Benchmarking nitrous oxide emissions in deciduous tree cropping systems

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Abstract. Nitrous oxide (N_2O) emissions contribute 6% of the global warming effect and are derived from the activity of soil-based microorganisms involved in nitrification and denitrification processes. There is a paucity of greenhouse gas emissions data for Australia's horticulture industry. In this study we investigated N_2O flux from two deciduous fruit tree crops, apples and cherries, in two predominant growing regions in eastern Australia, the Huon Valley in southern Tasmania (Lucaston – apples and Lower Longley – cherries), and high altitude northern New South Wales (Orange – apples and Young – cherries). Estimated from manual chamber measurements over a 12-month period, average daily emissions were very low ranging from $0.78\,g\,N_2O\text{-}N\,ha^{-1}\,day^{-1}$ in the apple orchard at Lucaston to $1.86\,g\,N_2O\text{-}N\,ha^{-1}\,day^{-1}$ in the cherry orchard in Lower Longley. Daily emissions were up to 50% higher in summer (maximum $5.27\,g\,N_2O\text{-}N\,ha^{-1}\,day^{-1}$ at Lower Longley) than winter (maximum $2.47\,g\,N_2O\text{-}N\,ha^{-1}\,day^{-1}$ at Young) across the four trial orchards. N_2O emissions were ~40% greater in the inter-row than the tree line for each orchard. Daily flux rates were used as a loss estimate for annual emissions, which ranged from $298\,g\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$ at Lucaston to $736\,g\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$ at Lower Longley. Emissions were poorly correlated with soil temperature, volumetric water content, water filled porosity, gravimetric water content and matric potential – with inconsistent patterns between sites, within the tree line and inter-row and between seasons. Stepwise linear regression models for the Lucaston site accounted for less than 10% of the variance in N_2O emissions, for which soil temperature was the strongest predictor. N_2O emissions in deciduous tree crops were among the lowest recorded for Australian agriculture, most likely due to low rates of N fertiliser, cool temperate growing conditions and highly efficient drip irrigation systems. We recommend that optimising nutrient use efficiency with improved drainage and a reduction in soil compaction in the inter-row will facilitate further mitigation of N_2O emissions.

Additional keywords: apples, cherries, fertiliser, global warming, greenhouse gas, nitrogen.

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Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) with 310 times the global warming potential of carbon dioxide (Ramaswamy *et al.* 2001). Despite comprising only 3.0×10^{-6} % of the earth's atmosphere, N_2O contributes ~6% of the warming effect caused by increased GHG emissions (Dalal *et al.* 2003). While the Australian Greenhouse Office (AGO 2001) estimates that agriculture is the second largest contributor of GHG emissions, agriculture contributes ~78% of all N_2O emissions. Furthermore, N_2O emissions from agricultural activities are expected to increase by 50% in the near future, due to greater fertiliser demand to meet the global food production needs (US EPA 2006).

An estimated two-thirds of global N_2O emissions are derived from the activity of soil-based microorganisms involved in nitrification and denitrification processes (Prather *et al.* 1995;

Dalal *et al.* 2003). These processes and thus N_2O emissions are strongly influenced by both environmental factors, such as soil moisture, oxygen availability and soil and air temperature, as well as management practices, specifically fertiliser and irrigation use, but also inter-row weed management, soil compaction and organic matter flux due to pruning and thinning (Davidson 1992; Tiedje 1994).

Uncertainty as to the relative contribution of different agricultural sectors to N_2O emissions is in part due to scarcity of data, which is compounded by considerable variance between studies due to differences in soils, climate, and management practices (Barton *et al.* 2008; Denmead *et al.* 2010).

The horticulture sector of Australia's agriculture industries contributes approximately \$8.7 billion to the national economy and is the third largest agricultural industry (Australian Bureau of Statistics 2012). The horticultural sector is diverse and

comprises many different commodities, each requiring its own unique production system including evergreen and deciduous fruit tree production, vegetable production, nuts, table grapes, turf and cut flowers. Consequently determining the N_2O emissions from horticulture is extremely complex. Despite the economic importance of the sector, emissions data for production horticulture are almost non-existent. Within the horticultural sector, apple and cherry production is estimated to occupy 10 600 ha (George 1999) or 37% of the total area for deciduous tree fruit crops. Apples and cherries are produced from higher altitude areas of southern Queensland and central New South Wales (NSW), to inland Victoria, Adelaide hills, Perth hills and south-western Western Australia and southern Tasmania.

Deciduous trees by their nature are highly effective utilisers of nitrogen (N) as they withdraw N from their leaves before leaf senescence into storage organs (roots, trunk and branches) during winter dormancy (Millard 1996). This stored N is remobilised for the current season's growth, which for some crops can contribute up to 50% of the total N requirement for the season (Millard and Neilsen 1989). Deciduous fruit tree crops are strong sinks for N, in which a large portion of N (30–60 kg ha^{-1}) is removed on an annual basis depending on crop load (Neilsen *et al.* 1997). As developing fruit have a strong demand for N over a short growth stage, growers tend to apply high rates of fertiliser to the soil over a short period pre-harvest to meet tree demands and/or post-harvest to facilitate storage of N by trees during winter dormancy. Similarly, deciduous fruit tree crops have a significant water requirement due to high crop water content (up to 85%) and transpiration losses during the summer months. N fertiliser application for mature apple trees broadly ranges from 30 to >200 kg N ha^{-1}, while irrigation requirements range from zero in rainfed areas to 1–5 ML ha^{-1} in cold climates and 5–9 ML ha^{-1} in Mediterranean climates (APAL 2013).

Given the paucity of GHG emissions data for the horticulture sector (Huang *et al.* 2012; Rowlings *et al.* 2013) there is an ongoing need to determine the spatial and temporal variations in N_2O fluxes from typical production systems within the sector. In response this study was established to determine annual N_2O emissions from two deciduous fruit tree crops, apples and cherries, in two predominant growing regions in eastern Australia: the Huon Valley, Tasmania and high altitude northern NSW. Furthermore, we sought to improve our

understanding of the influence of environmental factors such as soil temperature, volumetric water content (VWC), water filled porosity (WFP), gravimetric water content (GWC) and matric potential (MP) on N_2O emissions in two deciduous fruit tree production systems. Results are discussed in the context of potential management strategies for mitigating N_2O emissions within the deciduous fruit tree crop industries.

Materials and methods

Trial sites

Tasmania

Two greenhouse gas monitoring sites were established in the Huon Valley, Tasmania, at Lucaston in an apple orchard, and Lower Longley in a cherry orchard. The Huon Valley has a cool temperate climate with an average daily maximum temperature of 21°C in summer and 12°C in winter. Over the study period, Lucaston and Lower Longley received a total of 801 and 806 mm of rainfall respectively (Table 1). Rainfall patterns were similar at both sites with fairly uniform monthly totals, reflected in the low standard errors over the study period, representing a typical Huon Valley rainfall scenario (Fig. 1). Soils used for orchards in the Huon Valley mostly consist of texture contrast Kurosols and Chromosols (Isbell 2002) derived from Quaternary alluvium.

