

# Underlying Ecosystem Emissions Exceed Cattle-Emitted Methane from Subtropical Lowland Pastures

Samuel D. Chamberlain,<sup>1\*</sup> Elizabeth H. Boughton,<sup>2</sup> and Jed P. Sparks<sup>1</sup>

<sup>1</sup>Department of Ecology and Evolutionary Biology, Cornell University, E409 Corson Hall, Ithaca, New York 14853, USA; <sup>2</sup>MacArthur Agro-ecology Research Center, 300 Buck Island Ranch Road, Lake Placid, Florida 33852, USA

## ABSTRACT

Cattle are a major methane (CH<sub>4</sub>) source from pasture ecosystems; however, the underlying landscape can be a significant and unaccounted source of CH<sub>4</sub>. In general, landscape CH<sub>4</sub> emissions are poorly quantified, vary widely across time and space, and are easily underestimated if emission hotspots or episodic fluxes are overlooked. In this study, CH<sub>4</sub> emissions from subtropical lowland pastures were quantified using static chambers, eddy covariance, and mobile spectrometer surveys. Landscape emissions were the dominant CH<sub>4</sub> source, and cattle were responsible for 19–30% of annual emissions. The entire ecosystem emitted  $33.84 \pm 2.25 \text{ g CH}_4 \text{ m}^{-2} \text{ y}^{-1}$  as estimated by eddy covariance-measured fluxes. Landscape emissions were highly variable, and seasonal flooding drove high magnitude emissions from the underlying landscape. Large CH<sub>4</sub> emissions were observed from wetlands and, to a lesser extent, from the

entire landscape during the wet season. In contrast, during the dry season, there were no appreciable landscape CH<sub>4</sub> emissions, although canals, which cover only 1.7% of the total land area, were responsible for 97.7% of dry-season emissions. Ecosystem CH<sub>4</sub> fluxes, measured by eddy covariance, varied seasonally and positively correlated to water table depth, soil and air temperatures, and topsoil water content. The results presented here are the first to use mobile spectrometers to map biogenic CH<sub>4</sub> emissions at the landscape scale, and strongly suggest that the underlying landscape is a strong CH<sub>4</sub> source that must be considered in addition to cattle emissions.

**Key words:** methane; eddy covariance; mobile spectrometry; pasture; cattle; greenhouse gas budget; everglades; subtropics.

## INTRODUCTION

Pastures are globally widespread and play an important role in greenhouse gas exchange and

terrestrial carbon (C) storage. Pastures and rangelands cover approximately 22% of global ice-free surface and remove about  $0.2 \text{ Pg C y}^{-1}$  from the atmosphere (Ramankutty and other 2008; Follett and Reed 2010). These ecosystems are also major sources of methane (CH<sub>4</sub>), a greenhouse gas with a warming potential around 25 times higher than carbon dioxide (CO<sub>2</sub>) over a 100-year time horizon (Forster and other 2007). Pasture CH<sub>4</sub> sources are biogenic, and include cattle, saturated soils, and open water, where Archaea produce CH<sub>4</sub> under low-redox anaerobic conditions (Conrad 2007).

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\*Corresponding author; e-mail: sdc84@cornell.edu

Cattle and wetland emissions are important components of the global CH<sub>4</sub> budget, and emit roughly 80 and 105 Tg CH<sub>4</sub> y<sup>-1</sup> to the atmosphere, respectively (Bridgham and other 2006; Lassey 2007). Pasture CO<sub>2</sub> uptake is particularly high in tropical and subtropical regions and may offset CH<sub>4</sub> emissions from grazing cattle (Conant and Paustian 2002; Soussana and other 2010). However, CO<sub>2</sub> and CH<sub>4</sub> exchanges in these environments are rarely evaluated simultaneously.

To date, observations of pasture greenhouse gas exchange have focused primarily on temperate upland or peatland pastures. Cattle emissions are generally considered the dominant component of these pasture CH<sub>4</sub> budgets, and can be estimated with some degree of certainty using emission factors and cattle stocking data (Nieveen and other 2005; Allard and other 2007; Lassey 2007; Teh and other 2011; United States Environmental Protection Agency 2012). However, lowland pastures may exhibit considerable CH<sub>4</sub> emissions from the seasonally flooded landscape in addition to direct cattle emissions. Methane fluxes from seasonally flooded ecosystems are globally significant and highly uncertain (Melack and other 2004; Kirschke and other 2013). These landscape emissions tend to vary across time and space, are commonly driven by landform 'hotspots' or episodic fluxes, and are often difficult to estimate without direct measurement (Schrier-Uijl and other 2010a; Teh and other 2011).

Large areas of lowland pasture are located within the northern Everglades watershed of south Florida. Pasture development in the region was facilitated by large-scale drainage efforts that allowed year-round settlement of a once seasonally flooded ecosystem (Bohlen and other 2009). Unlike peatlands found in the Everglades to the south, the northern Everglades watershed is characterized by sandy mineral soils. The pre-drainage landscape was primarily dry and wet prairie containing a mosaic of embedded depressional wetlands, and sheet flow during the wet season would flood both prairie and wetlands. The watershed was heavily drained between 1940 and 1970 for flood control and cattle ranching (Swain and other 2013), and within the watershed today, improved pasture is the dominant land use and covers more than 35% of the total land area (Hiscock and other 2003). Improved pastures are actively managed, fertilized, and planted with introduced forage for livestock.

The northern Everglades watershed retains many pre-drainage characteristics. Although drainage and water management has reduced seasonal flooding, depressional wetlands and ditches rou-

tinely flood during the wet season, and entire pastures flood during heavy wet seasons (Bohlen and Gathumbi 2007; Bohlen and Villapando 2011). Flooded pastures may be responsible for high magnitude CH<sub>4</sub> emissions that vary across time and space, yet the magnitude of these fluxes remains unknown.

Pasture and other natural and managed ecosystem CH<sub>4</sub> fluxes are commonly quantified by eddy covariance, static chamber techniques, or a combination of these two (Allard and other 2007; Rinne and other 2007; Kroon and other 2010; Dengel and other 2011; Herbst and other 2011; Teh and other 2011; Baldocchi and other 2012; Hatala and other 2012; Wang and other 2012; Nicolini and other 2013; Olson and other 2013; Matthes and other 2014). Combining these methods allows for a more holistic understanding of variable ecosystem CH<sub>4</sub> fluxes. However, emission hotspots are often a significant component of ecosystem greenhouse gas budgets (Groffman and other 2009; Schrier-Uijl and other 2010a; Teh and other 2011), and important hotspots may be overlooked depending on sampling effort, chamber placement, and tower placement. To address this issue, this study mapped CH<sub>4</sub> concentrations spatially to ensure a complete consideration of hotspot emissions using a mobile wavelength-scanned cavity ring down spectrometer (WS-CRDS).

