Agriculture, Ecosystems and Environment 230 (2016) 191–198

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Automated monitoring of urination events from grazing cattle

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ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form 3 June 2016
Accepted 4 June 2016
Available online xxx

Keywords:
Urine sensor
Nitrogen
Ammonia emission
Spatial distribution

ABSTRACT

Urine patches deposited by grazing cattle represent 'hot-spots' of very high nitrogen (N) loading from which environmentally important losses of N may occur (ammonia and nitrous oxide emissions, nitrate leaching). Information on the quantities of N deposited to grazed pastures as urine, the spatial and temporal distribution of urine patches and how these may be influenced by pasture management practices is limited. The objectives of this study were to assess the potential of recently developed urine sensors for providing data on urination behaviour by grazing cattle and relate this to measurements of ammonia emissions from the grazed paddocks. A total of six trials were conducted across two sites; two on a 1 ha paddock at Easter Bush near Edinburgh using beef cattle (c. 630 kg live weight) and four on a 0.5 ha paddock at North Wyke in Devon using in-calf dairy heifers (c. 450 kg live weight). Laboratory calibrations were conducted to provide sensor-specific functions for urine volume and N concentration. The quantity and quality of data from the urine sensors improved with successive trials through modifications to the method of attachment to the cow. The number of urination events per animal per day was greater for the dairy heifers, with a mean value of 11.6 (se 0.70) compared with 7.6 (se 0.76) for the beef cattle. Volume per urination event (mean 1.8, range 0.4–6.4 L) and urine N concentration (range 0.6–31.5 g L^{-1}, excluding outliers) were similar for the two groups of cattle. Ammonia emission measurements were unsuccessful in most of the trials. The urine sensors have potential to provide useful information on urine N deposition by grazing cattle but suggested improvements including making the sensors lighter, designing a better method of attachment to the cow and including a more reliable location sensor.

1. Introduction

Cattle urine contains significant quantities of nitrogen (N), with concentrations typically in the range 2–20 g L^{-1} (Whitehead, 1995), mostly in a very labile form (Bristow et al., 1992). The relatively small area covered by a urine patch from cattle grazing at pasture therefore results in very high N loading rates to the soil, exceeding the capacity of the grass to fully utilise it. Urine patches therefore represent 'hot-spots' from which losses of N may occur through ammonia volatilisation, nitrate leaching and nitrous oxide emissions (Allen et al., 1996; Di and Cameron, 2007; Jarvis et al., 1989; Laubach et al., 2013) with potentially damaging impacts on the environment (Galloway et al., 2003).

The N content and spatial and temporal distribution of urine patches are important factors affecting these potential losses and may be influenced by cattle diet, grazing management, environment and season. Our ability to model N losses and utilisation in grazed pasture systems and to optimise management practices requires good information on cattle urination behaviour. In particular, model representation of the urine patch, with a high N loading to a small spatial area is important rather than assuming an even distribution of grazing N returns across the whole grazed paddock (e.g. Hutchings et al., 2007). Non-linearity between N loss and N loading to a urine patch (Ledgard, 2001) mean that scaling up based on estimates of average values for urine patch N loading may differ substantially from that which takes into account the variation in N concentration and volume per urination event and the possibility of urine patch overlap (Li et al., 2012). Additionally, it may be important to represent the spatial distribution of N returns in urine in relation to variation in soil and environment parameters (e.g. wetness, compaction, slope). However, to date, there have been few published data on urination behaviour by grazing cattle as field observations are difficult to make. Those that

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http://dx.doi.org/10.1016/j.agee.2016.06.006

have been made suggest that urine patch distribution and overall spatial extent can be influenced by factors including fence line positions, water tank positions, field slopes and preferred night resting areas (Auerswald et al., 2010; Augustine et al., 2013; White et al., 2001).

Betteridge et al. (2010) described an automated urination sensor which, when used in conjunction with a GPS unit, could give information on the timing and location of urination events by grazing cattle or sheep. They showed that urine patch distribution was very non-uniform for sheep and cattle grazing on hill pastures in New Zealand. Further development of the sensor by Betteridge et al. (2013) enabled measurement of urine volume and N content for each urination event and reported that frequency distribution patterns of urinary N concentration could have a large effect on modelled N leaching loss. The sensors also had the potential to record location of urination events, using ZigBee communication (www.zigbee.org) by triangulation with fixed location ZigBee reference nodes around the grazed paddock.

The objective of our study was to assess the potential of the urine sensors to provide detailed spatial and temporal data on urination behaviour and urine N content for grazing cattle. A secondary objective was to determine the proportion of the urinary N excreted by the grazing cattle that was subsequently lost to the atmosphere via ammonia volatilisation.

