-dried for 7 days and determined according to the British Standard BS ISO 10390:2005 *Determination of pH*, suspending the samples in distilled water.

Total carbon and nitrogen

The total C and N contents of the soil were determined using an Elemental Analyser (Elemental Vario EL). Samples were air-dried, ground and then placed in an oven at approximately 105°C for 2 hours. The samples were then weighed and packed into aluminium-foil capsules. The samples were loaded onto the carousel of the Elemental

Analysed and the total C and N contents, and C:N ratios were measured. Total C and N were only measured for Day 0 samples.

Mineral nitrogen

Mineral N was extracted, and determined as the concentrations of ammonium-N (nitrogen in the form of NH_4^+ ions) and total oxides of N ($\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$) in fresh soil. Extraction using 1M potassium chloride (KCl) was conducted the day following sampling on field moist soil (Time 0 (T0)). This was expedited since mineralisation continues after field extraction, potentially inflating the results. Following extraction, analysis was conducted using the Burkard Scientific SFA (Segmented Flow Analyser) – 2000 to determine $\text{NH}_4^+\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations.

Nitrogen mineralisation

To determine the long-term N mineralisation rate, a modified form of the assay of Alef (1995) was used. Two 20 g replicates of each sample were moistened with 6 ml (approximately 170% water holding capacity) of distilled water. One of the replicates was stored at -20°C (control), the other was incubated at 25°C for 11 Days. Following incubation, the mineral N was extracted using 0.5M potassium sulphate solution (K_2SO_4) from both sets of samples. $\text{NH}_4^+\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations were determined using the Burkard Scientific SFA. To determine the rate of mineralisation, the concentrations measured for mineral N directly following sampling (T0) were subtracted from the concentrations measured for the incubated long-term mineralisation (time 11 (T11)), and divided by the number of incubation days (11 days). This gave the mean daily rate of mineralisation over the 11 day period following field extraction.

Potential nitrification

To measure the rate of potential nitrification, the augmented nitrification assay of Wheatley *et al.* (2001) was adapted. Concentrations of ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) (4mM) and sodium chlorate ($\text{Na}(\text{ClO}_3)$) (15mM) were added to the soil sample to produce a water holding capacity of 200%. $(\text{NH}_4)_2\text{SO}_4$ was added to ensure nitrification was not inhibited by a lack of NH_4^+ , whilst $\text{Na}(\text{ClO}_3)$ prevented the conversion of $\text{NO}_2\text{-N}$ into $\text{NO}_3\text{-N}$. The samples were then placed on a side-to-side

shaker for approximately 72 hours to allow maximum respiration and aerobic activity. Following incubation, the samples were extracted using 1M KCl solution. NO₂-N concentrations were analysed using the Burkard Scientific SFA. Hourly potential nitrification rates were determined.

Dissolved organic carbon (Field DOC)

The amount of extractable organic carbon was measured on fresh, field-moist soil the Day following field extraction. The carbon was extracted using 0.5M K₂SO₄ solution. Following extraction, 5ml of the K₂SO₄ sample extract was mixed with 5ml of sodium polyphosphate (NaPO₃) reagent. Analysis was conducted using the Burkard Scientific SFA.

Microbial biomass (Flush DOC)

The British Standard BS 7755: Section 4.4.2:1997 *Determination of soil microbial mass – fumigation-extraction* method was followed. Samples were fumigated using chloroform to release the microbial matter. All samples, including both fumigated samples and the control were then extracted using 0.5M K₂SO₄ solution. Following extraction, 5ml of the K₂SO₄ sample extract was mixed with 5ml of NaPO₃ reagent. Analysis was then conducted using the *Burkard Scientific* SFA. The difference in extractable organic carbon between the fumigated and control samples is the ‘flush DOC’ and is indicative of the amount of microbial biomass.

Microbial respiration

The rate of respiration was measured using the Rapid Automated Bacterial Impedance Technique (RABIT, Ritz *et al.* 2006). The indirect impedance technique was applied whereby the change in electrical conductivity of the alkaline agar due to the ionisation of CO₂ was measured.

The RABIT operational conditions were set up as follows; test duration: 16 hours; time resolution: 6 minutes, temperature: 25°C, detection limit: 10 microsiemens.

The electrical signal is temperature dependant so temperature control is critical, therefore the laboratory air conditioning unit should ideally be set at 20 °C. However, at the time of the experiment for Day 14 and 42 samples, the air conditioning unit was not functioning. The ambient temperature of the laboratory peaked above 25°C. This may have had an impact upon the results.

For each sample 6 replicates were weighed. Three measured basal respiration, having only water added. The remaining three had 200mM of glucose applied so as to measure substrate induced respiration (SIR). Both solutions were added to produce a water holding capacity of 100%. To calculate the correct volumes it was necessary to conduct a water holding capacity test for each soil collected as each sampling occasion.

Statistical analysis

For data determined at the three sampling occasions, repeated measures analysis of variance (ANOVA) was applied using the programme Statistica, transforming the data where appropriate. A post-hoc multiple range test was applied to establish significant differences between means, using a significance level. Factorial ANOVA was used for single-timed data.

CHAPTER 4: Results

4.1 Soil temperature

The temperatures recorded were done so after the soil had been deposited and the actual temperature attained in the machine was likely to be greater. The highest temperature recorded was in treated soil at Depth 2 (Table 4.1). The highest temperature recorded for the control zones was 6°C lower than the treated soil. Peak temperatures for all samples, except for control Depth 2, occurred between 00:48 and 00:49 h post treatment, shortly before the ambient temperature peaked at 00:55 h (Appendix Di).

Table 4.1 Peak soil temperatures recorded over the 2 hours immediately following steaming treatment.

Location	Time since treatment (h:min)	Recorded peak soil temperature (°C)
Ambient	00:55	39.8
Treated, Depth 1	00:49	46.9
Treated, Depth 2	00:49	47.2
Control, Depth 1	00:35	41.1
Control, Depth 2	00:48	40.8

4.2 pH

There was no significant difference in pH between treated and control soils ($P>0.05$), with an overall mean of pH 6.1, nor any effect of depth upon pH (Table 4.2, Appendix Dii)

Table 4.2 Average pH for treated and control soil at Depth 1 and Depth 2 for Day 0 samples.

	Treated	Control
Depth 1 (0-5 cm)	6.09	6.11
Depth 2 (5-10 cm)	6.05	6.11

4.3 Total carbon and nitrogen

Total C and N concentrations on Day 0 were; total C, 2.59 %; total N, 0.24 % and C:N ratio, 11.0 %. Factorial ANOVA showed there to be no significance between levels of total C and N with respect to treatment or depth (Appendix Diii).

4.4 Mineral nitrogen

4.4.1 Mineral nitrogen: T0

Ammonium-N

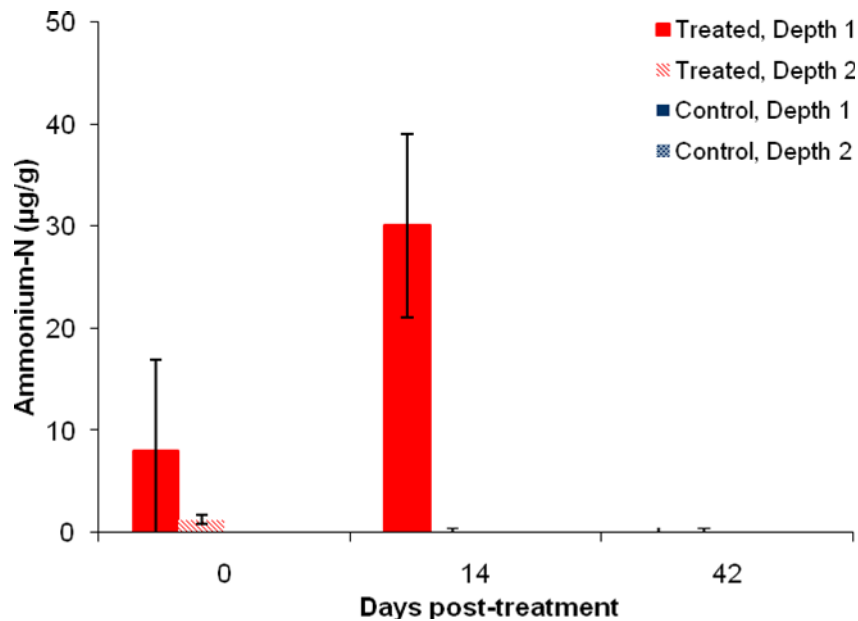


Figure 4.1 Mean ammonium-N for T0. Samples with no value were below the limit of detection. Error bars show standard error.

$\text{NH}_4^+\text{-N}$ was only detected in treated soil for Day 0, and treated soil, Depth 1 for Day 14 (Figure 4.1). Out of the concentrations recorded, treated soil, Depth 2 at Day 0 had the lowest value and treated soil, Depth 1 at Day 14 had the highest level, with almost a 4-fold increase than that recorded at Day 0 (Appendix Div). Whilst this data is not conducive to repeated measure ANOVA, there was an apparent treatment and time effect, as only treated soil at Day 0 and 14 had detectable levels.

