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Root exudate carbon mitigates nitrogen loss in a semi-arid soil

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ABSTRACT

The need for increased food production to support the growing global population requires more efficient nutrient management and prevention of nitrogen (N) losses from both applied fertiliser and organic matter (OM) decomposition. This is particularly important in semi-arid rainfed cropping soils, where soil water and temperature are the dominant drivers of N cycling rather than agricultural management. Here we used ^{14}C and ^{15}N techniques to examine how peptide/amino acid turnover, gross and net N transformation rates and nitrous oxide (N_2O) emissions responded to long-term plant residue additions and/or short-term root exudate additions. Soil was collected from a semi-arid rainfed field trial with one winter crop per year followed by a summer fallow period, where additional inputs of straw/chaff over 10 years had increased total soil organic C (SOC) by 76% compared to no extra additions (control). These field soils were incubated in the laboratory with or without a synthetic root exudate mixture at a range of temperatures reflecting regional field conditions (5–50 °C). Long-term plant residue additions (to build up total soil OM) did not decrease the risk of N loss as defined by the nitrification:immobilisation (*N:I*) ratio at most temperatures, so was not an effective management tool to control N losses. In comparison, short-term root exudate additions decreased the risk of N loss at all temperatures in both the control and plant residue treatment field soils. Increased net N mineralisation and decreased microbial C use efficiency at temperatures greater than 30 °C resulted in significant ammonium (NH_4^+) accumulation. Microbial decomposers appeared to use amino acid-C for growth but peptide-C for energy production. Findings indicate that the greatest risk of N loss in these semi-arid soils will occur during rains at the start of the growing season, due to inorganic N accumulation over summer fallow when there are high soil temperatures, occasional significant rainfall events and no growing plants to release root exudates. While most attempts to manipulate the soil N cycle have occurred during the winter cropping period, our findings highlight the need to manage N supply during summer fallow if we are to minimise losses to the environment from semi-arid soils.

1. Introduction

Concerns regarding food security, low fertiliser use efficiencies and the need to decrease greenhouse gas emissions necessitate the development of more sustainable agricultural systems. Semi-arid and arid regions cover approximately half of the global agricultural area (The World Bank, 2008) and are thus of major importance to food production and associated nutrient management. Sustainable agriculture in semi-arid regions presents unique challenges, especially in rainfed cropping systems, where rainfall and temperature are the main drivers of microbial activity and cycling of nutrients such as nitrogen (N; Noy-Meir, 1973; Hoyle and Murphy, 2011). Semi-arid regions in the Southern Hemisphere have experienced a drying trend since the 1970s predominantly at the start of the grain-growing season (April and May; Cai et al., 2012). Although there has been a reported 15% decrease in heavy winter rainfall between 1950 and 2003 (Nicholls, 2010), summer rainfall events that occur outside of the period of crop and annual pasture growth are increasing (Alexander et al., 2007). More summer rainfall is expected to increase soil organic matter (OM) decomposition and N supply at a time when there is limited or no plant N uptake (Murphy et al., 1998; Austin et al., 2004). Nitrogen supply in excess of microbial demand results in N release, which is at risk of loss to the environment if nitrified.

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Nitrogen losses are undesirable, potentially limiting crop yield and having detrimental off-site environmental impacts [e.g. N leaching and emissions of nitrous oxide (N_2O)]. Management practices that mitigate N losses therefore need to be developed. Losses of N are particularly difficult to mitigate when they are not in response to N fertiliser additions, but originate from soil OM decomposition. The timing of inorganic N release from soil OM decomposition is difficult to change (Hoyle and Murphy, 2011) as peptide and amino acid turnover is primarily regulated by water and temperature (Jones et al., 2009; Farrell et al., 2013). Instead, management options are more likely to succeed when targeting the subsequent fate of the released inorganic N. Nitrification is the key pathway for N loss, as nitrate (NO_3^-) is susceptible to leaching, and the greenhouse gas N_2O may be produced during and after nitrification (Wrage et al., 2001). One way to decrease potential N loss is by increasing microbial N immobilisation when plant N demand is low and thus decreasing the amount of inorganic N that is available for nitrification and loss (Crews and Peoples, 2005). The nitrification to immobilisation ratio, or *N*:*I* ratio, represents the balance between the N loss and retention pathways (Aber, 1992; Tietema and Wessel, 1992). This index has been correlated with NO_3^- leaching losses in temperate grassland and arable soils (Stockdale et al., 2002), but little is known about the behaviour of the *N*:*I* ratio in cropped soils from other climates.