2. Materials and methods

2.1. Urine sensors

Purposely designed urine sensors (AgResearch, Palmerston North, New Zealand) were used in the trials. The urine sensor was attached to the cow by gluing over the vulva, such that all urine flowed through the sensor, and was supported by attachment to the cows back. Development of the method of attachment and support continued throughout the trials from an initial configuration whereby Velcro straps were glued to the cow's back (Fig. 1a) to a final version where the weight of the sensor was better supported by a harness worn by the cow. Lateral movement of the sensor was minimised by supporting straps fixed to the lower end and a shroud was fitted to minimise risk of contamination by faecal material (Fig. 1b).

Urine flow through the sensor initiated sensor functioning and provided a time-stamp for the urination event. The urine flowed through a funnel within the sensor from which the majority drained away to the ground while a small subsample (10–20 mL) was retained in the bottom of the chamber. Urine volume for a given urination event was determined by recording the pressure head of urine (recorded every two seconds while urine was flowing) in the sensor funnel for the duration it takes to drain away. The area under the pressure × time curve was related to urine volume. Urinary N concentration was determined from the refractive index reading in the residual 10–20 mL of urine in the sensor. This residual urine was totally displaced by fresh urine at the next urination event; retention of this small volume of urine in the chamber minimised the likelihood of a mineral film forming on the refractive index sensor window. Urine sensors also included a ZigBee system for location of the sensor for each urination event relative to fixed position nodes located around the grazed paddocks.

The Rothamsted Research and SRUC Ethical Review Committees and associated professional veterinarian were involved throughout this study and were satisfied that the procedures and materials used did not adversely affect the cattle, with no significant skin damage around the vulva area from gluing and removal of the sensors and no impact on cattle behaviour. There were some problems in the earlier trials with the animals being aware of the sensor because of lateral movement e.g. while walking and this led to some instances of animal bucking and sensor detachment. However, as the method of attachment was improved, particularly through the use of lateral supports to minimise any lateral movement of the sensor (Fig. 1b), this was no longer a problem and from visual observations animals very quickly resumed normal behaviour after sensor attachment.

Fig. 1. Attachment of urine sensor to the cow: A, showing initial configuration using Velcro straps glued to cow; B, final configuration using a harness with top and side straps to support sensor weight and minimise lateral movement. GPS collar also shown on the beef cow in A.

Calibration functions were derived for each urine sensor for volume and N concentration using cattle urine collected from dairy cows during milking at a local dairy farm. Volume calibrations were performed by pouring volumes of between 1 and 4 L, in 0.5 L graduations, through the sensor and relating urine volume to the integral of the pressure × time curve. Nitrogen concentration calibrations were performed using cattle urine of known N concentration at four different dilutions and relating N concentration to the refractive index reading.

2.2. Trial sites

Two grazing trials were conducted in September and October 2012 using 14 beef cows (Charolais cross, Limousin cross and Aberdeen Angus cross, average live weight 630 kg) on a 1 ha paddock at Easter Bush, near Edinburgh, Scotland, and a further four trials conducted from July to September 2013 using between 7 and 12 in-calf dairy heifers (Holstein-Friesian, average live weight 450 kg) on a 0.5 ha paddock at North Wyke in Devon, England (Table 1). Both sites were permanent pasture, with total fertiliser N

Table 1
Details of the grazing experiments at Easter Bush (EB) and North Wyke (NW).

Expt.	Site	No. cattle	No. with urine sensors	Start of grazing	Urine sensor removal	End of ammonia emission measurement
1	EB	14	7	03/09/2012 19:00	06/09/2012 14:00	07/09/2012 09:00
2	EB	14	9	01/10/2012 11:00	05/10/2012 10:00	05/10/2012 11:00
3	NW	7	7	01/07/2013 16:00	05/07/2013 08:45	11/07/2013 14:00
4	NW	8	8	05/08/2013 12:00	09/08/2013 09:00	15/08/2013 09:15
5	NW	12	7	02/09/2013 12:40	06/09/2013 09:00	12/09/2013 09:15
6	NW	12	6	24/09/2013 11:15	27/09/2013 14:00	03/10/2013 11:25

applications of 140 and 160 kg ha^{-1} to Easter Bush and North Wyke (applied as two splits in March and May of 90 and 50 kg ha^{-1} at Easter Bush and 100 and 60 kg ha^{-1} at North Wyke), respectively, during the relevant year. Immediately prior to grazing, either all or a sub-set of the cattle were fitted with urine sensors, which were then removed 3–5 days later. At the Easter Bush site, cattle were also fitted with GPS tracking collars (AgTrex, BlueSky Telemetry, Aberfeldy, UK), which gave positional information at a 1-min resolution.