The Lucaston site consisted of 12-year-old 'Royal Gala/ Galaxy' trees on M26 rootstocks. Trees were grown in mounded rows running north-west–south-east trained as a central leader and spaced at ~1 m along rows and 4 m between rows. The orchard was irrigated during October–March with inline drippers (2.3 L h^{-1}) at 500-mm spacings along the tree line. Fertiliser was applied by a spreader along the mound shoulders as calcium nitrate at an annual rate of 40 kg N ha^{-1} split into a 15 kg N ha^{-1} pre-harvest (10 October 2013) and 25 kg N ha^{-1} post-harvest (3 April 2014). The Lower Longley site consisted of 12-year-old 'Simone' trees, grown on Colt rootstocks, pruned to a Spanish bush training system with tree spacing of 2 m and row spacing of 4.5 m. Row orientation was north-west–south-east with a considerable slope down from the northern end of the row. The orchard was drip-irrigated as described above and N was fertigated as six split fortnightly 25 kg N ha^{-1} of calcium nitrate and potassium nitrate along the tree line, commencing on 25 October 2013 at an annual rate of 150 kg N ha^{-1}.

Table 1.   Site conditions of four orchards

|	Site 1 Tas. Lucaston (apples)	Site 2 Tas. Lower Longley (cherries)	Site 3 NSW Orange (apples)	Site 4 NSW Young (cherries)
Location	42.993°S, 147.057°E	42.978°S, 147.141°E	33.296°S, 148.998°E	33.449°E, 148.209°S
Height above sea level (m)	53	330	863	439
Slope	3°	10°	2°	4°
Inter-row sward	Grass	Grass	Grass	Grass
Soil texture class	Sandy loam	Sandy loam	Loam	Sandy Loam
Soil type	Dermosol	Dermosol	Ferrosol	Ferrosol
Average crop yield per annum (t ha^{-1})	75	40	50	23
Annual rainfall (mm)	801	806	913	516
Monthly average (mm ± s.e.)	66.8 ± 9.6	67.5 ± 10.1	60.5 ± 9.3	39 ± 5.7
Ratio tree line : inter-row area per hectare	0.6	0.6	0.67	1.86
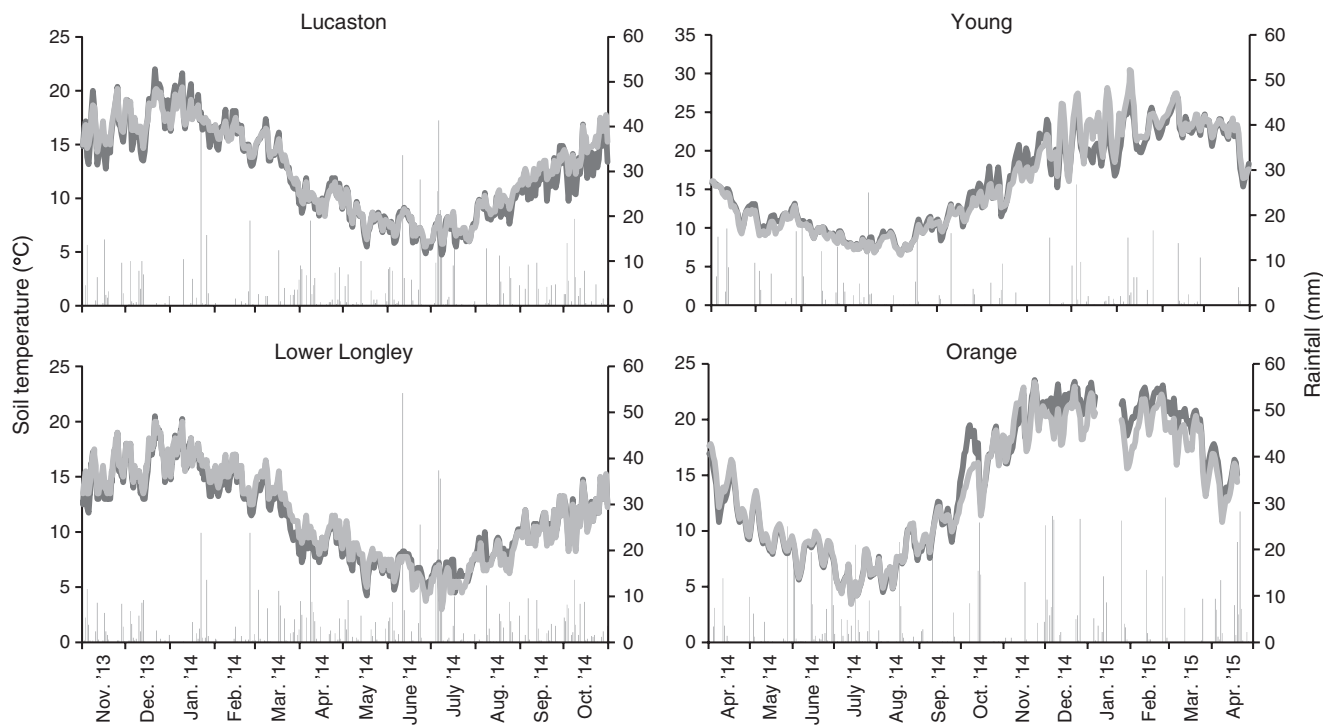
Fig. 1.   Daily rainfall and average daily soil temperature from apple and cherry orchards in Tasmania and New South Wales.

NSW

Two greenhouse gas monitoring sites were established in NSW: an apple orchard at Orange and a cherry orchard at Young. The Orange site has a continental climate with a notable difference in mean maximum temperature between summer and winter (25.7°C and 10.6°C respectively). Rainfall in the region is generally uniform across the year, averaging 859 mm. The climate at the Young site is classified as cool temperate with uniform precipitation across the year, averaging 591 mm. The annual maximum mean temperature (1991–2015) is 30.1°C in summer and 13.2°C in winter. Over the study period, the orchards at Orange and Young received total rainfall of 913 and 516 mm respectively with uniform monthly totals reflected in low standard errors between the monthly averages (Table 1).

The Orange site consisted of 8-year-old 'Pink Lady' or 'Sundowner' apple cultivars on M106 rootstocks, planted in double rows (1.5 m), spaced at 2.1 m along rows and 6 m between rows. The orchard was irrigated with under tree drip irrigation from November to May (harvest). The N fertiliser was applied via three fertigation events (1 February 2014, 10 February 2015 and 28 February 2015). At each fertigation, 4.75 kg N ha^{-1} was applied as potassium nitrate and mono ammonium phosphate along the tree line, resulting in annual rate of 14.3 kg N ha^{-1}. The Young site consisted of 10-year-old 'Van' or 'Lapins' cherry cultivars on Mahaleb rootstocks planted in single rows, spaced at 4.65 m apart and 6 m between rows. The orchard was irrigated by under tree micro-sprinklers from October to December (harvest). A total of 58.5 kg N ha^{-1} of N fertiliser was applied during the 2014–15 sample period. This was applied by hand as 21.7 kg N ha^{-1} of ammonium nitrate to

the tree row on the 8 August 2014, by fertigation as 9.2 kg N ha^{-1} of urea and calcium nitrate on the 15 October 2014 or as a post-harvest foliar spray at 27.6 kg N ha^{-1} on the 12 April 2015.