The goals of this work were to (1) quantify the spatial and temporal variability of landscape fluxes from subtropical pastures, (2) determine the controls of these fluxes, and (3) compare the magnitude of the underlying landscape fluxes to that of cattle grazing the landscape. To quantify these potentially variable fluxes, we used chambers to measure fluxes from dominant landforms across season and determined the response of pasture CH<sub>4</sub> fluxes to large episodic rain events, eddy covariance to measure the seasonal variability of ecosystem CH<sub>4</sub> fluxes, and mobile WS-CRDS surveys to map CH<sub>4</sub> concentrations during dry and wet seasons. To our knowledge, this is the first study to use WS-CRDS mobile surveys to map biogenic CH<sub>4</sub> emissions at the landscape scale. We expected emissions to be highly variable across time and space, and expected large emissions to be driven by wet-season flooding of low-lying landforms. We also expected that emission from the underlying landscape would approach the magnitude of emissions from cattle stocked within the pasture. This study quantifies variable ecosystem fluxes from subtropical pastures, provides a comparison between landscape and the cattle-emitted CH<sub>4</sub>, and estimates an overall CH<sub>4</sub> budget for subtropical lowland pastures in south Florida.

## METHODS

### Study Sites

All measurements were made between 2012 and 2014 within a single improved pasture (Griffin Park pasture; 92.1 ha) at the MacArthur Agro-Ecology Research Center (MAERC), a 4290-ha commercial cattle ranch and ecological field station (a division of Archbold Biological Station; N 27.1632004, W 81.187302). The Griffin Park pasture contains three depressional wetlands, cabbage palm hammocks, a network of drainage ditches, and regularly inundated canals. The pasture is planted with Bahia grass (*Paspalum notatum*), an introduced forage species, and is rotationally grazed by cattle. Cattle were grazed at a moderate density ( $\sim 1.6$  cow ha<sup>-1</sup>) recommended for south Florida pastures (Hersom 2002). Herbicide and fertilizer have not been applied to the pasture since August 2006 and April 2007, respectively. Soils are primarily poorly drained spodosols. The area averages 1300 mm of rain per year, 75% of which falls in the summer wet season (Gathumbi and other 2005).

### Eddy Covariance Measures

An eddy covariance tower within the pasture (N 27.1632004, W 81.187302) measured continuous fluxes of heat, energy, water vapor, CO<sub>2</sub>, and CH<sub>4</sub>. This tower is integrated within a five-tower array at MAERC measuring ecosystem fluxes from multiple land uses. A three-dimensional sonic anemometer measured wind speed and direction (CSAT3, Campbell Scientific Inc., Logan, UT, USA) and open-path infrared gas analyzers measured H<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> concentrations (LI-7500A and LI-7700, Licor Inc., Lincoln, NE, USA). All instrumentation was installed 2.6 m above the ground surface and interfaced with a LI-7550 datalogging system (Licor Inc, Lincoln, NE, USA). All data were collected at 10 Hz and transferred by modem for processing and analysis. Water table depth (m below surface) was monitored at the tower with a CS451 pressure transducer (Campbell Scientific Inc., Logan, UT, USA). Soil volumetric water contents (VWC; m<sup>3</sup> m<sup>-3</sup>) were measured at 5, 10, and 20 cm below land surface using CS-616 water content reflectometers (Campbell Scientific Inc., Logan, UT, USA). Soil and air temperatures (°C) were also measured at 5, 10, and 20 cm below land surface with copper–constantan thermocouples. All auxiliary measures were reported at 30-min intervals and logged to a CR3000 datalogger (Campbell Scientific Inc., Logan, UT, USA) time synchronized to the LI-7550.

All fluxes were computed as the covariance of vertical wind velocity and gas concentration over 30-min intervals. Raw data were screened for spikes, amplitude resolution, drop-outs, absolute value limits, and skewness and kurtosis with tests as described in Vickers and Mahrt (1997) and designated default in EddyPro 4.2 (Licor Inc., Lincoln, NE, USA). We applied double-rotation tilt corrections to align anemometer measurements with respect to mean wind streamlines, and used block averaging to calculate the mean wind speeds and gas concentrations over the 30-min flux interval. Time lags between the measured variables were corrected using the covariance maximization method. The Webb, Pearman, and Leuning corrections for density fluctuations were applied according to Webb and other (1980); fully analytic spectral corrections were applied according to Moncrieff and other (1997); and data quality was flagged according to Foken and other (2005). Quality flags range from 1 (best) to 9 (worst), and fluxes were rejected with flags greater than 6. We estimated the tower footprint according to Hsieh and other (2000). All the above corrections and data processing were completed in EddyPro 4.2 (Licor Inc., Lincoln, NE, USA). We used friction velocity ( $\mu^*$ ) filtering to remove all nighttime fluxes collected during periods of low turbulence ( $\mu^* < 0.14$  m s<sup>-1</sup>) following methods in Aubinet and other (2012). Overall, 53% of all the half-hourly fluxes were removed from the long-term dataset according to quality flag and  $\mu^*$ -threshold criteria.

### Mobile WS-CRDS Surveys

To quantify spatial heterogeneity of CH<sub>4</sub> emissions from the pasture, real-time CH<sub>4</sub> concentrations were measured using a mobile WS-CRDS (G2201-*i*, Picarro Inc., Sunnyvale, CA, USA) installed in an off-road vehicle (Ranger, Polaris Industries, Medina, MN, USA). This technique has been used to survey CH<sub>4</sub> leaks from refineries, industry, cities, and natural gas infrastructure (Shorter and other 1996; Farrell and other 2013; Leifer and other 2013; Phillips and other 2013; Jackson and other 2014). Air samples were drawn through perforations in ¼" Teflon tubing attached to the vehicle's front bumper ( $\sim 0.5$  m above ground surface) covered with PTFE membrane filters. We used the Picarro Investigator mobile system (Picarro Inc., Sunnyvale, CA, USA) in the wet season, and a self-designed custom system in the dry season. For both configurations, a 12-V battery bank supplied power, and GPS recorded location at 1-second intervals.

The Investigator system merged location data with G2201-*i* output using Picarro P3 software (Picarro Inc., Sunnyvale, CA, USA), whereas the custom system recorded GPS location (GPS18x, Garmin Ltd., Olathe, KS, USA) in a separate file and then WS-CRDS and GPS data files were merged post-survey. Time lags between GPS location and CH<sub>4</sub> measurements due to sample tubing length (~3.7 m) were corrected by measuring the time delay between gas standard injections at the bumper inlet and G2201-*i* response. GPS location was then matched with delay-corrected CH<sub>4</sub> concentration measurements during data processing. The G2201-*i* was calibrated with known standards of CH<sub>4</sub> in air (AirLiquide, Philadelphia, PA, USA).