2.3. Ammonia emission measurements

Ammonia emissions from the plot during the grazing period were measured using a backward Lagrangian stochastic (bLS) modelling approach (Flesch et al., 2007), based on measurements of ammonia concentration at fixed points around the grazed paddocks and of wind statistics using a sonic anemometer (Windmaster, Gill Instruments Ltd, Hampshire, UK). Ammonia concentrations were measured using two enhanced performance Los Gatos Economical Ammonia Analysers (Los Gatos Research, California, USA) and, at the North Wyke site using ALPHA passive samplers (Tang et al., 2001; Walker et al., 2014) at locations as shown in Fig. 2. The Los Gatos analysers were sampling at approximately 1-min intervals at a height of 1.4 m above ground through 15 m PTFE tubing with heat-trace to prevent condensation. The ALPHA samplers were used in triplicate at each of the four sampling locations shown in Fig. 2b, mounted at 1.5 m height and were changed every 24 h. The software 'Windtrax' (Thunder Beach Scientific, Nova Scotia, Canada) was used to estimate ammonia emission rates, using either 20 min average concentration and wind statistics or, for the ALPHA sampler derived concentrations using 24 h average concentration, wind speed and wind direction data. The use of longer sampling intervals with the bLS approach has been previously verified (Sanz et al., 2010; Sommer et al., 2005).

3. Results

3.1. Urine sensor calibration and performance

Typical calibration curves for urine volume and N concentration are given in Fig. 3. For urine volume, very good regression fits were obtained ($r^2 > 0.97$ in all cases) and the slope of the fitted line varied between 11.3 and 16.5 for the different sensors. Good calibration functions were also obtained for urine N concentration ($r^2 > 0.99$) with regression slope values varying between 0.109 and 0.116.

Data were not used from any sensors that on removal from the cow were found to be blocked or partially blocked by faeces or from any that were not capturing the entirety of urine flow (as identified through field observations). The proportion of sensors providing reliable data improved in the later experiments, as the method of sensor attachment to the cow was improved. Thus, the number of sensors remaining attached properly for periods of 1 day or longer also improved (Table 2).

One feature of the urine sensors which did not function well was the location recording, with no reliable data being recorded. The only location data in relation to urine events was that obtained using the GPS collars at the Easter Bush site. The 1-min interval

