Micrometeorological measurements of ammonia emissions during phases of the grazing rotation of irrigated dairy pastures

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Abstract

Large amounts of ammonia are emitted to the atmosphere from nitrogen fertilizers and animal production systems. While representing a loss to agriculture, emitted ammonia has important environmental effects. We report ammonia emissions from irrigated, fertilized pastures grazed intensively by dairy cattle at DPI Kyabram, measured in summer and autumn. The farming system is representative of dairy practice in south-east Australia. Irrigation bays are 65m x 365m and are grazed in rotation by 315 cows. After grazing for 2 to 3 days, the bays are fertilized with urea at 50kgN/ha and irrigated with 50mm of water. The regrowth period is about 1 month. Ammonia emissions were calculated through application of a Lagrangian model of atmospheric dispersion. Model inputs were ammonia concentrations on the boundaries of the bay, wind speed, wind direction, and atmospheric stability. Coefficients of variation for calculated fluxes were usually < 10%. Emissions from the pastures before grazing were negligible. Emissions from the whole herd during the grazing phases were 14.8 kgN in summer, but only 2.0 kgN in autumn, corresponding to emission factors of 12% and 1% for an assumed annual input of N in excreta of 150kgN cow^{-1} y^{-1}. Only 1% of the urea-N was lost when irrigation followed fertilization immediately, but 6% was lost when irrigation was delayed for 3 days. The dispersion model appears to be a very useful tool for assessing gas emissions from agricultural operations.

Key Words

Volatilisation, nitrogen balance, animal production systems, atmospheric dispersion, BLS model, greenhouse gases

Introduction

Ammonia (NH_3) emitted to the atmosphere has important environmental effects through the formation of aerosols that influence the earth's radiation balance and cloud-forming processes, and the eventual wet- and dry-deposition of nitrogen (N) compounds formed from NH_3. Deposition can lead to eutrophication and acidification of soils and water bodies, and the formation and emission of the greenhouse gas nitrous oxide (N_2O). It has long been recognized that agriculture is a major contributor of atmospheric NH_3 through the volatilization of NH_3 from fertilizers and animal wastes. Bouwman *et al.* (1997) consider that the microbial breakdown of urea and uric acid in animal excreta to ammonium (NH_4^+) and its subsequent volatilization to NH_3 represent the most important global source of atmospheric NH_3. Mosier *et al.* (1998, Table 7) estimate that the indirect emissions of N_2O resulting from N deposition are 50% of those arising from direct deposition of animal wastes on the soil. They and IPCC (1977) recommend that these indirect emissions be accounted for in making inventory estimates of N_2O emissions.

The intensification of dairy farming in south-east Australia in recent years and the exponential increase in use of N fertilizers in the industry (mainly urea) make it a potentially substantial contributor of atmospheric NH_3 (Eckard *et al.* 2003). However, there are large problems in quantifying both the input of N to grazed pastures and emission factors (the percentage of the N volatilised as NH_3). Estimates of the N input in excreta from well-fed, grazing dairy cows range from 80kgN y^{-1} (Bouwman *et al*. 1997) to almost 200kgN y^{-1} (Whitehead, 1995), while NH_3 emission factors vary from 3 to 4% (Bussink 1992; Ledgard *et al*. 1999) to 20% (Mosier *et al*. 1998). Sherlock and Goh (1984) found a large seasonal variability in emission factors: from 25% in autumn to 12% in winter. The median value from a number of studies is close to 7%, e.g., Bouwman *et al*. (1997), Misselbrook *et al*. (2000).

Measuring emissions during grazing episodes is difficult. Most of the studies made to date have used mass balance methods employing small plots grazed by a few cattle e.g., Eckard *et al*. (2003), but mass balance approaches are difficult to use with grazing herds because of the size of the area needed to contain hundreds of animals. Denmead *et al*. (1974) used a conventional flux-gradient micrometeorological technique to measure NH_3 emissions from 200 grazing sheep. However, the success

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of this approach depends on the animals being upwind of the measuring point. In the present study, we have measured the total emissions from a herd of 315 dairy cattle grazing pasture in areas ranging from 0.8 to 2.4ha using a newly-developed micrometeorological technique. The technique (described below) uses a backward-time Lagrangian stochastic (BLS) dispersion model due to Flesch *et al*. (1995, 2004) to calculate the surface flux of gas from a source area of arbitrary geometry, based on observations of wind speed and gas concentration at any point downwind. We have employed it to assess NH_3 emissions and emission factors for fertilized, irrigated, grazed pastures in south-east Australia.