We surveyed north-to-south transects to evenly sample the pasture and all major landforms, and conducted surveys at night when atmospheric turbulence was low. Gas concentrations at the land surface are generally higher at night due to decreased wind speed and increased atmospheric stability, and mobile surveys of CH<sub>4</sub> plumes are commonly conducted at night for this reason (Shorter and other 1996; Farrell and other 2013; Leifer and other 2013). The same transect was followed on four nights during the wet seasons (2013-08-23, 2013-08-25, 2013-09-01, 2013-09-02) and four nights during the dry seasons (2014-03-26, 2014-03-30, 2014-04-01, 2014-04-03). Data were visualized by kriging CH<sub>4</sub> concentrations across a coordinate grid (see *Statistical Analysis and Geostatistical Mapping* below). Emission maps were then compared to LIDAR remote sensing imagery of the pasture obtained from the MacArthur Agroecology Research Center (<http://www.archbold-station.org/html/datapub/data/spatialdata.html>). Kriged concentrations and uncertainties, as well as atmospheric and environmental conditions for all surveys, are presented in Supplemental Materials.

## Chamber Flux Measure

All chamber fluxes were measured between June 2012 and July 2014. Within each year, fluxes were measured in both dry and wet seasons. Wet-season (May–October) fluxes were measured during August–September 2013 and June–July 2014. Dry-season (November–April) fluxes were measured during February–March 2013 and March–April 2014. All chamber measurements took place within the pasture containing the eddy covariance tower. Landform fluxes were measured from improved pasture, palm hammocks, ditches, canals, and depression wetlands. Three chamber collars were installed 3 m from one another within each land-

form and sampled concurrently. Chamber fluxes from each landform were measured biweekly. Soil collars were inserted 3 cm into the ground and enclosed a 0.065-m<sup>2</sup> area. When the water level was too deep to insert collars (>3 cm above ground surface), fluxes were measured from the water surface using three floating chambers. Floating chambers enclosed a 0.037-m<sup>2</sup> area and 6.71-l volume. Soil and floating chambers were pressure vented to the atmosphere. Soil chambers were installed 5 days prior to initial sampling to minimize the impact of disturbance on measured fluxes.

Chamber headspaces were closed for 30 min, and four gas samples were withdrawn using a 60-ml syringe at 30 s, 10 min, 20 min, and 30 min after closure. Gas samples were transferred to 22-ml pre-evacuated gas vials sealed with Geo-Microbial Technologies septa (Geo-Microbial Technologies Inc., Ochsleata, OK, USA). All the samples were analyzed for CO<sub>2</sub> and CH<sub>4</sub> concentrations on a Picarro G2201-*i* analyzer equipped with a Picarro SSIM2 Small Sample Isotope Module (Picarro Inc., Sunnyvale, CA, USA). The G2201-*i* and SSIM2 were calibrated with known standards of CH<sub>4</sub> in air (Air Liquide, Philadelphia, PA, USA). All samples were analyzed within 3 months of collection. Methane travel standards (10 ppm) detected no leakage between collection and analysis. Chamber fluxes were calculated by applying a linear regression to concentrations over time ( $P < 0.05$ ), and the fluxes that did not meet the regression criteria were omitted from analyses. Exceptions were made when CH<sub>4</sub> concentration varied less than 0.2 ppm throughout the closure period. In such cases, fluxes that did not meet the  $P < 0.05$  linear regression criteria were set to zero. For floating chambers, ebullition fluxes were analyzed separately and were assumed to occur when CH<sub>4</sub> concentration abruptly and nonlinearly rose during chamber closure. Ebullition fluxes were calculated as the total concentration increase over the 30-min closure period.

Soil temperature (°C), volumetric water content (VWC; m<sup>3</sup> m<sup>-3</sup>), and water table depth (m below surface) was monitored at the time of chamber measurement. Soil temperatures were measured every 30 min at 5-cm depth with buried HOBO Pendant dataloggers (Onset Co., Bourne, MA). Volumetric water content (0–5 cm) was measured using a handheld TDR probe (ML2, Delta-T Devices Ltd. Cambridge, UK) and reported as the average of four measurements taken directly outside of the chamber base. Water table depth (m below surface) was measured from an augered well

at each chamber site. For each floating chamber, we measured water temperature ( $^{\circ}\text{C}$ ) at 30-min intervals with HOBO Pendant dataloggers (Onset Co., Bourne, MA).

### Stimulated Large Rain Event

Large rain events were defined as more than 2 in. of rain occurring over a 48-h period. From 1969 to 2012, rain events fitting these criteria have occurred in the northern Everglades watershed approximately four days per year (Florida Climate Center 2013). Two simulated rain events were conducted in February 2012. We simulated large rain events in the dry season to quantify the effect of episodic rains on pasture  $\text{CH}_4$  fluxes. We applied 2 in. of water over a  $0.5\text{ m} \times 1.5\text{ m}$  marked area containing three equidistant soil chambers. Water was spread evenly across the entire area over the span of 10 min using a large plastic tub with perforated holes in the base. Chamber fluxes were then measured at  $-1$ , 0.25, 1.5, 3.5, 6, 12, and 24 h after water addition using the methods described above.