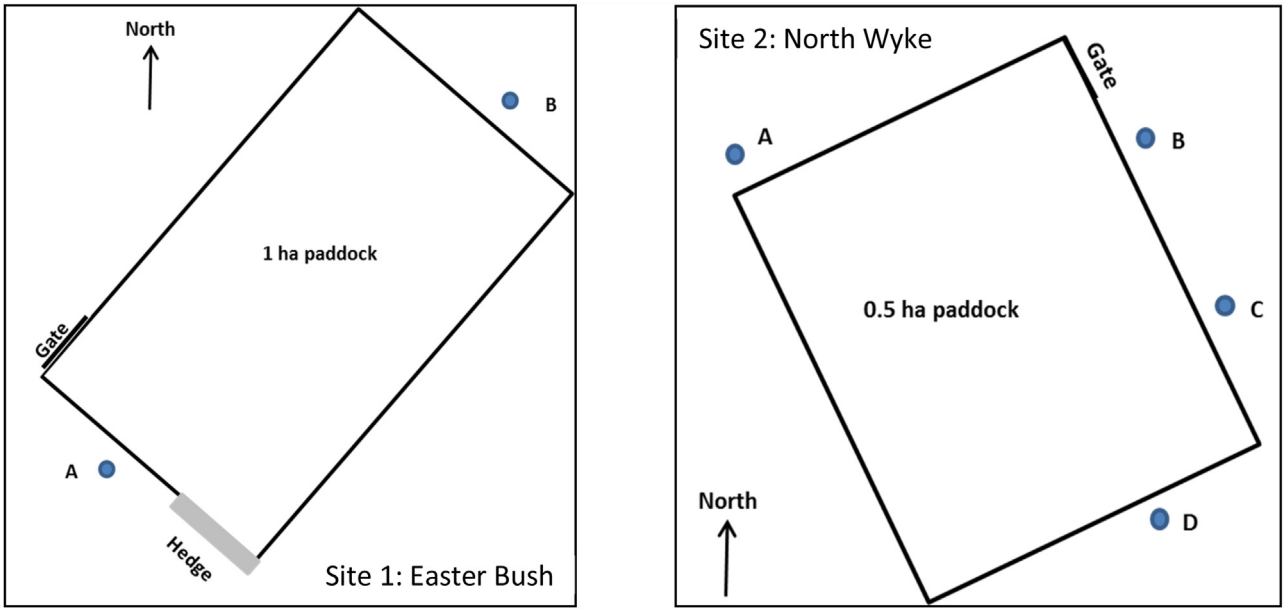

Fig. 2. Trial sites: Site 1, Easter Bush – 1 ha permanent pasture with ammonia concentration sampling locations (Los Gatos analysers) at A and B. Site 2, North Wyke – 0.5 ha permanent pasture with Los Gatos ammonia analyser ammonia concentration sampling locations at A and C and ALPHA passive ammonia samplers at A–D. Prevailing wind direction for both sites was SW.

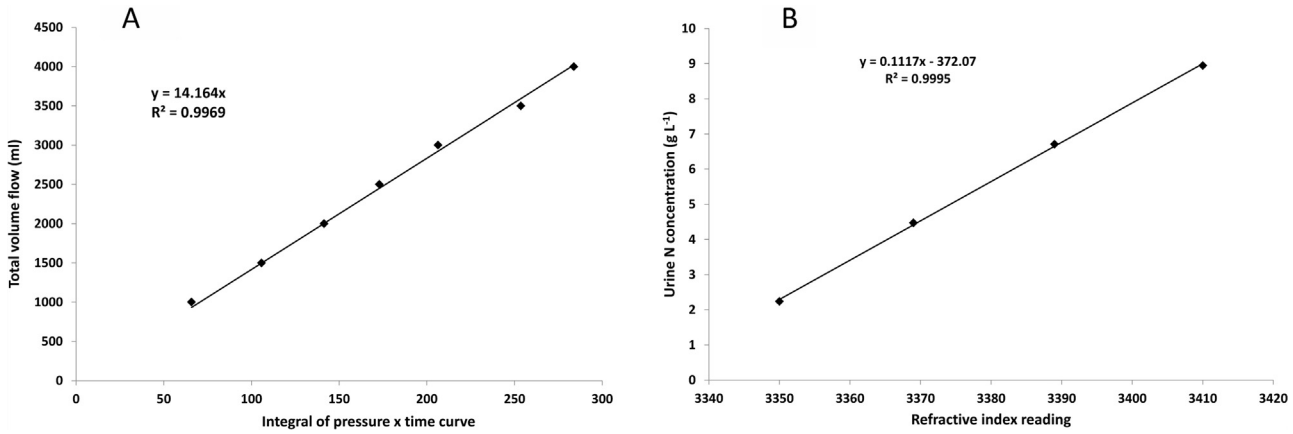

Fig. 3. Urine volume (A) and N concentration (B) calibration curves for one of the urine sensors used in the study.

Table 2
Urine sensor performance.

Expt.	No. sensors giving reliable data	Duration of data recording (h)			No. of sensors giving data for more than	
		Average	Minimum	Maximum	24 h	48 h
1	4	39	34	47	4	0
2	5	59	21	92	4	2
3	5	38	14	87	3	1
4	6	53	25	94	6	2
5	7	59	20	82	6	5
6	5	56	38	72	5	3

locations within the paddock over a single 24 h period of the four cattle for which sufficient urine sensor data were recorded are shown in Fig. 4 (open circles, individual animals not identified). In this period, the cattle showed a distinct preference for the SW part of the paddock, particularly along the fence lines (not shown). The gate to the paddock was in the W corner and there was a hedge along the SW boundary, an area which the animals used particularly for resting at night time. Urination events are also shown in Fig. 4, differentiated by daytime events (filled yellow circles) and night time events (filled blue circles). While there are insufficient data to draw strong conclusions, the night time events mostly occurred at the SW end of the field, where the animals predominantly rested at night, whereas daytime events were more distributed according to the animal presence across the paddock.

3.2. Urination behaviour

A total of 119 and 559 individual urination events were recorded for the beef and dairy cattle, respectively, with an average number of urination events per animal per day of 7.6 (n = 9, standard error = 0.76) for the beef cattle and 11.6 (n = 24, se = 0.70) for the dairy heifers. The frequency distributions in urine volume, N concentration and N loading per urination event were similar in shape for the beef and dairy cattle (Fig. 5). Four high values for dairy heifer urine N concentration (>35 g N L^{-1}) were considered to be outliers, possibly as a result of contamination of the cell window through which the refractive index measurement takes place, and were excluded from the analysis. Mean values were similar between the cattle types, with respective mean volumes of 1.75 (se 0.05) and 1.80 (se 0.08) L per urination event, mean urine N concentrations of 14.4 (se 0.33) and 13.1 (se 0.26) g L^{-1} and mean N loading of 25.6 (se 1.39) and 22.0 (se 0.66) g per urination event for the beef and dairy cattle, respectively. With the greater number of urination events per day, the urine N excretion was therefore greater for the dairy heifers than the beef cattle, with respective values of 255 and 194 g N per animal per day.