Nitrate-N

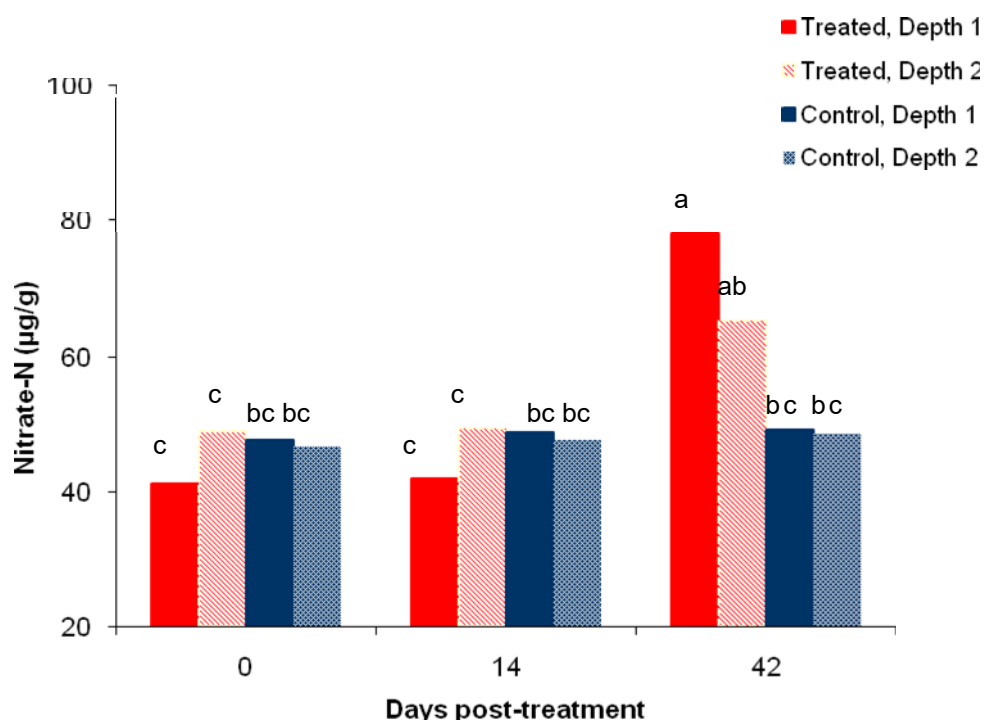


Figure 4.2 Mean nitrate-N for T0. A-C highlight significant means derived from logged transformed data. Those samples denoted with the same letter are part of a homogenous group.

Table 4.3 Analysis of variance for nitrate-N for T0 ($P = <0.05$). EMS = Error Mean Square.

Effect	P
Treatment	0.121
Depth	0.744
Treatment*Depth	0.486
Time	<0.001
Time*Treatment	<0.001
Time*Depth	0.061
Time*Treatment*Depth	0.025
EMS	<0.005

ANOVA showed there to be a 3-way interaction between time, treatment and depth (Table 4.3). The time effect, which is clearly demonstrated at Day 42 (Figure 4.2), is dependent upon both treatment and depth. For example, the amount of $\text{NO}_3\text{-N}$ in treated soil at Day 42 became greater in Depth 1 than in Depth 2. Both concentrations

were much larger in comparison to the control soil, a reversal on what had been shown previously at Day 0 and Day 14.

4.4.2 Mineral nitrogen: T11

Ammonium-N

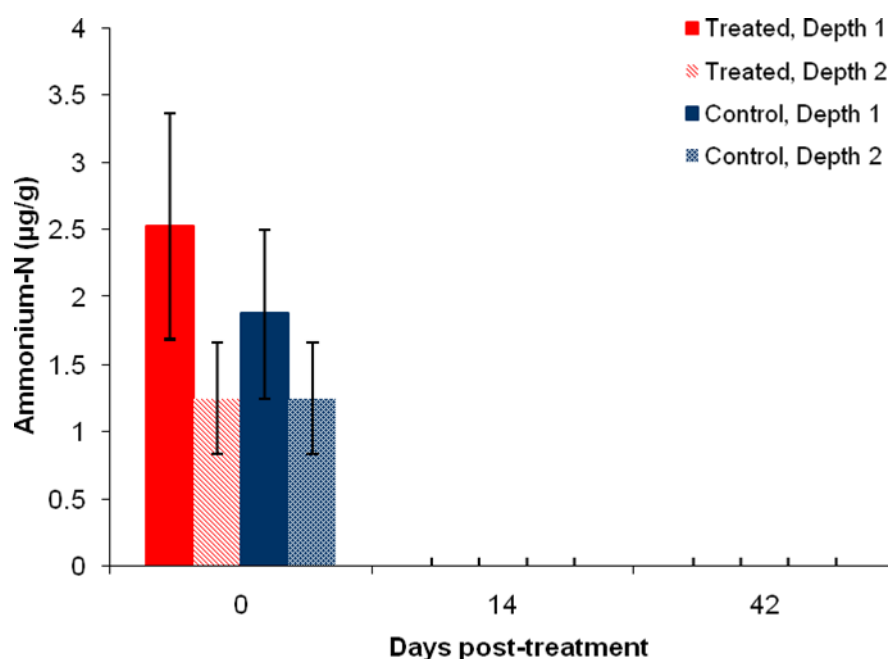


Figure 4.3 Mean ammonium-N for T11. Samples with no value were below the limit of detection. Error bars show standard error.

$\text{NH}_4^+\text{-N}$ was only detected at Day 0 (Figure 4.3). Although there was not enough data for repeated measures ANOVA, a depth effect for treated soil at Day 0 was apparent with Depth 1 having a much higher concentration than Depth 2, in comparison to the control soil. There was also an effect of time as $\text{NH}_4^+\text{-N}$ was only recorded at Day 0 (Appendix Dv).

Nitrate-N

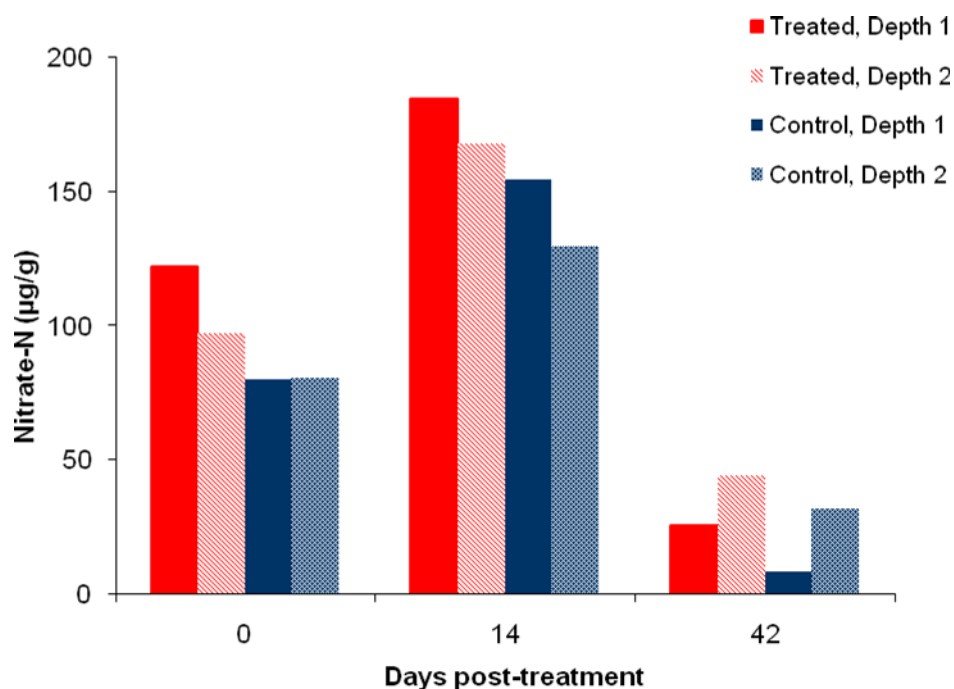


Figure 4.4 Mean nitrate-N for T11.

Table 4.4 Analysis of variance for nitrate-N for T11 (P= <0.05).

Effect	P
Treatment	0.001
Depth	0.172
Treatment*Depth	0.186
Time	<0.001
Time*Treatment	0.196
Time*Depth	0.032
Time*Treatment*Depth	0.771
EMS	1044

Levels of NO₃-N varied at each sampling occasion (Figure 4.4). This was demonstrated by repeated measures ANOVA, which indicated a strong significance of the effect time had across all samples (Table 4.4). There was a peak of NO₃-N at Day 14 for all samples, and a decrease at Day 42, demonstrating the time effect.

The change in NO₃-N across time differed with depth. This was demonstrated at Day 42. Previously at Day 0 and 14, Depth 1 had a higher NO₃-N level than Depth 2, with the exception of control soil at Day 0. However at Day 42 this changed, where Depth 2 became greater than Depth 1.

Treatment also had a significant effect upon NO₃-N (Table 4.4). Across all three sampling occasions, treated soil had a greater concentration of NO₃-N relative to the control (Appendix Dv).

4.4.3 Nitrogen mineralisation over an 11 day period

Nitrogen mineralisation rates were calculated using the formula:

$$\frac{T_{11}N_{\min} - T_0N_{\min}}{11}$$

Ammonium-N

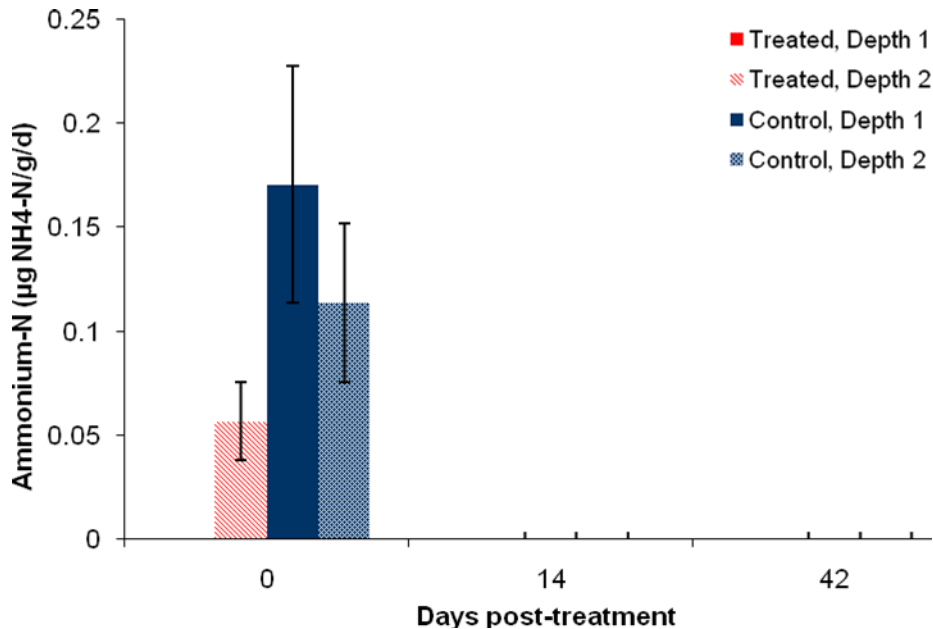


Figure 4.5 Mean rate of ammonium-N production per day over an 11 day period. Samples with no value were below the limit of detection. Error bars show standard error.

