Nitrogen use efficiency and nitrogen balance in Australian farmlands

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Abstract
Farms producing crops and animal products occupy 14% of the Australian land mass. Within this agricultural land, 7% consists of intensive industries (dairy, horticulture and viticulture, sugar cane, cotton, irrigated cereals and feedlots) for which the input of fertiliser nitrogen (N) is typical of such industries worldwide. The sugar and dairy industries are adjacent to populated and environmentally fragile water bodies where nitrate (and phosphate) runoff and leaching contributes to water pollution. The nitrogen use efficiency (NUE) of these industries is low but NUE for the inland irrigated rice and cotton industries are relatively high. The remaining 93% of agricultural land grows dryland crops and animal products (wheat, coarse grains, canola, grain legumes, cattle meat, sheep meat, and wool) partly from continuous crops, partly permanent pasture and partly from phased crop-pasture systems. Until the mid-1990s the source of most of the N in dryland crops was from mining the soil organic matter and increasingly, since the 1950s, from N built up from biological N-fixation by legume-based pastures grown in phased rotation. Export of N in products from dryland farms exceeded the input from N fertiliser. Since the mid 1990s N fertiliser input increased to an average of about 45 kg N ha^{-1}, only about half of which is taken up by crops. Of the rest, most is retained in the soil after harvest and about one quarter is lost from denitrification, ammonia volatilisation and leaching. Overuse of N fertiliser in dryland farming is rare because neither products nor fertiliser are subsidised. Arid and semi-arid land occupies 86% of the continent, half of which is not used for production and the other half produces cattle meat, sheep meat and wool with no fertiliser input. The source of N is rain, biological N fixation and redistribution from dust, the amounts of which are greater than the controlled N inputs in the agricultural regions. The feature of N cycling in Australia that distinguishes it from other developed countries is the importance of natural N sources, reflecting the extensive and relatively young agricultural system.

Keywords: nitrogen budget, nitrogen use efficiency, ^{15}N, denitrification, leaching, ammonia volatilisation

Introduction
The emphasis of international research on nitrogen (N) in agricultural systems has changed from the goal of increasing nitrogen use efficiency (NUE) to profitably use N to produce food and fibre, to concerns about the environmental damage from surplus reactive N, particularly from fertiliser, in the natural environment. The purpose of this paper is to summarise both strands of research in Australia. We distinguish between the national and agricultural N balances because the N balance of the vast non-agricultural zones may disguise or even swamp the agricultural N balance. In the agricultural zones, the goals of high NUE and low leakage of reactive N are compatible. We discuss prospects for improving fertiliser NUE.

Soil N levels
The conventional wisdom is that Australian soils are ancient and infertile (PMSEIC 2010). Deep weathering has influenced soil patterns in parts of Australia, particularly in regions that are climatically unsuited for farming (McKenzie et al. 2004). However there are extensive areas of agricultural soils in south-eastern Australia that were enriched by Quaternary aeolian deposits (McKenzie et al. 2004) as well as productive alluvial soils in eastern Australia with minor weathering and even small areas of soil formed on basalt flows that post-date human occupation. Elsewhere in southern Australia soil N levels increased from the pre-farming levels due to biological nitrogen (N) fixation from the extensive use of pasture legumes (Grace and Oades 1994; Ladd and Russell 1983). In many undisturbed Australian agricultural soils the total N content was, by international standards, consistent with their water balance, temperature and texture; for example the average N content of one of the most widespread agricultural soil types, the red-brown earths (Chromosols, Dermosols, Kandosols and Sodosols) was 1.5 g kg^{-1} before intensive agriculture (Stace et al. 1968), comparable with undisturbed soils

in parts of the United States (Arkansas and Mississippi) with a similar mean annual temperature of about 15 °C (Jenny 1941). Levels of natural total N may be low in some Australian soils because they are sandy and located in dry and warm environments. The original nutrient content of soil in Australia before agriculture, as in agricultural soils everywhere, becomes decreasingly relevant to production and off-site effects as fertiliser supplies more of the nutrients removed in crops and livestock.

Change in soil N levels

Long-term experiments in Australia show that the total N (and organic C) content of soils decreases with continuous cropping and crop-fallow systems. Clarke and Russell (1977) reviewed many experiment that quantified N removed by crops during the first half of the twentieth century. The experimental crops received no N fertiliser and the low yield levels and rates of soil-N depletion were unrepresentative of current cropping systems. Table 1 reports more recent observations and experiments where yields were representative of current crops. In some of these cases the rate of decrease with continuous cropping appears to be linear when measured over periods of several decades but is non-linear over a longer period, falling to a new equilibrium. This pattern of decrease is expressed as a half-life of total N in the soil. Averaged over the data in Table 1, the half-life of total N in the soil is about 30 years. The next question is the extent of N mining in Australian cropping lands. To answer this we need to know the number of crops harvested from an average arable field. Based on the annual increase in area of dryland crops (3.2 % from 1850 to 2014), the estimate is 30, assuming that a field is continuously cropped after the first harvest. This assumption is almost certainly an overestimate and the actual number of crops per field is probably less than 30. This estimate, combined with the estimated half-life of soil N, suggests that about half the total N has been mined from cropping land.