There was obvious diurnal variation in the urine volume, N concentration and N loading per urination event for the dairy heifers (Fig. 6), with maximum volume per event in the early hours of the morning and minimum at midnight, and minimum urine N concentration in the middle of the day. This pattern was consistent across all four trials at the North Wyke site (experiments 3–6). There were insufficient data from the beef cattle trials to evaluate diurnal variation.

3.3. Ammonia emissions

For all trials, the data from the Los Gatos Economical Ammonia Analysers were insufficiently robust to be used. Despite initial calibration of both instruments against a standard, there was significant drift in the recorded values for subsequent calibration checks between instruments that was of a similar (or greater) order of magnitude to the expected differences in upwind and downwind concentrations. The emissions from the grazed paddocks were therefore below the limit of detection for the Los Gatos instruments used in this way.

Using the ALPHA samplers with a 24 h exposure time was also generally insufficient to be able to reliably measure ammonia emissions from the grazed paddocks. For two of the trials (experiments 5 and 6), there was no significant difference between the amount of ammonia collected on the exposed ALPHA samplers and that on the unexposed blank samplers. For experiments 3 and 4, exposed sampler concentrations were above those of the blanks and emission estimates could be made using the bLS modelling approach. Average measured fluxes were 0.11 and 0.57 kg ha^{-1} d^{-1} NH_3-N for experiments 3 and 4, respectively, which represented 8.6 and 33.5% of the estimated urine N deposition to the pastures during the grazing period. However, these results are not

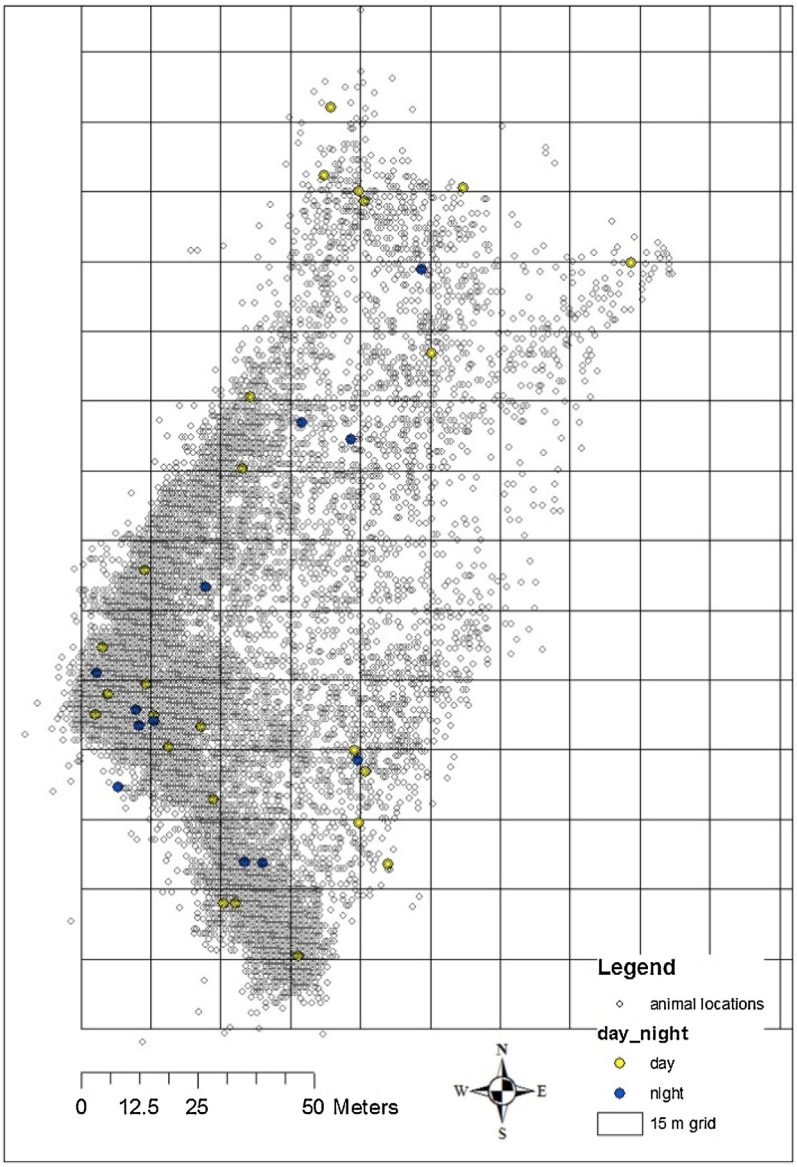

Fig. 4. Map showing 1-min intervals for animal locations (open circles) and day and night time urination events (yellow and blue circles, respectively) for 4 monitored grazing beef cattle over a 24 h period at the Easter Bush site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

considered reliable and further research is required to gather valid ammonia emission data using this method.