At all trial sites, herbicides were used to keep the tree line free of weeds. Pests and diseases were managed by the grower in accordance with commercial practices.

Soil N$_2$O emissions

N$_2$O emissions were measured using static non-flow through chambers, comprising a mounting collar and a detachable chamber. At the two Tasmanian field sites, chambers were ~9 L (240 mm diameter × 200 mm in height) with 0.046 m^2 surface area. Chambers were lined with Mylar to reflect UV and fitted with air-stones for passive pressure compensation to minimise the influence of heating from solar insulation. Collars were inserted 100 mm into the soil and remained in place throughout the trial. The collars each had three rows of 3.6-mm holes to allow for root penetration, and projected 50 mm above the soil surface. At Lucaston, eight static chambers were installed in October 2013, four in the tree line and four in the inter-row of the orchard. At Lower Longley, six chambers were installed, three in the tree line and three in the inter-row. At both sites, where chambers were installed in the tree line, 16-mm holes were drilled (then sealed) into the collar sidewall to allow the dripper irrigation line to pass through the collar. Each chamber top was fitted with an iButton (Maxim) temperature sensor that logged air temperature inside the chamber at 5-min intervals. For both sites, N$_2$O was sampled weekly during the peak growing season (November–April) and once monthly during the winter period (May–August). More frequent (every second day) sampling events coincided with fertiliser

application in November and March and a large rainfall event in July 2014. During collection events, the chamber top was secured to the collar with clips and a rubber O-ring to prevent air movement. The atmosphere in each chamber was sampled sequentially over a one-hour period at 0, 30 and 60 min intervals, starting at ~10 a.m. to represent the average daily temperature. Samples were extracted through a butyl rubber septa located centrally on the chamber top using a 25-mL glass gas-tight syringe (SGE, 25MDR-LL-GT,Melbourne Australia); the sample was then injected into a 12-mL Exetainer (Labco, High Wycombe, Buckinghamshire, UK) to ~2 atm.

At the two NSW field sites, the static non-flow through chambers were slightly smaller than those used in Tasmania (diameter 243 mm, height 205 mm and installed volume of 7.3 L) but otherwise the same. At each of the NSW sites, eight collars were installed in the tree line and eight randomly located in the inter-rows. Sampling was conducted every two weeks, and more frequently during the growing season (October–March). Chamber air samples were collected from the static chambers at 0, 30 and 45 min after lids were sealed using a 25-mL gas-tight syringe (SGE, 25MDR-LL-GT), and introduced into pre-evacuated 12-mL Exetainer (Labco) vials with grey silicon septa. Chamber temperature was measured during sampling using a TP3001 digital thermometer.

Gas analysis

Samples were analysed on an Agilent 7890A gas chromatograph fitted with a Gilson (GX 271) auto sampler. The system had two channels leading to μ-ECD and FID detectors. N$_2$O was analysed by μ-ECD. The sample was loaded onto a 1000-mL sample loop, and then injected onto a 1-m Porapak Q pre-column. Gases were then passed onto a 2-m Porapak Q column for further separation. The pre-column was back-flushed to remove moisture after the analytes had passed onto the analytical column. Relative standard deviation (based on seven replicate injections) for N$_2$O was <2%. For each batch of samples, a range of standards, controls and blanks were included for quality control purposes (van Zwieten *et al.* 2010).

Soil properties

At all sites, soil temperature was measured at 10 cm depth every hour using iButtons (DS1920, Maxim, San Jose, USA) temperature logger. In the Tasmanian sites, soil moisture probes (Decagon,10HS, Pullman, USA) were installed at 5–10 cm below the soil surface to record VWC (cm^3 cm^{-3}) at hourly intervals in the inter-row and tree line under the irrigation dripper in two locations at Lucaston and one location at Lower Longley. In the NSW sites, VWC was measured in the tree line at 10, 20, 30 and 50 cm depth using a continuously logging capacitance soil moisture probe (EnviroSCAN, Sentek Sensor Technologies, Stepney, Australia).

In the Tasmanian field sites, soil was sampled along the tree line and inter-row of three experimental rows at three locations in November 2013 and July 2014. Soil samples were taken from 0–10 cm depth adjacent to the drippers in the tree line and next to the installed gas chambers in the inter-row. Samples were collected by 'pogo stick' in which four plugs were collected ~20 cm apart and mixed from which a representative subsample was obtained. Soil subsamples were air-dried, then gently disaggregated in a mortar and pestle and sieved to <2 mm. The NO$_3^-$ content was determined by placing 8 g of dried soil in a 50-mL centrifuge tube which was extracted in 40 mL of 2 M potassium chloride over 18 h. The tubes were centrifuged at 12.6 *g* for 10 min and a 10-mL subsample was filtered through a 0.45-μm syringe filter. The NO$_3^-$ analysis was performed on a Westco Smartchem 200 discrete analyser, following the US EPA Method 353.2 (US EPA 1993).

For all sites, total N (%) and total carbon (C, %) were also determined from a fine-ground sample (Retsch MM200 ball mill, Dusseldorf, Germany) of 20–30 mg using an oxidative combustion analyser (Perkin Elmer CHN-S 2400, Waltham, USA) (Table 2). Soil bulk density of the A1 horizon was determined at all sites using three 60 mm × 61 mm cores following Cresswell and Hamilton (2002). GWC was determined by drying the entire core at 105°C for 24 h. Total porosity (TP) and WFP were calculated from bulk density, assuming a particle density of 2.65 g cm^{-3} and 98% saturation (Table 2). At the two Tasmanian sites, infiltration was measured in triplicate using a 20 mm diameter, single ring, constant head, infiltrometer in both the tree line and inter-row areas. The infiltration ring was inserted 3 cm and sealed on the outside with compacted soil slurry, water was maintained at head of 0.5–1.5 cm (variation due to surface elevation) for ~20–40 min to ensure establishment of steady-state conditions. Saturated hydraulic conductivity and sorptivity were estimated (Reynolds and Elrick 1990; Reynolds 2008) in which α (macroscopic capillary length equivalent to the wetting front suction) was estimated to be 0.12 (Table 1). At Lucaston, MP was calculated from the van Genuchten–Mualem equation (Mualem 1976; van Genuchten 1980). The soil water retention and conductivity parameters as input for the equation were determined using the extended HYPROP evaporative flux approach (Peters and Durner 2008). In the Tasmanian sites, a subsample of soil from each chamber location was sent to AgVita Analytical (Devonport, Tasmania) for labile C analysis using the permanganate method based on Weil *et al.* (2003). Potential N mineralisation was performed following the anaerobic incubation method of Curtin and Campbell (2008).