Table 1. Decreases in total N in the top 10 cm of soils in dryland cropping systems in Australia.

Cropping system	Location	Years of observations	Half-life of soil total N (years)	Reference
Continuous sorghum	Narayan, Qld	10	18	Russell (1981)
Fence-line comparisons, cereals	119 farms, 6 soil types, S. Qld	1-70	27-67	Dalal and Mayer (1986)
Continuous wheat, no N fertiliser	Hermitage, Qld	14	36	Dalal (1992)
Fallow-wheat, no N fertiliser	Waite Institute, SA	68	40	Grace and Oades (1994)
Continuous wheat, no N fertiliser	Waite Institute, SA	68	48	Grace and Oades (1994)
Continuous wheat, no N fertiliser	Wagga Wagga, NSW	18	27	Helyar et al. (1997)
Continuous wheat, no N fertiliser	Wagga Wagga, NSW	25	18	Heenan et al. (2004)
Continuous wheat, +50 kg N ha^{-1}	Wagga Wagga, NSW	25	22	Heenan et al. (2004)
Wheat-broadleaf with tactical N	Harden, NSW	19	14	Angus et al. (2006)
Continuous cereal, no N fertiliser	Theodore, Qld	23	34	Dalal et al. (2013)

There are few comparable estimates from long-established farming regions internationally, where early farmers undoubtedly mined soil N. In the warm environment of Tanzania the half-life of topsoil N under maize receiving no N inputs over 15 years (Solomon et al. 2000). In the cooler North Dakota environment, topsoil N under long-term wheat-fallow receiving no N inputs for 45 years (Schimel 1986) had an estimated half-life of 65 years.

The modern equivalent of mining soil fertility is to pump natural gas as a feedstock for ammonia synthesis, and this is equally unsustainable in the long term. There is little data about the ‘equilibrium’ level of soil N after long-term cropping. A notable result among the long-term experiments is that applying N fertiliser to continuous crops had little effect on the depletion rate of soil total N (Russell 1981; Heenan et al. 2004).

Many Australia studies showed that pastures replenish soil total N and C (e.g. Ladd and Russell 1983; Grace and Oades 1994; Helyar et al. 1997), and phased crop-pasture systems dominated the dryland farming systems in southern Australia from the 1950s to the early 1990s. These systems maintained soil N and C with little N fertiliser provided about half the farm grew pastures (Angus and Peoples 2012). It is possible, but expensive, to replenish soil N (and C) in a continuous cropping system when stubble retention is combined with applied fertiliser N, P and S to maintain the ratios of these nutrients in soil (Kirkby et al. 2016).

Factors influencing the ability of soil to supply N to crops include the amount and quality of soil organic matter and residues, disturbance, moisture and temperature regimes (Campbell et al. 1981). An indicator of soil-N supply is the mineral N content in agricultural soils (typically to a depth of 60 cm) before sowing winter crops. Fillery (2001) reported a mean value of 98 kg N ha^{-1} from a survey of experiments after pasture in Western Australia. Results from the laboratory of Incitec-Pivot Ltd representing hundreds of farm samples in Eastern Australia indicate a mean value of 80 kg N ha^{-1} in the top 60 cm. These values are higher than comparable measurements in Western Europe and North America, probably because of the relatively high levels of total N and because the generally high temperatures in Australia promote mineralisation. Potentially mineralisable N stores in south-eastern Australia range from 8% of the total N in burnt systems to 22% after 15 years of residue retention (Gupta et al. 1994).

Fertiliser N use

Before the mid 1990s most of the N fertiliser used in Australian agriculture was for high-value crops such as horticulture and sugar cane. The average application to dryland crops at the time, mostly wheat and barley, was less than 5 kg N ha^{-1}. Crops in south-eastern Australia received less than average and those on less fertile Western Australian soils received more, as did those in Queensland where soil N had not been replenished with pastures. The reason for the generally low rate was not lack of research and extension, but because wheat yield did not reliably respond to applied N at the time (Colwell and Morton 1984).

