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The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems

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Supplementary material S1

Nutritive characteristics of leucaena forage

Table S1.1 Dry matter (DM), organic matter (OM), nitrogen (N), neutral detergent fibre (NDF) and acid detergent fibre (ADF) of available forage diets at two field sites (Belmont and Brian Pastures Research Stations) during each methane measurement campaign. Further details are given in the methods and in Harrison et al. (2015).

	Belmont				Brian Pastures	
Date	March/April 2013		June/July 2013		March/April 2014	
Animal age (days)	465-479		542-591		818-846	
	Pasture	*Leucaena*	*Pasture*	*Leucaena*	*Pasture*	*Leucaena*
			Forage analyses			
DM (g/kg)	931	910	939	930	942	923
OM (g/kg DM)	895	927	912	919	877	909
N (g/kg DM)	11.8	60.3	8.0	38.6	3.0	36.3
NDF (g/kg DM)	692	225	728	377	766	222
ADF (g/kg DM)	389	189	458	247	588	160
			Diet composition (faecal near infra-red spectroscopy)			
Diet CP (%)	7.9	12.0	8.6	12.9	6.1	9.0
In vivo DMD (%)	56.9	59.6	59.4	63.0	55.7	58.3

Harrison, M.T., McSweeney, C., Tomkins, N.W., Eckard, R.J., 2015. Improving greenhouse gas emissions intensities of subtropical and tropical beef farming systems using Leucaena leucocephala. Agricultural Systems 136, 138-146.

Supplementary material S2

Methane measurement protocols, WindTrax emissions calculations and assumptions

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Background to the field laser enteric methane measurement protocols are given in Harrison MT, McSweeney C, Tomkins NW, Eckard RJ (2015) Improving greenhouse gas emissions intensities of subtropical and tropical beef farming systems using Leucaena leucocephala*. Agricultural Systems 136, 138-146.*

Belmont Research Station experiment layout

Methane (CH_4) emissions were calculated from cattle grazing treatment (leucaena, n=29) and control (pasture, n=30) paddocks, with each paddock containing 28 to 30 animals . These dedicated source areas, in which animals were confined for daily emission measurements, were separated by approximately 250 m (Fig. 1). Open path lasers (GasFinder 2.0, Boreal Laser Inc., Edmonton, AB, Canada) measured line averaged CH_4 concentrations on paths adjacent to each paddocks . With a motorized pan-tilt aiming unit (PTU D300, FLIR Motion Control Systems, Burlingame, CA, USA) each laser was sequenced to measure two paths running parallel to the paddock edges at about 25 meters north and west of each paddock. A separate "background" laser was located upwind and more than 200 m from the paddocks.

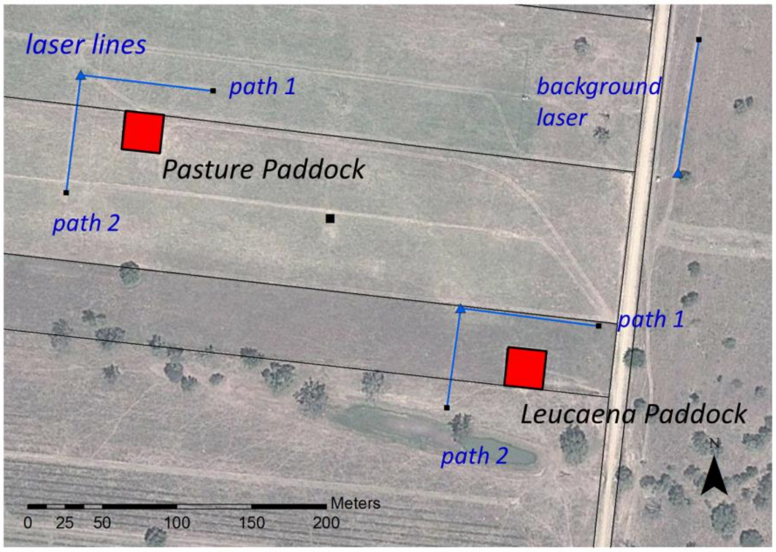

Figure S2.1 *Map of the Belmont Research Station study layout.*

Field laser calibration

During analysis of the Belmont data we found the laser concentrations on the different measurement paths were not consistent with respect to one another. This was despite a procedure where lasers were cross-calibrated in side-by-side placements prior to the studies. This inconsistency was responsible for poor results in earlier calculations. To give sensible results we resolved this inconsistency using the approach outlined below.