$\text{NH}_4^+\text{-N}$ production was only detected at Day 0 for treated soil, Depth 2 and control soil at both depths (Figure 4.5). The rate of $\text{NH}_4^+\text{-N}$ production was greatest in control soil Depth 1. The lowest rate was found in treated soil, Depth 2, almost one third less than the control. There was an inadequate amount of data for repeated measures ANOVA but results suggest that there was a treatment and time effect upon the rate of $\text{NH}_4^+\text{-N}$ production (Appendix Dvi).

Nitrate-N

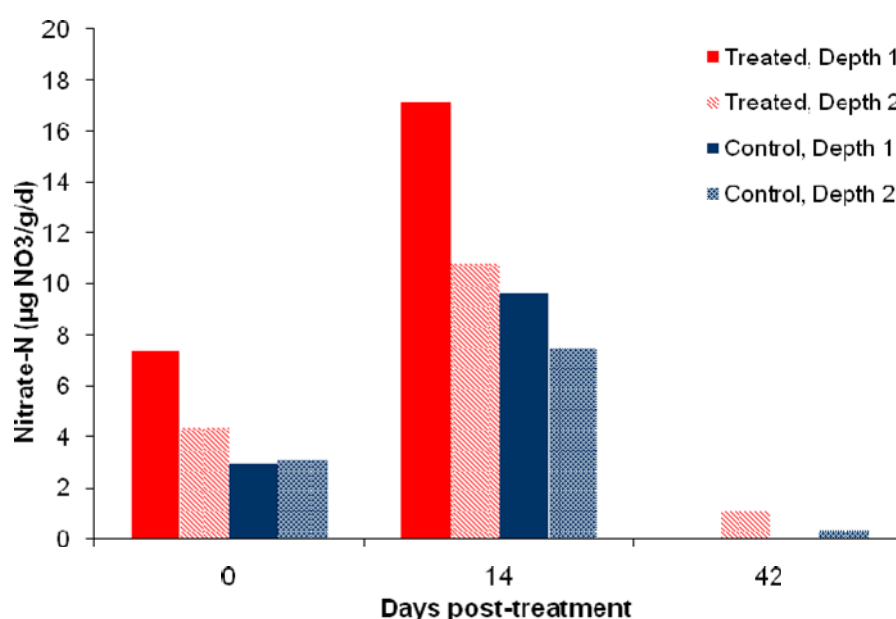


Figure 4.6 Mean rate of nitrate-N production per day over an 11 day period. Samples with no value were below the limit of detection.

Table 4.5 Analysis of variance for nitrate-N production ($P < 0.05$).

Effect	P
Treatment	0.003
Depth	0.051
Treatment*Depth	0.210
Time	<0.001
Time*Treatment	0.047
Time*Depth	0.052
Time*Treatment*Depth	0.340
EMS	6.896

Repeated measures ANOVA has shown NO₃-N rates to vary with time, treatment and depth across all samples. The effects of treatment and depth also depended upon time (Table 4.5). The effect of time is demonstrated at Day 14 where all samples peaked in their NO₃-N production rates, which was followed by a decrease at Day 42 where treated and control soil at Depth ,1 fell below the limit of detection (Figure 4.6). This also encompasses the treatment and time effect. Previously at Day 0 and 14, rates of NO₃-N had remained higher in the treated soil, but at Day 42, the control soil had the greatest production rate. The depth effect across time was also demonstrated at Day 42. At Day 0 and 14, Depth 1 had a higher NO₃-N rate than Depth 2, but at Day 42, Depth 1 fell below the rate of Depth 2 for both treated and control (Figure 4.6, Appendix Dvi).

Mineral nitrogen

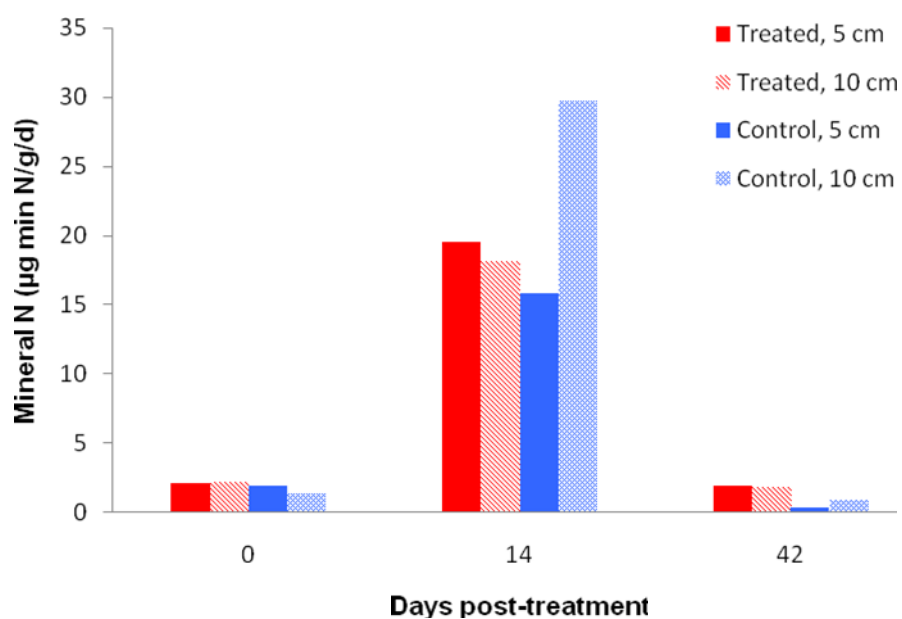


Figure 47 Mean rate of nitrogen mineralisation per day over an 11 day period.

Table 4.6 Analysis of variance for nitrogen mineralisation ($P = <0.05$).

Effect	P
Treatment	0.809
Depth	0.497
Treatment*Depth	0.406
Time	<0.001
Time*Treatment	0.748
Time*Depth	0.620
Time*Treatment*Depth	0.489
EMS	106.4

Mineralisation rates differed across all samples with time (Table 4.6). This was shown at Day 14 when N mineralisation rates peaked in all samples. Rates at Day 0 and 42 did not differ greatly (Figure 4.7).

4.6 Potential nitrification

Nitrite-N

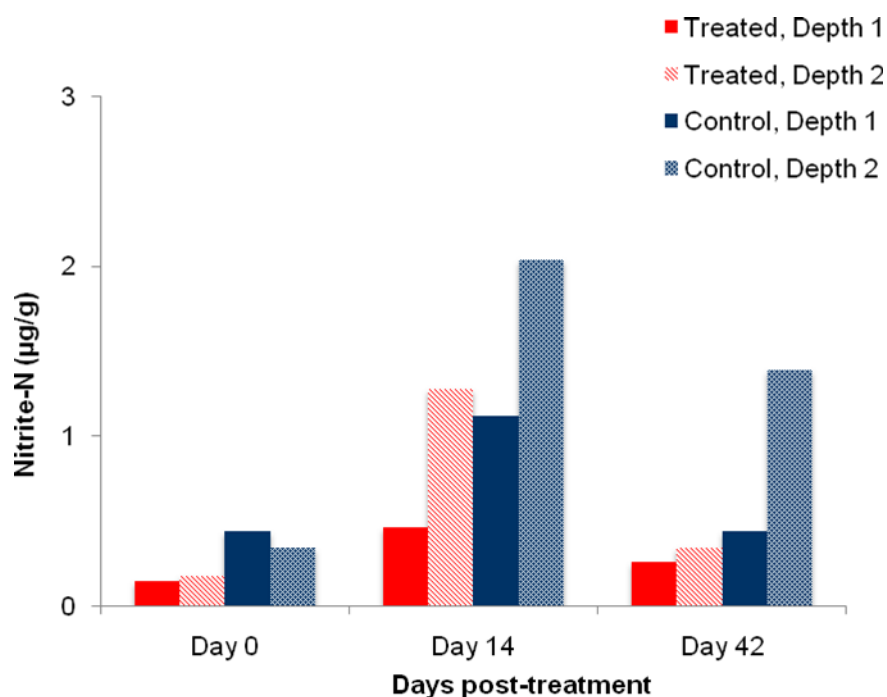


Figure 4.8 Mean potential nitrification.

Table 4.7 Analysis of variance for potential nitrification ($P = <0.05$).

Effect	P
Treatment	0.024
Depth	0.043
Treatment*Depth	0.495
Time	<0.001
Time*Treatment	0.285
Time*Depth	0.027
Time*Treatment*Depth	0.271
EMS	0.197

Time affected potential nitrification rates across all samples but depended upon depth. This was shown at Day 0 where rates were at their lowest for all samples, but increased at Day 14. $\text{NO}_2\text{-N}$ levels differed with depth across all samples both independently and dependently of time. On all three sampling occasions, Depth 2 had a greater $\text{NO}_2\text{-N}$ than Depth 1, except for the control soil at Day 0 showing the effect of time (Figure 4.8). $\text{NO}_2\text{-N}$ also differed with treatment across all samples. At all occasions, $\text{NO}_2\text{-N}$ remained lower in treated soil compared to the control (Appendix Dvi).