### Methane Budget and Cattle Emission Estimates

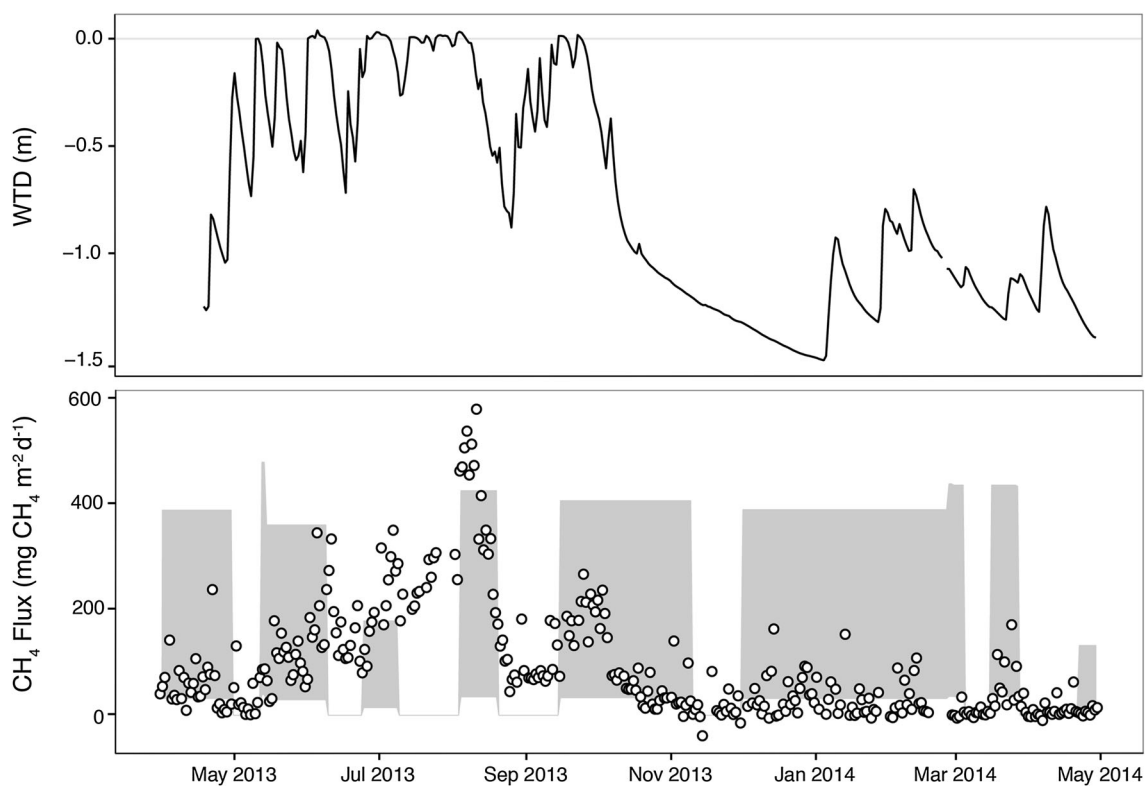
Annual  $\text{CH}_4$  budgets were estimated using three strategies: (1) scaling from spatially weighted landform fluxes, (2) eddy covariance, and (3) total cattle emissions estimated by Tier 2 IPCC guidelines. All budgets were calculated from 2013-05-01 to 2014-04-30. This time period was chosen to cover one annual wet-dry cycle. For the chamber-based budget, we estimated the areal extent of each landform in GoogleEarth Pro (Google Inc., Mountain View, CA, USA) weighing the contribution of each landform flux by percent land cover of the entire pasture. Wet-season fluxes were applied from 2013-05-01 to 2013-10-31, and dry-season fluxes were applied from 2013-11-01 to 2014-04-30. Only fluxes measured within the one-year time frame were applied with the exception of wet-season hammock fluxes. For wet-season hammock fluxes, we applied values measured during the wet season in 2014 because no hammock fluxes were measured during the wet season in 2013.

The annual eddy covariance budget was calculated as the sum of 365 daily mean  $\text{CH}_4$  fluxes. Daily fluxes were estimated following the methods outlined in Rinne and other (2007). For days with data coverage greater than 33%, daily fluxes were calculated as the mean of all half-hourly measurements scaled over the 24-h day. Diurnal var-

iation in half-hourly fluxes was not observed in either season, and we therefore did not introduce systematic bias to daily estimates by scaling daily datasets with greater than 33% coverage. Days with less than 33% coverage were gap-filled by linear interpolation. Fourteen percent of days in the year were gap-filled, and the longest gap-filled period was nine days.

Total cattle emissions were estimated for the Griffin Park pasture using IPCC Tier 2 emission factors generated from cattle management data supplied by MAERC and suggested input data for Florida beef cattle (IPCC 2006; EPA 2014). Emission factors were estimated for both direct  $\text{CH}_4$  emissions from enteric fermentation and  $\text{CH}_4$  emissions from manure deposited on pasture. Cattle emission estimates were generated using herd size, average weight, percent of cows pregnant, and forage information for herds grazing the Griffin Park pasture from 2013-05-01 to 2014-04-30. Using IPCC Tier 2 guidelines, we estimated gross energy intake ( $\text{MJ d}^{-1}$ ) and consequent emission factors ( $\text{kg CH}_4\text{ animal}^{-1}\text{ y}^{-1}$ ) for two sub-categories of cattle grazing the pasture: (1) mature nonpregnant cows and (2) mature pregnant cows. These categories were chosen based on the availability of sufficient cattle management data. A complete discussion of the Tier 2 estimation process is further outlined within Supplemental Materials. Manure and enteric fermentation  $\text{CH}_4$  budgets were calculated at a daily time scale accounting for herd size and the percentage of herd pregnant within the pasture. Cattle emission estimates were then divided by the total area of the Griffin Park pasture (92.1 ha) to yield comparable units of  $\text{g CH}_4\text{ m}^{-2}\text{ y}^{-1}$ .

Cattle management data were also used to bound the potential contribution of enteric fermentation emissions to the eddy covariance-measured fluxes, assuming cattle were (1) equally dispersed across the entire pasture (by dividing daily enteric fermentation emissions by the entire pasture area), or (2) all located within the tower footprint area (by dividing daily enteric fermentation emissions by the annual mean 90% tower footprint area). These estimates are presented in Figure 1 and were used to place general bounds on the potential contribution of the enteric fermentation-emitted  $\text{CH}_4$  to net ecosystem fluxes. Footprint area was estimated by calculating the 90% footprint fetch and lateral spread using models outlined in Hsieh and other (2000) and Detto and other (2006), respectively. The footprint area was averaged across the entire measurement period so that potential cattle emissions reflected changes in stocking density, rather



**Figure 1.** Water table depth (WTD; *top panel*) and daily mean CH<sub>4</sub> fluxes (*bottom panel*) measured by eddy covariance. The shaded area on the *bottom panel* represents the potential range of cattle-emitted CH<sub>4</sub> throughout the measurement period. The 90% flux footprint area was averaged over the entire measurement period to normalize potential cattle emissions, and was calculated according to models in Hsieh and other (2000) and Detto and other (2006).

than day-to-day variability, in the footprint area. The estimated footprint area (fetch = 541 m, lateral spread = 177 m, area = 75207 m<sup>2</sup>) encompassed 8% of the total pasture area. These theoretical cattle enteric fermentation emission bounds are referred to throughout as ‘potential cattle emissions.’

### Statistical Analysis and Geostatistical Mapping

All spatial survey data were kriged in R 3.0.1 using the ‘sp’ and ‘gstat’ packages (R Core Team 2013). Pasture CH<sub>4</sub> concentrations were interpolated across a 2 m × 2 m two-dimensional coordinate grid (460 × 590 grid cells) using ordinary kriging. A semivariogram was produced from the measured concentrations, and the kriged concentrations were predicted using the exponential model:

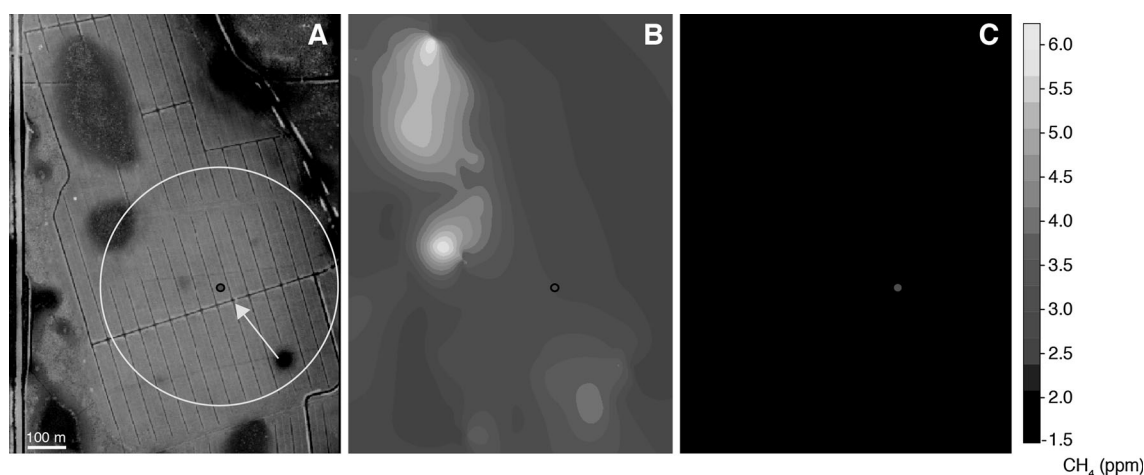
$$\gamma(h) = C_0 + C_1 \cdot \left[1 - e^{-\left(\frac{h}{a}\right)}\right] \quad \text{when } |h| > 0 \quad (1)$$

where  $h$  is the distance between locations,  $\gamma(h)$  is the predicted semivariance at a distance  $h$ ,  $C_0$  is the nugget,  $C_0 + C_1$  is the sill, and  $a$  is the range.

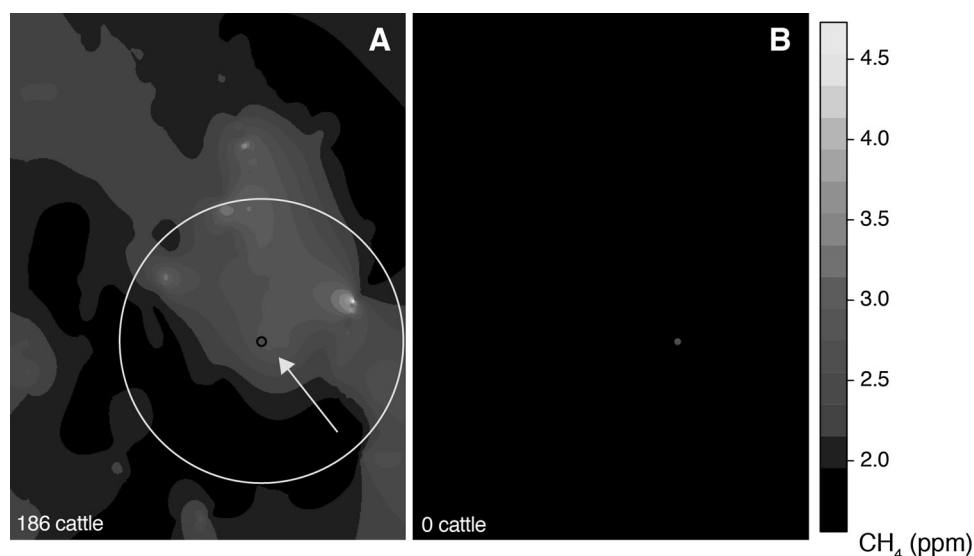
We used Kruskal–Wallis nonparametric ANOVA to evaluate whether landform CH<sub>4</sub> fluxes exhibited significant spatial and temporal variability; Mann–Whitney U tests to determine whether landform fluxes varied seasonally; and Tukey’s HSD analyses to determine significant mean differences for comparisons between environmental variables and fluxes in the simulated rain treatment. Linear regression was used to determine significant relationships between environmental variables, landform fluxes, and daily-averaged ecosystem fluxes. Methane fluxes were logtransformed to meet assumptions of normality. All regressions of eddy covariance fluxes to environmental variables were conducted on daily-averaged values due to high levels of random error in half-hourly fluxes.

### RESULTS

Ecosystem CH<sub>4</sub> fluxes, measured by eddy covariance, were high from the pastures. Emissions peaked during the wet season (May–October) when the water table rapidly approached the land



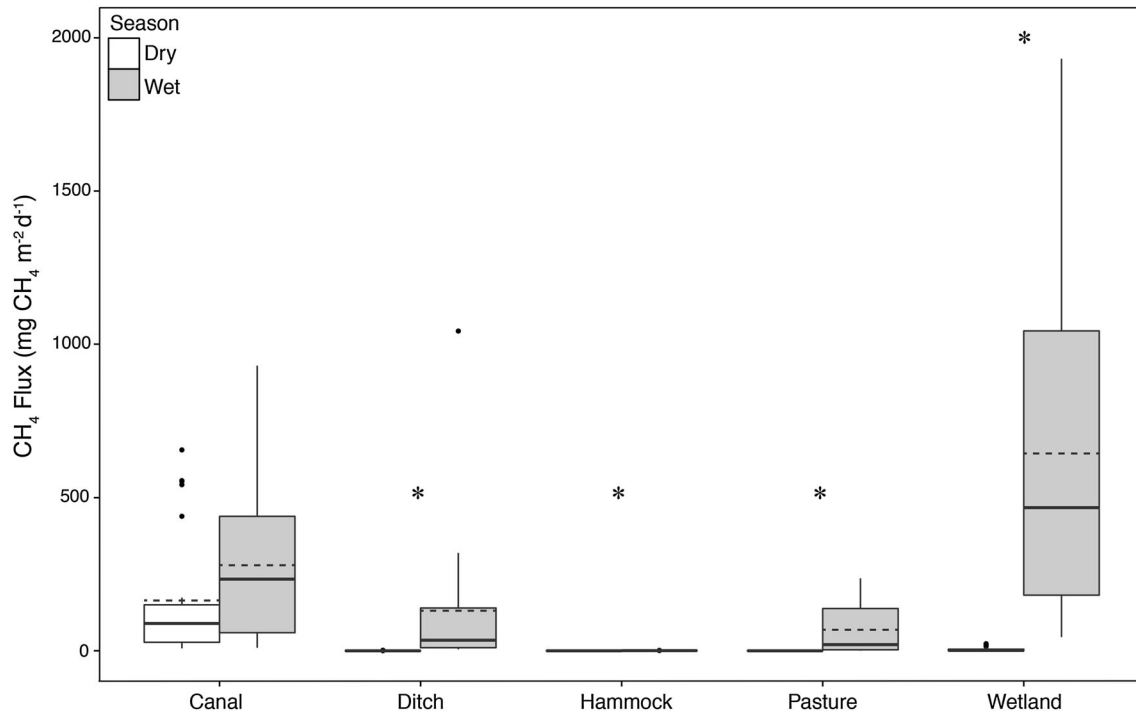
**Figure 2.** LIDAR imagery (**A**) and kriged CH<sub>4</sub> concentrations above pasture in wet (**B**) and dry (**C**) seasons. Darker zones on LIDAR map are areas of lower surface elevation and correspond to depression wetlands, ditches, and canals. The dots on **A**, **B**, and **C** mark the location of the eddy covariance tower. The circle and arrow on **A** represent the mean annual 90% daytime tower footprint (286 m) and predominant wind direction, respectively.