4. Discussion

The urine sensors have enabled us to collect data in an automated way from a large number of urination events from grazing cattle across multiple animals on multiple occasions. This would have been extremely difficult, if not impossible, to achieve through manual sampling and observation. The sensors used in this study, as designed by AgResearch (Betteridge et al., 2013) were a considerable improvement on those described by Betteridge et al. (2010) in that they measure volume and N concentration for each urination event in addition to timing. Unlike the sensors used by Betteridge et al. (2010), which were attached to the animals by insertion into the vagina, those used by Betteridge et al. (2013) and in this study were non-invasive. However, potential effects on animal welfare must still be taken into consideration, hence the inclusion the Rothamsted Research and SRUC ethical review committees and associated veterinarians.

Inter-animal and temporal variation in urination behaviour (amounts, location) and N concentration require the sampling of sufficient animals and occasions to provide representative data and, as discussed above, the urine sensors have the potential to provide this. However, improvements to sensor design and functioning could be made to increase the reliability and quality of data captured. As noted above, the method of sensor attachment was improved throughout the study resulting in increased duration of monitoring. This could be further refined to increase the proportion of sensors remaining attached for three days or longer. Reducing sensor weight (currently c. 1.3 kg) may also help with this. The ZigBee system for location recording did not work successfully in any of the trials, possibly because of the presence of the cattle interfering with the signals between sensors and reference nodes, so for spatial information the sensors should be combined with the use of GPS devices, ideally co-located with the sensors (GPS collars will give location displaced from the urine patch by approximately 2 m but with an unknown orientation).

The urination frequency, volume and N content data observed in this study compare well with literature values. Selbie et al.