Methods

Experimental

The research was conducted at DPI Kyabram in northern Victoria (36°20'S, 145°04'E). The soil at the site is a red chromosol containing about 30% clay. The pastures were a mixture of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and paspalum (*Paspalum dilatatum*) that had invaded over time. Irrigation bays were 65m x 365m. The herd comprised 315 Holstein dairy cows. In the grazing rotation practised at the time of our studies, pasture bays were grazed over 2 or 3 days. Urea fertilizer was applied almost immediately after grazing at 50kgN ha^{-1}, and the pastures were flood-irrigated with approximately 50mm of water as soon as possible afterwards. A regrowth period of approximately 1 month was then allowed before the pastures were grazed again. Ammonia emissions from pasture bays were measured with the BLS technique at various stages of the rotation: before, during and after grazing, after application of urea fertiliser, and after irrigation. Measurements were made in late summer (Series 1) and in autumn (Series 2).

The BLS model

As outlined by Flesch *et al*. (1995), assuming a horizontally uniform surface source and an atmosphere in horizontal equilibrium, the average horizontal wind speed U and concentration C observed at any height z_m are known to satisfy the relationship
where Q is the surface emission rate within the source area, z_0 is the surface roughness, L is the Obukhov stability length, h is the depth of the surface layer, and G denotes the set of variables characterizing the source: its shape and outline, orientation with respect to the wind, and its position with respect to the location where U and C are observed. If n is determined, then measurements of U and C determine Q. The BLS model determines n by tracing an ensemble of fluid element (particle) trajectories backward in time from a downwind sensor to their points of touchdown on the ground upwind. This defines the contributions of source and background (outside the source) to the concentration measured by the sensor and hence to the horizontal flux of particles there. A schematic of the procedure is given in Figure.1. As Eq.(1) indicates, the input requirements are source geometry, surface roughness, atmospheric stability and sensor height and location. We note that the model assumes a uniform surface source, whereas NH_3 emissions from grazing occur from scattered point sources: dung and urine patches. However, the recent work of Laubach and Kelliher (2004) on a similar problem, viz., the measurement of methane emissions from a herd of grazing dairy cows, demonstrates that point to point variation on this spatial scale is not sufficient to invalidate the uniformity assumption. In our applications we have employed a commercial package based on the BLS model, called WindTrax[3] (available from Thunder Beach Scientific, 4B-1127 Cartaret Street, Halifax, Nova Scotia, Canada B3H 3P2.)

