

Influence of organic residues and soil incorporation on temporal measures of microbial biomass and plant available nitrogen

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Abstract

Aims Despite our current understanding of plant nitrogen (N) uptake and soil N dynamics in arable systems, the supply and demand of N are infrequently matched as a result of variable seasonal and soil conditions. Consequently, inefficiencies in N utilisation often lead to constrained production and can contribute to potential environmental impacts. The aim of this study was to examine the influence of plant residue quality (C/N ratio) and extent of residue incorporation into soil on temporal changes in soil mineral N and the associated plant N uptake by wheat in the semi-arid agricultural production zone of Western Australia.

Methods Oat (*Avena sativa*); lupin (*Lupinus angustifolius*) and field pea (*Pisum sativum*) were incorporated into a Red-Brown Earth using varying degrees of mechanical disturbance (0 to 100% residue incorporated). Soil samples for inorganic N (NO_3^-

and NH_4^+) profiles (0–50 cm), microbial biomass-C (0–50 cm) and plant N uptake were taken throughout the growing season of the subsequent wheat (*Triticum aestivum*) crop. Grain yield and yield components were determined at harvest.

Results Despite observed treatment effects for plant residue type and soil disturbance, fluctuations in inorganic N were more readily influenced by seasonal variability associated with wet-dry cycles. Treatment effects resulting from residue management and extent of soil disturbance were also more readily distinguished in the NO_3^- pool. The release of N from crop residues significantly increased ($p=0.05$) with greater soil-residue contact which related to the method of incorporation; the greater the extent of soil disturbance, the greater the net supply of inorganic N. Differences in microbial biomass-C were primarily associated with the type of plant residue incorporated, with higher microbial biomass generally associated with legume crops. No effect of residue incorporation method was noted for microbial biomass suggesting little effect of soil disturbance on the microbial population in this soil.

Conclusions Despite differences in the magnitude of N release, neither crop type nor incorporation method significantly altered the timing or pattern of N release. As such asynchrony of N supply was not improved through residue or soil management, or through increased microbial biomass in this semi-arid environment. N fluxes were primarily controlled by abiotic factors (e.g. climate), which in this study

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dominated over imposed agricultural management practices associated with residue management.

Keywords Nitrogen · Asynchrony · Residue quality · Semi-arid · Dryland agriculture

Introduction

Globally, crop growth and production is constrained by the most limiting mineral or environmental resource—the availability of which may vary temporally and/or spatially. Nutrients are often a key constraint to maximising crop production, either in terms of their abundance or availability, with inorganic fertilisers often used to supplement soil derived nutrient sources to better match supply and demand. Nitrogen (N) in particular is globally recognised as one of the key nutrients that limits crop production in farming systems as well as one of the more readily managed due to the availability of mineral N fertilisers. Synchronising the quantity, timing and location of soil N supply relative to crop demand must be achieved to increase the efficiency of fertiliser use in agricultural systems, and managed to minimise losses of N from the system that contribute to increased environmental risk. However due to the influence of environmental modifiers on biologically mediated processes, both the supply of, and demand for biologically derived N can be difficult to predict and thus consider within management decision support systems.

Supply capacity (quantity and timing) is influenced by the amount and type of organic material, size of particulate matter, extent of soil contact and microbial turnover (Kumar and Goh 2000). Demand capacity includes the microbial requirement for N (i.e. immobilisation) and plant uptake, with additional loss of N occurring from the rooting zone (Thorup-Kristensen et al. 2003). These N fluxes are primarily controlled by abiotic factors (e.g. climate; soil attributes) which influence microbial activity and often dominate over the impact of agricultural management practices such as tillage, rotation and residue management (Andrén et al. 1999; Murphy et al. 2003). In many Australian farming systems the amount of N cycling through soils during a year would indicate sufficient N supply for optimal crop growth without the requirement for fertiliser applications (Murphy et al. 1998; Fillery 2001). Where insufficient amounts of N are released by soils or where supply capacity is not well matched

with plant demand, N supply must be managed using mineral N fertilisers (Murphy et al. 2009).

In dryland cropping systems of semi-arid parts of Australia low fertiliser N application rates (typically 50–80 kg N ha⁻¹ for an expected 2 tonne wheat grain yield) and widespread distribution of sub-soil constraints to root growth (e.g. acidity, Al³⁺ toxicity, soil compaction, soil borne diseases and nematodes) means that up to 80% of crop N uptake can be supplied via biological processes (Angus 2001). This contrasts with temperate systems where approximately 50% of crop N uptake is from fertilisers (Jenkinson 2001). It is unclear whether differences in crop recovery of N from fertiliser and plant residues (especially legumes) is predominantly soil or climate driven, but it is likely that there will be both a spatial component in terms of the physical co-location of N in relation to plant roots (Thorup-Kristensen 2001) and a temporal component where N recovery may extend over a number of years. Closer co-location of N with plant roots during periods of water stress when biologically derived N may be taken up more rapidly may be a factor. However since asynchrony is a feature of many agricultural systems, the use of mineral N fertilisers remains an important component of crop N uptake commonly adopted to overcome the difficulties of matching the timing and magnitude of biological supply with plant N demand. This is particularly relevant where the supply of N is less than optimal during critical early growth stages that determine yield potential (prior to terminal spikelet, during tiller initiation and grain filling). In Western Australia, the fate of early N is dependent on soil type, condition and rainfall events. For example on a coarse textured sand, the ability of a plant to access N may be restricted as it leaches ahead of the rooting profile of annual crops. Similarly due to the dependence on winter and spring rainfall for crop growth and grain fill, early N can result in a large potential yield which is later constrained by lack of available water. Thus the efficient use of N is also dependent on climatic conditions suited to optimise plant growth.