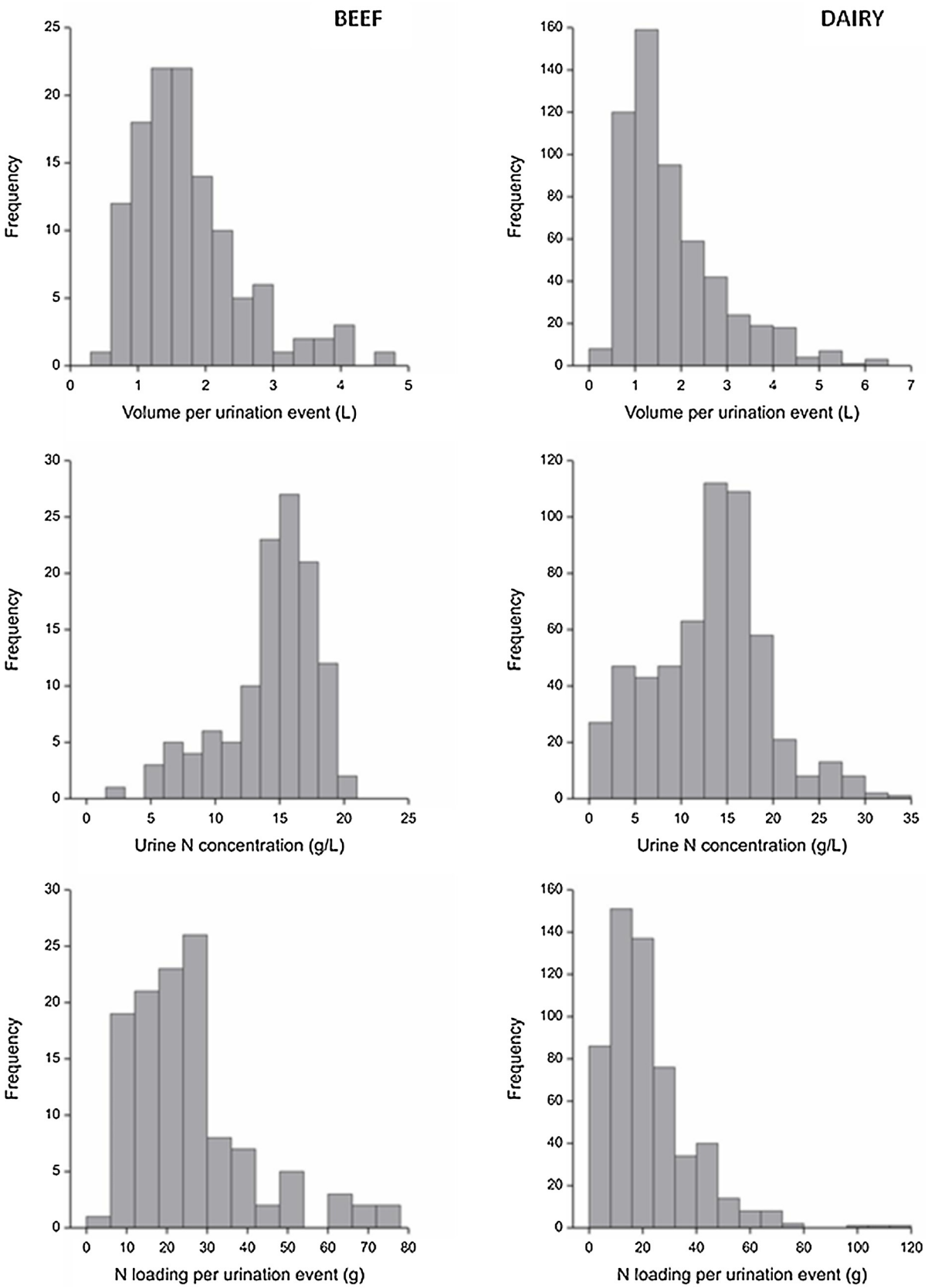

Fig. 5. Frequency distribution plots for urine volume, N concentration and N loading per urination event for beef (left hand graphs) and dairy (right hand graphs) cattle.

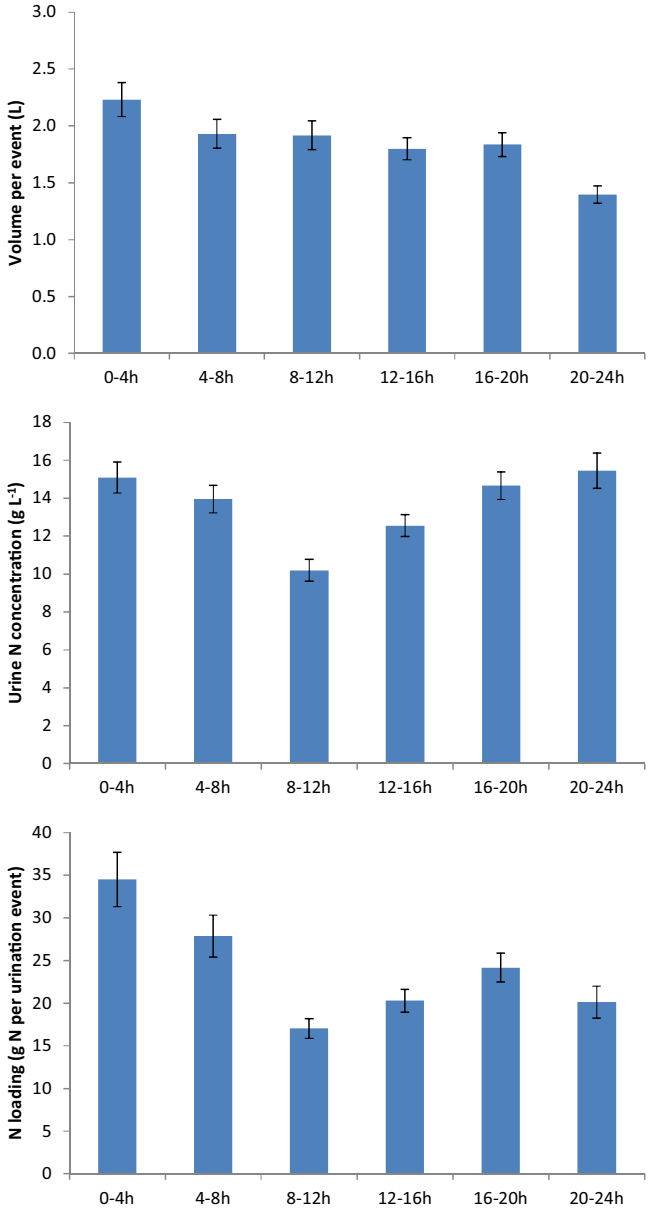

Fig. 6. Diurnal variation in volume, N concentration and N loading per urination event for dairy heifers. Error bars indicate ± 1 standard error of the mean value.