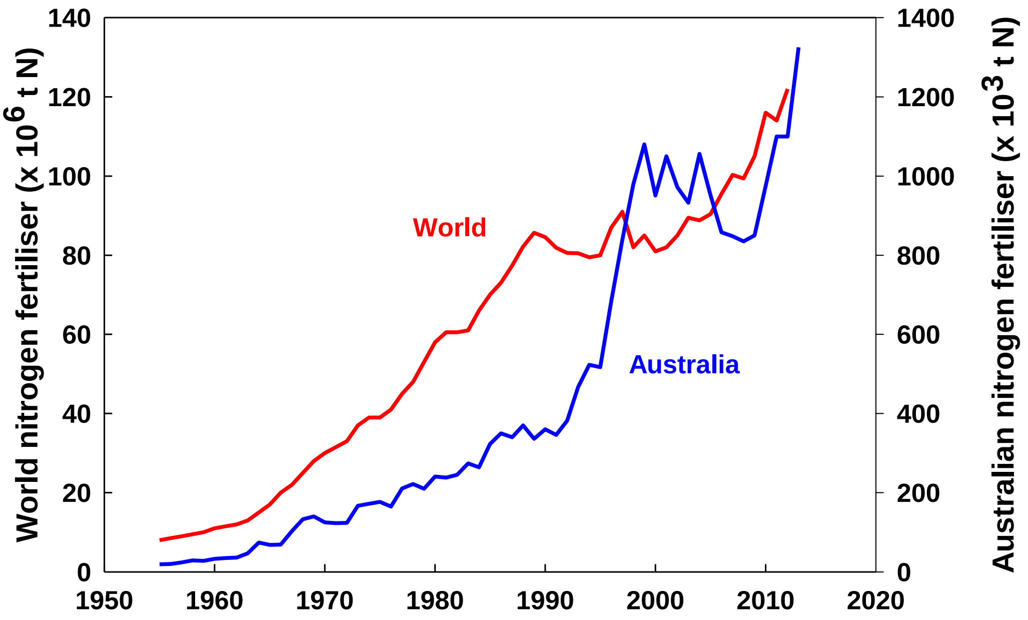

Fig. 1. Changes in N fertiliser use in Australia and the world. The sources are Angus 2001, Fertiliser Australia (www.fertilizer.org.au) and FAOSTAT (www.fao.org).

The growth in N-fertiliser usage in Australia was slow compared to the rest of the world before the mid 1990s (Fig. 1) but for the rest of that decade there was a boom in N-fertiliser use, mostly as inputs to wheat and other dryland crops. This boom closely accompanied increased canola area and lime application. Canola provided the first widely grown break crop in Australia and wheat grown after canola responded more reliably to N fertiliser than wheat after wheat (Angus 2001).

The lime application was needed because canola is acid sensitive and it also enabled other acid-sensitive crops to be grown. Other factors that encouraged farmers to apply N at this time were the availability of efficient fertiliser spreaders and increased premiums for high grain protein. The use of N fertiliser stabilised during the millennium drought of 2002-2009, after which usage resumed its upward course (Fig. 1). Most of the N fertiliser is now applied to dryland crops at the relatively low rate of 45 kg N ha^{-1} (Table 2). Intensive crops and pastures occupy a relatively small area of land but receive larger application rates.

Table 2. Estimated N-fertiliser use for Australian agriculture, based on estimated areas for 2010-2014 ABARES (2015), national fertiliser use in 2014 is from Fertilizer Australia (www.fertilizer.org.au) and industry fertiliser use is from fertiliser-industry estimates.

		Area (M ha)	Average fertiliser use (kg N ha^{-1})	Total fertiliser use (Mt N)
Dryland crops*		24	45	1.08
Intensive farming				
	Cotton	0.44	300	0.09
	Dairy pastures	2.00	100	0.20
	Irrigated cereals**	0.31	100	0.03
	Sugar cane	0.36	150	0.06
	Viticulture and horticulture	0.50	100	0.05
Other				
	Sports-fields, parks and gardens	0.1	200	0.02
	Licks and stockfeed			0.03
Total				1.59

*Wheat, barley, canola, sorghum, oats, triticale
** Rice, maize, wheat

Myers (1984) proposed a simple budget of N inputs and output to estimate N-fertiliser requirement for a single field, in this case a wheat crop which represents the largest crop and consumer of N (Table 3). When this topic was visited previously (Angus 2001), the average N fertiliser application to wheat was 30 kg N ha^{-1}, which represented about one third of the N total supply, the remainder coming from depletion of soil total N and the recent N fixed by pasture legumes and a small contribution from crop legumes. At that time, the supply of N fertiliser worldwide provided about half of the supply to world agriculture (Jenkinson 2001). Applying the same approach to update estimates for all Australian dryland crops in 2014, we estimate that fertiliser provides about 45% of the total N input. In Table 3, mineralisation is partitioned into the contributions from mining the soil and N-fixation by previous pastures. The procedure was to first estimate N-fixation, assuming 50% pasture on the farm from 1950 until 2014 and mineralisation of legume residues according to the rates estimated by Angus and Peoples (2012). The contribution from soil mining was then estimated from the difference between total N-mineralisation and the contribution from N-fixation. Other estimates in Table 3 are the amounts of soil-N retention and losses. Both are based on the fate of ^{15}N fertiliser reviewed in Fig. 2, increased to account for the flow of non-fertiliser N to these pathways. This allocation is based on measurements showing that NUE of native soil N was similar to NUE of fertiliser for dryland wheat (Angus et al. 1998).

Table 3. Nitrogen budget for an average Australian wheat crop, updated from Angus (2001)

		kg N ha^{-1}	Totals (kg N ha^{-1})
Crop N demand	Yield 2.0 t ha^{-1}, 10.5% grain protein	37	
	Straw N (one-third of grain N)	12	
	Rhizodeposited N (34% of total plant N)*	25	74
N supply	Fertiliser	45	
	Rain and dust	5	
	Mineralisation		
	Mining soil N	31	
	N-fixed from previous pastures	31	112
Soil-N retention		24	

Losses**	14	38

*Wichern et al. (2008)
**leaching, ammonia volatilisation and denitrification of fertiliser and other N

Australian N budget
The land area of Australia is the sixth largest of the ~200 countries but crops and improved pastures make up a relatively small part of the total area and intensive animal industries are relatively small compared with other developed countries (Table 4).