Lasers paths were cross-calibrated with each other using an in-situ approach. Each laser was selectively cross-calibrated against the background laser during restricted wind directions when the different laser paths were exposed to the same “fresh-air” (background) concentration:

- Wind from 0 to 80 degrees: the background and north paths (path 1) should give the same background CH_4 concentration,
- Wind from 185 to 210 degrees: background and west paths (path 2) should give the same background concentration.

Measurement periods (10 min each) having a wind direction within the above ranges were used to develop multipliers to force the concentrations of various laser paths to match that of the standalone laser. This goal was to eliminate systematic measurement errors due to: 1) any errors in the measured laser path lengths; 2) the possibility of errors due to different laser signal levels on the different paths; 3) different conditions of the different laser reflectors. In a final step, all the cross-calibrations were adjusted to give agreement based on one reference laser. This above approach was discussed with the laser manufacturer (Boreal Laser).

The in-situ cross-calibration procedure worked well except for:

- March 2013 measurements for cattle grazing Leucaena pastures. The path 2 cross-calibration was unstable (the multiplier was highly variable over the calibration period). We have no explanation for this behavior, and chose not to use the path 2 laser line.
- June 2013 measurements for cattle grazing Rhodes grass pastures. The path 1 cross-calibration was unstable as described above. We chose not to use the path 1 laser line.
- March 2014 measurements for both grazing groups. There were no wind directions that allowed the cross-calibration of the path 2 laser line, and the path 2 laser line was not used.

Data filtering

Emissions were calculated using the freely available WindTrax dispersion model software. The software combines the MO–LS model described by Flesch et al. (2004) with mapping capabilities. Not all observation periods allow for good calculations and filtering criteria were used to eliminate periods in which: 1) the concentration measurements were believed to be inaccurate or unrepresentative; and 2) when the WindTrax dispersion calculations were potentially inaccurate.

Laser criteria

The following criteria were used to remove potentially inaccurate or unrepresentative concentration measurements:

- Laser observations < 50% of potential. This criterion eliminates any period where the laser observations corresponded to less than 50% of the potential measurement period (5 min of a 10 min observation).
- $R^2_{min} < 98$. R^2 is a parameter given by the laser for each observation, and relates to the quality of the concentration measurement from the laser. We eliminate all data where $R^2 < 98$. This eliminated periods when the spectrum from the reference cell did not match that from the sample spectrum.
- 4,000 < Light Level < 12,000. Light Level is an operating parameter related to the strength of the returning laser beam. The manufacturer advises that concentration measurements may be inaccurate if the signal level falls outside this range.

WindTrax criteria

Not all observation periods are expected to give good emissions estimates. The following criteria were used to remove error-prone periods and have been used in previous studies.

- $u^*_{thres} = 0.05$ m s^{-1}. This criterion removes low windspeed periods when the friction velocity u^* is less than a threshold u^*_{thres}. We use a lower threshold for u^* than many earlier studies in order to increase our dataset. Flesch et al. (2014) concluded that a low u^*_{thres} (0.05 instead of 0.15 m s^{-1}) introduces outliers in the calculated emission data set, but results in little change in the overall average accuracy.

- $|L|_{thres} = 2$ m. This is a criterion that excludes periods when the atmospheric stratification is extreme. When the absolute value of the Obukhov length L falls below the threshold $|L|_{thres}$. This criterion has been used in earlier studies (Flesch et al., 2004).

- $z_{0\text{-}thres} = 0.25$ m. This criterion uses the calculated surface roughness z_0 to indicate periods when the wind does not conform to the meteorological assumptions in WindTrax (i.e., Monin Obukhov similarity). For sites with a plant canopy we expect z_0 to fall within the broad range of 5 to 25% of the canopy height. Here a z_0 above $z_{0\text{-}thres} = 0.25$ m would indicate wind conditions that violate WindTrax assumptions.

- $tdcov_{thres} = 0.95/1.00$. This important criterion is based on the fractional coverage of the downwind laser measurement "footprint" over the paddock area. For some wind directions the plume from the cattle paddock only "glances" the path of the lasers. This is a concern; the plume edge carries greater model uncertainty, since extreme trajectories at the plume margin are less predictable, and the laser footprint only covers a portion of the source area (which may or may not contain animals in any particular observation). This can lead to poor estimates of the average paddock emissions. And if the footprint only covers a portion of the paddock, slight errors in the wind observations (particularly wind direction) can introduce dramatic errors in the emission estimates. To avoid these problems we removed periods where the fractional laser footprint *tdcov* covers less of the paddock than the threshold $tdcov_{\text{thres}}$ of either 0.95 or 1.00. We prefer to use $tdcov_{\text{thres}}$ = 1.00, but due to limited data periods we also include results using a relaxed threshold of 0.95. This type of filtering is routinely used in the analysis of WindTrax data (Flesch et al., 2007).