Historically, the impact of crop residues on N cycling in Australia has been undervalued. However, evidence of significant nutrient flushes under wind-rowed crops and the export of nutrients from hay paddocks, has resulted in a heightened awareness for the role of crop residues in nutrient cycling. Therefore primary manipulation of the soil N cycle could be

achieved by altering plant composition (i.e. organic matter quality; C/N ratio), or via the retention and export of crop residues (Murphy et al. 2007; Thorup-Kristensen and Dresboll 2010; Puttaso et al. 2011). Although the chemical composition of plant materials is not constant (Gunnarsson and Marstorp 2002), determination of the C/N ratio can be used to estimate crop residue decomposition (Douglas and Rickman 1992) and indicate whether net mineralisation or immobilisation of soil N is likely (Marstorp and Kirchmann 1991). The aim of this study was to examine the influence of plant residue quality (C/N ratio) and extent of residue incorporation into soil on temporal changes in soil mineral N and the resultant plant N uptake in wheat in the semi-arid agricultural production zone of Western Australia.

Materials and methods

Field site description

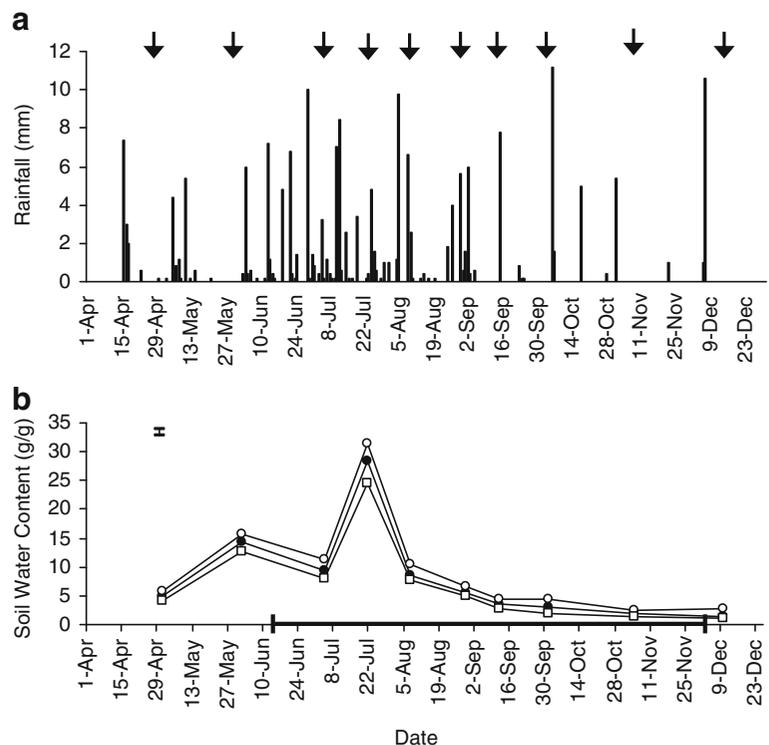
The study area was located west of Beverley (32° 06' S, 116° 52' E) on a trial established in the medium rainfall (325 to 450 mm annually) region of Western

Australia on a Red-Brown Earth (Red Chromosol, 1.2% total organic carbon, pH(CaCl₂) 5.9). Minimum and maximum temperatures during the growing season averaged 7.1 (−1.5 to 17.9°C) and 18.7°C (10.3 to 33.9°C) respectively (Fig. 1a). A lower than average annual rainfall reached 214 mm of which 163 mm fell during the winter cereal growing season (May to October; Fig. 1a). This indicated a potential wheat yield of between 1.46 and 1.94 t ha^{−1} based on 15–20 kg grain production mm^{−1} effective rainfall (calculated using 30% of rainfall January–March as stored water, 60% of rainfall from April, 100% of rainfall May–November and estimating losses by soil evaporation of 80 mm in total).

Experimental design and plant sampling

The rotation phase at the time of sampling was wheat (*Triticum aestivum* L.). The trial was seeded in 6-row plots (1.75 m in width, 20 m in length) in a split block design with three replicates and treatment structures of crop type and management. Plots were sown (direct drilled; 180 mm row spacing) on June 13th, with 150 kg ha^{−1} DAPSCZ (di-ammonium phosphate with added sulphur, copper and zinc; N:P:S percent-

Fig. 1 **a** Rainfall (mm) received at the site and time of sampling (indicated by arrows) and **b** average soil water content (g/g) measured seasonally after implementation of oat (white square), lupin (black circle) and field pea (white circle) residues at Beverley on a Red Chromosol (0–50 cm). Capped bar represents LSD ($p=0.05$) for residue treatment × sampling time interaction. The horizontal bar represents the wheat growing season for this trial year



age composition 15:17:2; copper 0.75%; zinc 1.0%) basal fertiliser, and 75 kg ha⁻¹ urea (46% N) surface broadcast 6 weeks after sowing. Wheat cultivar ‘Carnamah’ was sown at 75 kg ha⁻¹ (after adjustment for seed size and assuming a field emergence of 80%) to achieve a target density of 120 plants m⁻². Previously, blocks had been sown to one of three common rotational crops suited to this region and soil type with different C/N ratios to simulate variable rates and amounts of nutrient release – oat (*Avena sativa* cv. ‘Toodyay’); lupin (*Lupinus angustifolius* L. cv. ‘Tanjil’); field pea (*Pisum sativum* L. cv. ‘Cooke’) with C/N ratios of 40/1, 13/1 and 16/1 respectively. Crops were sown at optimal seeding rates with 110 kg ha⁻¹ superphosphate basal fertiliser and 40 kg ha⁻¹ urea (46% N) surface broadcast on oat plots. In early spring (September) of the year prior to sowing the wheat, treatments which consisted of different degrees of plant residue incorporation (Table 1) were implemented at flowering to cause different rates of nutrient release from crop residues, the exception being the control which was taken through to grain harvest (i.e. no residue retained).