Table 4. Nitrogen balance (M t y^{-1}) of inputs and outputs in Australian regions in 2014, based on the methods of Denmead (1990), McLaughlin et al. 1992) and Galbally et al. (1992) with amounts updated by ABARES (2015) and land areas by ABARES (2010). The transfers represent (1) spatial N movement in dust storms and (2) conversion of organic to mineral N, representing a loss from the soil due to mining and input to the crop.

Zone	Non-agricultural (309 M ha)	Pastoral (355 M ha)	Dryland farming (97 M ha)	Intensive (4 M ha)
Input				
N in rain	0.6	1.2	0.3	
Biological N fixation	0.8	1.1	3.2	0.02
Fertiliser N			1.08	0.36
N offtake in products				
Crop products			-0.9	-0.26
Animal products*		-0.02	-0.1	-0.1
Losses				
Ammonia**	-1.7	-2.1	-0.6	-0.2
Denitrification			-0.3	-0.6
Nitrate leaching and runoff			-0.1	
Biomass burning (net NO_x)	-0.3	-0.2	-0.1	
Transfers***				
N in dust storms	±0.3	±0.3		
Soil organic to mineral N			±0.7	±0.1
Balance	-0.6	-0.1	2.5	-0.6

*Empty liveweight of slaughter animals, milk and clean wool
** Loss from plant communities, soil, urine, and urea fertiliser
*** Not included in balance

The estimates of the N balance of the Australian continent follow the work of Denmead (1990), McLaughlin et al. (1992) and Galbally et al. (1992), updated by the area and yield of crops and numbers of livestock, and separated into 4 regions to provide context for the agricultural regions. The regions are non-agricultural land in the arid zone and mountainous conserved forests, pastoral land in semi-arid regions, dryland farmland consisting of the “wheat-sheep” and “high rainfall” zones and intensive industries in irrigated and high-rainfall regions. Small values and well documented data justify reporting with a precision of 10,000 t N, but for other data the precision is 100,000 t N at best.

Table 4 suggests that in the non-agricultural, pastoral and intensively farmed land the N inputs and outputs are similar. In the dryland farming zone there is a positive N balance, mainly due to N-fixation of pastures. This input is probably not associated with the phased crop-pasture system in which pasture area has been decreasing, but due to N-fixation by permanent pastures. Inputs and outputs of N in the zones are discussed in the following sections

Arid rangelands
The inland arid and semi-arid zones make up most of the national estate. Part of these zones have no agricultural production and the rest consist of pastoral properties that produce cattle and sheep with the only N input from atmospheric deposition and biological N fixation. The amounts per hectare are small but the amount over the whole area far exceeds the N offtake in meat and wool. There is no evidence of N accumulation or

depletion within historical time in these regions but there is a significant amount of N lost and redistributed in dust-storms. These events occur most frequently when strong winds coincide with a period of drought and most of the particles are lifted from the arid inland and some are lifted from farmland. McTainsh et al. (2005) reported an average of 62 dust storms each year from 1960 to 2002 in Australia, most of which remain in the arid zone and only the largest reach the coast. They estimated that a large dust storm in 2002 contained 3.35-4.85 Mt of particulates. A later large dust storm reported by Aryal et al. (2012) contained 10.6% organic matter. Assuming an 'average' dust storm half the size estimated by McTainsh et al. (2005) and an organic matter content of 10.6%, of which an estimated 4% was N, we come up with an annual estimate 0.5 Mt of N redistributed within the Australian continent or blown into the sea. This represents redistribution of 0.7 kg N ha^{-1} across the arid zone.

Other inputs of N in the arid rangelands are from rainfall and biological N fixation. The contribution from rain is calculated from the land area, mean annual rainfall and the N concentration in rainwater, 0.5 mg L^{-1}, based on measurements of Wetselaar and Hutton (1963) and Crockford and Khanna (1997). The main source of N deposited in rain is not thunderstorm activity (Wetselaar and Hutton 1963) but the products of biomass burning and ammonia released from urine voided by grazing animals (Denmead 1990; Galbally et al. 1992). There is likely to be biological N fixation from various symbiotic (e.g. *Acacia* and other leguminous shrubs and forbs, *Casuarina*, *Macrozamia* and lichens) and non-symbiotic associations (Gupta et al. 2006), cyanobacterial soil crusts, free-living microbes and the gut bacteria of cellulose-digesting termites (Evans et al. 2011). Non-symbiotic N-fixation is likely to be greater in northern than in southern Australia because of generally lower soil-N status and high temperatures during the wet season.