Emissions results

Data filtering significantly reduces the number of 10 min observation periods available for emission calculations. The amount of good emission data ranged from 7 to 235 periods depending on the experiment and the touchdown coverage criterion.

To estimate the uncertainty in an emission rate measurement we adopt a simple conceptual model of the WindTrax emission calculation and carry out a conventional uncertainty analysis. The WindTrax calculation for a measurement period is simplified and conceptually written as:

$$Q=\Delta C*K \tag{1}$$

Where Q is the calculated emission rate, ΔC is the measured concentration difference between the upwind and downwind laser ($C_{\text{down}} - C_{\text{up}}$), and K is the WindTrax model dispersion coefficient for the observation (i.e., $Q/\Delta C$). Uncertainty in Q (δQ) results from the uncertainty in the measured ΔC ($\delta\Delta C$) and the WindTrax K (δK). Assuming the uncertainties are random and independent, the error propagation rule gives the fractional uncertainty in Q (Taylor, 1982). Assuming that the uncertainties are random and independent, the error propagation rule for the model in Eq. (1) gives the fractional uncertainty in Q from the fractional uncertainties in ΔC and K:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta(\Delta C)}{\Delta C}\right)^2 + \left(\frac{\delta K}{K}\right)^2} \tag{2}$$

We estimate the uncertainty in the measured concentration (δC) of the individual lasers is between 0.02 and 0.04 ppm. If we take δC = 0.04 ppm, the uncertainty in a concentration difference ΔC is $\delta(\Delta C) = (2\ \delta C^2\ )^{1/2}$ = 0.057 ppm.

A rigorous determination of the uncertainty in the WindTrax model calculation δK is a difficult problem given the complexity of the WindTrax model and the number of model inputs (which have their own uncertainties). We turn to tracer release studies that have documented the accuracy of the WindTrax model in calculating emissions. Harper et al. (2010) includes an appendix where the results of several WindTrax verification studies are tabulated. The results of these studies indicate that the relative uncertainty in a WindTrax calculation is 0.20 (given by the standard deviation of the fractional uncertainty in the various experimental datasets). We thus assume the relative uncertainty δK/K = 0.20.

Table S2.1. *Emissions rates calculated from the Leucaena and pasture paddocks for the three experiments. Results are presented for two choices of WindTrax touchdown coverage (0.95 and 1.0) and are expressed in g CH_4 hd^{-1} d^{-1}. The average emission rate (Ave), the standard deviation of the emission rates (Std Dev) and the number of 10 min observation periods (Nobs) are given.*

	Touchdown coverage >= 0.95				**Touchdown coverage = 1.00**		
Experiment	**Ave**	**Std Dev.**	**Nobs**		**Ave**	**Std Dev.**	**Nobs**
March 2013							
Leucaena	179	189	180		150	132	109
Pasture	177	101	292		185	99	229
June 2013							
Leucaena	135	112	235		133	105	183
Pasture	165	124	96		161	91	70
March 2014							
Leucaena	281	142	35		277	113	23
Pasture	279	96	31		249	80	7

The calculated average emission rates from the Leucaena and pasture paddocks are given in in Table S2.1 and Fig. S2.2. Average emission rates ranged from 133 to 281 g CH_4 hd^{-1} d^{-1}. Some notable features of this dataset:

- Increasing the $tdcov_{\text{thres}}$ from 0.95 to 1.0 acted to reduce the standard deviation of the emission calculations (i.e., removed outliers), particularly for the Leucaena March 2013 results. This argues for using a high $tdcov_{\text{thres}}$ if possible. However, we note the large number of observations that are lost as the threshold is increased from 0.95 to 1.0.
- The March 2014 dataset is limited by the number of good observation periods. This makes it difficult to impose the preferred $tdcov_{\text{thres}} = 1.0$ filtering criteria, which decreases our confidence in the 2014 results. Even with a relaxed $tdcov_{\text{thres}} = 0.95$ the number of observations in 2014 is much smaller than the 2013 experiments.
- The uncertainties of the individual emission observations are large, often above 50% (Fig. S2.3). This high uncertainty is due to the relatively low concentration rise downwind of the paddocks (ΔC) compared to the estimated uncertainty in the laser measurement (0.057 ppm). We note the occurrence of negative emission rates in the dataset. In the vast majority of cases the negative values are not different from zero (i.e., the uncertainty range of the measurement spans zero). Negative emission values are inevitable given the relatively small concentration rises being measured, and these values are mirrored by erroneously large emission rates with similarly high uncertainty.
- Even though the measurement uncertainty of the individual 10 min emission rates is large, the uncertainty in the overall average emission rate is surprisingly small. This is due to the fact that the addition of random errors in the summing process (to give averages) tends to cancels out uncertainties: the uncertainty in the sum of a set of observations is given by the square root of