Increased microbial N immobilisation and decreased potential for N loss could be achieved through manipulation of soil carbon (C) availability. Soil organic C (SOC) and N cycles are inextricably linked: both N mineralisation and immobilisation pathways are mediated by heterotrophic microorganisms, which require C from organic sources for growth and production of energy. When heterotrophic immobilisers are limited by C compared to N, net production of inorganic N occurs, which is then at risk of nitrification and subsequent loss (Barraclough, 1997). In contrast, organic sources with high C:N ratios can stimulate immobilisation. The majority of our understanding about soil C and N cycling processes has been gained through research in temperate and humid environments, but N cycling appears to behave unexpectedly in semi-arid regions, particularly in warm and dry seasons (Parker and Schimel, 2011; Sullivan et al., 2012). For example, in Californian grassland soil, net N mineralisation rates and nitrification potentials are greater during the warm dry summer than during the cooler, wetter winter, resulting in greater NH_4^+ pools in the summer (Parker and Schimel, 2011). In addition, in south-west Australian soils, heterotrophic N immobilisation becomes constrained at temperatures greater than 30 °C, and mineralisation–immobilisation turnover becomes decoupled, resulting in the accumulation of inorganic N (Hoyle et al., 2006; Luxhøi et al., 2008). This mineralisation–immobilisation turnover decoupling at elevated temperatures was hypothesised to be due to C substrate limitation, caused by microorganisms consuming available C faster than C could be replaced by diffusion from nearby soil microsites (Hoyle et al., 2006). We hypothesised therefore that increasing soil C availability will decrease the potential of N loss (i.e. decrease the *N*:*I* ratio), especially at elevated temperatures that occur during summer in some semi-arid soils.

Soil organic C content and availability may be increased by agricultural management practices. These practices include plant residue inputs over the longer term (Dick, 1992; Liu et al., 2014), or shorter term rhizosphere processes such as inputs of labile C from root exudates and mycorrhiza (Jones et al., 2004; Kaiser et al., 2014). The objective of this research was to understand how different sources of C alter N transformations in arable semi-arid soil. Specifically, we investigated how long-term soil amendment with plant residues and/or short-term root exudate additions affected (a) N decomposition pathways; and (b) the subsequent fate of N and risk of N loss as defined by the *N*:*I* ratio, under conditions reflective of both summer and winter temperatures in semi-arid soils.

2. Methods

2.1. Study site and field soil collection

Soil was collected from a field research site approximately 221 km north-northeast of Perth in the agricultural production zone (wheatbelt) of Western Australia (30.00° S, 116.33° E). The soil is a sand (92% sand, 2% silt, 6% clay) and classified as a Basic Regolithic Yellow-Orthic Tenosol (Australian soil classification; Isbell, 2002), or a Haplic Arenosol (IUSS Working Group WRB, 2007). The area has a semi-arid climate with cool, wet winters and hot, dry summers (Fig. 1). At the weather monitoring station closest to the study site (Dalwallinu, 30.28°S, 116.67° E) the historical mean annual rainfall is 288 mm and mean monthly temperatures range from 5.8 to 35.3 °C (1997–2013 data; Commonwealth of Australia Bureau of Meteorology, http://www.bom.gov.au/climate/data). Soil temperatures at 5 cm depth at the research site ranged from 6.2 to 45.6 °C (2008–2012; measured using a CS Model 107 Temperature Probe, Campbell Scientific, Logan, Utah, USA).

The field site consisted of two plant residue treatments: (i) import of additional plant residues to the soil (i.e. build-up of total soil OM; defined as '+OM') and (ii) control soil (i.e. no additional plant residue inputs; defined as 'No OM'). The +OM addition consisted of 20 t ha^{-1} of barley straw, canola chaff and oaten chaff in 2003, 2006 and 2010 respectively. This represented an additional input to soil of 27 t C ha^{-1}, of which 7.9 t C ha^{-1} was retained as SOC (i.e. microbial C use efficiency of 29%). This equated to 76% more SOC and 57% more total N in +OM soil than in No OM control soil (Table 1). All field plots were tilled using offset disks before seeding to 10 cm depth and seeded with knife point tines to 10 cm depth. Treatment plots (80 m by 10 m) were randomly allocated to three replicate blocks when the experimental site was established (2003), and have since been planted to an annual crop each winter (lupin-wheat-wheat rotation).

Soil was collected (Ap horizon; 0–10 cm) from each of the three replicate field treatments in May 2011 while the soil was dry (0.012 g H_2O g^{-1} dry soil) and before winter rain commenced. A composite soil sample of 18 cores (7 cm diameter, 10 cm depth) was collected from each treatment plot in a zigzag sampling pattern, sieved (<2 mm) and stored at 4 °C until further analysis. Each field replicate ($n = 3$) was kept separate for use in the laboratory experimental design.

2.2. Laboratory experimental design

To investigate how long-term plant residue inputs and/or short-term root exudate additions affected soil N cycling at different temperatures, soils collected from the two field treatments (+OM and No OM; as described above) were incubated with (+RE) or without (No RE) synthetic root exudates at four or seven temperatures depending on soil process (details below), with three replicates per field treatment. Low molecular weight organic matter (LMWOM) turnover was investigated at four soil incubation temperatures (5, 15, 30 and 50 °C), while the other N transformation rate measurements were investigated at seven temperatures (5, 10, 15, 20, 30, 40 and 50 °C). Laboratory experimental conditions reflected soil temperatures ranging from winter cropping (5 °C) to summer fallow (50 °C). Synthetic root exudates were used to simulate conditions when plants are present in the soil. The root exudate solution consisted of D-glucose (6.75 mM); D-fructose and D-sucrose (1.35 mM each); succinic acid, citric acid, L-malic acid and