Dryland farming

Farming in this zone consists of permanent pasture grazed by sheep and cattle, continuous cropping, and phased crop-pasture sequences. For the period from 1850 to 2000 crop area grew at an average annual rate of 3.2 % (Angus and Good 2004) as crops replaced, and continue to replace, pastures. The expansion has been partly within established farming regions and partly as expansion into new regions in Western Australia, Queensland and along the low-rainfall and high-rainfall boundaries of the cropping region (Kirkegaard et al. 2011). The only source of N for the first century of crop production was from mining the soil, initially through continuous cropping and then through fallow-crop sequences (Donald 1965). Soil N was replenished by biological N-fixation by legumes in improved pastures after the 1950s, triggered by a high wool price and encouraged by a federal bounty on the application of phosphate fertiliser (Henzell 2007). Soil total N is maintained when improved pastures (i.e. with a high proportion of legumes) make up about half the farm area (Angus and Peoples 2012). The area of pastures that significantly contribute to the N balance is difficult to estimate; the total area defined by ABARE (2010) as Grazing Modified Pastures is 72 M ha, but the north eastern part of this zone has relatively few legumes and a major source of N for livestock in the region is urea blocks, which represent much of the 30,000 t of N used as licks and stockfeed (Table 1). A more realistic estimate of the area of pastures that contribute to the N balance is 50 M ha at an annual rate of 60 kg N ha^{-1} (Peoples et al. 2012). This is consistent with the estimate of McDonald (1989) who found annual increments in soil N from legume based pastures ranging from 19-117 kg N ha^{-1} (average 63 kg N ha^{-1}) from 15 studies across southern Australia. Crop legumes also contribute to the N balance of dryland farms but make up only about 5% of the crop area.

Rainfall is variable in most of the dryland farming zone, particularly in the north east. Yield of dryland crops can be partly buffered from the rainfall with fallows and other moisture-retaining methods, but yield is still strongly tied to rainfall during the growing season. The variable yield potential presents a challenge for N management. Applying an average amount of N fertiliser can result in underfertilisation in some seasons and overfertilisation in others. Many graingrowers adopt a tactical approach to N management, aiming to delay application of fertiliser until the yield potential is more predicable during the stem-elongation phase. They then topdress an amount based on a simplified version of the N budget in Table 3 and aim to synchronise the times of N supply and demand. Crops and livestock are increasingly integrated on mixed farms with grazing of vegetative crops by sheep and cattle, the effect of which is greater reliance on fertiliser N rather than biologically fixed N (Virgona et al. 2006). Livestock also graze crop stubble and increase the accumulation of soil mineral N, because the consumption of high-C residues reduces N immobilisation (Hunt et al. 2016). Crops growing after canola also benefit from increased N mineralisation (Ryan et al. 2006).

Irrigation and high-rainfall farming
Most of the irrigated land lies on semi-arid plains along the inland rivers of eastern and south-eastern Australia. The yields and N input to summer-growing crops: cotton, rice, maize, wheat, dairy pastures and horticultural and viticulture crops, are high by international standards. The area of irrigation is limited by the amount of irrigation water which, during drought, is conserved for perennial crops and milking cattle. The area of annual crops and hence N-use is therefore highly variable. NUE is generally greater than for dryland crops because N-fertiliser can be washed into the root zone soon after application. Poor irrigation management leads to denitrification losses due to prolonged periods of soil saturation (Mathers et al. 2007). There are no reports of leaching below the root zone but Weaver et al. (2013) measured large accumulation of nitrate at the bottom of the cotton root zone.

High-rainfall farming land is along the south-west, south-east and east coasts where it is concentrated between the Great Dividing Range and the ocean. The largest users of N fertiliser in this zone are dairying, sugar cane and horticulture. Gourley et al. (2012) surveyed Australian dairy farms and found an average NUE of 26%, based not only on fertiliser but also on fodder imported to the farm. Bell et al. (2016) report NUE for sugar cane but no comparable data are available for horticulture. Raised beds are being increasingly employed to manage waterlogged cropping soils across southern Australia (MacEwan et al. 2010).

Nitrogen use efficiency and losses
Nitrogen use efficiency (NUE) is expressed in many ways but in this case we refer mainly to apparent above-ground recovery of fertiliser N (AARFN) because this enables comparisons to be made between species and takes some account of grain protein. There are more complete and complex assessments of NUE that consider both yield and grain protein responses to fertiliser N, and their relative profitability (Fischer et al. 1993; Angus 1995).
For irrigated crops in the semi-arid zone AARFN is over 70% for well managed cotton (Rochester and Bange 2016) and well managed medium-grain rice (Angus et al. 2016), both at yield levels on farms that are high by world standards. AARFN in dryland crops can be much lower. In a survey of 60 commercial dryland wheat crops in south-eastern Australia those that were most likely to give large N responses (mid-season topdressing, early sowing, low N status and following a break crop) the average AARFN was 36% (Angus and van Herwaarden, unpublished). However the average agronomic efficiency (the additional grain per unit of additional fertiliser N) was 13 while the N:grain price ratio was 6.0. At these prices it was profitable for farmers to apply N-fertiliser to grain crops, even with low NUE. The low NUE is consistent with the results of experiments that traced ^{15}N fertiliser applied to 57 wheat crops in Australia (Fig. 2). At maturity 44% of the fertiliser was in crops, 34% in soil and 22% was not recovered, presumably lost by one or more of the processes of denitrification, leaching and ammonia volatilisation. Losses exceeding 20% of applied N are also consistent with dairy (Stott and Gourley 2016; Rowlings at al. 2016) and sugar cane production systems (Bell 2016). Pilbeam (1996) showed that amount of fertiliser N in the soil at maturity was relatively greater in the generally dry environments in Australia than in wetter environments where more of the labelled N was present in the crop. The relatively large amount of fertiliser-N retained in the soil may include some immobilisation which represents a financial loss; the longer the delay before re-mineralisation, the greater the financial loss. Finding ways to reduce immobilisation and losses could increase NUE. For example it may be possible to minimise contact between fertiliser and immobilising and denitrifying microbes by deep banding, concentrating urea or ammonia in mid-row bands or deep bands, or by in-crop side-banding. Concentrating ammonium in bands delays nitrification and hence reduces losses by denitrification and leaching (Wetselaar et al. 1973; Angus et al. 2014). Banding promotes slow release of fertiliser N to the crop.