4.7 Organic carbon

4.7.1 Field DOC

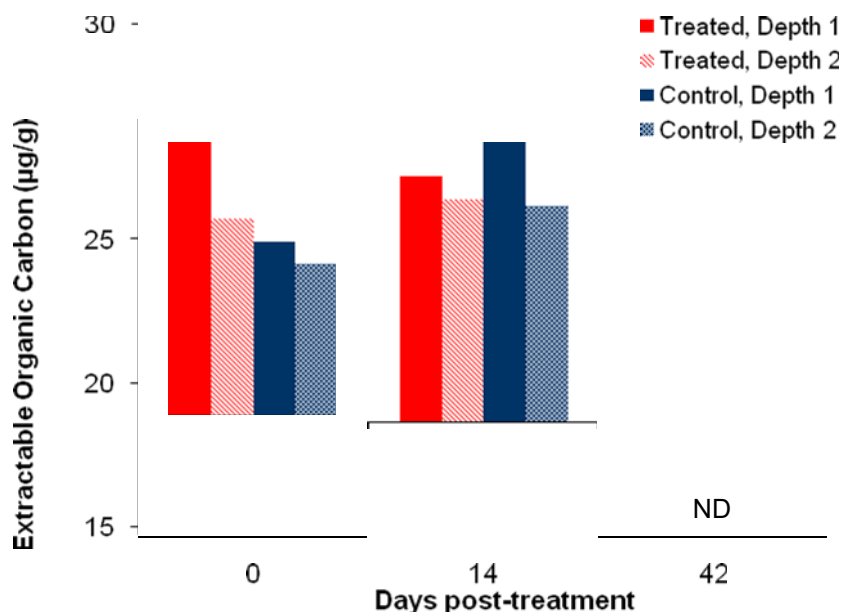


Figure 4.9 Mean field DOC. ND = Not determined

Table 4.8 Analysis of variance for field DOC (P = <0.05).

Effect	P
Treatment	0.063
Depth	0.007
Treatment*Depth	0.788
Time	0.273
Time*Treatment	0.262
Time*Depth	0.931
Time*Treatment*Depth	0.530
EMS	12.71

Due to a fault with the SFA it was not possible to analyse data collected at Day 42. Field DOC varied with depth across all samples (Table 4.8). At both Day 0 and 14, extractable organic carbon was lower in Depth 2 in comparison to Depth 1, for both treated and control soil (Figure 4.9). Although treatment effect has a P value of 0.063, due to the large field-scale of the project it should still be considered as marginally significant. A treatment effect was demonstrated at Day 0, where treated soil had a higher organic carbon content than the control for both depths (Appendix Dvii).

4.7.2 Flush DOC

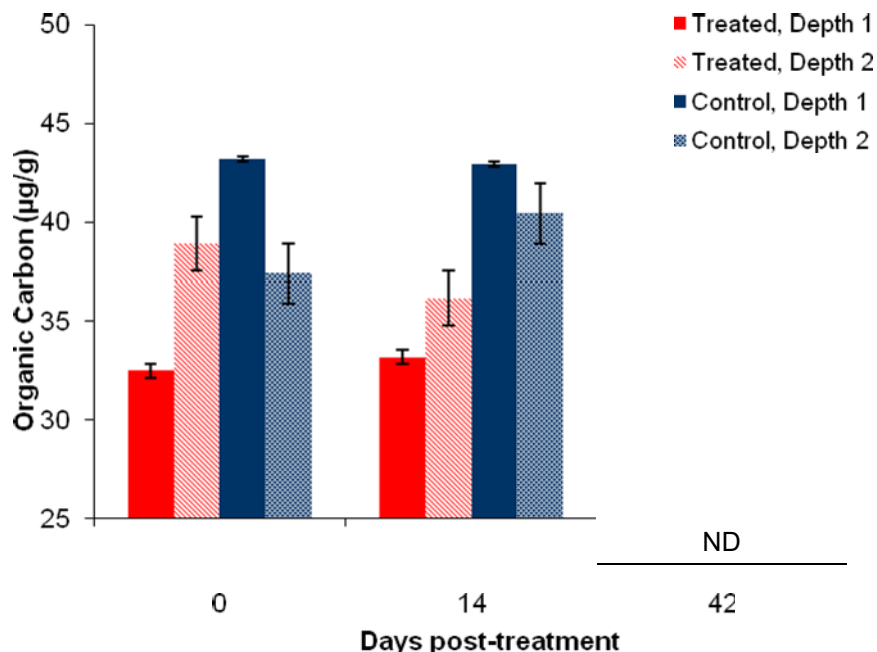


Figure 4.10 Mean flush DOC. Error bars show standard error. ND = Not determined.

Table 4.9 Analysis of variance for flush DOC ($P < 0.05$).

Effect	p
Treatment	0.084
Depth	0.930
Treatment*Depth	0.177
Time	0.958
Time*Treatment	0.729
Time*Depth	0.989
Time*Treatment*Depth	0.632
EMS	92.92

Due to a fault with the SFA it was not possible to analyse data collected at Day 42. Repeated measures ANOVA showed there to be no significant effect upon flush DOC (Table 4.9). There was no clear significant effect of time or depth upon flush DOC, and only a weak effect of treatment ($P < 0.10$), with overall means of 35.2 and 41 mg/g for control and treated soil respectively (Appendix Dvii).

4.8 Microbial activity

4.8.1 Basal respiration

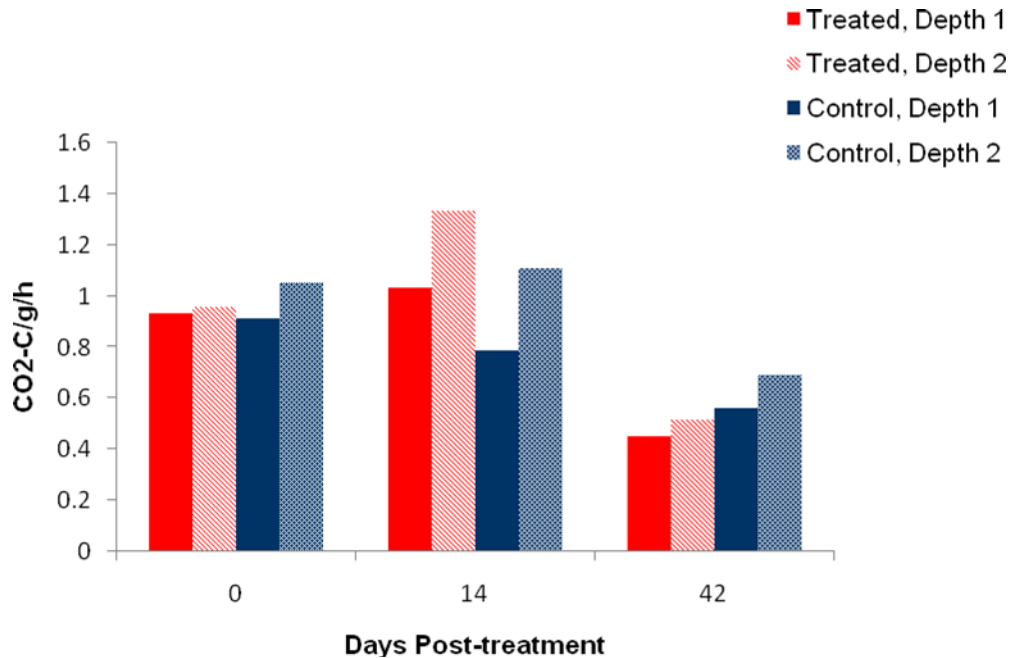


Figure 4.11 Mean basal respiration.

Table 4.10 Analysis of variance for basal respiration ($P < 0.05$).

Effect	P
Treatment	0.835
Depth	0.064
Treatment*Depth	0.703
Time	<0.001
Time*Treatment	0.107
Time*Depth	0.359
Time*Treatment*Depth	0.966
EMS	0.061

Basal respiration differed with time across all samples (Table 4.10). This is demonstrated at Day 42 where basal respiration rates decreased in all samples compared to Day 0 and 14 (Appendix Dviii).

4.8.2 Substrate induced respiration

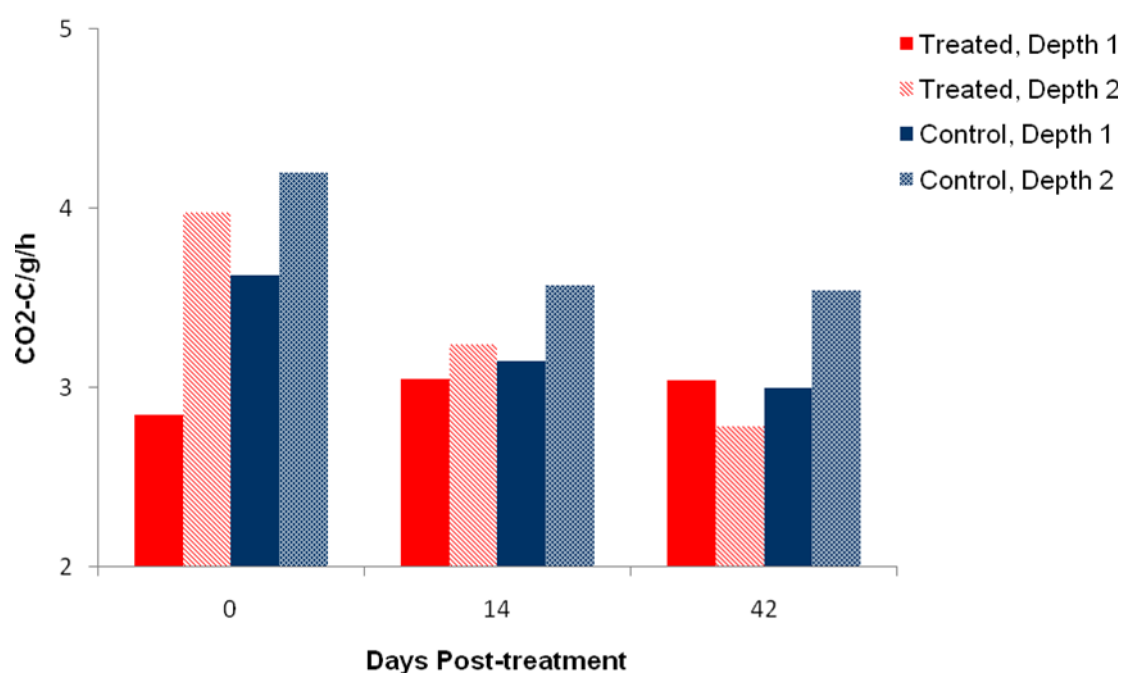


Figure 4.12 Mean substrate induced respiration.

Table 4.11 Analysis of variance for substrate induced respiration ($P < 0.05$).

Effect	p
Treatment	0.062
Depth	0.029
Treatment*Depth	0.659
Time	0.035
Time*Treatment	0.793
Time*Depth	0.237
Time*Treatment*Depth	0.291
EMS	0.360

SIR differed with depth across all samples (Table 4.11). Apart from at Day 42 in treated soil, Depth 1 remained lower than Depth 2 for both treated and control soil (Figure 4.12).