Data analysis

The flux rate, F$_{N2O}$, was calculated using Eqns 1 and 2 (Scheer *et al.* 2014). All N$_2$O flux rates were corrected for the actual air temperature during the measurement and recorded as μg N$_2$O-N m^2 h^{-1}:

$$F_{N_2O} = \frac{b \times V_{CH} \times MW_{N_2O\text{-}N} \times 60 \times 10^6}{A_{CH} \times MV_{corr} \times 10^9} \quad (1)$$

where A$_{CH}$ is basal area of the measuring chamber (m^2), *b* is increase in concentration (ppb min^{-1}), MW$_{N_2O}$-N is molecular weight of N$_2$O-N (28 g mol^{-1}), MV$_{corr}$ is temperature-corrected molecular volume (m^3 mol^{-1}) and V$_{CH}$ is volume of the measuring chamber (m^3)

$$MV_{corr} = 0.02241 \times \left(\frac{273.15 + T}{273.15}\right) \quad (2)$$

where MV$_{corr}$ is defined above, *T* is air temperature during the measurement (°C) and 0.02241 m^3 is the molar volume

Table 2. Soil physical characteristics from the four trial orchards
–, Denotes missing data

		Lucaston (apples)	Lower Longley (cherries)	Orange (apples)	Young (cherries)
Bulk density (g cm^{-3})	Tree line	1.21	1.03	1.42	1.48
	Inter-row	1.32	1.18	1.53	1.49
Field infiltration rate (cm h^{-1})	Tree line	13.77	11.66	–	–
	Inter-row	0.49	1.19	–	–
pH	Tree line	6.27	6.4	6.7	4.6
	Inter-row	6.37	6.5	6.6	5.8
Total N (%)	Tree line	0.26	0.23	0.14	0.11
	Inter-row	0.17	0.28	0.13	0.13
Nitrate (mg kg^{-1})	Tree line	5.44	4.3	6.9	6.5
	Inter-row	2.53	3.1	5.7	5.7
Total organic C (%)	Tree line	4.31	3.31	1.6	1.3
	Inter-row	2.33	4.14	1.4	1.6
C : N ratio, soil	Tree line	16.6	14.4	11.3	12.1
	Inter-row	13.7	14.8	11	11.8
Labile C (ppm)	Tree line	400	345	–	–
	Inter-row	442	394	–	–
Mineralisation rate (μg N g soil^{-1} day^{-1})	Tree line	0.76	–	–	–
	Inter-row	3.45	–	–	–

of an ideal gas at 1 atm and 273.15K (Aylward and Findlay 1974).

A linear regression (r) was computed using the Pearson's correlation coefficient to determine the quality of the slope relationship and flux rates were discarded if $r < 0.8$. Daily N$_2$O fluxes from each site were calculated by averaging hourly flux from each replicate and multiplying the data by 24. Cumulative seasonal fluxes for each site were calculated by integrating daily N$_2$O fluxes via linear interpolation over the study period.

Associations among N$_2$O emissions and soil environmental variables (soil temperature, VWC, WFP, GWC and MP) were assessed using Pearson's correlation in SPSS Version 22. Correlations were performed for each site, sampling location within site (tree line and inter-row) and for each season using the combined dataset from all sites. A multiple linear regression using a stepwise approach was used to develop a model to predict N$_2$O emissions from soil environmental variables using SPSS. This was undertaken in SPSS using the dataset from Lucaston, as this was the only site where data from all soil environmental variables were complete over the study period.

Auxiliary measurements

Emission factors were calculated uncorrected for background emission over the 12 months and expressed as the percentage of the total fertiliser N applied that was emitted as N$_2$O-N. The emissions intensity of each treatment was calculated as the ratio of N$_2$O emissions in relation to crop yield and relates to how much N$_2$O was emitted per tonne of fruit harvested. Direct N$_2$O emissions were converted to carbon dioxide equivalents (CO$_2$eq) within a 100-year horizon by multiplying by a radiative forcing potential equivalent to CO$_2$ of 310 (IPCC

2001). Yield-scaled emissions for this perennial system (CO$_2$eq Mg^{-1}) were calculated by dividing annual N$_2$O emissions (CO$_2$eq ha^{-1} year^{-1}) for the annual production cycle by total apple or cherry yield (Mg ha^{-1}). In each orchard, fruit yield was measured at harvest using Millennium Mechatronics pallet scales or by harvesting a random sample of whole trees and multiplying yield by orchard tree number.

Results

Site conditions

Average daily soil temperature ranged from 4°C in winter to 21°C in summer in the Tasmanian orchards and 5 to 26°C in the NSW orchards (Fig. 1). In Tasmania, daily soil temperature was consistently >13°C from early November to mid-April; whereas in NSW, daily soil temperature was >13°C between late September to mid-April (Fig. 1).

At Lucaston and Lower Longley, a substantially higher infiltration rate was observed in the tree line (13.77 and 11.66 cm h^{-1} respectively) than the inter-row (0.49 and 1.19 cm h^{-1} respectively) most likely due to mounding of the sandy loam topsoil at both sites for drainage purposes (Table 2). This was also reflected in an increased bulk density of the inter-row (1.32 and 1.18 g cm^{-3} respectively) at both sites compared with the tree line (1.21 and 1.03 g cm^{-3} respectively). Consequently, WFP was consistently higher along the inter-row than the tree line but never exceeded 80% or dropped below 40% over the study period (data not shown). Due to logger failure, only 60 days of soil moisture data was recorded at Lower Longley, where a similar trend was found for the period recorded. At Orange, bulk density of the inter-row was 1.53 g cm^{-3} and was higher than the tree line (1.42 g cm^{-3});

however, at Young, bulk density of the inter-row (1.49 g cm^{-3}) was almost identical to the tree line (1.48 g cm^{-3}). Considerable variation in WFP was measured at the wetter Orange site, ranging from 15% in summer to 85% during winter. At Young, WFP ranged from 15% in summer to 65% in winter (data not shown).

Soil NO$_3^-$ levels measured in November 2014 at Lucaston and Lower Longley were higher along the tree line (5.44 and 4.3 mg kg^{-1} respectively) than in the inter-row (2.53 and 4.14 mg kg^{-1} respectively). There was a similar trend for row and inter-row NO$_3^-$ levels at Orange (6.9 and 5.7 mg kg^{-1} respectively) and Young (6.5 and 5.7 mg kg^{-1} respectively) (Table 1). Total N (%), total organic C (%) and the C : N ratio were substantially higher in the Tasmanian than the NSW orchards. At Lucaston and Lower Longley respectively, labile C was substantially higher in the inter-row (442.3 and 394.3 ppm) than the tree line (400 and 344.7 ppm).

