Where does the nitrogen go? Soil sources and sinks in Western Australia cropping soils

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Key messages

- In-season soil nitrogen (N) mineralisation can be a significant source of N to crops, but has not been well characterised for WA cropping soils. Improving the synchrony of soil N supply and crop demand could result in changes to N fertiliser inputs and better efficiency of use.

- Loss of N fertiliser to the atmosphere via ammonia (NH_3) volatilization may be as high as 29% from WA, however findings are restricted to two field-based studies using granular urea. Nitrogen leaching from WA cropping soils can also be significant during the growing season (14 –72 kg N/ha), however measurements have been confined to deep sands.

- Further research is needed quantify soil N mineralisation and NH_3 volatilisation rates under current WA farming practises, including incorporating findings into decision support tools.

Aims

To describe the supply and loss of N from soils in WA dryland cropping systems. Specifically we investigated soil N supply via net soil N mineralisation, plus N loss pathways including NH_3 volatilisation and other gaseous losses, and N leaching.

Method

We reviewed the scientific literature and collated soil N mineralisation, NH_3 volatilisation, N_2O and N_2 emission, and N leaching rates reported for WA dryland cropping systems.

Results

Ammonia volatilisation

Volatilisation is the loss of N to the atmosphere as NH_3 gas from livestock urine patches and N fertiliser applied to the soil surface. All fertilisers that contain ammonium (NH_4^+), or can produce NH_4^+ (e.g. urea) are susceptible to NH_3 volatilisation when applied to the soil surface (Freney et al, 1983). Ammonia volatilisation from urea requires the hydrolysis of the urea by the enzyme urease (Bremner and Douglas, 1971). The extent of the losses varies depending on fertiliser placement, soil type, soil pH and pH buffering capacity, crop residue management and environmental conditions (Sommer et al., 2004).

Ammonia volatilisation has been directly measured at one site in the WA grainbelt and indirectly calculated from another (Fillery and Khimashia, 2016). Ammonia volatilisation was directly was directly measured from an acidic soil in Merredin cropped to wheat, and following the application of urea (30 kg N/ha) to the soil surface. Losses were estimated using a field-based non-intrusive micrometeorological method. Cumulative NH_3 losses after 12 days represented 29% of the N applied, which is at the upper range of values reported for Australian cropping soils (e.g. Schwenke et al. 2014). These losses were consistent with values indirectly calculated from a study site at Regans Ford.

A variety of strategies to decrease NH_3 losses from cropping soils have been investigated in Australia. This has included decreasing stubble retention and using urea coated with N-(n-butyl) thiophosphoric triamide (i.e. 'green' urea) to inhibit the enzyme urease (Bacon and Freney, 1989; Turner et al, 2010; Schwenke et al, 2014). Applying green urea decreased NH_3 losses by up to 89% in comparison to applying urea, but the results have not consistent across all Australian studies (Turner et al, 2010; Schwenke et al, 2014).

Nitrous oxide and dinitrogen gas emissions

Nitrous oxide (N_2O) and dinitrogen (N_2) emissions represent another gaseous loss pathway for N fertiliser applied to cropping soils. Both gases are produced in soils by microorganisms under particular soil conditions. Denitrification is the reduction of nitrate (NO_3^-) to N_2, with N_2O an intermediary gaseous product (Wrage et al, 2001). Denitrification occurs in anaerobic microsites in the soils when there is sufficient NO_3^- and available carbon. Nitrification converts soil

NH_4^+ to NO_3^- under aerobic conditions, and like denitrification, incomplete conversion results in N_2O emissions (Wrage et al, 2001). Applying N fertilisers, whether synthetic or organic, enhances soil microbial production of N_2O and N_2 (Davidson, 2009; Smith et al, 2012).

Quantifying N_2O and N_2 emissions from soils is challenging. Losses vary spatially, and differ from day-to-day in response to factors that regulate production and subsequent emission of these gases (Butterbach-Bahl et al, 2013). Soil N_2O emissions are most often measured in the field using manual (static) or fully automated chambers. Chamber measurements are short-term (e.g. hourly), repeated in intervals of hours (automated systems) to weeks (manual systems), and are in turn integrated across time to calculate annual losses. The ability of chambers methods to adequately quantify N_2O losses relies on the user characterising N_2O emissions during the year, in particular peak emissions following N fertiliser applications and soil re-wetting, which may contribute up to 70% of the total annual flux (e.g. Barton et al, 2008).