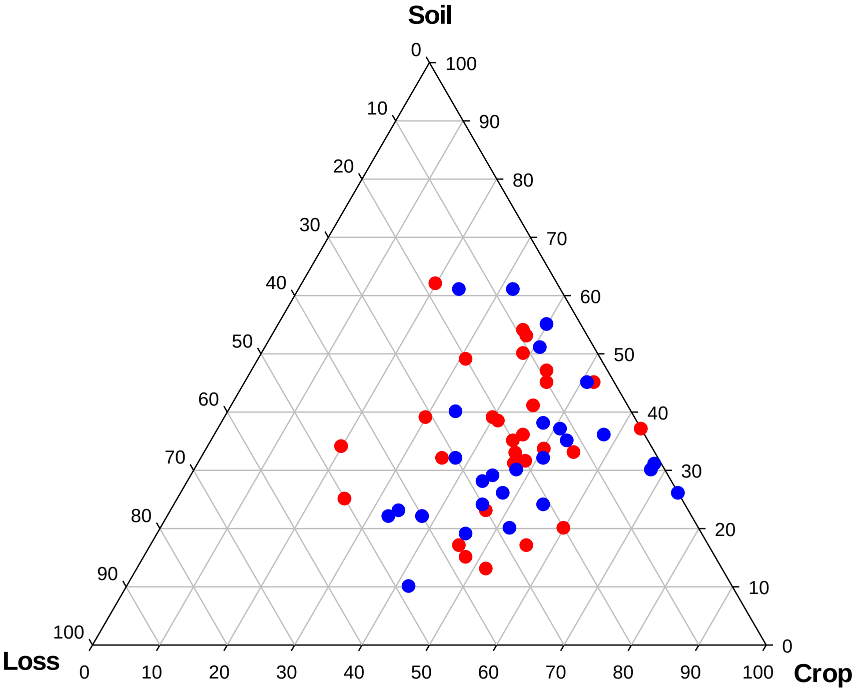

Fig. 2. Fate of ^{15}N fertiliser applied to Australian grain crops (red for duplex soils and blue for uniform clays). The ^{15}N was measured in above-ground plant parts and soil, both sampled at crop maturity. Unaccounted ^{15}N is reported as loss. The mean for all studies was 44% in crop, 34% in soil and 22% loss and there was little difference between duplex and clay soils. Data sources are Australian experiments reported by Pilbeam (1996) and Freney et al. (1992) and more recent studies by Lam et al. (2012), De Antoni et al. (2014), Bell et al. (2015), Harris et al. (2015), Schwenke and Haigh (2016) and Wallace et al. (2016).

Previous improvements in NUE of Australian dryland crops have come about mostly by increasing crop-N demand through early sowing, controlling root disease, correcting acidity and micronutrient deficiency and by increasing the yield potential by plant breeding. Increasing N demand by the crop leads to more rapid N uptake and so less exposure of the fertiliser to immobilisation and the loss pathways.

Denitrification

Studies reviewed by Chen et al. (2008) and Grace (2015) showed that loss of fertiliser N by denitrification is common in Australian crops. Since most of the fertiliser N is applied to crops and pastures during winter and spring the rate of denitrification is probably limited by temperature. Assuming that most of the N loss estimated from Fig. 2 represents denitrification, the annual N loss from the 1.59 M t of fertiliser N (Table 2) would be <0.35 M t. Less research has been conducted on losses from non-fertiliser sources of N, but the results of Pi et al. (1999) show large losses of N mineralised from organic matter in eastern Australia when the soil is warm and wet. The most widespread occurrence of warm and wet soil is during floods in summer and autumn. One extensive flood on the plains of eastern Australia in January 2011 covered 1.7 x 10^8 ha, mostly in cropping and grazing land. This area is equivalent to the combined areas of France, Germany, the Netherlands, Belgium, Denmark and Norway, and much of this land remained inundated for over a month in mid-summer. No measurements of denitrification are reported for this event, but it would be reasonable to assume that all the soil NO_3^- would be denitrified. A conservative estimate of the soil NO_3^- is 20 kg N ha^{-1} in the top 0.6 m, based on the lowest values of soil samples that pass through the commercial laboratories and from surveys in research laboratories. Assuming that this amount, the total denitrification from this one flooding event would be 2.6 M t of N. Such flooding events are infrequent but still represent a loss of N comparable with, or greater than, the loss from fertiliser. Denitrification is also significant in water bodies and Harris (2001) concluded that >75% of dissolved N could be lost through this pathway.