Temporal and spatial variability of N$_2$O emissions

Mean daily N$_2$O emissions over the 12-month period were very low, ranging from 0.78 g N$_2$O-N ha^{-1} day^{-1} in the apple orchard at Lucaston to 1.86 g N$_2$O-N ha^{-1} day^{-1} at the cherry orchard in Lower Longley. Mean daily N$_2$O emissions from the tree line were low (<1.31 g N$_2$O-N ha^{-1} day^{-1}) but similar across all orchards (Table 3). Mean daily emissions from the inter-row were consistently higher for each orchard but did not exceed 2.44 g N$_2$O-N ha^{-1} day^{-1}. The highest daily flux recorded (irrespective of sampling location) was 13.86 g N$_2$O-N ha^{-1} day^{-1} in the cherry orchard at Lower Longley, whereas the lowest daily flux of 0.09 g N$_2$O-N ha^{-1} day^{-1} was in the apple orchard at Lucaston. Mean daily emissions within seasons

followed a similar trend of higher inter-row emissions than the tree line with few exceptions (Fig. 2). N$_2$O emissions were almost double in summer compared with other seasons for all orchards, with the exception of the cherry orchard at Young. Greatest variation in N$_2$O emissions within orchards was also observed in summer with daily inter-row fluxes twice that of the tree line at each site. N$_2$O emissions during winter (<0.9 g N$_2$O-N ha^{-1} day^{-1}) were consistently the lowest recorded for the Tasmanian orchards. In NSW, N$_2$O emissions were lowest (<0.91 g N$_2$O-N ha^{-1} day^{-1}) during autumn for Orange and summer for Young.

Cumulative emissions reached 890 g N$_2$O-N ha^{-1} year^{-1} in the inter-row at Lower Longley but were as low as 230 g N$_2$O-N ha^{-1} year^{-1} in the tree line at Lucaston (Table 3). The substantial spatial variation in daily N$_2$O fluxes within the tree line and inter-row static chamber replicates were reflected in the high standard errors. When added and corrected for the actual area within the orchard that the tree line and inter-row occupied, maximum cumulative emissions (736 g N$_2$O-N ha^{-1} year^{-1}) were recorded at Lower Longley with the least (298 g N$_2$O-N ha^{-1} year^{-1}) for Lucaston (Fig. 3).

Associations between daily N$_2$O fluxes and soil environmental variables for each orchard, sampling location and season are described in Table 4. Soil temperature showed a weak positive but significant correlation with N$_2$O emissions for all sites, with the exception of a negative correlation for Young ($r = -0.157$). Overall, N$_2$O emissions were negatively correlated with summer soil temperatures ($r = -0.211$). Indeed, at all sites, daily N$_2$O fluxes >5 g N$_2$O-N ha^{-1} day^{-1} were only observed for soil temperature >13°C. There were relatively weak, contrasting associations between soil temperature and N$_2$O emissions between the tree line and inter-row for all sites

Table 3. Mean for each season, minimum and maximum mean daily N$_2$O emissions (g N$_2$O-N ha^{-1} day^{-1}) and estimated cumulative yearly N$_2$O emissions (g N$_2$O-N ha^{-1} year^{-1}) from the manual chambers installed in apple and cherry orchards
Errors represent s.e.

		Lucaston (apples)	Lower Longley (cherries)	Orange (apples)	Young (cherries)
Mean		0.78 ± 0.30	1.86 ± 0.69	1.68 ± 0.24	1.55 ± 0.43
	Tree line	0.63 ± 0.09	1.31 ± 0.46	1.26 ± 0.21	1.23 ± 0.32
	Inter-row	0.93 ± 0.51	2.44 ± 0.93	2.10 ± 0.26	1.88 ± 0.54
Minimum	Tree line	0.14	0.41	0.52	0.2
	Inter-row	0.09	0.15	0.32	0.25
Maximum	Tree line	3.8	5.19	3.53	6.02
	Inter-row	5.53	13.86	5.72	5.33
Winter	Tree line	0.23 ± 0.04	0.76 ± 0.23	1.3 ± 0.19	1.45 ± 0.25
	Inter-row	0.17 ± 0.07	0.86 ± 0.32	1.22 ± 0.12	2.47 ± 0.4
Spring	Tree line	1.11 ± 0.04	1.08 ± 0.31	1.3 ± 0.13	1.29 ± 0.16
	Inter-row	1.08 ± 0.57	1.04 ± 0.26	2.91 ± 0.13	0.91 ± 0.13
Summer	Tree line	0.74 ± 0.13	2 ± 0.6	1.63 ± 0.35	0.56 ± 0.06
	Inter-row	2.02 ± 1.27	5.27 ± 2.12	3.43 ± 0.53	1.23 ± 0.23
Autumn	Tree line	0.44 ± 0.16	1.41 ± 0.71	0.79 ± 0.16	1.6 ± 0.83
	Inter-row	0.44 ± 0.14	2.59 ± 1.03	0.84 ± 0.27	2.91 ± 1.4
Cumulative	Tree line	230 ± 34	479 ± 169	468 ± 38	438 ± 22
	Inter-row	339 ± 187	891 ± 340	656 ± 102	619 ± 56
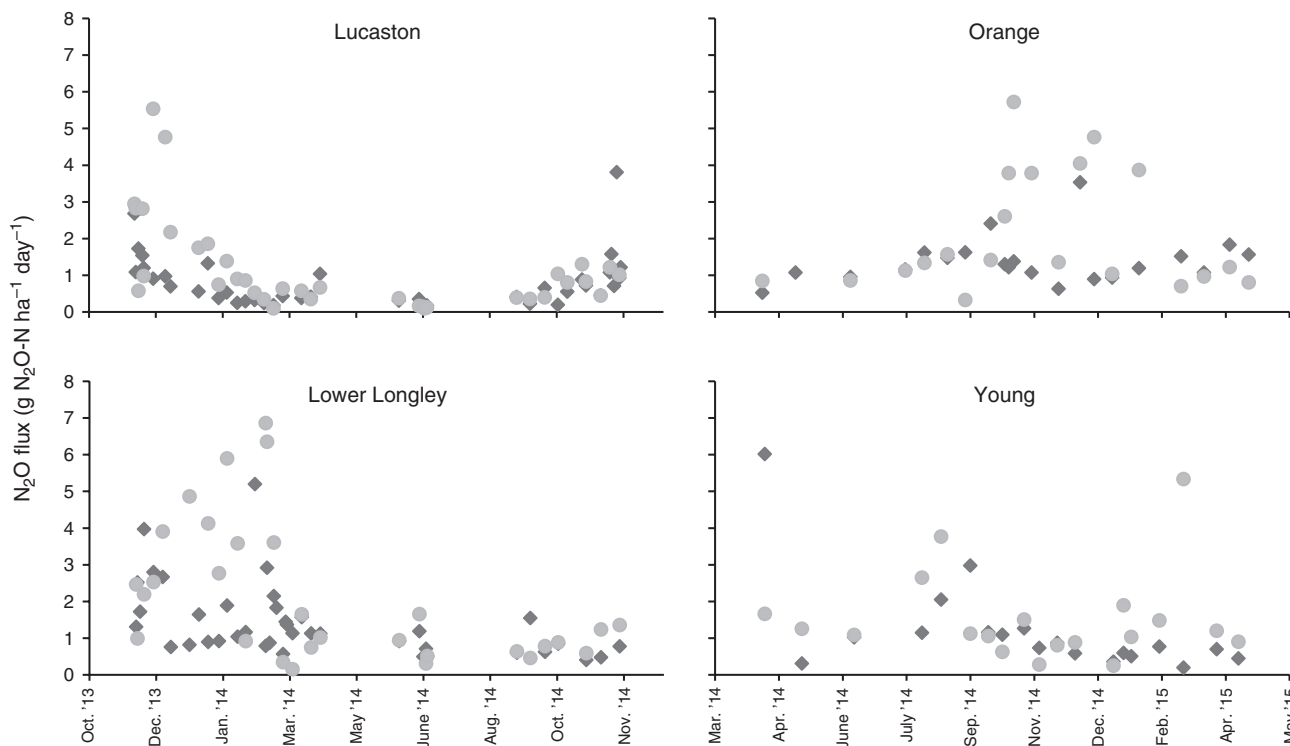
Fig. 2. Average daily N_2O ($g\,N_2O\,ha^{-1}\,day^{-1}$) emissions from apple and cherry orchards in Tasmania and New South Wales.
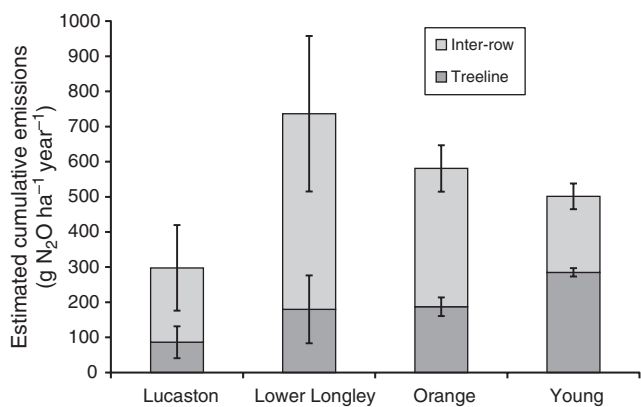
Fig. 3. Cumulative N_2O ($g\,N_2O\,ha^{-1}\,year^{-1}$) emissions from apple and cherry orchards in Tasmania and New South Wales.