Fifteen annual N_2O emissions have been reported for lupins and various N fertilised crops in WA (Table 1). Losses have been estimated using automated field-based chambers that measured emissions on a subdaily basis. Studies have been conducted on duplex and deep sands, with granular urea applied at a range of application rates depending on the crop and year (0–100 kg N/ha). Measurements of *in situ* N_2 emissions have not been reported for Western Australian cropping soils; it is best measured using ^{15}N tracer methods (McGeough et al. 2012; Kulkarni et al. 2013).

Nitrous oxide emissions reported from WA cropping soils have been small (0.02–0.27 kg N/ha/yr) and represented <0.12% of applied N fertiliser (Table 1). Including grain legumes in cropping rotations has not enhanced N_2O emissions during or the growing season or between growing seasons in WA studies (Barton et al, 2011; Barton et al, 2013); unlike studies conducted in Eastern Australia and overseas (e.g. Barton et al, 2011; Grace 2015). Although increasing soil carbon increased N_2O emissions at Buntine, the losses represented <0.12% of the N fertiliser applied (L. Barton, pers. comm). Developing strategies for mitigating N_2O fluxes from cropping soils in our region is challenging (and possibly not warranted based on current data) as losses occur between growing seasons in response to summer rainfall rather than N fertiliser applications. Strategies that control soil N supply from nitrification following soil wetting, or immobilise excess inorganic N via soil microbial or plant uptake, would be expected to decrease the availability of N for subsequent N_2O emission. Increasing the efficiency of the nitrification process by increasing soil pH (via liming) decreased N_2O emissions from an acidic soil following summer rain (Barton et al. 2013).

Table 1. Annual nitrous oxide emissions (N/ha/yr) for Western Australia dryland cropping soils

Location	Crop and treatment	Soil carbon (%)	N fertiliser (kg N ha^{-1})	Study period and duration (days)	N_2O emission (kg N/ha/yr)	Reference
Buntine	canola+OM	1.20	100[a]	Jun. 2012–Jun. 2013; 365	0.14	Barton (pers. comm)
Buntine	canola	0.64	100[a]	Jun. 2012–Jun. 2013; 365	0.02	Barton (pers. comm)
Buntine	barley+OM	1.20	100[a]	Jun. 2013–Jun. 2014; 365	0.27	Barton (pers. comm)
Buntine	barley	0.64	100[a]	Jun. 2013–Jun. 2014; 365	0.02	Barton (pers. comm)
Cunderdin	wheat	0.98	100[a]	May 2005–May 2006; 354	0.11	Barton et al. (2008)
Cunderdin	canola	0.98	75[a]	May 2007–May 2008; 356	0.13	Barton et al. (2010)
Cunderdin	lupin	0.98	0	May 2008–May 2009; 349	0.13	Barton et al. (2011)
Wongan Hills	wheat+lime	1.03	75[a]	Jun. 2009–Jun.2010; 371	0.05	Barton et al. (2013)
Wongan Hills	wheat	1.03	75[a]	Jun. 2009–Jun.2010; 371	0.06	Barton et al. (2013)
Wongan Hills	lupin+lime	1.03	0	Jun. 2009–Jun.2010; 371	0.05	Barton et al. (2013)
Wongan Hills	lupin	1.03	0	Jun. 2009–Jun.2010; 371	0.04	Barton et al. (2013)
Wongan Hills	wheat+lime	1.03	50[a]	Jun. 2010-Jun./2011; 364	0.04	Barton et al. (2013)
Wongan Hills	wheat	1.03	50[a]	Jun. 2010-Jun./2011; 364	0.07	Barton et al. (2013)
Wongan Hills	wheat+lime	1.03	20[a]	Jun. 2010-Jun./2011; 364	0.06	Barton et al. (2013)
Wongan Hills	wheat	1.03	20[a]	Jun. 2010-Jun./2011; 364	0.06	Barton et al. (2013)

[a]Urea; OM, organic matter.

Nitrogen leaching

Nitrogen leaching occurs from cropping soils when water drains through the soil and beyond the rooting zone. Any N not taken up by the crop, immobilised in soil organic matter, denitrified or volatilised to gaseous N compounds is susceptible to leaching when drainage occurs. The extent of N leaching will also be affected by the rate that dissolved N moves through the soil profile. Crop N uptake and soil biological processes often occur at greater rates in the surface- than the sub-soil. Nitrogen fertiliser practices that maximise the contact time between the dissolved nutrients and the surface soil should increase crop N uptake and soil 'retention', and therefore decrease the risk of N leaching. The extent of leaching beyond the surface soil will also vary depending on amount and intensity of rainfall, soil texture and structure, and the extent of the crop rooting zone. Nitrogen losses will be less in those soil types where soil drainage moves evenly through the entire soil profile ('matrix' flow) than in soil types were soil water moves through macropores such as down cracks, along old root channels and worm holes ('preferential' flow) (Barton et al., 2004).