**Figure 3.** Kriged CH<sub>4</sub> concentrations above dry-season pasture with (**A**) and without (**B**) grazing cattle. Increased CH<sub>4</sub> concentrations in the pasture with grazing cattle correspond to the location of cattle herds; 186 cattle were present in **A**. The dots on **A** and **B** mark the locations of the eddy covariance tower. The circle and arrow on **A** represent the mean annual 90% daytime tower footprint (286 m) and predominant wind direction, respectively.

surface and flooded the pasture (Figure 1). At the onset of the dry season (November–April), the water table retreated from the land surface to about 1 m below surface, and CH<sub>4</sub> emissions reduced to near zero fluxes concurrently. Positive emission spikes were observed throughout the dry season (Figure 1). Cattle were rotationally grazed at a moderate stocking density ( $\sim 1.6$  cows ha<sup>-1</sup>) throughout the pasture during the measurement period and likely contributed to the observed ecosystem fluxes. Potential cattle emissions (enteric fermentation only) are represented in Figure 1 as

the gray-shaded range on the bottom panel. Upper bounds of the shaded range assume all cattle within the pasture were located within the mean tower footprint area ( $\sim 8\%$  of total pasture area), and the lower bounds assume all cattle were equally dispersed throughout the pasture. Potential cattle emissions are zero when no cattle were stocked within the pasture. Comparing the measured fluxes with potential cattle emission estimates suggest that cattle may be responsible for the observed dry-season emission spikes when cattle graze within the tower footprint (Figure 1). During the wet



**Figure 4.** Wet- and dry-season  $\text{CH}_4$  fluxes ( $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ) from major pasture landforms. *Solid lines* are medians, *dashed lines* are means, *boxes* are the interquartile ranges (IQR), and *whiskers* are  $\pm 1.5$  IQR. *Asterisks* denote significant differences in  $\text{CH}_4$  fluxes between seasons for each landform (Mann–Whitney U,  $P < 0.05$ ).

**Table 1.** Landform Area (ha), Percent Cover, and Fluxes of  $\text{CH}_4$  ( $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ) in Subtropical Lowland Pastures

| Landform | Area  | % Cover | Dry season                 | Wet season                  | Annual                      |
|----------|-------|---------|----------------------------|-----------------------------|-----------------------------|
| Canal    | 1.55  | 1.7     | $166.97 \pm 42.44\text{a}$ | $280.35 \pm 64.70\text{a}$  | $213.98 \pm 37.13\text{ab}$ |
| Ditch    | 3.68  | 4.0     | $0.08 \pm 0.07\text{b}$    | $267.22 \pm 150.88\text{a}$ | $117.36 \pm 68.46\text{a}$  |
| Hammock  | 8.48  | 9.2     | $-0.42 \pm 0.09\text{b}$   | $0.52 \pm 0.11\text{a}$     | $0.02 \pm 0.13\text{a}$     |
| Pasture  | 68.3  | 74.2    | $-0.27 \pm 0.04\text{b}$   | $67.46 \pm 13.99\text{a}$   | $30.32 \pm 7.60\text{a}$    |
| Wetland  | 10.06 | 10.9    | $2.79 \pm 0.95\text{b}$    | $692.72 \pm 110.10\text{b}$ | $327.46 \pm 66.40\text{b}$  |

Standard errors reported for all landform fluxes. Letters indicate significant differences between mean fluxes (Tukey's HSD,  $P < 0.05$ ).

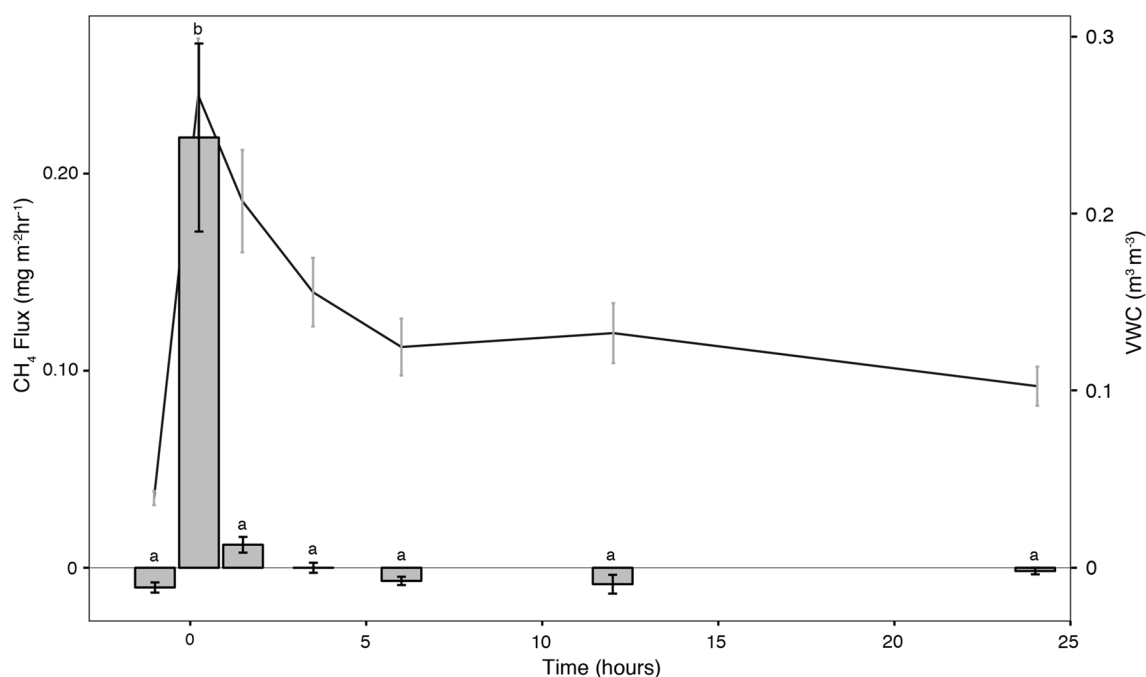
season, ecosystem fluxes generally exceeded potential cattle emissions and persisted in the absence of cattle, strongly suggesting soil and water  $\text{CH}_4$  sources (Figure 1).

Ecosystem  $\text{CH}_4$  fluxes were positively correlated to fluctuations in the water table ( $r^2 = 0.49$ ,  $P < 0.0001$ ), topsoil water content ( $r^2 = 0.54$ ,  $P < 0.0001$ ), and soil temperature ( $r^2 = 0.46$ ,  $P < 0.0001$ ). Water table depth and topsoil water content were highly co-linear ( $r^2 = 0.94$ ;  $P < 0.0001$ ). No other related environmental variables displayed correlation coefficients greater than 0.90. The daytime 90% tower fetch averaged 286 m over the entire measurement period and encompassed

improved pasture, ditches, and some depressional wetlands (Figure 2).