with the exception of Lower Longley. N_2O emissions decreased as VWC and WFP increased at all sites, except Young in the tree line with an opposite effect ($r = 0.372$). The strongest association between N_2O emissions and WFP was during winter ($r = -0.506$), which matched the trends found within sites. N_2O emissions were consistently associated with decreasing GWC at all sites and within the tree line and inter-row. The strongest association was again in winter ($r = -0.743$), largely driven by data for Young. A very weak positive yet significant association between N_2O emissions and MP was found in the Lucaston tree line ($r = 0.159$).

The model produced from the stepwise regression analysis (Table 5), accounted for only 9% of the variability in the measured data driven by soil temperature (partial $r^2 = 0.072$) and WFP (partial $r^2 = 0.021$). Splitting the data into sampling location within the orchard improved the predictive capacity of the regression model to 24.5% for the tree line but reduced it to 3.7% for the inter-row, driven largely by soil temperature.

Discussion

Temporal and spatial variability of N_2O emissions

Average daily N_2O emissions averaged across the four orchards representing a temperate deciduous tree cropping system was $1.47\,g\,N_2O\text{-N}\,ha^{-1}\,day^{-1}$. Considerable variability in N_2O emissions was found between sites, within orchards and treatment replicates and between seasons, reflected in the high standard errors of the means (Table 3). The magnitude of the maximum daily values more closely followed N_2O emissions from Australian rainforests (Rowlings *et al.* 2012) than perennial tree crops receiving N fertiliser and irrigation (Pang *et al.* 2009; Rowlings *et al.* 2013; Xia *et al.* 2014; Ge *et al.* 2015). Pang *et al.* (2009) reported an average of $9.35\,g\,N_2O\text{-}N\,ha^{-1}\,day^{-1}$ and Ge *et al.* (2015) reported an average of a much higher $36\,g\,N_2O\text{-N}\,ha^{-1}\,day^{-1}$ for apple orchards in China – both were orders of magnitude above the average reported here. In another study of horticulture crops from sub-tropical soils, Huang *et al.* (2012) reported average daily N_2O emissions of 4.6, 5.9 and $3.3\,g\,N_2O\text{-N}\,ha^{-1}\,day^{-1}$ for mango, custard apple and pineapple respectively.

Table 4. Associations between daily soil environmental conditions: soil temperature, volumetric water content (VWC), water filled porosity (WFP), gravimetric water content (GWC) and matric potential (MP), with N₂O emission rates measured using manual chambers from apple and cherry orchard soils over a 12-month period

Significance ($P < 0.05$ and $P < 0.01$) estimates are indicated by * and ** respectively; –, denotes missing data

	Soil temperature	VWC	WFP	GWC	MP
Site					
Lucaston	0.103*	–0.169**	–0.159**	–0.169**	0.03
Tree line	0.260**	–0.250**	–0.210**	–0.207**	–0.159*
Inter-row	0.11	–0.11	–0.11	–0.13	–0.02
Lower Longley	0.294**	–0.378*	–0.385*	–00.32	–
Tree line	0.229*	–0.39	0.20	–0.39	–
Inter-row	0.354**	–0.36	–0.42	–0.36	–
Orange	0.162*	–0.08	–0.01	–0.05	–
Tree line	–0.05	–0.07	–0.01	–0.27	–
Inter-row	0.249*	0.01	–	–0.26	–
Young	–0.157*	0.354**	0.362**	–0.55	–
Tree line	–0.348**	0.372**	0.362**	–0.83	–
Inter-row	–0.03	–0.83	–	–0.84	–
Season					
Autumn	0.03	–0.02	0.09	–0.02	0.15
Winter	–0.17	–0.506**	0.05	–0.743**	0.20
Spring	0.09	–0.02	0.07	–0.173*	0.14
Summer	–0.211**	0.07	0.06	0.01	–0.10

Table 5. Multiple regression analysis using a stepwise approach of the soil environmental variables on N₂O (g N₂O ha⁻¹ day⁻¹) emissions from four deciduous fruit tree crop orchards