$$\frac{UC}{Q} = n = f(z_m, z_0, L, h, G) \qquad (1)$$

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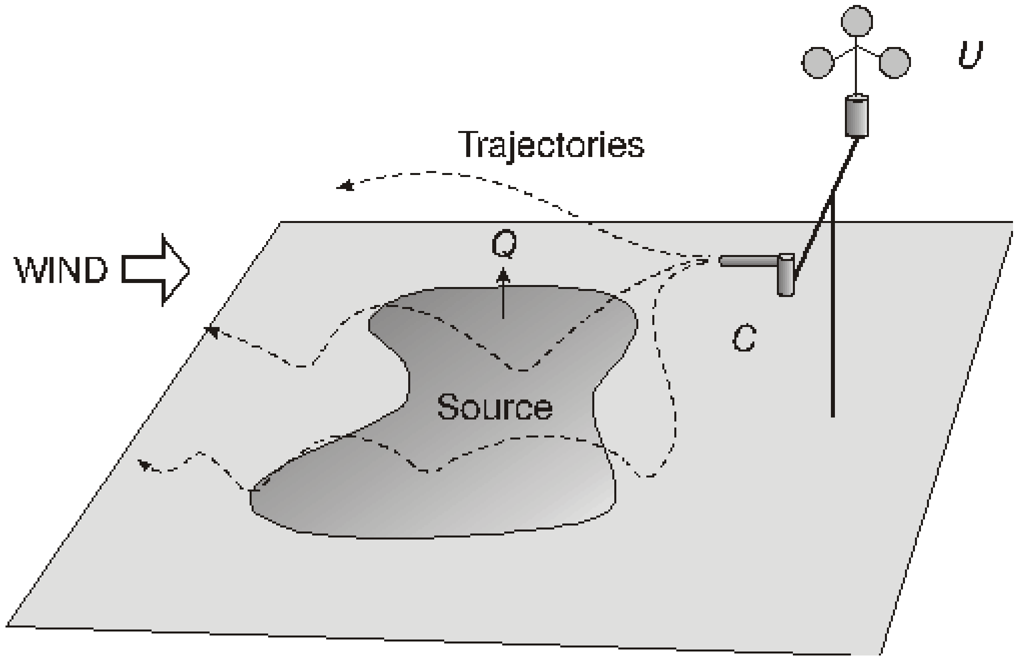

Figure 1. Backward trajectories from sensor to source- and background-areas. The BLS model counts touchdowns in both areas in 50,000 simulated trajectories in order to calculate the contributions of each area to the concentration measured by the sensor. *U* denotes wind speed at the point of measurement, *C* concentration and *Q* the surface flux in the source area.

Model application
The Kyabram site is heavily instrumented for measuring emissions of N_2O from the pastures and all the micrometeorological measurements necessary for the present study were already available, i.e., wind speeds, wind directions and atmospheric stability. Ancillary measurements of air and soil temperature, soil moisture content and evaporation rate were also available.

Ammonia sensors
Ammonia samplers (Leuning *et al.* 1985) were used to measure the horizontal flux of NH_3, i.e. *UC*. In order to apply the BLS model, NH_3 concentrations *C* were calculated from the horizontal fluxes measured by the samplers by dividing the latter by wind speed *U*. This procedure might underestimate concentrations by an amount whose magnitude is still uncertain, but could be as much as 15% (Leuning *et al*. 1985).

<u>Series 1.</u> In the first series of measurements, two adjoining pasture bays were grazed in rotation. Half of one bay was grazed on each of 4 successive days. Urea was applied to both bays on the seventh day and irrigation was commenced immediately afterwards. Ammonia emissions were calculated by the model from observations of wind direction, wind speed at 0.7, 1.4 and 2.8m, and measurements of NH_3 concentrations made with samplers mounted at the same heights at 4 locations on the boundaries of each bay, as illustrated in Figure 2. If the background concentration is known, the BLS model can calculate the surface flux in the source area from observations at just one point downwind. If the background is unknown, observations at 2 points are required. If more than 2 observations are available to the model, the problem is “overdetermined” and the model calculates the best fit answers for background and surface flux. This was the usual situation in our study. In Series 1, there were 18 observations available. Overdetermination is to be preferred because it minimises the effects of errors in the concentration measurements, and increases the number of simulated backward trajectories and touchdowns resulting in the model ”seeing” more of the source area than it would with 1 or 2 sampling points. Coefficients of variation for the calculated fluxes were usually < 10%.