SIR also differed with time across all samples. This is demonstrated at Day 0 where all samples, except for treated soil, Depth 1, peaked (Appendix Dviii).

CHAPTER 5: Data Analysis and Discussion

5.1 Soil temperature

As seen in Table 4.1, the difference in temperature between treated and control soils was not as great as was expected, with only a 6 °C difference at Depth 1. The target temperature of the machine was 70 °C but it is unknown whether this was reached during field application. Soil does not retain heat for very long, particularly in field conditions. It is therefore likely that the peak temperatures recorded in this circumstance were not a result of the steaming but related to the ambient temperature. As shown in Table 4.1, the peak temperature of treated soil at both depths, and control soil at Depth 2 occurred 6 – 7 minutes before the ambient temperature peaked. The reliability of the temperature loggers is also questionable as they were encased in plastic, possibly distorting their ability to record temperature accurately.

5.2 pH

pH was found not to be significantly affected by either treatment or depth. However, previous studies have reported changes in soil pH as a possible consequence of heat perturbations either affecting the activity of nitrifying bacteria and therefore the concentrations of nitrogen in its various forms, or by acidifying the soil through organic matter decomposition (Egli *et al.*, 2006; Tanaka *et al.*, 2003). As previously suggested, it is possible that the steaming treatment did not reach the target temperature which may have prevented any significant changes in the soil pH.

5.3 Total carbon and nitrogen

Concentrations of total C and N were not significantly affected by either treatment or depth, rather the effects were upon specific forms C and N.

5.4 Nitrogen cycling

5.4.1 Mineral nitrogen: T0

Between Day 0 and 14 there appeared to be an accumulation of $\text{NH}_4^+\text{-N}$ in treated soil, Depth 1 (Figure 4.1). This coincided with low levels of $\text{NO}_3^-\text{-N}$ in treated soil, Depth 1 for Day 0 and 14, which may have been a response to the $\text{NH}_4^+\text{-N}$ accumulation (Figure 4.2).

At Day 42, no $\text{NH}_4^+\text{-N}$ was detected in any of the samples, and yet there was a significant rise in $\text{NO}_3^-\text{-N}$, particularly in treated soil demonstrating the treatment effect across time (Figure 4.2). Accumulation of $\text{NH}_4^+\text{-N}$ and consequent surges in $\text{NO}_3^-\text{-N}$ have been found in previous similar studies following soil thermal treatments (Barberi *et al.*, 2009; Loenen *et al.*, 2003; Tanaka *et al.*, 2003). It is likely that the build up of $\text{NH}_4^+\text{-N}$ caused the lower concentrations of $\text{NO}_3^-\text{-N}$ in treated soil at Day 0 and 14, as well as the following increase in $\text{NO}_3^-\text{-N}$ as $\text{NH}_4^+\text{-N}$ levels fell below the limit of detection at Day 42.

5.4.2 Mineral nitrogen: T11

The accumulation of $\text{NH}_4^+\text{-N}$ at Day 0 was still apparent after the 11 day incubation with detection in the control soil as well as the treated (Figure 4.3). Levels in Depth 1 remained higher than Depth 2 suggesting a depth effect caused by the steaming treatment. However, $\text{NH}_4^+\text{-N}$ levels for treated and control soil, Depth 2 were the same, indicating that after the 11 day incubation there was no longer a treatment effect at this depth.

At Day 14 and Day 42, no $\text{NH}_4^+\text{-N}$ was detected suggesting that the build up of $\text{NH}_4^+\text{-N}$ had stopped. This correlated with an increase of $\text{NO}_3^-\text{-N}$ between Day 0 and Day 14 in all samples, including the control suggesting that it may also have been affected by the treatment, although to a lesser extent. At Day 42, levels of $\text{NO}_3^-\text{-N}$ were significantly reduced (approximately a 7-fold decrease) with lower concentration at Depth 1 than in

Depth 2. This is likely to be caused by environmental factors rather than the soil steaming.

The results from T0 and T11 suggest that actual nitrification was inhibited following treatment. This would have caused the apparent accumulation of $\text{NH}_4^+\text{-N}$ as the oxidation process of converting it into $\text{NO}_3^-\text{-N}$ would have been inhibited. The initial accumulation of $\text{NH}_4^+\text{-N}$ at T0 for Day 0 decreased in treated soil, Depth 1 over the 11 day period (Figure 4.1 and Figure 4.3). It is possible that during the 11 day incubation period, actual nitrification began to recover.

5.4.3 Potential nitrification

Between Day 0 and Day 14 there was a rise in $\text{NO}_2^-\text{-N}$ levels indicating that potential nitrification was initially inhibited (Figure 4.8). Levels were lower in treated soil, particularly in Depth 1 as it was more affected by the steaming, and therefore had a greater suppression of potential nitrification. There was a rise in control soil over the three sampling occasions as indicated by the significant treatment effect, suggesting that it may also have been affected by the steaming. Again, the decrease in levels at Day 42 is likely to have been caused by environmental factors rather than the steaming treatment.

5.4.3 Mineralisation rates

The production of $\text{NH}_4^+\text{-N}$ was much greater in the control soil compared to the treated soil (Figure 4.5), suggesting that the production of $\text{NH}_4^+\text{-N}$ had been slowed by the soil steaming, particularly at Depth 1 for treated soil, where levels were below the limit of detection.

Between Day 0 and Day 14 there was a significant rise in the rate of $\text{NO}_3^-\text{-N}$ production (Figure 4.6). Rates were greater in treated soil than the control for both days, and greater still at Depth 1. This could possibly be a result of the initial $\text{NH}_4^+\text{-N}$

accumulation (Figure 4.1 and Figure 4.3). The lower rate of $\text{NO}_3\text{-N}$ in control soil, Depths 1 and 2 at Day 0 corresponded with the $\text{NH}_4\text{-N}$ rate (Figure 4.5).

A possible reason for the large rise in $\text{NO}_3\text{-N}$ between Day 0 and 14 is because of the high levels recorded at T11, and lower concentrations at T0. As previously suggested, the results have indicated that during the 11 day incubation the system began to recover, demonstrating a 'self-healing' capacity indicative of resilience (Kibblewhite *et al.*, 2008).

Nitrogen mineralisation reflects the results previously highlighted. Rates were low at Day 0 potentially due to actual nitrification being suppressed, therefore $\text{NH}_4\text{-N}$ built up and was not being converted into $\text{NO}_3\text{-N}$. The higher rates at Day 14 were due to the suggested recovery of the soil system, where accumulated $\text{NH}_4\text{-N}$ was being transformed into $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$. Readings at Day 42 were thought to be due environmental factors.

As has been discussed, actual nitrification appeared to have shown little resistance to changes within the soil environment due to the soil thermal treatment. However, a degree of resilience has been shown with a potential recovery of actual and potential nitrification at approximately Day 14. It is likely that alterations to the measured components of the N-cycle caused by soil steaming were within the system's capability, causing no permanent loss in soil health.

5.5 Microbial respiration

5.5.1 Basal respiration

As mentioned previously in the methodology, the temperature of the laboratory was higher than the ideal, reaching, and possibly exceeding 25 °C. Therefore, the results detected are questionable as to how reliable they are. The only significant effect demonstrated by repeated measures ANOVA was the effect of time. This is shown at Day 42, where, similar to the N results, rates of basal respiration decreased, more so in

treated soil (Figure 4.11). Day 42 results could have been caused by nutrient uptake by carrots limiting the availability of substrates to the microbes, or by environmental variables. The day prior to sampling at Day 42, there was heavy rain causing the soil to become saturated. If the moisture content of the soil was too high, the microbial population would go into survival mechanisms slowing down any activity. If there was suppression in microbial activity, this could possibly have caused the suppression of potential and actual nitrification due to the inactivity of nitrifying bacteria. Tanaka *et al.* (2003) and Roux Michollet *et al.* (2008) suggest that the suppression of nitrification is a result of alterations to the ammonia and nitrate oxidising bacteria.

5.5.2 Substrate induced respiration

SIR demonstrated a depth effect across all three sampling occasions. At Day 0, Depth 1 for both treated and control had a lower SIR than Depth 2, indicating a surface effect. By Day 14, this effect was less obvious, potentially demonstrating that microbial biomass had recovered. At Day 42, SIR in treated soil, Depth 2 was lower than SIR at Depth 1. This could be a result of the development of the crop as previously mentioned.

Overall, microbial respiration (both basal and SIR) indicated less variance than the measured components of N-cycle. It is possible that sub-components of the microbial community were greater effect by the heat treatment than others. However, the respiration results reflect the activity of the entire microbial community and it is not possible to determine which populations are displaying greater respiration and activity.

5.6 Carbon cycling

5.6.1 Field DOC

DOC decreased with depth but this was not related to the treatment and is a well known general characteristic of soil. There was a marginal significance caused by the treatment as seen at Day 0 where there appeared to be a flush of carbon within the treated soil which was greater at Depth 1 than at Depth 2. This effect has also been

noted by other authors. This could be due to the steaming treatment encouraging the decomposition or leaching of organic matter out of the soil system (Egli *et al.*, 2006).

5.6.2 Flush DOC

There was limited evidence for a decrease in microbial biomass C, caused by the steaming, but this parameter was prone to relatively large variation. Hence there is a suggestion that microbial biomass was reduced by the heat treatment. The lack of data for Day 42 means it is not possible to establish if this subsequently recovered. Similarly to the respiration data, microbial biomass C does not differentiate between different populations of microbes which could be important. For example, Kuan *et al.* (2006) found that the resilience of organic matter decomposition is related to the microbial community structure.

CHAPTER 6: Conclusion and Recommendations

6.1 Concluding remarks

The steaming treatment caused several changes within the soil environment. Results showed a build up of NH_4^+ -N directly following treatment, coinciding with low NO_3^- -N levels and low potential nitrification. When the accumulated NH_4^+ -N declined, both NO_3^- -N levels and potential nitrification increased. This suggests a potential suppression in actual nitrification, from which the soil system was able to recover, showing a degree of resilience by this process. The rate of N mineralisation also reflected this, with a peak rate at Day 14 indicating a recovery in actual nitrification. Carbon cycling appeared to be less affected by the treatment, although conclusions are limited by the lack of data.