WFP, water-filled porosity; VWC, volumetric water content

	Parameter estimate	Standard error	F-value	P-value	Partial r^2	r^2
Lucaston ($n = 334$)						
Intercept	–0.408	0.169	17.042	0.016		0.093
Soil temperature	0.022	0.005		0.000	0.072	
WFP	–0.548	0.233		0.019	0.021	
Tree line ($n = 190$)						
Intercept	0.587	0.266	20.173	0.029		0.245
VWC	–1.862	0.910		0.042	0.102	
Soil temperature	0.020	0.005		0.000	0.091	
WFP	–1.048	0.495		0.035	0.052	
Inter-row ($n = 144$)						
Intercept	–0.714	0.173	5.419	0.000		0.037
Soil temperature	0.021	0.009		0.021	0.037	

The maximum daily flux from any of the four sites was 13.9 g N₂O-N ha⁻¹ day⁻¹, which occurred in the inter-row where no N fertiliser or irrigation was applied. For all sites the maximum daily flux of the tree line, where N fertiliser and irrigation was applied, was in the range of 3.8–6.0 g N₂O-N ha⁻¹ day⁻¹ (Table 3).The absence of large N₂O emission pulses in this study is not considered to be an artefact of the sampling systems. While it is possible that static chamber sampling can miss pulse events, the frequency of sampling and reactive sampling around specific events (such as increased sampling in the spring and summer months following fertiliser application) in this study should have captured pulse events if they occurred. Furthermore, under the same sampling conditions, N₂O pulses exceeding 20 g N₂O-N ha⁻¹ day⁻¹ were observed in a companion study (N. Swarts unpubl. data) related to high fertiliser applications carried out by our research team. Therefore, we consider that the reported values for N₂O emissions from the four orchards of this study accurately reflected the processes occurring in this land-use.

The estimated annual soil N₂O emissions from four commercial perennial tree crop orchards in temperate south-east Australia varied within 0.30–0.74 kg N₂O-N ha⁻¹ year⁻¹ (Fig. 3). These values represent very low annual N₂O emissions compared with other cropping systems (Scheer *et al.* 2012, 2013; Shi *et al.* 2013; De Antoni Migliorati *et al.* 2014). In contrast, N₂O emissions from apple orchards were reported as 3.22–44.30 kg N₂O-N ha⁻¹ year⁻¹ in China (Pang *et al.* 2009; Xia *et al.* 2014). Furthermore, the results from this study are at the low end reported for grapes (0.56–3.92 kg N₂O-N ha⁻¹ year⁻¹; Garland *et al.* 2014), and similar to those reported for almonds (0.53–0.80 kg N₂O-N ha⁻¹ year⁻¹; Schellenberg *et al.* 2012).

Given the limitations of integrated scaling from manual chamber sampling (Smith and Dobbie 2001) as recognised above, this study suggests that Australian tree orchard systems are making relatively minor contributions to overall GHG emissions of the country; however, testing over multiple seasons and in a variety of orchard systems is required to further validate this finding. We propose that the low emissions found in this study were due to judicious management of irrigation and N fertiliser application through tree line drippers with regimes well suited to the local soils and tree uptake requirements.

The four commercial orchards, on which this study focussed, used frequent low-intensity irrigation via under tree drip or micro-sprinkler systems with fertiliser applied as multiple split applications. In this study, the VWC of the soil rarely exceeded field capacity as determined by the van Genuchten retention function at $\Psi = -10$ kPa, suggesting that the upper soil layers in the tree line would have remained aerobic for all but very short periods. Thus the irrigation management used across the four sites, which was based on objective soil water measures, would have minimised anaerobic soil conditions. This reduces the likelihood of denitrification being a major pathway for N₂O emissions (Russow *et al.* 2000; Rashti *et al.* 2015). Instead, it is likely that nitrification is the main pathway for N₂O emissions as oxygen availability is generally not limiting for the soil microorganisms when WFP is below 60–70% (Bollmann and Conrad 1998). This has additional significance in this study as 50–100% of the applied N was as NO₃⁻ (Table 1) and was not susceptible to loss via the nitrification pathway.

Across the four sites in this study, the rate of N fertiliser application was not a strong determinant of annual N₂O emissions. For example, the NSW apple orchard received only 10% of the N fertiliser (15 kg N ha⁻¹) applied to the Tasmania cherry orchard (150 kg N ha⁻¹) but the N₂O emissions (552 g N₂O-N ha⁻¹ year⁻¹) were 75% of those from the Tasmania cherry orchard (736 g N₂O-N ha⁻¹ year⁻¹). The use

of multiple split N-fertiliser applications would have more closely matched the N requirement of the trees during the growing season (Tagliavini *et al*. 1996). The lack of correlation between the rate of N fertiliser application and the magnitude of subsequent N_2O emissions in perennial crops was highlighted by Rowlings *et al*. (2013). The rate of N fertiliser clearly increases the risk of N_2O emissions, but the actual emissions are more closely associated with soil environmental conditions than the quantity of fertiliser.

N_2O emissions are biologically driven (Dalal *et al*. 2003) and it was expected that relatively low soil temperatures (<14°C for half the year) experienced at all four sites (i.e. temperate climate) and consistently distributed rainfall between seasons were likely to have played an important role in reducing N_2O production. Soil temperature, well known to be a major determinant of emissions timing and intensity and consequently, was significantly (although weakly) associated with N_2O emissions over the study period. Increased emissions were observed as expected, when soil temperatures were higher in three sites, with the exception of Young. At these three sites, the cherry crop at Lower Longley and the apple crops at Orange and Lucaston were not harvested until mid-February and late March respectively. This required considerable irrigation inputs that maintained relatively moist conditions in the orchard. In contrast, the cherry orchard at Young was harvested in late November and irrigation ceased completely at this time to conserve the limited water resource in the region. Although soil temperatures were the highest in Young in summer, soil moisture (VWC) was lowest, substantially limiting capacity for N_2O production.

Spatial variation in N_2O emissions is attributed to soil aeration as governed by gas diffusion (van der Weerden *et al*. 2012). This parameter is difficult to measure and so WFP is used as a proxy in field studies investigating N_2O emissions (Pang *et al*. 2009; Rowlings *et al*. 2012); however, gas diffusion in soils depends on the relative volumetric fractions of water and air. Furthermore, volumes of air and water in soil at given values of WFP will be influenced by the bulk density of the soil (Castellano *et al*. 2010). As such, Farquharson and Baldock (2008) proposed that VWC is more appropriate for estimating the spatial and temporal variability of N_2O emissions for different soils, and further supported by van der Weerden *et al*. (2012). In our study, relationships between VWC and WFP and N_2O emissions were consistently weak but almost identical for each site, sampling location and season with the exception of winter, when VWC was more strongly correlated. This was not surprising, as the TP and bulk density used to calculate WFPS from VWC were similar between the tree line and inter-row for each site. VWC and WFP for the Lower Longley, Lucaston and the inter-row at Young showed an atypical significant negative (weak) influence on N_2O emissions. Elevated emissions are linked to WFP > 60% (Chantigny *et al*. 1998; Helgason *et al*. 2005) and VWC > 0.55 cm³ cm⁻³ (van der Weerden *et al*. 2012), conditions rarely seen in the orchards during the study period. For these sites, during winter when WFP and VWC were highest, soil temperatures were extremely low and accounted for the negative correlation observed and the moderately negative correlation between VWC and N_2O emissions in winter ($r = -0.506$). In stark contrast to this was the moderate

positive correlation of VWC ($r = 0.372$) and WFP ($r = 0.362$) with N_2O emissions in the tree line at Young, most likely due to the early application of fertiliser and generally warmer soil temperatures of the site during the winter–spring periods.