Ammonia and nitrogen oxide exchange with the atmosphere
Ammonia escapes to the atmosphere from soil, plants, burning biomass and animal excreta (Denmead 1990). Soils and plants can also capture NH_3 from the atmosphere. The extent of NH_3 loss from native vegetation is uncertain, but Denmead (1990) considered this pathway to be the main net source of ammonia to the atmosphere. The second largest agricultural source of atmospheric ammonia is from the urine of grazing cattle, sheep and kangaroos. The amounts are estimated following the methods of Denmead (1990) with contemporary livestock numbers, which in 2014 amounted to 300 million sheep equivalents. Ammonia loss from the extensive arid zone dominates these losses and the amounts almost balance N deposition in rainfall and may in fact represent the same material. The levels of atmospheric ammonia are relatively low over most of Australia but downwind of large cattle feedlots are comparable with those in western Europe and north eastern North America (Denmead et al. 2014), representing free fertiliser to farms but environmental damage to water bodies and native vegetation growing on poorly buffered soil.

Burning biomass releases nitrogen oxides that, like ammonia, are mostly returned to the land in rain (Galbally et al. 1992). Fires in the arid zone were traditionally started by the indigenous practice of firestick farming (Gammage 2011). This traditional practice of relatively frequent 'cool' burns protected the landscape from less frequent 'hot' wildfires, mostly started by lightning, which are now the main form of biomass burning (Burrows et al. 2006). In the dryland farming zone burning cereal stubbles is usually by 'cool' fires and certainly results in loss of N to the atmosphere. However the long-term reduction in total soil N is not significantly greater than with retained stubble, which decomposes within months or years (Angus et al. 2006). Stubble retention appears to be increasing with the adoption of trash-clearing seed drills which reduce the need for the time-consuming process of burning stubbles.

Ammonia loss to the atmosphere from dryland crops is mostly from hydrolysis of urea applied to the surface of moist alkaline soil which contains urease, typically in plant residues. In Australia the situations in which this is most likely to occur are dairy pastures (Eckard et al. 2003) or crops growing on alkaline soils or with heavy residues where >20% of fertiliser can be lost as ammonia (Turner et al. 2012). The model of Fillery and Khimashia (2016) shows that drilling urea into the soil or topdressing before rain can reduce these losses to zero. In our experience most farmers use rainfall forecasts in planning to topdress urea.

Nitrate leaching and runoff
Nitrate leaches from the topsoil into the subsoil or groundwater when there is nitrate in the soil profile and the water supply exceeds the water-holding capacity. The largest losses are on coarse-textured soil in regions and seasons when the water balance is positive for part of the year, such as in winter-rainfall regions of southern Australia and in the wet season in northern Australia. There are relatively few observations of nitrate leaching in Australia and most of those reported in Table 6 are on the wet fringe of the dryland farming region or in an intensive farming region. Anderson et al. (1998) measured up to 106 kg N ha^{-1} leached from a coarse-textured soil in a relatively high rainfall part of the dryland farming region of Western Australia. Extrapolations to other parts of the region using a simulation model suggested that the long-term mean quantity of leaching varied from zero on a loamy sand in a dry environment to 50 kg N ha^{-1} y^{-1} on a sand in a wet environment (Milroy et al. 2008).

Table 5. Australian examples of nitrate leaching below the root zone and groundwater contamination.

Location	Source of nitrate	Quantity	Reference
Nitrate leaching			
Southeast Queensland	Fallow-wheat with summer rainfall	19 kg N ha^{-1} y^{-1}	Turpin et al. (1998)
Mallee fallow-wheat sequence	Mineralised N during fallows	Accumulation >500 kg N ha^{-1}	D Roget (unpublished)
Sugar deltas and coast	Fertiliser from sugar land	30-50 kg N ha^{-1} y^{-1}	Quoted by Rasiah et al. (2003)
Western Australian crop land	Fertiliser and mineralised N	17-59 kg N ha^{-1} y^{-1}	Anderson et al. (1998)
Southern NSW	Fertiliser and mineralised N	4 kg N ha^{-1} y^{-1}	Poss et al. (1995)
Southern NSW	Annual pasture	9-15 kg N ha^{-1} y^{-1}	Ridley et al. (2001)
Southern Australia,	Pastures where annual rainfall >450 mm	15-35 kg N ha^{-1} y^{-1}	Ridley et al. (2004)
Groundwater contamination			
Southeast South Australia	Annual pasture legumes	7 mg NO_3-N L^{-1}	Dillon (1988)
Central Australia groundwater	Holocene leaching from termite mounds	<80 mg NO_3-N L^{-1}	Barnes et al. (1992)

North Queensland (1454 wells)	Sugar cane	86% of wells < 20 mg NO_3-N L^{-1}	Thorburn et al. (2003)

Along the wetter fringe of the dryland farming regions of eastern Australia winter rainfall is less intense and nitrate leaching is about half the values in Western Australia. In the examples for eastern Australia listed in Table 5 nitrate leaching could be reduced with more intensive management, for example growing perennial rather than annual pastures (Ridley et al. 2001), by earlier sowing of crops and splitting N fertiliser (Anderson et al. 1998) or by double cropping (Turpin et al. 1998). Improved management had less effect on leaching in Western Australia. Nitrate leaching is an infrequent occurrence on most dryland cropping farms in eastern Australia because the soil water-holding capacity is generally sufficient to contain the surplus of rainfall over potential evapotranspiration.