Nitrogen leaching from soils is best quantified directly, and throughout the year to account for seasonal changes in soil N availability (Addiscott, 1996). Measuring N leaching for an extended period will also account for any effects of establishing the experiment (e.g., soil disturbance) on N leaching. Nitrogen can be leached as NO_3^-, NH_4^+ and as organic N. It has often assumed that NO_3^- is more susceptible to leaching than other forms of N as the solid phase of most soils has a net negative charge, and so repels negatively charged anions such as NO_3^-. However, organic N leaching can also be significant from agricultural soils (Murphy et al., 2000).

Nitrogen leaching has been measured from two study sites on deep sands cropped to wheat following a grain legume or pasture, and in the absence of N fertiliser (Table 2). Nitrogen leaching losses have been estimated by measuring NO_3^- losses (to a depth of 1.0–1.5m) using either porous (suction) cup lysimeters in combination with soil hydrological models or soil lysimeters fitted with anion exchange resin traps at the base. Nitrate leaching losses have ranged from 14 to 72 kg N/ha during the growing season, and 14 kg N/ha in one study where losses were measured for a year. Greatest losses during the growing season have occurred from soils cropped to wheat following lupin (Table 2).

Table 2. Nitrogen leaching (NO_3-N/ha) for Western Australia dryland cropping soils

Location	Crop (previous)	Soil texture	Nitrogen fertiliser (kg N/ha)	Study period and duration (days)	Nitrogen leached (kg N/ha)	**Reference**
Moora	lupin (wheat)	sand	0	Jun.1994–Sept.94; 97	24	Anderson et al. (1998)
Moora	lupin (wheat)	sand	0	Apr.1995–Aug.95; 125	35	Anderson et al. (1998)
Moora	lupin (wheat)	sand	0	Jun.1996–Aug.96; 58	23	Anderson et al. (1998)
Moora	lupin (wheat)	sand	0	Jun.1995–Jun.96; 353	14	McNeil and Fillery (2008)
Moora	wheat (wheat)	sand	0	Jun.1994–Sep.1994; 97	24	Anderson et al. (1998)
Moora	wheat (lupin)	sand	0	Apr.1995–Aug.1995; 125	59	Anderson et al. (1998)
Moora	wheat (lupin)	sand	0	Jun.1996–Aug.1996; 58	42	Anderson et al. (1998)
Moora	wheat (lupin)	sand	0	Jun.1996–Nov.96; 161	72	McNeil and Fillery (2008)
Moora	wheat (pasture)	sand	0	Apr.1995–Aug.1995; 125	34	Anderson et al. (1998)
Moora	wheat (pasture)	sand	0	Jun. 1996–Aug. 1996; 58	43	Anderson et al. (1998)

The risk of N leaching from deep sands may be greater than what measurement data indicates. Modelled NO_3^- leaching losses from deep sands in the WA grainbelt were up to 116 kg/N/ha during the growing season in the absence of N fertiliser applications (Asseng et al., 1998; Wong et al., 2006). Long-term simulations (1910–1990) showed the greatest risk of NO_3^- leaching occurred in years when soil mineral N was elevated at the start of the cropping season (89.5 kg N/ha in surface 150cm), with a 50% probability that 46 to 53 kg N/ha would be lost beyond 150cm of a deep sand during the growing season (Asseng et al., 1998). Elevated soil mineral N concentrations may occur following a grain legume crop or in response to summer rainfall when the soil is fallow (e.g., Anderson et al., 1998; Barton et al., 2013). Similarly for another deep sand in the WA grainbelt, simulation modelling predicted NO_3^- leaching losses from 0 to 25.5 kg N/ha per year depending on soil texture (Wong et al., 2006). Simulation modelling has demonstrated 'splitting' N fertiliser applications between seeding and post-seeding is likely to decrease NO_3^- leaching losses from deep sands (Asseng et al., 1998; Wong et al., 2006).

Soil net N mineralisation

Net N mineralisation is the net balance between N supply from soil organic matter (and plant residues) and N losses (e.g. immobilisation into soil organic matter, NH_3 volatilisation, leaching). Net N mineralisation can occur all year round. Between-growing seasons, net N mineralisation is most often measured and reported as the difference (kg N/ha) in mineral N in the soil profile (up to 2.0m) between harvest and the subsequent break of season. Whereas in-season measurements generally use *in situ* incubation of intact cores (Raison et al., 1987; Stein et al., 1987) or a variation of this method (Anderson et al., 1998). In-season measures are generally conducted for 2 to 6 weeks at a time, and either run continuously or are repeated at intervals; and then calculated by summing the total N mineralised over a specified time and represented on a daily basis per unit area.