Large variability was observed in the spatial structure and magnitude of  $\text{CH}_4$  plumes between dry and wet seasons (Figure 2). Interpolated concentration maps were compared with LIDAR imagery from the site to identify  $\text{CH}_4$  emission sources across the pastures. Darker zones on the LIDAR imagery are lower topographically and correspond to depressional wetlands, ditches, and canals within the pasture landscape (Figure 2A). Methane concentration plumes were the largest above depressional wetlands during the wet season (Figure 2B), and the wet-season background  $\text{CH}_4$  concentrations were 33%





**Figure 5.** Methane fluxes (*bar*;  $\text{mg m}^{-2} \text{h}^{-1}$ ) and topsoil (0–5 cm depth) volumetric water contents (*line*;  $\text{m}^3 \text{m}^{-3}$ ) following simulated rain event. Mean and standard error are presented for both fluxes and topsoil water content. The rain event occurred at time zero, and *letters* above  $\text{CH}_4$  flux values indicate significant differences between fluxes (Tukey's HSD < 0.05).

higher than dry-season background concentrations (Figure 2B, C). No cattle were present in the pasture during these surveys. These results suggest that wetlands were a dominant  $\text{CH}_4$  source and the entire pasture landscape was producing  $\text{CH}_4$  during the wet season. Observed wet-season  $\text{CH}_4$  concentrations ranged from 1.92 to 2.42 ppm with maximum concentrations in the range of 3.95–6.90 ppm across all wet-season surveys (Supplemental Materials). Dry-season concentrations were relatively uniform and near atmospheric background across the pastures (Figure 2C), suggesting that the pasture landscape was not producing significant levels of  $\text{CH}_4$  during the dry season. When no cattle were present, dry-season  $\text{CH}_4$  concentrations ranged from 1.78 to 1.87 ppm with a maximum of 2.06 ppm (Supplemental Materials).

Cattle produced observable  $\text{CH}_4$  concentration plumes when herds were grazing the pasture (Figure 3). Cattle-derived plumes approached the magnitude of wet-season wetland plumes (Figure 2B), although cattle emissions were irregularly structured due to the transient and point source nature of the cattle-emitted  $\text{CH}_4$  (Figure 3A). Cattle  $\text{CH}_4$  plumes fell within the tower footprint (Figure 3A), also suggesting that cattle may be responsible for the observed ecosystem emission spikes

(Figure 1). Cattle were present in two of the four dry-season surveys and in none of the wet-season surveys (Supplemental Materials). When cattle were present, dry-season  $\text{CH}_4$  concentrations ranged from 1.83 to 1.84 ppm with a maximum in the range of 2.17 to 4.53 ppm, considerably larger than the range of observed concentrations in dry-season surveys when no cattle were present.

Methane fluxes from major landforms displayed high spatial and temporal variability (Figure 4; Table 1). Fluxes varied among landforms during the dry season (Kruskal–Wallis,  $P < 0.0001$ ), wet season (Kruskal–Wallis,  $P < 0.0001$ ), and independent of season (Kruskal–Wallis,  $P < 0.0001$ ; see Table 1 for post-hoc comparisons). Volumetric water content, soil temperature, and water table depth all varied across landforms (Kruskal–Wallis,  $P < 0.005$ ). During the dry season, emissions from canals ( $166.97 \pm 42.44 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ,  $n = 24$ ) and wetlands ( $2.79 \pm 0.95 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ,  $n = 36$ ) dominated the total flux, and negligible fluxes were observed from the remaining landforms. Ditches emitted  $0.08 \pm 0.07 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$  ( $n = 23$ ), and minor  $\text{CH}_4$  uptake was observed in hammocks ( $-0.42 \pm 0.09 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ,  $n = 10$ ) and pastures ( $-0.27 \pm 0.04 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ ,  $n = 34$ ). In contrast, during the wet season, all

landforms emitted CH<sub>4</sub>. Canals (280.35 ± 64.70 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, *n* = 17), ditches (267.22 ± 150.88 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, *n* = 18), hammocks (0.52 ± 0.11 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, *n* = 9), pastures (67.46 ± 13.99 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, *n* = 28), and wetlands (692.72 ± 110.10 mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>, *n* = 32) all generated positive fluxes (Figure 4; Table 1).

Fluxes from ditches (Mann–Whitney U, *P* < 0.0001), hammocks (Mann–Whitney U, *P* = 0.0003), pastures (Mann–Whitney U, *P* < 0.0001), and wetlands (Mann–Whitney U, *P* < 0.0001) varied among seasons. Canal fluxes did not vary seasonally and were the only landforms flooded year round (Figure 4). For all landforms, fluxes were higher from open water (Kruskal–Wallis, *P* < 0.0001). Ebullitive fluxes from open water were the highest emissions recorded, which comprised 7% of all the reported fluxes.

Experimental watering resulted in pulse CH<sub>4</sub> emissions (Figure 5). Fifteen minutes after the simulated rain event, CH<sub>4</sub> fluxes increased from -0.008 ± 0.002 to 0.236 ± 0.052 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> (Tukey's HSD, *P* < 0.0001), and topsoil water content increased from 0.039 ± 0.004 to 0.267 ± 0.032 m<sup>3</sup> m<sup>-3</sup> (Tukey's HSD, *P* < 0.0001). Within 1.5 h of simulated rain, CH<sub>4</sub> fluxes returned to near zero (0.013 ± 0.005 mg m<sup>-2</sup> h<sup>-1</sup>) and were not higher than pre-treatment fluxes. All the remaining time points up to 24 h did not vary from pre-treatment fluxes (Figure 5). Over the course of simulated rain treatments, CH<sub>4</sub> fluxes positively correlated to topsoil water content (*r*<sup>2</sup> = 0.26, *P* = 0.0005).

Overall, the pastures emitted between 33.84 ± 2.25 and 36.76 ± 6.57 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup>, as estimated by eddy covariance and spatially weighted chamber fluxes, respectively. Enteric fermentation emission factors were estimated to be 58.9 ± 9.1 and 63.9 ± 9.8 kg CH<sub>4</sub> animal<sup>-1</sup> y<sup>-1</sup> for nonpregnant and pregnant cows, respectively. Manure emission factors were estimated to be 2.0 ± 0.3 and 2.2 ± 0.3 kg CH<sub>4</sub> animal<sup>-1</sup> y<sup>-1</sup> for nonpregnant and pregnant cows, respectively. These emission factors are similar to Tier 1 emission factors reported by the IPCC (2006). Cattle grazing the pasture produced an estimated 8.0 ± 1.2 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> from enteric fermentation and 0.3 ± 0.1 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> from deposited manure.