Above-ground plant biomass and residue N concentration was also measured to estimate potential soil N supply resulting from residue treatments. Oat treatments achieved the highest biomass (4.6 tha⁻¹), but demonstrated lower tissue N concentration (11 mg g⁻¹) in comparison to lupin (2.2 tha⁻¹, 35 mg g⁻¹) and field pea (3.2 tha⁻¹, 28 mg g⁻¹) treatments. This resulted in a potential N supply from aboveground plant residue of 50 kg N ha⁻¹ (oat), 77 kg N ha⁻¹ (lupin) and 91 kg N ha⁻¹ (field peas).

Soil sampling

Disc permeameters were used to determine *in-situ* hydraulic properties (sorptivity, steady state flow rate,

hydraulic conductivity) of soil prior to sowing (4 sample sites within each of 3 replicate treatments to determine spatial heterogeneity) on plots where oat treatments had previously been imposed. Sorptivity was determined from the slope of the water entry–square root of time (Philip 1957) relationship in the early stage of infiltration after the sand cap is fully wetted. The steady state flow rate was determined from the slope of the straight line between water entry and time once the infiltration rate has become constant.

Soil was sampled periodically under the spring wheat crop to assess changes in soil water content (Fig. 1b), inorganic nitrogen (NO₃⁻ and NH₄⁺; Fig. 2) and microbial biomass (Fig. 6). Initial soil sampling was conducted on 1 May at depths of 0–10 cm, 10–30 cm and 30–50 cm. Subsequent soil sampling was then conducted using composite soil samples collected at nine further sampling times (2 Jun, 5 Jul, 22 Jul, 8 Aug, 30 Aug, 12 Sep, 2 Oct, 5 Nov, 10 Dec) from residue management treatments. Soil was collected using a hand auger (150 mm diameter). A composite sample of 3 cores was collected from each plot, sieved (<4 mm) and stored field moist at 4°C for up to 6 day prior to characterising key physical and chemical (Table 2) soil properties.

Plant observations and sampling

Plant establishment was determined on each plot (3 sample sites per plot; 0.42 m⁻²) 4 weeks after sowing. Average leaf and tiller number (5 sample sites per plot, 5 plants) were determined 6 weeks after sowing at approximately terminal spikelet. Crop biomass and tissue N concentration (N%; 2 sample sites per plot; 0.83 m⁻²) were used to calculate N uptake in the above-ground dry matter at anthesis. Grain yield was assessed using a small plot mechanical harvester on an area 1.44 m wide and 20 m in length. Grain quality

Table 1 Estimated percentage (%) of crop residue incorporated below the soil surface on application of various plant residue incorporation practices at Beverley on a Red Chromosol. All

	Harvest (control)	Desiccation (brown manure)	Offset discs (green manure)	Disc plough (green manure)	Mouldboard plough (green manure)
Oat residue	0	0	37	58	100
Field pea residue	0	0	70	88	100
Lupin residue	0	0	80	95	100

brown and green manure plots were chemically desiccated, with green manure residues then incorporated into soil

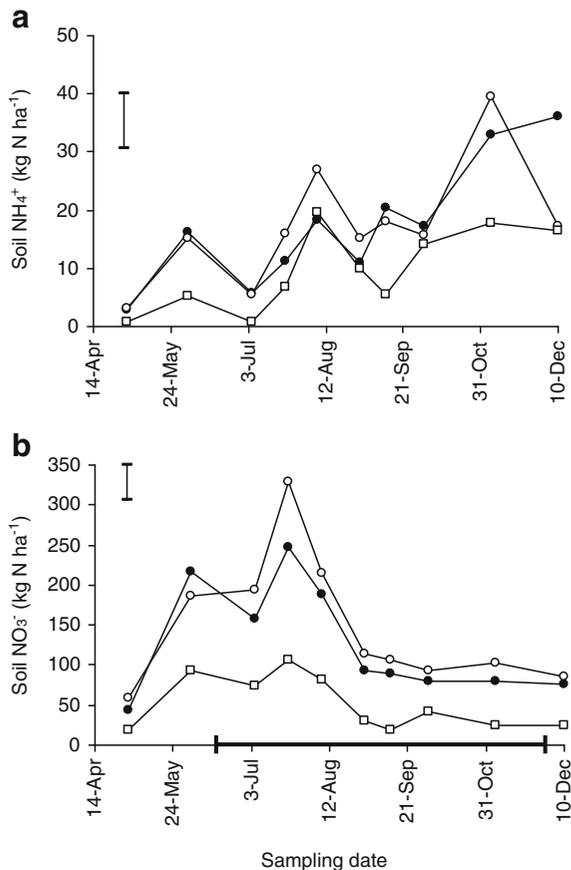


Fig. 2 **a** Soil NH_4^+ and **b** soil NO_3^- concentrations (kg N ha^{-1}) measured seasonally after implementation of oat (white square), lupin (black circle) and field pea (white circle) residues at Beverley on a Red Chromosol. Data is the sum of 0–10 cm, 10–30 cm and 30–50 cm intervals for all incorporation treatments. Capped bars represent LSD ($p=0.05$) for residue \times sampling time interaction. The horizontal bar represents the wheat growing season for this trial year

in each plot was assessed for grain protein (%), hectolitre weight (weight by volume in kg/hl), and small grain screenings (% <2 mm). At harvest, plots were also sampled by hand and used to estimate head number, spikelet number, floret number, grain number and average grain weight for each treatment.