Low N_2O emission rates were observed between late autumn through to early spring irrespective of the WFP and VWC (Table 4.). We attribute these emissions to the low soil temperatures which were in the range (on average) of $13-18$°C over the four sites during the study period. Across the four sites, N_2O emissions classified as moderate (10–100 g N_2O-N ha⁻¹ day⁻¹) from European cool temperate soils (Conen *et al*. 2000) or 16–160 g N_2O-N ha⁻¹ day⁻¹ from Australian tropical soils (Wang and Dalal 2010) were only observed for soil temperatures >14°C. However, as observed with other studies, single parameter correlations of soil environmental variables, while significant, only explained a small amount of the variation in N_2O emissions due to the preconditions required before N_2O emissions were observed (e.g. Ding *et al*. 2007; Schellenberg *et al*. 2012). Indeed, in this study, no consistent pattern emerged in the relationship between daily N_2O flux and soil temperature and soil water measurements either in the tree line or inter-row, between seasons or sites. This may be due in part to the overall very low emissions captured during the course of the study period, the high spatial and temporal variability within the dataset and that there were multiple interacting factors in this complex biogeochemical process. The stepwise regression analysis captured <10% of the total variability of the Lucaston dataset. Splitting the analysis between the tree line and inter-row improved the predictive capacity up to 24% for the tree line but reduced it to <4% for the inter-row. Soil temperature was a significant key predictor in all three models; however, partial coefficients were still very weak with $r^2 < 0.072$. The VWC was the best predictor in the tree line regression model, most likely due to the influence of irrigation via dripper lines over the apple growing season.

Tree line v. inter-row emissions

The 40% greater average N_2O emissions from the grassed inter-row at all sites, compared with the tree line were unexpected (Fig. 2, Table 2). In all orchards in this study, N fertiliser and irrigation were applied only to the tree line. As a result, the higher substrate availability and soil moisture would have been expected to be more conducive to N_2O emissions from the tree line. This should have been most pronounced in the cherry orchard where the equivalent of 150 kg N ha⁻¹ was applied on the tree line along with irrigation, while no fertiliser or irrigation was applied to the inter-row. Despite this, average N_2O emission in the inter-row was almost double that of the tree line at this site (2.44 and 1.31 g N_2O-N ha⁻¹ day⁻¹ respectively).

Large N_2O emissions from the inter-row were observed in a vineyard with a legume cover crop but not when the inter-row was bare fallowed (Garland *et al*. 2014). Increased N_2O emissions are often observed due to the addition of C and N from plants, which stimulates nitrification and denitrification (Bouwman *et al*. 2002). Consequently, it is speculated that the grass sward in the orchard inter-rows would have increased the input of C into the soil and so stimulated greater microbial activity, particularly in the top 10 cm where the bulk of the grass

root mass exists. This is consistent with the inter-rows having higher labile C in the Tasmanian orchards and rates of N mineralisation at the Lucaston orchard (Table 2). At the Tasmanian sites, the orchards were heavily mounded (up to 40 cm) by scraping the sandy loam topsoil from the inter-row into the mound, to facilitate drainage and soil volume in the tree line, while leaving a very shallow, bleached, low-C A2 horizon above a deep clay subsoil within the inter-row. These soils had little macroporosity, which with compaction by tractor traffic means that they had little capacity to drain or store soil water, as demonstrated by the 10-fold reduction in infiltration compared with topsoils in the tree line. Consequently, during rainfall or irrigation soils in the inter-row rapidly approached field capacity compared with the more porous high C soils in the tree line.

Implications for management

Overall, the contribution of the apple and cherry orchards of the current study to global warming potential associated with N_2O emissions was very low on an area basis. When expressed on a yield basis, the emissions intensity was in the range of 1.6–3.2 and 4.6–6.4 kg CO_2eq Mg^{-1} for apples and cherries respectively. By comparison the N_2O derived emissions intensity of the major grain crops of wheat and maize were reported at 166 and 185 kg CO_2eq Mg^{-1} respectively (Linquist *et al*. 2012), or 80.8 CO_2eq Mg^{-1} for almond kernel (Schellenberg *et al*. 2012). The order of magnitude lower values estimated for apples and cherries were maintained even when the values were expressed on a dry matter basis, principally due to the low annual emissions from the orchard crops in this study. On a dry weight yield basis, the emissions intensity was in the range of 11.6–46.8 and 22.7–66.6 kg CO_2eq Mg^{-1} for apples and cherries respectively. The benefits of yield-scaling to produce emissions intensity is that it takes into account both the need for food production and environmental impacts, in this case contribution to global warming. Clearly, comparing fresh fruit to grains and other more dried products is complicated by the differing moisture contents. At present, there is no overarching system to allow different food products to be compared. However, the use of emissions intensity will be useful for comparing across differing production systems for the same food product. As an example, the Cool Farm Tool (Hillier *et al*. 2011) is used across the processing tomato industry globally to consider the global warming potentials of differing production systems. Extension of this approach more widely in the fresh food sector is still in its infancy but should be encouraged, as exclusive use of area-based impacts can lead to low-yielding management practices in the pursuit of reducing environmental impacts.

Based on the findings of this study, perennial cropping systems such deciduous fruit tree cropping have substantially lower N_2O emissions compared with other agricultural systems. It is highly likely that N_2O emissions would be lower in these systems generally given the length of time soil temperatures are <13°C, as these crops require winter chill to break dormancy in spring (Greer *et al*. 2006). However, given that fertiliser application in deciduous tree cropping systems is generally post-harvest during the warmer summer–autumn months when soil temperatures are at their highest, potential remains to mitigate emissions through increased fertiliser use efficiency.

Although not tested here, optimising N fertiliser inputs to meet tree demand will facilitate a reduction in both emissions production and N leaching below the root zone, as more N is utilised by the trees. Further research to test emissions production under optimised fertiliser regimes will enable better determination of mitigation strategies based on fertiliser management.

Improved management of the inter-row areas, where consistently higher N_2O emissions were recorded, is possible – for example, bare fallow, but this will require consideration of the trade-off against potential increases in erosion and loss of soil C associated with bare fallow. Additionally, investigating the effect of growing cover crops, composting and side throwing of mower clippings and prunings to the tree line to increase soil C on N_2O emissions is necessary. Improved drainage in areas of the orchard prone to waterlogging is likely to mitigate N_2O emissions as well as using standard width machinery to minimise compacted areas of the inter-row.

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