Rates of microbial activity also demonstrated an inhibition. SIR decreased relative to the control displaying an initial depth effect, possibly suggesting that nitrifying bacteria were negatively affected, causing the apparent suppression in nitrification. However, the results for microbial respiration are not as clear as the N-cycle results. It is possible that certain microbial populations were less resistant than others. This would explain the clear effect upon actual and potential nitrification, but why the overall activity of microbes does not strongly correlate.

It is not possible to suggest whether or not the nitrifying bacteria have fully recovered within the sampling time. At Day 42, it is evident that factors other than the steaming were influencing the soil system; potentially environmental factors and the development of the crop. To increase confidence in the system's ability to recover, further research is needed, particularly in the longer-term. Overall however, it appears that whilst steaming does cause changes within the soil environment, the affected components are able to recover. This means the system still has the ability to function and provide its regulatory and provisioning services within the short-term following soil steaming treatment.

It is possible to accept the original hypothesis that the soil system demonstrated resilience, and showed signs of recovery following the perturbation caused by the heat treatment. However, based upon the results and final conclusions, nitrification appeared to be less resilient than other measured aspects of the soil system, but still displayed signs of recovery by Day 14.

6.2 Recommendations for further research

It was challenging to determine the actual soil temperatures during and immediately following thermal treatment, and therefore hypothesise as to the likely magnitude of the heating effects. Hence a more accurate temperature profiling is recommended.

Due to time restraints it was not possible to analyse the phenotypic structure of the microbial communities in the system, for example by phospholipid fatty acid extraction (PLFA). This would have indicated the composition of the microbial communities present, highlighting which populations were more or less resilient to the treatment, and their recovery time.

As has been suggested, factors other than the thermal treatment influenced the soil system at Day 42. It is possible that the crop had an overriding effect on physicochemical and biochemical characteristics after a certain amount of time following the treatment. To understand the extent to which steaming continued to have an effect it is advisable to have an additional control where the crop was planted but the soil was not thermally treated. This would make distinguishing between the treatment effects and crop effects more robust. It is possible that the control soil was affected by the steaming also, due to the close proximity of the treated soil. It may therefore be appropriate to sample before the steaming is applied within both the control and treated plots. This would provide a background calibration of the original state of the soil. Sampling over a longer period of time may also be preferable, through the life of the crop and post-harvesting. This would enable demonstration of the long-term effects that steaming may have as well as providing a more accurate picture of the resistance and resilience of the soil system.

Further research should also be conducted on a variety of soil types. The soil in this study was a sandy texture. A soil with a higher loam or clay content may have a greater heat capacity which would possibly affect the response of the soil system.

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Appendices

Appendix Di

Temperature loggers

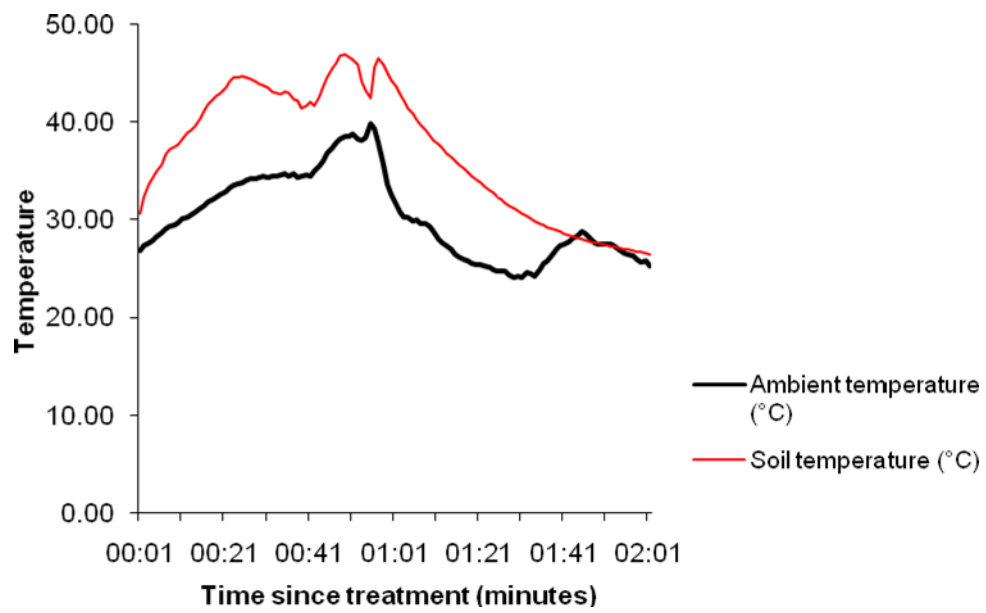
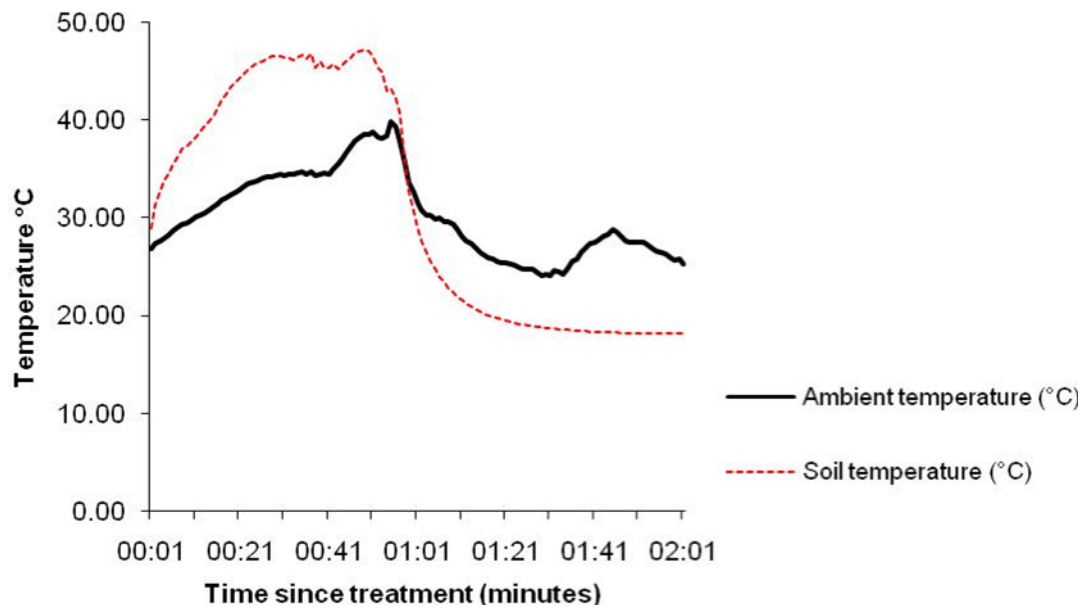


Figure Di a Average recorded soil temperature of treated soil at 5 cm depth.



Figur

e Di b Average recorded soil temperature of treated soil at 10 cm depth.

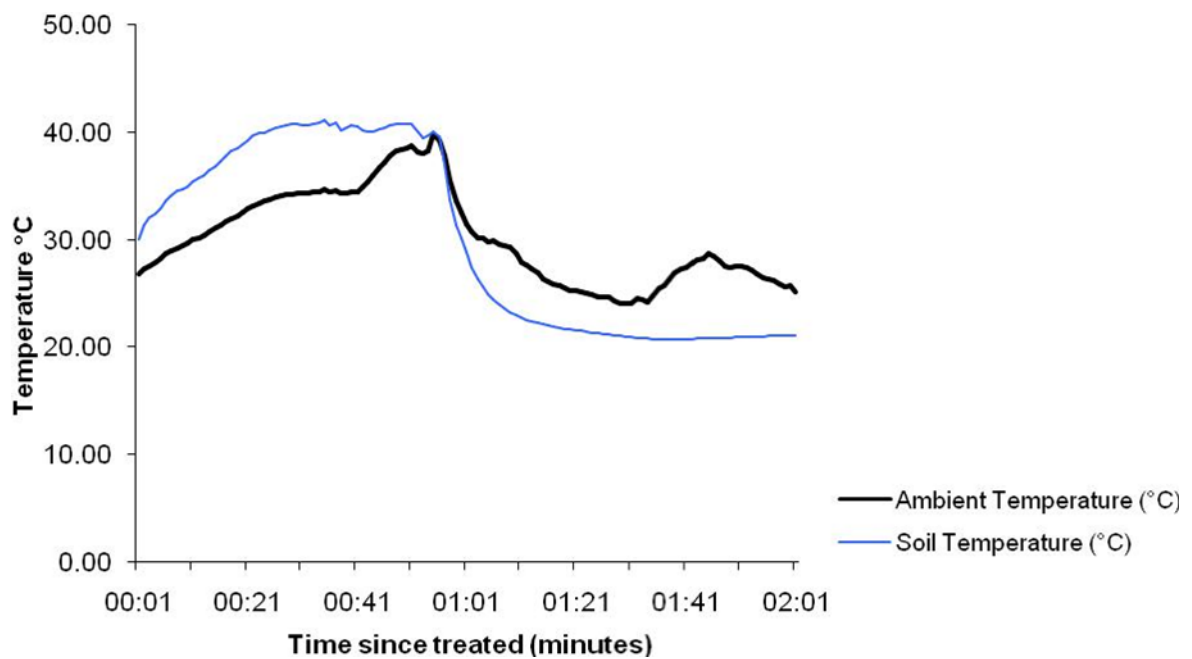


Figure Di c Average recorded soil temperature of untreated soil at 5 cm depth.