Laboratory analyses

Microbial biomass-C (MB-C; Wu et al. 1990) was determined by fumigation extraction on soil adjusted to 45% water holding capacity. Moist soils (20 g dry weight equivalent) were fumigated with chloroform containing amylene (0.006% v/v) as the stabilising agent for 24 h to determine the flush of C by

extraction with 80 ml 0.5 M K_2SO_4 for 1 h. Filtered extracts (Whatman No. 42) were frozen at -20°C until analysed for total oxidisable C (Shimadzu Model 5050, Kyoto, Japan). MB-C was calculated from the flush in organic-C between fumigated and non-fumigated soil. Data was then adjusted by a k_{EC} factor of 0.45 for MB-C (Wu et al. 1990).

Soil inorganic N was determined by extraction with 80 ml 0.5 M K_2SO_4 (soil: solution ratio = 1:4) for 1 h. Filtered extracts (Whatman No. 42) were analysed for NH_4^+ concentration colorimetrically using the salicylate-nitroprusside method (Krom 1980; Searle 1984) and NO_3^- concentration using the hydrazinium reduction method (Kamphake et al. 1967; Kempers and Luft 1988) on a Skalar Auto-analyser (Skalar San plus).

Statistical analysis

Repeated measures analysis of variance was used where appropriate after testing for normal distribution to determine significant treatment effects using GENSTAT (Payne et al. 2007). The focus of the analysis was to examine soil trends over time, and examine the effects of residue management techniques. Statistical analysis of plant components (ANOVA and REML) was performed using Genstat. Due to a spatial trend observed in trial blocks at harvest, grain yield data was analysed using REML for each crop species separately.

Table 2 Basic soil properties (0–10 cm) determined prior to implementing residue treatments at Beverley on a Red Chromosol. Data is the site average ($n=4$ composite samples)

Soil property	Average measured value ($n=4$) \pm SEM
^a Total C (g kg^{-1})	12 \pm 0.2
Dry bulk density of soil (Mg m^{-3})	1.3 \pm 0.04
Soil $\text{pH}_{\text{CaCl}_2}$	5.9 \pm 0.1
Electrical conductivity _{1:1} (Ds m^{-1})	0.06 \pm 0.01
Inorganic N (mg kg^{-1} soil)	9 \pm 1.4 ($\text{NH}_4\text{-N}^+$) 3 \pm 0.1 ($\text{NO}_3\text{-N}^-$)
Phosphorous (Colwell P; mg kg^{-1} soil)	58 \pm 1.1
Potassium (Colwell K; mg kg^{-1} soil)	158 \pm 17.4
Sulphur (mg kg^{-1} soil)	10 \pm 0.1
Reactive iron (mg kg^{-1} soil)	687 \pm 146.5

^a Walkley and Black (1934)

Results

Soil properties

Ammonium was the initial dominant form of inorganic nitrogen at this site, accounting for 75% of plant available N present prior to implementing crop residue treatments (Table 2). Initial phosphorous (P) concentrations were sufficient for plant growth and production but relatively high reactive iron content (Australian Perry Ag Lab Soil Audit) indicated some potential for low plant availability due to greater soil P retention (Table 2). Low sulphur (S) concentration in soil was unlikely to constrain plant growth due to the application of a basal fertiliser which contained adequate amounts of S.

A moderate to high infiltration rate (Peverill et al. 1999) was observed for oat treatments (not measured on other crop residue treatments), with significantly slower sorptivity ($p < 0.05$) in both harvested and mouldboard treatments and in the steady state flow rate in mouldboard treatments (Table 3). Bulk density (0 to 10 cm) was influenced by soil treatment ($p < 0.07$) and was lowest under mouldboard plough treatments (Table 3).

Soil water content

Crop residue had a significant effect ($P < 0.001$) on soil water content (measured as % gravimetric water) depending on sampling time, with significantly higher soil water content under field pea residues compared to either lupin or oat residue treatments (Fig. 1b). This was dominated by differences in soil water content measured in the 30–50 cm soil layer (data not presented).

Inorganic nitrogen

Legume residue treatments with a narrower C/N ratio generally had higher ($P = 0.05$) amounts of plant

available N (NH_4^+ and NO_3^-) present in soil to a depth of 50 cm (Fig. 2a, b) compared to those treatments which had oat residues returned. Average NH_4^+ concentration was highest ($P < 0.001$) under legume treatments prior to seeding on June 13th but had declined rapidly by the July sample date (Fig. 2a). Seasonal variability in NH_4^+ was generally greater than differences observed among treatments and NH_4^+ concentrations increased with time (Fig. 2a). Nitrate was the dominant form of inorganic N at this site following imposition of management treatments. Soil NO_3^- was significantly ($P < 0.001$) higher for both lupin and field pea residues, compared to oat residue (Fig. 2b) and coincided with periods of high soil water content (Figs. 1b and 2b). Soil NO_3^- more closely followed seasonal changes in soil water during the latter part of the growing season (Figs. 1b and 2b), with increasing concentrations of NH_4^+ observed as the soil began to dry (Fig. 2a).