(2015), in a review of available literature, noted that daily urine volume and frequency varied widely. They reported an average frequency of urination of 10–12 events per day for cattle (range 5–18 within individual studies), similar to that of 8–12 events per day reported by Whitehead (1995). The average volume per urination event was reported as 2.1 L for dairy cattle and 1.2 L for beef cattle but within individual studies was in the range ` 0.9–20.5 L across all cattle (Selbie et al., 2015). Mean cattle urine N concentration for cattle was given in the range of 2–20 g L^{-1} by Whitehead (1995). The meta-analysis performed by Selbie et al. (2015) gave mean values of 6.9 and 7.2 g L^{-1} for dairy and beef cattle, respectively, grazing a predominantly grass diet, somewhat lower than our mean values from the present study. Mean daily N excretion in urine from the present study of 194 and 255 g for beef and dairy cattle, respectively, is at the upper end of the ranges given by Whitehead (1995) of 80–240 and 80–320 g d^{-1} for dairy cows and steers, respectively. Dennis et al. (2011) and Oudshoorn et al. (2008) report urination frequencies for grazing dairy cows of 8.6 and 6.2 events per day, respectively, while Orr et al. (2012) reports a value for beef cattle (mean live weight of 570 kg) grazing a moderately improved sward of 7.0 events per day. Orr et al. (2012) reported a lower mean volume per urination event of 0.8 L and urine N concentration of 10.8 g L^{-1}. Betteridge et al. (2013) reported a mean volume per event of 2.1 L, with a range 0.3–7.8 L for grazing non-lactating dairy cows and mean urine N concentration of 9.5 g L^{-1} (range 1.2–24.7 g L^{-1}).

Betteridge et al. (2013) also reported a clear diurnal pattern to the N loading per urine patch (mean 18.1 g N per urination event), as found in this study (Fig. 6), with values during the night being greater than those during the daytime and discuss the importance of this with respect to the spatial distribution of the urine patches. The higher N loading of the night-time patches have greater potential for nitrate leaching and gaseous N losses, which may be further exacerbated if regular night-time camping areas are used which are relatively small in comparison with day-time roaming/grazing resulting in greater probability of urine patch overlap. The reason for the greater N loading at night is not clear, but may be related to the diurnal pattern of intake by the cattle (no observations made), with urine N concentration increasing from the morning to evening (Fig. 6). Additionally, there was some evidence of urination frequency being lower overnight (data not shown), presumably as the cattle were less active, and volume per urination was greatest during the 0–4 h period of the day (Fig. 6).

Ammonia emissions measured from individual urine patches, e.g. using dynamic chambers, may account for up to 30% of the urine N deposited (Lockyer and Whitehead, 1990; Misselbrook et al., 2014). However, a proportion of this emission will be re-deposited to the pasture very local to the urine patch, so emissions measured at the field level using micrometeorological techniques will generally give lower emission estimates (Asman, 1998). Misselbrook et al. (2015) derived an emission factor for the UK inventory of ammonia emissions from agriculture of 6% of urine returns at grazing being volatilised as NH_3-N based on a number of field studies using micrometeorological measurement techniques (including Bussink, 1994; Jarvis et al., 1989) with individual emissions reported in the range 0–10% of urine N deposited. Laubach et al. (2013), also using micrometeorological techniques, reported higher emissions from a grazing trial in New Zealand, with an emission factor of 25% of urine N which is approaching the upper value measured in our study (although as has been noted above, emission results from the present study are not considered reliable).

5. Conclusions

The urine sensors as used in this study provided an automated means of monitoring urination events from grazing cattle although improvements to sensor attachment and location monitoring are needed. A total of 678 urination events were recorded throughout the study across the beef and dairy cattle. Frequency of urination was greater for the dairy heifers than the beef cattle at 11.6 and 7.6 events per day, respectively. Mean urine volume, N concentration and N loading per urination event were similar across the two cattle types with ranges of 0.4–6.4 L, 0.6–34.4 g N L^{-1} and 0.3–114 g, respectively. There was clear diurnal variation in urine N concentration and hence N loading per urination event. Mean daily urine N excretion was 225 and 194 g for dairy and beef cattle, respectively. The methods used to measure ammonia emissions provided unreliable data. Further work is needed to gather valid ammonia emission data using these methods.

Acknowledgements

The authors gratefully acknowledge the University of Edinburgh farm manager for allowing access to the Easter Bush study field and to SRUC technical staff in the management of the livestock throughout the trial. Valuable assistance was also provided by the North Wyke farm staff and field support team. Funding for this study was provided by the UK Government through Defra project AC0116. Rothamsted Research is sponsored by the Biotechnology and Biological Sciences Research Council.

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