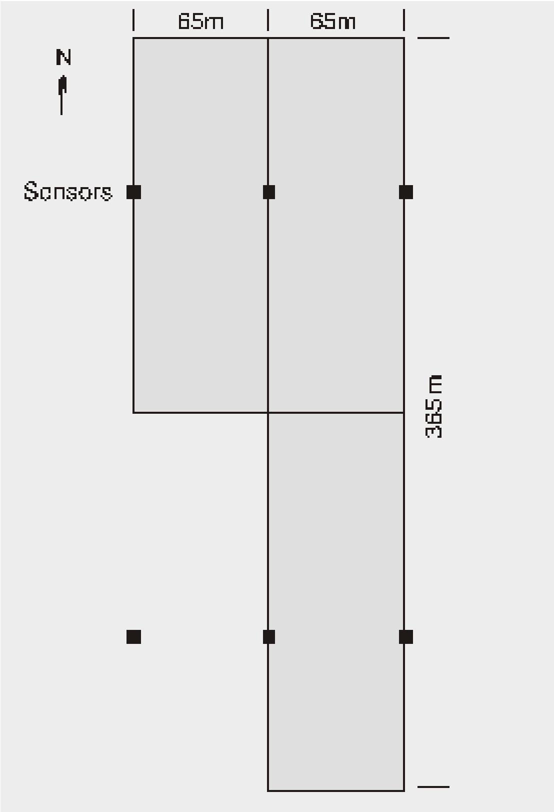

Figure 2. Emitting area (hatched) and location of sensors ■ on 3rd day of grazing in Series 1 (1½ bays grazed).

During grazing episodes, samplers were left unchanged as long as winds persisted in the same direction, which was often for the approximate 7 hours of grazing each day. However, they were changed whenever wind direction changed markedly, which was sometimes as often as 3 hours. Samplers were exposed at the same locations in the periods between grazing episodes, but were left unchanged for the entire period.

Series 2. The same 2 bays were grazed, but the grazing rotation was longer; bays were grazed one-third at a time, the 6 sessions occupying 5 days. Urea was applied at the end of the grazing period, but irrigation was delayed for 3 days. The placement of sensors also was different; wind speeds were measured at heights of 1.4m and 2m and samplers were located at those heights on the corners of each of the grazed sections. There were thus 24 inputs to the BLS model.

Results and Discussion

Series 1

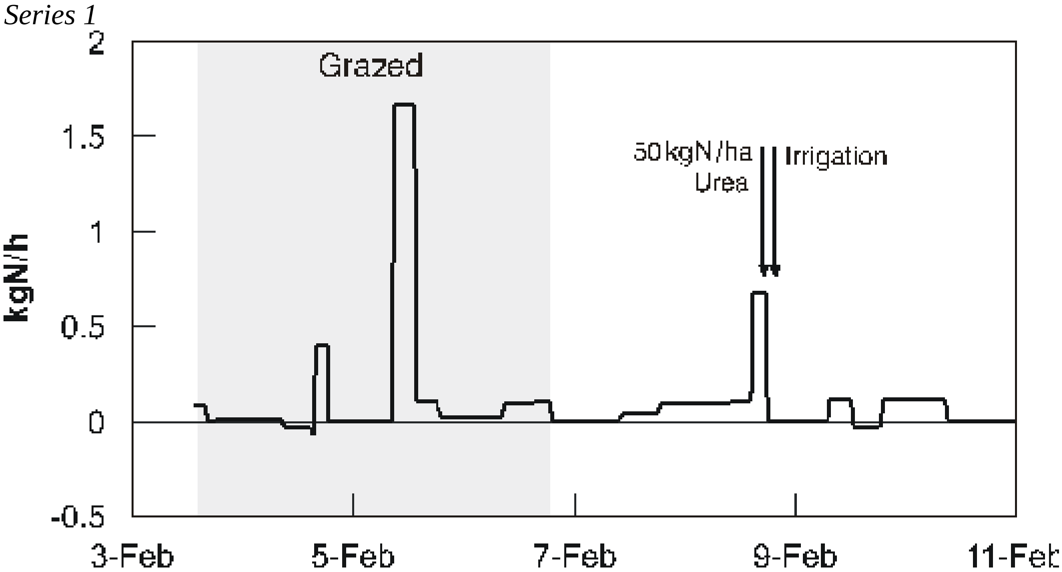

Figure 3. Time course of NH_3 emissions at different stages of the rotation in Series 1.