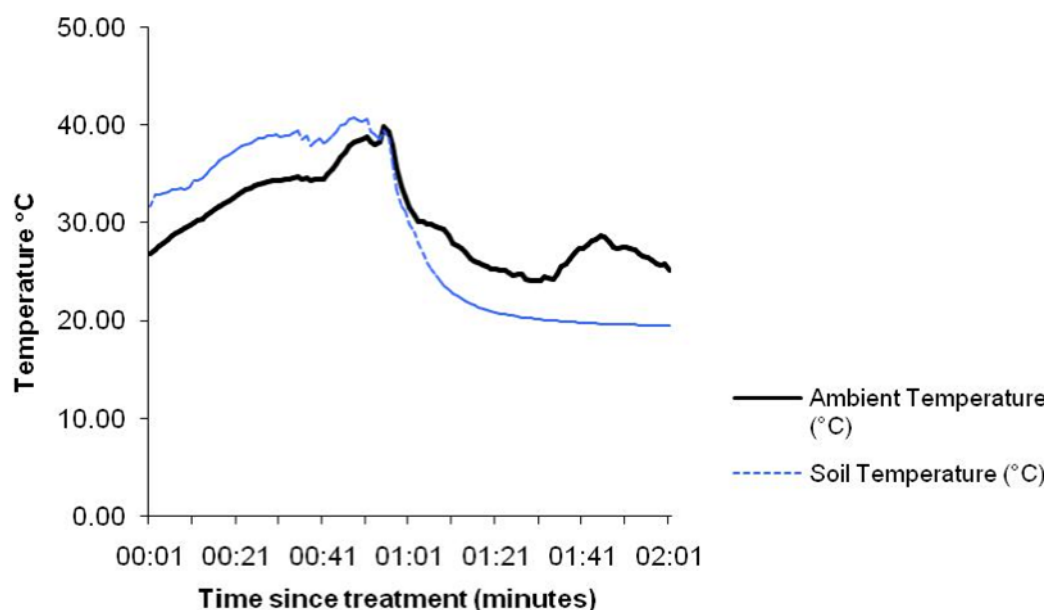


Figure Di d Average recorded soil temperature of untreated soil at 10 cm depth.

Appendix Dii

pH

Table Dii. a pH level for soil samples taken on Day 0.

	Block	Treatment	Depth (cm)	pH
	2	Treated	0 - 5	6.075
		Untreated	0 - 5	6.112
		Treated	5 - 10 cm	6.030
		Untreated	5 - 10 cm	6.116
	3	Treated	0 - 5	6.231
		Untreated	0 - 5	6.153
		Treated	5 - 10 cm	6.136
		Untreated	5 - 10 cm	6.150
	4	Treated	0 - 5	5.984
		Untreated	0 - 5	5.990
		Treated	5 - 10 cm	5.986
		Untreated	5 - 10 cm	6.009
	5	Treated	0 - 5	6.067
		Untreated	0 - 5	6.167
		Treated	5 - 10 cm	6.049
		Untreated	5 - 10 cm	6.177

Table Dii. b Analysis of variance for pH level.

	SS	Degr. of - Freedom	MS	F	p
Treatment	0.0062	1	0.0062	0.99	0.336998
Depth	0.0010	1	0.0010	0.16	0.697444
Error	0.0816	13	0.0063		

Appendix Diii

Total carbon and nitrogen

Table Diii. a Total carbon, total nitrogen and C/N ratio for soil samples taken at Day 0.

Code	Sample	Carbon (%)	Nitrogen (%)	C/N ratio
Treated 0 - 5	3480	2.43	0.22	10.95
Treated 0 - 5	3484	2.51	0.23	10.72
Treated 0 - 5	3488	2.60	0.23	11.12
Treated 0 - 5	3492	2.73	0.25	10.88
Treated 5 - 10	3482	2.57	0.23	11.17
Treated 5 - 10	3486	2.59	0.24	10.95
Treated 5 - 10	3489	2.59	0.23	11.05
Treated 5 - 10	3494	2.71	0.25	10.98
Untreated 0 - 5	3479	2.53	0.23	11.04
Untreated 0 - 5	3483	2.51	0.23	10.91
Untreated 0 - 5	3487	2.62	0.23	11.18
Untreated 0 - 5	3491	2.68	0.25	10.89
Untreated 5 - 10	3481	2.55	0.23	11.01
Untreated 5 - 10	3485	2.50	0.23	11.03
Untreated 5 - 10	3490	2.65	0.24	11.18
Untreated 5 - 10	3493	2.66	0.25	10.74

Carbon

Table Diii. b Mean total carbon concentrations (%).

Total Carbon (%)		
	Treated	Control
Depth 1 (0-5 cm)	2.56	2.58
Depth 2 (5-10 cm)	2.61	2.59

Table Diii. c Analysis of variance for total carbon concentrations

	SS	Degr. of - Freedom	MS	F	p
Treatment	0.0000	1	0.0000	0.00	0.977912
Depth	0.0033	1	0.0033	0.43	0.521672
Error	0.0996	13	0.0077		

Nitrogen

Table Diii. d Mean total nitrogen concentrations (%)

Total Nitrogen (%)		
	Treated	Control
Depth 1 (0-5 cm)	0.23	0.23
Depth 2 (5-10 cm)	0.24	0.24

Table Diii. e Analysis of variance for total nitrogen concentrations.

	SS	Degr. of - Freedom	MS	F	p
Treatment	0.000001	1	0.000001	0.01	0.908654
Depth	0.000009	1	0.000009	0.12	0.731059
Error	0.000986	13	0.000076		

Appendix Div

Mineral nitrogen: T0

Table Div. a Raw data for mineral nitrogen T0. Zero values were below the limit of detection

Treatment	Depth	Day 0 Ammonium-N (µg/g)	Day 14 Ammonium-N (µg/g)	Day 42 Ammonium-N (µg/g)	Day 0 Mineral N (µg/g)	Day 14 Mineral N (µg/g)	Day 42 Mineral N (µg/g)	Day 0 Nitrate (µg/g)	Day 14 Nitrate (µg/g)	Day 42 Nitrate (µg/g)
Treated	0-5	9.76	10.02	0.00	41.48	105.22	54.84	31.72	32.57	94.73
Treated	0-5	2.49	22.42	0.00	47.23	99.66	12.46	44.74	44.85	77.23
Treated	0-5	12.18	52.75	0.00	56.01	115.55	17.56	43.83	45.21	62.72
Treated	0-5	7.44	35.06	0.00	52.06	115.21	12.35	44.62	45.08	79.03
Treated	5-10	0.00	0.00	0.00	42.90	50.02	85.88	42.90	42.52	53.98
Treated	5-10	0.00	0.00	0.00	44.23	65.00	14.80	49.15	50.00	69.04
Treated	5-10	5.01	0.00	0.00	55.14	65.07	26.86	50.13	50.05	63.49
Treated	5-10	0.00	0.00	0.00	54.11	77.55	17.03	54.11	55.03	75.41
Control	0-5	0.00	0.00	0.00	38.27	32.65	9.98	43.06	45.20	37.41
Control	0-5	0.00	0.00	0.00	41.99	47.42	7.32	46.93	47.42	51.23
Control	0-5	0.00	0.00	0.00	43.79	47.56	12.02	48.66	50.06	50.47
Control	0-5	0.00	0.00	0.00	46.78	55.18	16.90	51.70	52.67	57.93
Control	5-10	0.00	0.00	0.00	36.41	40.15	19.86	41.26	42.65	44.69
Control	5-10	0.00	0.00	0.00	31.88	42.59	17.03	39.24	40.08	46.22
Control	5-10	0.00	0.00	0.00	51.54	45.14	36.99	56.44	57.68	49.32
Control	5-10	0.00	0.00	0.00	44.85	50.18	34.68	49.84	50.18	54.50

Ammonium-N

Table Div. b Mean ammonium-N for T0.

Ammonium-N (µg/g)	Day 0		Day 14		Day 42	
	Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)	7.96	0.00	30.06	0.00	0.00	0.00
Depth 2 (5-10 cm)	1.25	0.00	0.00	0.00	0.00	0.00

Nitrate-N

Table Div. c Mean nitrate-N for T0.

Nitrate (µg/g)	Day 0		Day 14		Day 42	
	Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)	41.23	47.59	41.93	48.84	78.43	49.26
Depth 2 (5-10 cm)	49.07	46.69	49.40	47.65	65.48	48.68

Appendix Dv

Mineral nitrogen: T11

Table Dv. a Raw data for mineral nitrogen T11. Zero values indicate that levels were below limit of detection.

Treatment	Depth	Day 0 Ammonium- N (µg/g)	Day 14 Ammonium- N (µg/g)	Day 42 Ammonium- N (µg/g)	Day 0 Mineral N (µg/g)	Day 14 Mineral N (µg/g)	Day 42 Mineral N (µg/g)	Day 0 Nitrate (µg/g)	Day 14 Nitrate (µg/g)	Day 42 Nitrate (µg/g)
Treated	0-5	5.09	0.00	0.00	127.33	230.25	64.82	122.24	229.50	64.07
Treated	0-5	0.00	0.00	2.40	124.41	145.70	19.20	124.41	144.96	16.08
Treated	0-5	2.51	0.00	0.00	115.44	255.32	21.08	112.93	254.57	20.38
Treated	0-5	2.49	0.00	0.00	131.84	294.21	2.42	129.36	293.46	1.69
Treated	5-10	2.49	0.00	0.00	136.86	158.63	102.00	134.37	157.89	101.26
Treated	5-10	0.00	0.00	0.00	84.67	183.43	16.37	84.67	182.69	15.67
Treated	5-10	2.51	0.00	0.00	95.34	111.06	40.13	92.83	110.32	39.38
Treated	5-10	0.00	0.00	0.00	77.77	222.81	22.49	77.77	222.07	21.74
Control	0-5	2.49	0.00	0.00	87.26	130.87	9.66	84.77	130.13	8.93
Control	0-5	0.00	0.00	0.00	64.92	160.03	7.09	64.92	159.28	6.38
Control	0-5	2.50	0.00	0.00	82.61	172.97	7.28	80.11	172.23	6.55
Control	0-5	2.51	0.00	0.00	92.73	157.07	12.53	90.22	156.32	11.78
Control	5-10	0.00	0.00	0.00	82.78	142.95	12.12	82.78	142.20	11.39
Control	5-10	0.00	0.00	0.00	67.50	172.78	36.82	67.50	172.03	36.08
Control	5-10	2.50	0.00	0.00	87.56	74.68	42.21	85.06	73.93	41.51
Control	5-10	2.50	0.00	0.00	89.93	131.79	39.04	87.43	131.05	38.35

Ammonium-N

Table Dv. b Mean ammonium-N for T11/

Ammonium-N (µg/g)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1	0-5 cm	2.52	1.88	0.00	0.00	0.60	0.00
Depth 2	5-10 cm	1.25	1.25	0.00	0.00	0.00	0.00

Nitrate-N

Table Dv. c Mean nitrate-N for T11.