Leached nitrate and particulate N contribute to N pollution of surface water bodies. The concentration of N in most streams that drain areas of permanent pasture in Victoria exceed official guidelines (Ridley et al. 2004), and there is evidence of leaching into shallow groundwater. There are few measurements of nitrate leaching to the water table, which is normally tens of metres below the surface in the dryland farming region. High concentration of nitrate in groundwater is not of much public concern in Australia because relatively small amounts of groundwater are used for human consumption. In fact the largest areas of groundwater affected by high nitrate levels are not due to fertiliser. One is in arid central Australia due to leaching of N that had been biologically fixed by termite gut bacteria in geological time (Barnes et al. 1992). Another large area of high-nitrate groundwater, in a winter-rainfall region of South Australia, is of agricultural origin but from mineralisation of organic N derived from biological N-fixation by clover (Dillon 1988).

Offsite damage from leaching and runoff have been extensively studied in Australia. Damage to the Great Barrier Reef is the most grievous consequences of N (and P) leaching and runoff from near-coastal sugar cane fields and particulate erosion from inland grazed grassy woodlands, discussed in this conference by Bell et al. (2016). There is also N (and P) runoff into the estuaries and coastal lagoon along the southwestern, southern and eastern coastline (Harris 2001). These water bodies periodically become eutrophied by nutrients sourced from diffuse and point sources in cleared catchments. Eutrophication is not exclusively a problem of farming and there is evidence of algal blooms in rivers and lagoons before white settlement, presumably because of concentration of nutrients during drought. Harris (2001) concluded that the N and P discharge to Australian coastal waters was small compared to those in the Northern Hemisphere because of less atmospheric N deposition, lower population densities and less fertiliser use. Eutrophication in Australian coastal lagoons is normally N-limited and there are frequent N-fixing cyanobacterial blooms. It thus becomes important to minimise movement of P into the water courses. For the Gippsland Lakes Roberts et al. (2012) concluded that the most cost-effective methods to reduce contamination were by enforcing existing regulations on the large sources of P from the dairy industry.

Another serious effect of nitrate leaching is acidification of poorly buffered soil in southern Australia (Helyar and Porter 1989). In this case NO_3^- in the topsoil, mostly originating from biological N fixation by pastures, and more recently from N fertiliser, leaches into the subsoil along with alkali and alkali-earth metals, which are then replaced by protons adsorbed onto clay minerals in the topsoil. The lime needed to neutralise this acidity is an additional cost of fertiliser or fixed N that has only partly been met in dryland cropping systems and hardly at all in permanent pastures.

Conclusions

Based on budgetary approximations, the N balance of the Australian continent appears to be slightly positive, mainly because of N-fixation by legume-based pastures in the dry farming zones. In the other zones the N balance is about neutral and the stability of N in the vast arid zone buffers changes in the agricultural zones. The episodic contributions from natural N processes of redistribution in windstorms and denitrification during large floods are comparable with the N amounts in fertiliser.

In the intensive farming zone there are areas of N surplus in the sugar and dairy industries from which reactive N leaks into some coastal and near-coastal water bodies. In southern Australia, at least, the proposed solution is to enforce current regulations, particularly on manure management in the dairy industry.

The net accumulation of N in the dryland farming zone has not caused obvious environmental damage, although soil acidification, partly due to leaching of nitrate to the subsoil, is a less visible but still important problem for both the intensive and dryland farming zones. The obvious solution of applying lime is being implemented for cropping systems. More profitable animal industries will be needed to pay for liming permanent pastures. The N surplus in permanent pastures shows a need for Sustainable Intensification (Godfray al. 2014), for example by introducing more cropping.

The decreased amount of soil N in cropping areas is a consequence of mining existing soil N stocks, which has been partly offset by N-fixation by legume-based pastures grown in phased rotation with crops, and by fertiliser. The future contributions of N-fixation and fertiliser will depend on the relative profitability of cropping and animal industries based on pasture. If the current trend towards continuous cropping continues, meeting crop-N demand with fertiliser rather than mined soil N will be a challenge unless the currently low NUE is improved. New approaches to fertiliser management, combined with mid-season tactical application, are needed to improve NUE and our suggestion is to concentrate on reducing the loss from denitrification and the economic loss from immobilisation. To minimise the potential for N immobilisation and denitrification, a suggested approach is to increase the spatial separation of fertiliser from most of the microbes responsible for these processes, or temporarily inactivate them by placing N fertiliser beneath the microbe-rich topsoil or concentrating it in thin bands.

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