There were few differences in average NH_4^+ concentrations measured under crop residue treatments, with the exception of mouldboard plough treatments which resulted in a higher ($P = 0.05$) amount of NH_4^+ for all crop residues (Fig. 3a) compared to other incorporation methods. The much larger differences observed in soil NO_3^- concentration, were primarily associated with residue quality, oat residues resulted in less NO_3^- than legume residues (Fig. 3b). Incorporation method also influenced soil NO_3^- under legume treatments, with increased soil disturbance often resulting in greater release of NO_3^- (Fig. 3b).

Soil inorganic N under different soil treatments varied through the season in oat (Fig. 4a, b), lupin (Fig. 4c, d) and field pea (Fig. 4e, f) residue treatments. Despite differences in the magnitude of N supply, in each case the pattern of supply was similar for both NH_4^+ (Fig. 4a, c, e) and NO_3^- (Fig. 4b, d, f). The influence of crop residue and soil

Table 3 Infiltration properties of soils assessed on selected treatments prior to seeding at Beverley on a Red Chromosol. Data is presented for selected oat residue treatments

Treatment	Sorptivity (mm hr ⁻¹)	Steady state flow rate (mm hr ⁻¹)	Bulk density (0–10 cm; Mg/m ⁻³)
Harvest (control)	50a	202ab	1.38b
Dessication (brown manure)	60ab	254b	1.34ab
Offset discs (green manure)	67b	251b	1.37b
Mouldboard plough (green manure)	52a	167a	1.29a
LSD ($p = 0.05$)	12	52	0.07

^a Disc plough not assessed

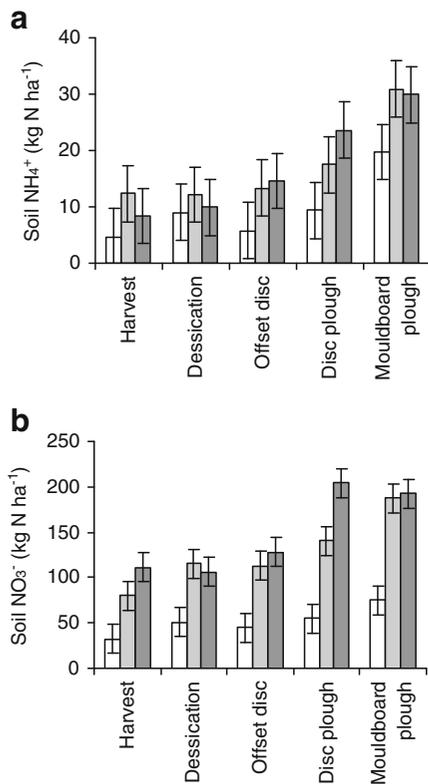


Fig. 3 Average soil inorganic nitrogen (kg N ha^{-1}) measured as (a) $\text{NH}_4\text{-N}^+$ and (b) $\text{NO}_3\text{-N}^-$ and after implementation of oat (white square), lupin (□) and field pea (■) residue treatments at Beverley on a Red Chromosol (0–50 cm). Capped bars represent LSD ($p=0.05$) for main treatment effects. Data is the average of 10 sampling periods

treatments on plant available NH_4^+ was more evident after 30th August and increased with time, reaching a maximum in October (Fig. 4a, c, e). Differences in NO_3^- concentrations predominantly occurred prior to this date and were relatively short lived (approximately 8 weeks), experiencing a rapid decline in August (Fig. 4b, d, f). The dessication (brown manure) and mouldboard plough treatments which demonstrated the greatest differences in residue treatment and soil disturbance from the control (harvest) have been presented here for each crop. Regardless of crop type there were few differences ($P=0.05$) observed in the amount of NH_4^+ under harvest and brown manure treatments (Fig. 4a, c, e). Availability of soil NH_4^+ was greatest in mouldboard plough treatments in early August and again after September, releasing more N than the brown manure and harvest treatments during these sampling periods (Fig. 4a). The amount of NH_4^+ supply under mould-

board plough treatments was highest under field pea treatments (Fig. 4e).

Microbial biomass

The MB-C fluctuated between 100 and 600 kg C ha^{-1} (Fig. 5a) with a significant interaction ($P<0.001$) observed between crop residue type and sampling time. This was generally associated with differences between oat and legume residues both prior to August, and at around anthesis (30 July–12th September sample dates; Fig. 5a). Differences were less readily observed in the soil surface (0–10 cm; Fig. 5b) compared to the subsurface layer (10–30 cm; Fig. 5c).

MB-C was significantly influenced ($P<0.001$) by sample depth, with a lower concentration of MB-C at depth (10–30 cm, 30–50 cm) than in the soil surface (0–10 cm) for all treatments (data not presented). In the soil surface, mouldboard and disc plough treatments had significantly lower MB-C ($p<0.01$) than in other treatments (data not presented).