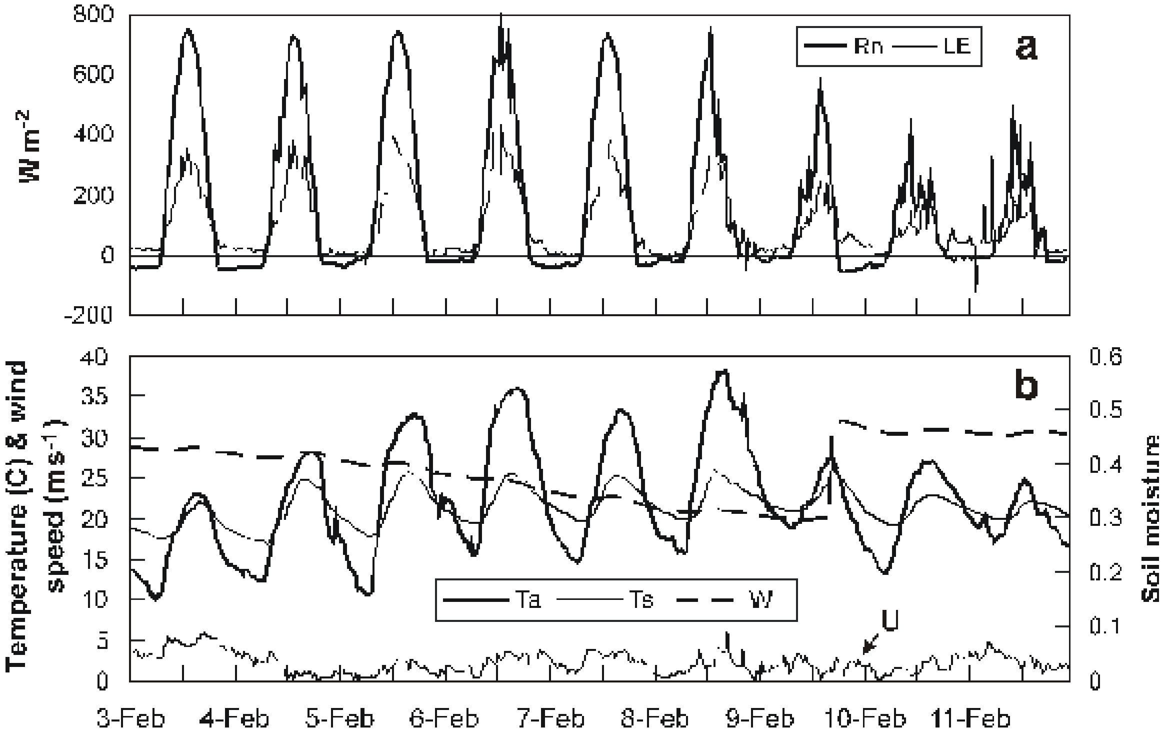

Figure 4. Meteorological conditions during Series 1. (a) Net radiation, Rn, and the latent heat equivalent of evaporation, LE. (b) Air temperature at 2m T_a, soil temperature at 0.04m depth T_s, volumetric soil water content at 0.04m depth W, and wind speed at 2m U.

Figure 3 shows emissions calculated during various stages of the rotation. In this case, measurements commenced on the first day of grazing. Note that emissions are expressed in kgN/h rather than kgN/ha because they represent volatilization of NH_3 produced by the whole herd, regardless of the areas involved. During the first day of grazing and the following night, the source area was half of 1 bay. It was a whole bay for the next 24h, 1½ bays for the next 24h (as shown in Figure 2), and 2 bays thereafter. Emissions increased over the time of grazing, reaching a maximum on the 3rd day, and they continued after grazing had ceased. Emissions were negligible over night, presumably because of the frequent presence of dew. The high rates of volatilization observed by day were probably due to the extreme weather conditions that prevailed: high temperatures, high surface soil moisture contents, moderately strong winds, and high evaporation rates (Figures. 4a and 4b), all conditions conducive to rapid hydrolysis of urea and loss of NH_3 (Sommer *et al*. 2004). As anticipated, the addition of urea had only a small impact on NH_3 emission since the fertilizer was washed into the soil almost immediately by the subsequent irrigation. For the whole series, 14.8 kgN were lost by volatilization during grazing and 2.2 kgN after urea application. These figures were calculated by multiplying the emission rates for each of the measuring periods depicted in Figure 3 by the length of the period (h) and summing the period emissions over the time of the relevant rotation phase.