## DISCUSSION

This study demonstrates that underlying landscape emissions are the dominant components of ecosystem pasture emissions, and cattle are responsible for approximately 19–30% of the annual

CH<sub>4</sub> emissions. The majority of cattle-emitted CH<sub>4</sub> was produced by enteric fermentation, and emissions from manure comprised only 2–6% of the total cattle emissions. These results suggest that cattle are not the dominant CH<sub>4</sub>-emission source in subtropical lowland pastures, and ecosystem emissions are instead driven by large fluxes from the flooded landscape. As expected, landscape emissions were highly variable across time and space (Figures 1, 2, 4) and were driven strongly by seasonal flooding and landform hotspots. Wetlands were the dominant CH<sub>4</sub> source, cover 10.9% of the pasture area, and were responsible for 53.5% of the total wet-season flux. Canals were dry-season emission hotspots, and emitted 97.7% of dry-season CH<sub>4</sub> while covering only 1.7% of the landscape (Table 1). The results presented here highlight the importance of accounting for all potential emission sources, rather than assuming cattle are the dominant CH<sub>4</sub>-emission source in pasture ecosystems. Such assumptions are generally valid in upland or well-drained ecosystems, but landscape emission sources need to be considered in low-lying flooded environments.

This work also suggests that large rains can stimulate episodic CH<sub>4</sub> emissions from pasture soils (Figure 5). However, these emissions are short lived and small, likely due to the rapid percolation of rainwater through dry sandy soils. The rain-induced emissions we observed (0.236 ± 0.052 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>) were low compared with wet-season fluxes, and were similar to dry-season wetland fluxes (0.116 ± 0.040 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>). Given the frequency of large rain events (4 per year; Florida Climate Center, 2013), the short duration of rain-induced emissions, and the high magnitude of wet-season ecosystem fluxes, it is unlikely that periodic rain-induced emissions are a significant component of the pasture CH<sub>4</sub> budgets.

Fluxes from the pastures were high compared with a number of natural and managed ecosystems. Nicolini and other's (2013) review of eddy covariance CH<sub>4</sub> studies reported mean fluxes of 2.61 ± 1.25 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> for forests (*n* = 20), 8.98 ± 3.47 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> for croplands (*n* = 6), and 27.13 ± 5.07 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> for wetlands (*n* = 59). The estimates presented here for subtropical pasture emissions are considerably higher than fluxes from other managed grasslands and pastures, and were on the high end of reported wetland fluxes (Nicolini and other 2013). Annual pasture CH<sub>4</sub> emissions are larger than estimates from temperate peatland pastures (Hendriks and other 2010; Schrier-Uijl and other 2010b; Teh and other 2011; Baldocchi and other 2012; Hatala and

other 2012), are similar to estimates from subtropical flooded savannahs and bottomland forests (Otter and Scholes 2000; Yu and other 2008), are at the low end of estimates from tropical wetlands and floodplains (Devol and other 1990; Mitsch and other 2010; Nahlik and Mitsch 2011). Annual pasture emissions are also higher than those reported for nearby Everglades' ecosystems, which range from 1.46 to 29.89 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup>, although pastures fall within the high range of emissions reported for Everglades dwarf red mangroves, swamp forests, and artificial impoundments (Harris and other 1988; Bartlett and other 1989; Whiting and other 1991). These comparisons indicate that lowland pastures are a strong and unaccounted for CH<sub>4</sub> source in regional greenhouse gas inventories. Pastures are the most common land use in the northern Everglades (Hiscock and other 2003) and appear to be a major regional source of CH<sub>4</sub>. Large annual emissions from these pastures cannot be attributed to direct cattle emissions, and the estimates presented here remain within the high range of Everglades' wetland budgets if cattle-emitted CH<sub>4</sub> (8.3 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup>) is removed from the annual budget.

High input of organic matter from cattle waste or recent photosynthate may be responsible for the large emissions we observed compared with nearby Everglades' ecosystems. Flooded manure deposits are potential CH<sub>4</sub> emission hotspots and are unlikely completely captured with the current estimation methodologies. Our manure emission estimates were calculated according to IPCC guidelines for the manure deposited on open pasture, a predominantly aerobic manure management system. Actual manure emissions are likely higher during the periods of flooding when manure is deposited directly in or leached into standing water; however, the magnitude and duration of these emissions are difficult to estimate due to the transient nature of flooding and manure deposition. In addition, the methanogenic potential of pasture soil likely varies widely between subsurface sandy horizons (>10-cm depth) and surface organic horizons (<10-cm depth), and the magnitude and variability of wet-season emissions may be driven by transient flooding of surface organic soils. Quantifying the relative importance of cattle waste versus soil organic matter as substrate for methanogenesis will improve our understanding of the variable and high magnitude fluxes from these pastures.

Preliminary eddy covariance measurements from this tower as well as partner towers in similar ecosystems suggest that pastures in the region are weak net sinks of CO<sub>2</sub>, but are greenhouse gas

sources when CH<sub>4</sub> emissions from the landscape and cattle are included (Nuria Gomez-Casnovas, personal communication). Nitrous oxide emissions have yet to be quantified; but given the anoxic nature of the systems during flooding, they likely contribute to the pasture greenhouse gas source strength.

Our assessment suggests that improved pastures in this region are a net greenhouse gas source. However, the source or sink strength of the pastures likely varies widely between wet and dry years, and long-term measurements will be necessary to fully understand and estimate average greenhouse gas exchange. This work presents information from a relatively wet year. The region also experiences drought on a regular basis, and particularly in dry years, the water table does not reach the land surface (Bohlen and Villapando 2011). Therefore, it is likely that pasture CH<sub>4</sub> emissions vary widely among years due to fluctuations in the pasture hydroperiod.

Water retention and wetland restoration programs are common throughout this region, and alter pasture hydroperiods. Water-retention programs aim to reduce phosphorus (P) loading to the Everglades, and effectively not only reduce water-nutrient levels but also increase pasture flooding (Bohlen and Villapando 2011). Pastures in the northern Everglades watershed are the primary source of P loading to the Everglades, and ranchers are currently compensated to retain water on pastures through state and federal agencies (Bohlen and other 2009). The effect of increased pasture flooding on CH<sub>4</sub> emissions is not known, but it is likely that increasing the pasture hydroperiod leads to an extended period of landscape CH<sub>4</sub> emissions. Further research is needed to evaluate the effect of water management practices on greenhouse gas emissions from these pastures.

The results from this study suggest that subtropical lowland pastures are a strong regional source of CH<sub>4</sub>, and unlike upland pasture ecosystems, cattle are not the dominant emission source. Landscape emissions varied widely across time and space, and high-magnitude emissions were driven by wet-season flooding of pastures and low-lying landforms. The annual emission estimates were high compared with Everglades' wetlands and other pastures ecosystems, indicating subtropical pasture ecosystems are potentially large and unaccounted for CH<sub>4</sub> sources in regional greenhouse gas inventories. These results highlight the need for full accounting of potential greenhouse gas fluxes, and demonstrate that cattle may not be the dominant CH<sub>4</sub> source in lowland pasture ecosystems.

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