Nitrate-N (µg/g)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1	0-5 cm	122.23	80.01	184.50	154.49	25.56	8.41
Depth 2	5-10 cm	97.41	80.69	168.24	129.80	44.51	31.83

Appendix Dvi

Nitrogen mineralisation over an 11 Day period

Table Dvi. a Raw data for nitrogen mineralisation over an 11 Day period.

Treatment	Depth	Day 0 Mineral N (µg min N/g/d)	Day 14 Mineral N (µg min N/g/d)	Day 42 Mineral N (µg min N/g/d)	Day 0 Ammonium- N (µg min N/g/d)	Day 14 Ammonium- N (µg min N/g/d)	Day 42 Ammonium- N (µg min N/g/d)	Day 0 Nitrate-N (µg min N/g/d)	Day 14 Nitrate-N (µg min N/g/d)	Day 42 Nitrate-N (µg min N/g/d)
Treated	0-5	7.80	0.00	0.91	0.00	0.00	0.00	8.23	17.90	0.00
Treated	0-5	7.02	0.00	0.61	0.00	0.00	0.22	7.24	9.10	0.00
Treated	0-5	5.40	0.00	0.32	0.00	0.00	0.00	6.28	19.03	0.00
Treated	0-5	7.25	0.00	0.00	0.00	0.00	0.00	7.70	22.58	0.00
Treated	5-10	8.54	0.00	1.47	0.23	0.00	0.00	8.32	10.49	4.30
Treated	5-10	3.68	0.00	0.14	0.00	0.00	0.00	3.23	12.06	0.00
Treated	5-10	3.65	0.00	1.21	0.00	0.00	0.00	3.88	5.48	0.00
Treated	5-10	2.15	0.00	0.50	0.00	0.00	0.00	2.15	15.18	0.00
Control	0-5	4.45	0.00	0.00	0.23	0.00	0.00	3.79	7.72	0.00
Control	0-5	2.08	0.00	0.00	0.00	0.00	0.00	1.64	10.17	0.00
Control	0-5	3.53	0.00	0.00	0.23	0.00	0.00	2.86	11.11	0.00
Control	0-5	4.18	0.00	0.00	0.23	0.00	0.00	3.50	9.42	0.00
Control	5-10	4.22	0.00	0.00	0.00	0.00	0.00	3.77	9.05	0.00
Control	5-10	3.24	0.00	1.80	0.00	0.00	0.00	2.57	11.99	0.00
Control	5-10	3.28	0.00	0.47	0.23	0.00	0.00	2.60	1.48	0.00
Control	5-10	4.10	0.00	0.40	0.23	0.00	0.00	3.42	7.35	0.00

Ammonium-N

Table Dvi. b Mean ammonium-N.

Ammonium-N ($\mu\text{g min N/g/d}$)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1	0-5 cm	0.00	0.17	0.00	0.00	0.05	0.00
Depth 2	5-10 cm	0.06	0.11	0.00	0.00	0.00	0.00

Nitrate-N

Table Dvi. c Men nitrate-N.

Nitrate ($\mu\text{g min N/g/d}$)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1	0-5 cm	7.36	2.95	17.15	9.60	0.00	0.00
Depth 2	5-10 cm	4.39	3.09	10.80	7.47	1.07	0.36

Mineral nitrogen

Table Dvi. d Mean mineral nitrogen.

Mineral N ($\mu\text{g min N/g/d}$)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1	0-5 cm	2.06	1.81	19.52	15.79	1.83	0.32
Depth 2	5-10 cm	2.13	1.33	18.09	29.70	1.75	0.84

Appendix Dvii

Potential nitrification

Table Dvii. a Raw data for potential nitrification

Treatment	Depth	Day 0 Nitrite (µg/g)	Day 14 Nitrite (µg/g)	Day 42 Nitrite (µg/g)
Treated	0-5	0.06	0.58	0.28
Treated	0-5	0.13	0.42	0.36
Treated	0-5	0.13	0.50	0.16
Treated	0-5	0.26	0.34	0.24
Treated	5-10	0.13	0.85	0.28
Treated	5-10	0.13	0.67	0.44
Treated	5-10	0.19	1.00	0.16
Treated	5-10	0.26	2.60	0.49
Control	0-5	0.45	0.85	0.16
Control	0-5	0.45	1.35	0.69
Control	0-5	0.19	0.67	0.24
Control	0-5	0.65	1.59	0.68
Control	5-10	0.19	1.01	0.76
Control	5-10	0.45	1.51	2.35
Control	5-10	0.13	2.10	0.24
Control	5-10	0.58	3.54	2.21

Table Dvii. b Mena nitrite-N.

Nitrite (µg/g)	Day 0		Day 14		Day 42	
	Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)	0.15	0.44	0.46	1.12	0.26	0.44
Depth 2 (5-10 cm)	0.18	0.34	1.28	2.04	0.34	1.39

Appendix Dviii.

Field DOC

Table Dviii. a Raw data for field DOC. ND = Not determined.

Treatment	Depth	Day 0 ExtracTable Organic Carbon µg/g	Day 14 ExtracTable Organic Carbon µg/g	Day 42 ExtracTable Organic Carbon µg/g
Treated	0-5	26.86	17.39	ND
Treated	0-5	24.80	26.09	ND
Treated	0-5	24.05	25.38	ND
Treated	0-5	22.21	25.21	ND
Treated	5-10	24.65	18.98	ND
Treated	5-10	21.81	23.91	ND
Treated	5-10	21.20	22.59	ND
Treated	5-10	19.69	25.44	ND
Control	0-5	19.43	25.28	ND
Control	0-5	22.52	23.49	ND
Control	0-5	22.99	25.09	ND
Control	0-5	19.22	24.85	ND
Control	5-10	24.58	17.99	ND
Control	5-10	18.77	21.75	ND
Control	5-10	18.01	26.40	ND
Control	5-10	19.84	23.97	ND

Table Dviii. b Mean field DOC. ND = Not determined

Field ExtracTable Organic Carbon (µg/g)	Day 0		Day 14		Day 42	
	Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)	24.48	21.04	23.52	24.68	ND	ND
Depth 2 (5-10 cm)	21.84	20.30	22.73	22.53	ND	ND

Flush DOC

Table Dviii. c Raw data for flush DOC. ND – Not determined.

Treatment	Depth	Day 0 Flush DOC (µg/g)	Day 14 Flush DOC (µg/g)	Day 42 Flush DOC (µg/g)
Treated	0-5	26.97	53.03	ND
Treated	0-5	40.07	16.77	ND
Treated	0-5	26.53	30.15	ND
Treated	0-5	36.33	32.74	ND
Treated	5-10	33.93	36.70	ND
Treated	5-10	29.63	35.14	ND
Treated	5-10	30.46	34.27	ND
Treated	5-10	61.52	38.43	ND
Control	0-5	42.67	50.93	ND
Control	0-5	37.81	36.38	ND
Control	0-5	48.74	35.11	ND
Control	0-5	43.38	49.25	ND
Control	5-10	37.66	33.67	ND
Control	5-10	33.60	39.40	ND
Control	5-10	30.99	42.13	ND
Control	5-10	47.32	46.46	ND

Table Dviii. d Mean flush DOC. ND = Not determined.

Flush DOC (µg/g)	Day 0		Day 14		Day 42	
	Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)	32.47	43.15	33.17	42.92	ND	ND
Depth 2 (5-10 cm)	38.88	37.39	36.13	40.42	ND	ND

Microbial respiration

Table Dviii. e Raw data for microbial respiration.

Treatment	Depth	Day 0 Basal (Water)	Day 14 Basal (Water)	Day 42 Basal (Water)	Day 0 SIR (Glucose)	Day 14 SIR (Glucose)	Day 42 SIR (Glucose)
Treated	0-5	1.09	1.15	0.30	3.79	3.00	3.10
Treated	0-5	0.95	0.93	0.78	1.10	3.10	2.61
Treated	0-5	0.96	0.94	0.37	3.60	3.19	2.91
Treated	0-5	0.73	1.11	0.35	2.89	2.90	3.54
Treated	5-10	1.18	1.11	0.55	3.39	3.16	2.47
Treated	5-10	0.85	1.18	0.43	4.54	3.03	3.36
Treated	5-10	1.06	0.85	0.51	3.81	3.17	2.16
Treated	5-10	0.75	2.18	0.57	4.15	3.60	3.14
Control	0-5	1.06	0.95	0.85	3.93	3.18	1.42
Control	0-5	0.74	0.93	0.50	3.22	2.91	4.01
Control	0-5	1.08	0.89	0.56	3.88	2.85	3.47
Control	0-5	0.78	0.38	0.34	3.48	3.65	3.09
Control	5-10	1.15	1.04	1.12	4.65	3.86	3.18
Control	5-10	0.94	0.95	0.47	3.62	3.18	3.85
Control	5-10	1.14	1.56	0.66	4.36	3.32	3.10
Control	5-10	0.99	0.89	0.51	4.18	3.92	4.03

Basal respiration

Table Dviii. f Mean basal respiration.

Basal Respiration (CO ₂ -C/g/h)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)			0.932492 0.563805	0.914931		1.031293 0.788463	0.449217
Depth 2 (5-10 cm)			0.959454 0.690544	1.053288		1.33355 1.110227	0.518218

Substrate induced respiration

Table Dviii. g Mean substrate induced respiration.

SIR (CO ₂ -C/g/h)		Day 0		Day 14		Day 42	
		Treated	Control	Treated	Control	Treated	Control
Depth 1 (0-5 cm)			2.844658	3.629081	3.047394	3.147004	3.041152
Depth 2 (5-10 cm)			3.97509	4.200558	3.239508	3.56886	2.782265