Effect of treatments on plant establishment, plant biomass, N uptake and grain yield

Despite a significant ($p<0.01$) increase in seeding depth under mouldboard plough treatments (data not presented), all seed was placed at a depth no greater than 4 cm. Plant establishment ranged from 178 to 201 plants m^{-2} . Estimates of plant growth at 6 weeks after sowing indicated the tillering capacity of wheat was significantly decreased ($p<0.001$, $\text{LSD} = 0.3$) under oat residue (1.1 tillers/plant) compared to lupin or field pea residues (1.7 tillers/plant). A significant ($p=0.05$, $\text{LSD}=0.2$) decline in the number of leaves per plant was also demonstrated in treatments where crops were taken through to harvest (3.6 leaves/plant) compared to residue treatments (3.9 leaves/plant). Differences in plant biomass (dry matter production) measured under different crop residue treatments were also observed at anthesis with significantly ($p<0.01$, $\text{LSD} = 0.6$) lower biomass under oat residue treatments (5.4 tha^{-1}) than in either lupin (7.8 tha^{-1}), or field pea treatments (8.4 tha^{-1}).

Wheat biomass and tissue N content were also significantly lower after harvested treatments than in other treatments, resulting in significantly lower N uptake at both anthesis ($P=0.001$) and harvest ($P<0.001$) (Table 4). Significantly lower plant biomass

Fig. 4 Inorganic nitrogen (NH_4^+ and NO_3^- ; kg N ha^{-1}) measured seasonally following harvest (*black up-pointing triangle*), brown manure (*multiplication sign*) and mouldboard plough (*white diamond*) treatments of oat (**a, b**), lupin (**c, d**) and field pea (**e, f**) residues at Beverley on a Red Chromosol. Data is the sum of 0–10 cm, 10–30 cm and 30–50 cm intervals. *Capped bars* represent LSD ($p=0.05$) for treatment \times sampling time interaction. The *horizontal bar* represents the wheat growing season for this trial year

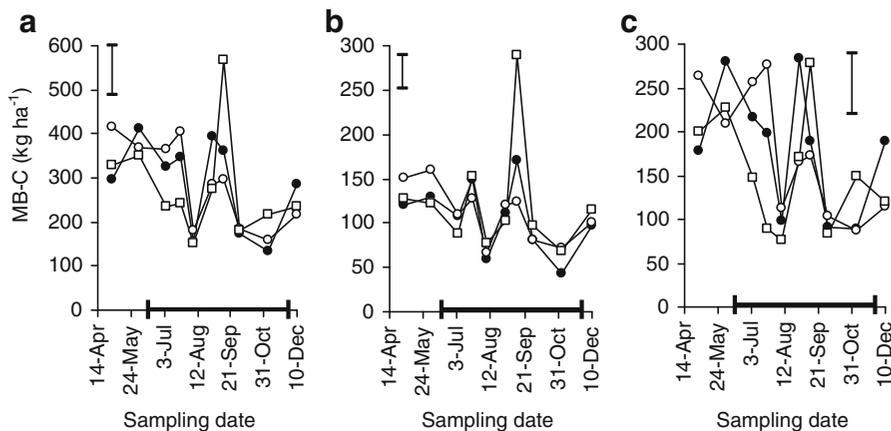
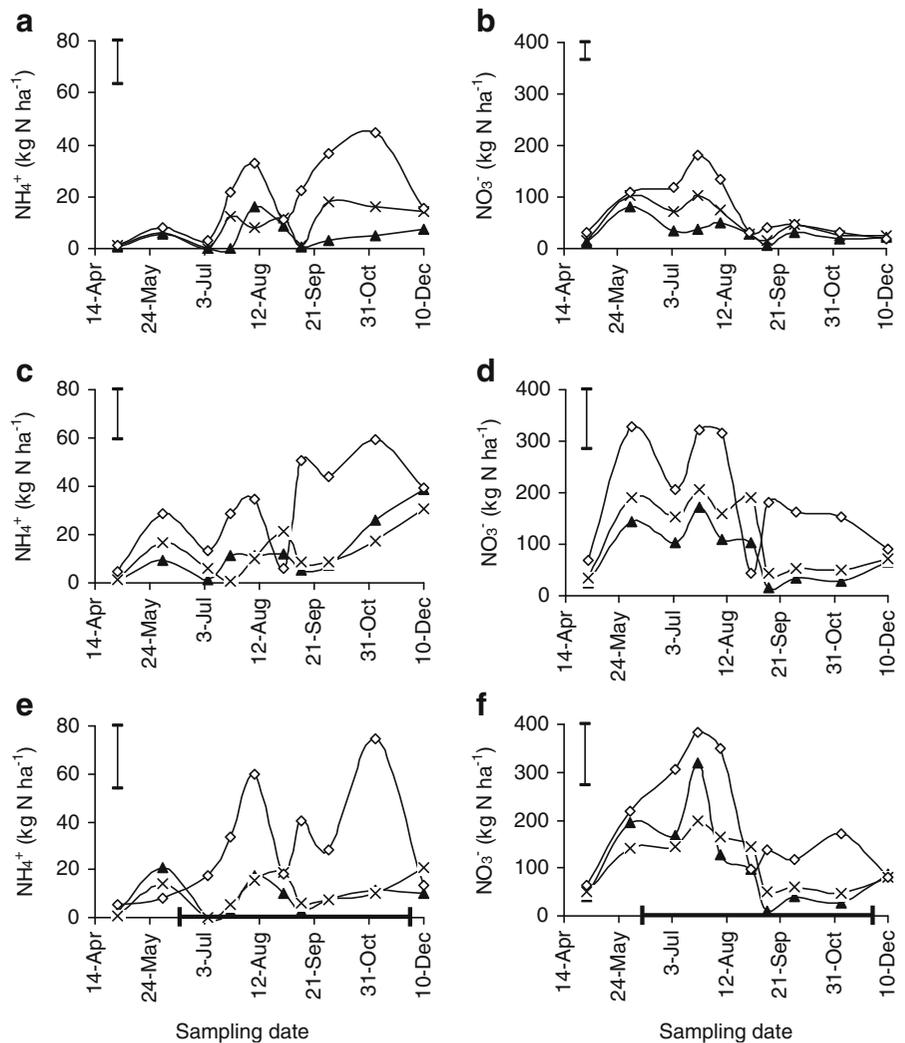