Series 2:

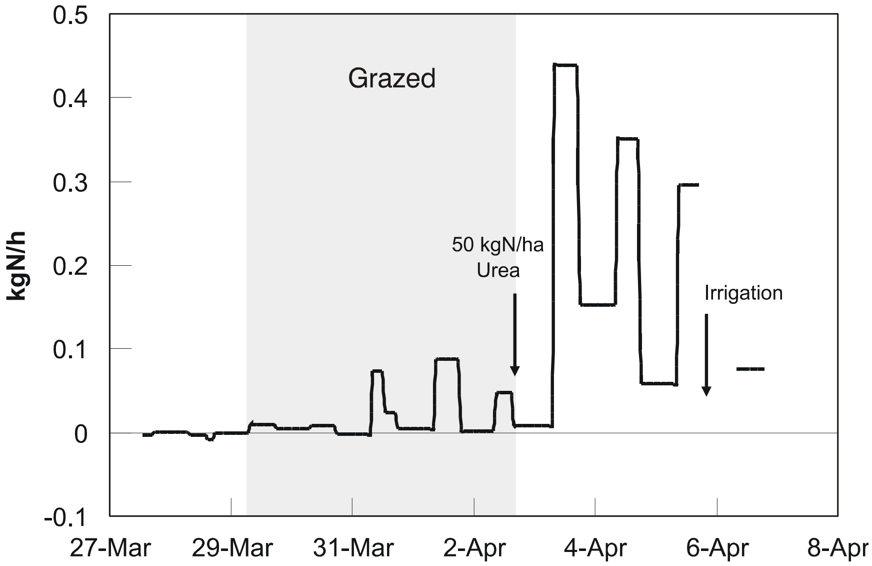

Figure 5. Time-course of NH_3 emissions in Series 2.