the sum of squares of the individual uncertainties (i.e., a small value). In the case illustrated in Fig. S2.3 the average emission rate is 185 g hd^{-1} d^{-1}, while the measurement uncertainty is only 11 g hd^{-1} d^{-1}.

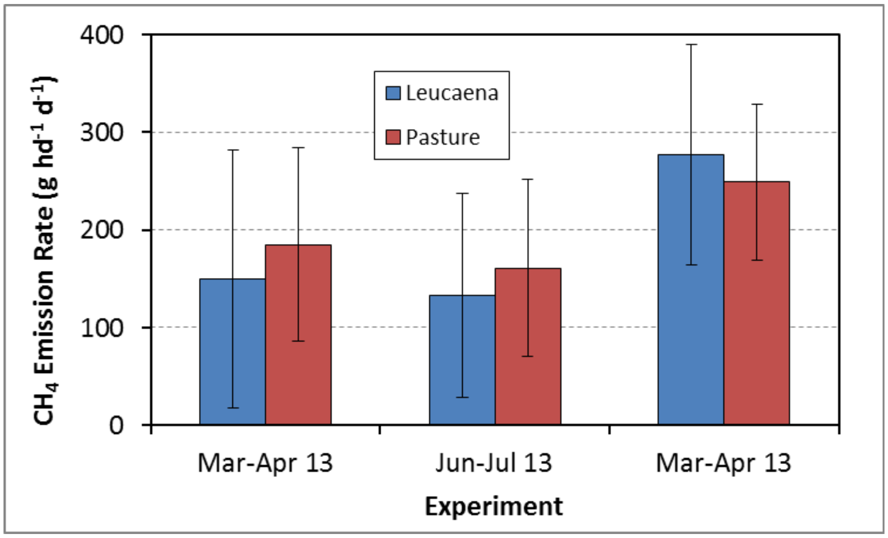

Fig. S2.2. *Comparison of daily emission rates (per animal) from the Leucaena and pasture paddocks over the three experiments. Here we display the results using tdcov$_{thres}$ = 1.0.*

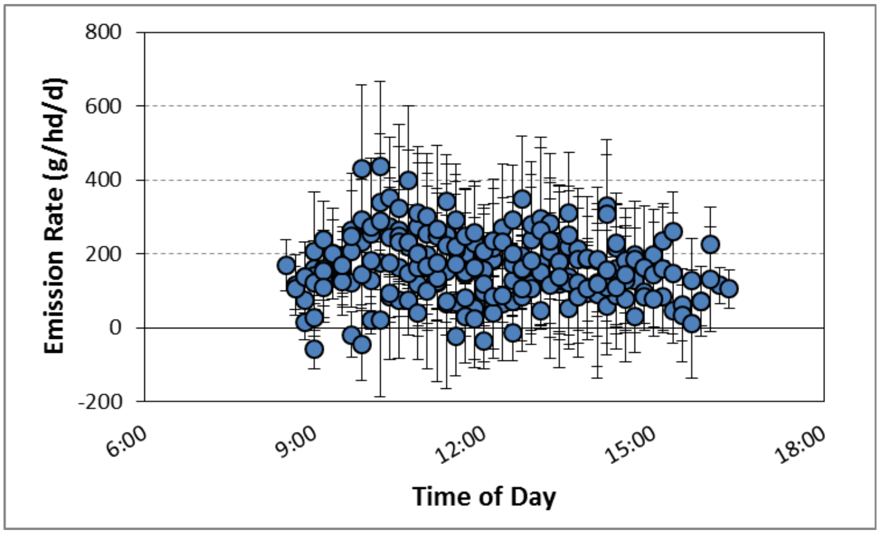

Figure S2.3. *Example of calculated emission rates (10 min averages) plotted versus time-of-day of measurement (pasture, March 2013). Error bars represent the measurement uncertainty of the calculation.*

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