Fig. 5 Total microbial biomass-C (MB-C; kg ha^{-1}) measured seasonally to a depth of (a) 0–30 cm, (b) 0–10 cm and (c) 10–30 cm after implementation of oat (*white square*), lupin (*black square*) and field pea (*white circle*) residues at Beverley on a

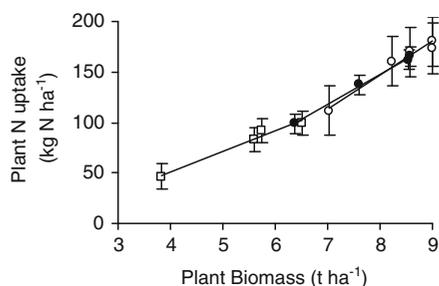
Red Chromosol (0–30 cm). *Capped bars* represent LSD ($p=0.05$) for crop residue \times sampling time interaction. The *horizontal bar* represents the wheat growing season for this trial year

Table 4 Wheat characteristics observed under different residue management treatments at Beverley on a Red Chromosol. Data is the average of oat, lupin and field pea residue treatments

Treatment	Anthesis dry matter (t ha ⁻¹)	Tissue N content (g kg ⁻¹)	N uptake at anthesis (kg N ha ⁻¹)	N uptake at maturity (kg N ha ⁻¹)
Harvest (control)	5.8	14.5	86a	294a
Dessication (brown manure)	7.2	17.7	129b	369bc
Offset discs	7.3	17.7	130b	358b
Disc plough	7.8	18.3	145b	401bc
Mouldboard plough	8.0	17.9	146b	417bc
LSD ($p=0.05$)	0.7	1.6	17	49

and tissue N in wheat ($P=0.007$) was measured under oat treatments and contributed to lower total N uptake ($P=0.001$) measured in above ground biomass compared to legume treatments (Fig. 6). A strong association was observed for plant biomass and plant N uptake in wheat under oat ($y=20.5x-31.0$; $R^2=0.97$), lupin ($y=29.7x-89.9$; $R^2=1.0$) and field pea ($y=33.3x-119.4$; $R^2=0.97$) residue treatments (Fig. 6).

Plant N uptake, grain yield and grain protein measured in wheat under field pea residues were demonstrably lower where peas were harvested (Table 5). Brown manure treatments (i.e. zero residue incorporation) yielded 9% higher than harvested peas, with a significant increase in grain protein also observed. Green manures (offset disc, disc plough, mouldboard plough) yielded between 20 and 31% higher than where harvested and had higher grain protein than either harvested peas or brown manure (Table 5). Despite high grain protein at this site, the amount of small grain that passed through a 2 mm sieve was below 2.5% for all treatments (Table 5).

**Fig. 6** Nitrogen uptake (kg N ha⁻¹) measured at anthesis in wheat after oat (white square), lupin (black circle) and field pea (white circle) residue treatments at Beverley on a Red Chromosol. Capped bars represent LSD ($p=0.05$) for soil residue management treatments within each crop type

Differences observed in plant biomass of wheat measured at anthesis under lupin residues, were reflected in grain yields, with significantly lower grain yields ($P<0.001$) observed in harvest treatments (Table 5). Few differences were observed between soil treatments for grain protein with the exception of the disc plough treatments in which a higher percentage of grain was also screened (Table 5). Plant N uptake measured in wheat under oat residues was demonstrably lower than under the legume crops. Differences in wheat biomass measured at anthesis were reflected in final grain yield and grain protein, with significantly lower ($P<0.001$) values observed for oats taken to harvest compared to other treatments. Grain yields for crop residue treatments demonstrated yield increases of between 14 and 33% (Table 5). Grain screenings were also higher under harvested treatments, than for green manures (Table 5).

Discussion

The total amount of N mineralised and the time-course of mineralisation have been changed successfully using typical temperate crop residues (Gunnarsson and Marstorp 2002) by combining different quality residues during decomposition. In this study, the net availability of soil N to a depth of 50 cm was also influenced by residue quality, but there were no differences observed between treatments in the time-course of N supply. Soil available N was primarily the result of organic matter mineralisation prior to sowing in June as demonstrated by increasing concentrations of both NH_4^+ and NO_3^- after the May 1st sample date (Fig. 2a, b). The buildup of NH_4^+ after 30th August suggests a rate limiting step in the conversion of

Table 5 REML analysis for N uptake at anthesis (kg N ha⁻¹), grain yield (t ha⁻¹) and protein (%) of wheat at maturity under field pea, lupin and oat green manure treatments. Data is the average of all treatments