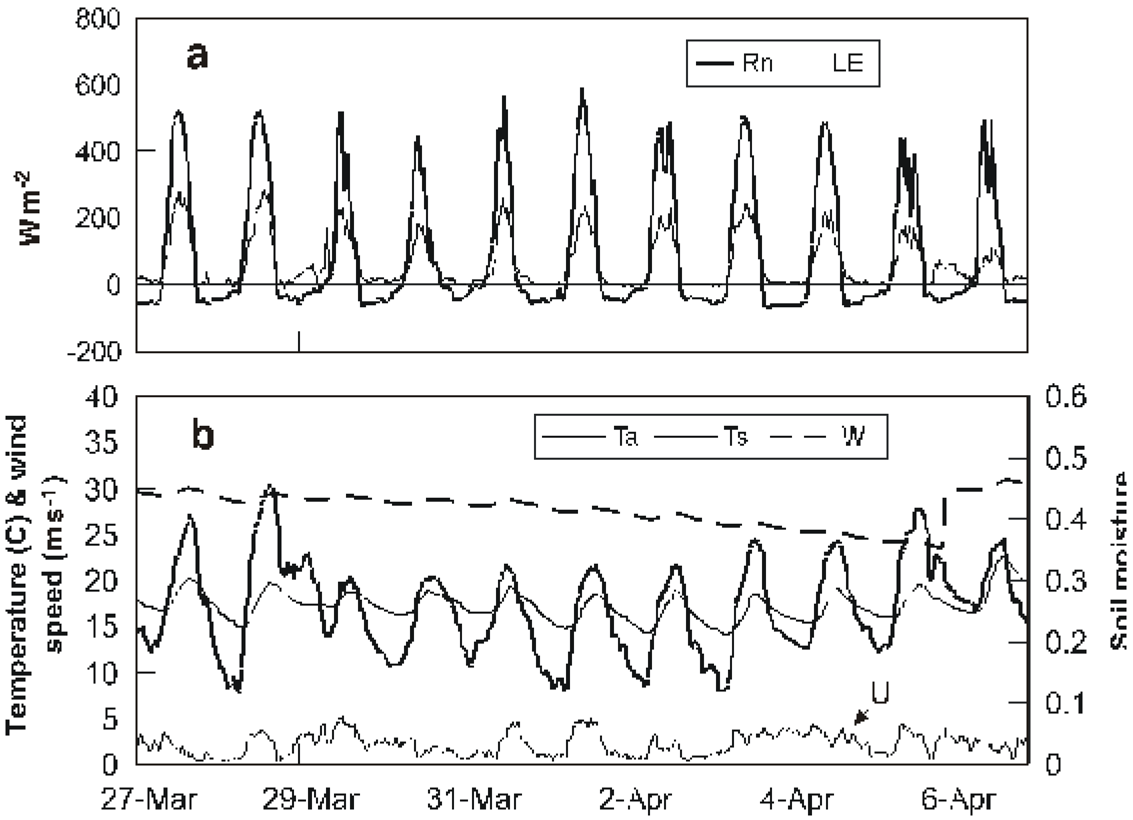

Figure 6. Meteorological conditions during Series 2. Symbols as in Figure 4.

The time-course of volatilization in Series 2 is shown in Figure. 5. Note the change of scale from Figure 3. In the 2 days before grazing commenced, there was a net uptake of NH_3 from the air by the pasture as observed by Eckard *et al*. (2003), but it was small. If extended to the whole of the non-grazing period in the rotation at this time of year, it would amount to about 1.5kgN. Much the same pattern of loss during grazing was observed as in Series 1: negligible volatilization by night and a build-up to near the maximum rate by the third day after grazing commenced. However, rates of volatilization were only about one-tenth those observed in Series 1, temperatures and evaporation rates being considerably lower (Figures. 6a and b). On the other hand, the loss of NH_3 after urea application was much higher than in Series 1 because of the delayed irrigation. For Series 2, only 2.0 kgN were volatilized during grazing, but 14.4kgN after urea application.

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Emission factors

Unfortunately, the input of N in animal excreta in our study is unknown. However, it is possible to compare our results with those from similar studies by expressing them as emissions per animal. Table 1 summarises a number of published emission rates for dairy cattle. The results for the present study take into account the periods for which the animals grazed the pasture (24h in Series 1 and 45h in Series 2). Our summer rates are high, but plausible in the weather conditions that prevailed then (Figure 4a, b). The autumn rates seem rather low, but the reason is not obvious. The full seasonal picture still remains to be established, but the results to date appear to be comparable with those from other sources, particularly the Australian rates observed by Eckard *et al*. (2003). If we adopt a literature value of 150kgN cow^{-1} y^{-1} for the N input from grazing dairy cows, the emission factor for Series 1 would be 12% and for Series 2, 1%.

Table 1. Daily emissions of NH_3-N from pastures during grazing by dairy cattle.

Source	**Country**	**gN $animal^{-1}$ d^{-1}**
Misselbrook *et a*l. (2000)	UK	16.9
Bouwman *et al*. (1997)	Europe	17.5
Ledgard *et a*l. (1999)	New Zealand	30.1
Bussink (1992)	Netherlands	39.8
Eckard *et al*. (2003)	Australia	39.8
Mosier *et al*. (1998)	USA	43.8
Present study:		
Summer	Australia	47.1
Autumn	Australia	3.4

The measurements of NH_3 emission after urea application emphasise the value of immediate irrigation. Only 1% of the urea-N was lost when irrigation followed fertilization immediately, but 6% was lost when irrigation was delayed for 3 days.

Concluding remarks

Much remains to be done to establish the full seasonal emission picture. The main thrust of the present paper has been to describe the use of the BLS technique for measuring gas emissions from agricultural operations, particularly from animal production systems. It is a very useful tool for such investigations. It is flexible, can handle irregular shapes and small and large plots or herds, requires simple input data, and allows easy computerized data analysis through WindTrax. The ability to measure emissions from a whole herd should greatly improve the precision of our estimates because of the much greater sample size. The advent of open-path technologies employing lasers and infrared spectroscopy measuring average concentrations over path-lengths of hundreds of meters will enhance the use of the BLS model since the sensors will "see" emissions from a much greater source area and emissions can be measured virtually instantaneously. Ammonia, methane and N_2O are amongst the gases relevant to animal production studies that can be measured in this way.

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