A total of three publications report net N mineralisation resulting from SOM turnover or provide sufficient information to calculate mineralisation rates (Table 3) from WA field sites. These include six between-season values and three in-season values. Studies have been conducted predominately on slightly acid to acid soils, with sandy to sandy clay loams textures, with no N fertiliser applied (Table 3). In some studies measures have been reported in-field for periods of up to 2 years (Anderson et al., 1998), whereas for others it has been as short as a few weeks.

Net N mineralised from cropping soils has ranged from -0.16 to 0.5 kg N/ha per day in WA with net immobilisation of N noted in some systems (Table 3). Between-season net N mineralisation rates have ranged from 0.1 to 0.2 kg N/ha per day, with significant accumulation of mineral N before sowing often reported in response to summer rainfall (and when plant N uptake is negligible).The length of the fallow season, extent of summer rainfall events and any losses resulting from plant uptake strongly influence the contribution of between-season mineralisation to annual net N mineralised. By contrast, in-season net mineralisation rates have ranged from -0.16 to 0.5 kg N/ha per day. Rotation (Anderson et al., 1998), tillage (Cookson et al., 2008) and stubble retention (Hoyle et al., 2006) have had small, but variable, influences on net N mineralisation across soil types and environments through its influence on substrate availability (Hoyle et al., 2006; Fisk et al., 2015).

Overall, annual net N mineralisation has ranged from 43 to 122 kg N/ha in the surface of WA soils (Anderson et al. 1998, Murphy et al. 1998). The relative contribution of between-season and in-season net N mineralisation rates to annual net N mineralisation rates can vary from year-to-year. For example, during dry fallow conditions the contribution of between-season mineralisation was between 14 and 21% of total net N mineralised each year at a study site in Moora, whereas as the same location the contribution of between-season mineralisation was between 25 and 53% during a wet fallow (Anderson et al., 1998). Slow mineralisation rates are evident under cooler conditions (<15°C; June, July and August), with daily mineralisation rates increasing during September and October with increasing temperature and rapid mineralisation during summer in response to rainfall events. As mineralisation slows under dry conditions, average daily rates for mineralisation between-season are often lower than the in-season rates as there are less days with sufficient moisture available for mineralisation to occur.

Table 3. Net N mineralisation rates (kg N/ha/d) reported between-season and in-season for Western Australia dryland cropping soils

Location	Crop (previous crop)	Topsoil texture	Soil carbon (%)[a]	Sampling depth (cm)	Study period	Between-season (kg N/ha/d)	In-season (kg N/ha/d)	Reference
Moora	wheat (lupin)	sandy	1.21	0–21	Nov.1994–Jun.1995	0.1		Anderson et al. (1998)
Moora	wheat (lupin)	sandy	1.21	0–21	Nov.1995–Jun.1996	0.2		Anderson et al. (1998)
Moora	wheat (lupin)	sandy	1.21	0–21	Jul.1995–Nov.1995		0.3-0.5	Anderson et al. (1998)
Mingenew	wheat (wheat)	sandy	0.6	0–21	Jun.2010–Jul.2010		0.3	Flower et al. (2012)
Cunderdin	wheat (wheat)	sandy clay loam[b]	1.0	0–21	May.2010–Jun.2010		0.1	Flower et al. (2012)
East Beverley	wheat (wheat)	loamy sand	0.88	5, 10	May.1994–Nov.1994	0.1-0.2	0.25	Murphy et al. (1998)
	wheat (lupin)	loamy sand	0.88	5, 10	May.1994–Nov.1994		0.34	Murphy et al. (1998)
East Beverley	wheat (pasture)	loamy sand	0.88	5, 10	May.1994–Nov.1994		-0.16	Murphy et al. (1998)

[a]0–10 cm; [b]Alkaline soil.

Conclusion

Better utilisation of N fertiliser in WA cropping system requires an understanding of the timing and magnitude of N release from soil organic matter via mineralisation, as well as an understanding of the conditions whereby major losses from the soil can occur. The extent and timing of soil N supply (net N mineralisation) has been reported from a limited number of locations in the grainbelt, but demonstrates up to 0.5 kg N/ha may be released in a day during the growing season. Nitrogen leaching and NH_3 volatilisation represented significant losses of soil N in the studies reviewed, however the number of field-based measurements is extremely limited. Further research is needed quantify soil N mineralisation and NH_3 volatilisation under current WA farming practises, and incorporate into decision support tools.

References

Reference list available on request.

Key words

Ammonia volatilisation, nitrogen leaching, nitrous oxide, soil mineralisation

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