	N uptake at anthesis (kg N ha ⁻¹)	Grain yield (t ha ⁻¹)	Protein (%)	Screenings (% <2 mm)
Field pea treatments				
Harvest	112a	1.97a	14.1a	1.9b
Dessication (brown manure)	161b	2.15b	14.5b	1.5a
Offset discs	170b	2.37c	14.8bc	2.4c
Disc plough	180b	2.51c	14.9c	2.1bc
Mouldboard plough	173b	2.59cd	15.1c	1.8ab
SED (<i>p</i> =0.05)	(<i>p</i> =0.07) 50	(<i>p</i> <0.001) 0.14	(<i>p</i> <0.001) 0.3	(<i>p</i> =0.012) 0.3
Lupin				
Harvest	99a	1.98a	14.8a	2.4ab
Dessication (brown manure)	143bc	2.31b	15.1a	2.6bc
Offset discs	137b	2.44b	14.9a	2.2ab
Disc plough	162cd	2.45b	15.5b	3.0c
Mouldboard plough	166d	2.42b	14.9a	2.1a
SED (<i>p</i> =0.05)	(<i>p</i> <0.001) 20	(<i>p</i> <0.001) 0.14	(<i>p</i> =0.044) 0.3	(<i>p</i> =0.167) 0.4
Oats				
Harvest	46a	1.66a	12.6a	3.6c
Dessication (brown manure)	84b	2.05c	14.2bc	3.3bc
Offset discs	83b	1.90b	14.0b	3.1bc
Disc plough	92b	2.08c	14.4bcd	2.9ab
Mouldboard plough	99b	2.21d	14.6d	2.4a
SED (<i>p</i> =0.05)	(<i>p</i> =0.008) 24	(<i>p</i> <0.001) 0.09	(<i>p</i> =0.025) 0.3	(<i>p</i> <0.001) 0.5

NH₄⁺ to NO₃⁻. The peaks in NH₄⁺ observed (in mouldboard plough treatments in particular; Fig. 4a) coincide with periods of low microbial biomass (Fig. 5a, b, c) and declining soil water content (Fig. 1). This might suggest nitrifier activity has been constrained at an earlier stage than mineralisation under drying soil conditions and in highly disturbed systems. This is reinforced by differences in microbial biomass in the surface layers of mouldboard plough treatments. Increased soil N supply was also associated with a greater degree of soil disturbance; with more rapid conversion of N from NH₄⁺ to NO₃⁻, as well as a greater distribution through the soil profile (e.g. mouldboard treatment). These differences may be due in part to an increased rate of soil organic matter breakdown associated with greater disruption of soil aggregates, residue particle size or placement (Kumar and Goh 2000), and changes in soil water dynamics influencing microbial decomposition. Soil NO₃⁻ production (nitrification) was more closely aligned with changes in soil water than NH₄⁺

production (mineralisation) which is consistent with mechanistic studies for this environment (Gleeson et al. 2010). However, depletion of soil NO₃⁻ may have been associated with increased plant N uptake during the latter part of the growing season.

Asynchrony of N supply is a primary influencer of N use efficiency and can be characterised either by i) an adequate supply of available N in soil when demand is low, or ii) low availability when crop demand is high. This disjoint between supply and demand, as previously noted is strongly influenced by climatic and soil properties which influence soil water, biological pathways and the ability of a crop to capture that N (i.e. plant root growth). For example, different wheat cultivars have demonstrated variation in N efficiency from both fertiliser and soil sources (Anderson and Hoyle 1999) which were linked to differences in rooting patterns. Therefore, any soil constraints to root and/or plant growth due to low water availability, temperature stress, poor soil fertility, 'hostile' sub-soil conditions or disease, can

effectively decrease plant demand for N. Consequently crop N demand can vary significantly from season to season.

Increasing N efficiency in dryland agricultural systems requires strategies to both increase the storage capacity of soil water (and hence nutrients) and promote more effective ‘capture’ of N by plants. On-farm management to remove soil constraints such as compaction (deep ripping) and water-logging (raised beds) increase root penetration and enable greater root distribution, and thus increase the potential for plants to capture N. Increasing early root vigour (Richards and Lukacs 2002) and/or developing root architecture that allows a greater proportion of soil N to be accessed through changes in root distribution (Dunbabin et al. 2003) can be achieved through selective breeding. In semi-arid environments improving water use efficiency and N use efficiency are often closely linked. Given the seasonal fluctuations observed at this site (Fig. 2), the changes in N supply at any one sampling period are likely to be influenced by the degree of plant residue to soil contact (Sparling et al. 1995), but ultimately regulated by climatic events.

Plant available N supply was greatest where legume crop residues were retained and with increased amounts (or burial) of soil disturbance as previously reported by other workers (Schomberg et al. 1994). This observed increase in mineralisation of fresh organic matter is influenced by the fragment size of residue, which decreased with increasing extent of disturbance, thus increasing the surface area of residues available to microbial breakdown. The magnitude of N release from crop residues appeared sufficient for supply during the first 4 weeks of plant growth. However, differences in tiller formation 6 weeks after sowing, and crop biomass and N uptake measured in wheat at anthesis indicate the influence of imposed treatments was evident from an early stage and suggests the wheat crop was N limited—particularly during late autumn and spring under oat residue treatments. This is consistent with previous studies noting N immobilisation and slower release of nutrients from poor quality residues (i.e. high C/N ratio) associated with less extensive decomposition (Amato et al. 1987). Consequently, the crop residues and soil treatments which provided the greatest supply of plant available N resulted in the highest grain yield. Despite the lower than average growing

season rainfall, the measured grain yields matched (and in the case of lupin and field pea treatments often exceeded) their yield potential based on calculated available water. In a growing season unconstrained by available water, it is possible that treatment differences in yield response may have been greater. Findings highlight that i) the timing of soil N supply was regulated by climatic factors and despite differences in the magnitude of N release, neither crop type nor incorporation method significantly altered the timing or pattern of N release in this semi-arid environment and that ii) N-rich crop residues can increase grain yield, even in dry years.

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