**How does deforestation for cropland affect trace gas production at depth in Southeastern Amazonian soils?**

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**Abstract**

Over the last 30 years, Amazonia has been home to extraordinary growth in agricultural production, in part from agricultural expansion, but also due to more intense management on Amazonia’s existing croplands. Because neotropical soils, which are relatively acidic, depleted in base cations, and clay rich, differ greatly from temperate soils that are home to most of the globe’s high-productivity croplands, it remains unclear how intense agricultural management will impact soil nutrient cycling and greenhouse gas (GHG) emissions on tropical croplands. We use field measurements to estimate how cropland intensification in Mato Grosso, Brazil affects the emission of nitrous oxide (N2O), carbon dioxide (CO2) and methane (CH4), along with soil N dynamics. In this system, soybean cropland intensification occurs when maize is planted directly after soybean harvest (double cropping) and fertilized twice with inorganic N. We find that N2O is a surprisingly small loss pathway of nitrogen: dry season N2O emissions in single-cropped (soybean only) fields, double-cropped (soybean/maize) fields and reference tropical forest are uniformly near zero, or 0-0.5 ngNcmˆ2hr. Surprisingly, wet season emissions rates remain low as well, between 1-4 ngNcmˆ2hr, for both cropland types and reference forest, with isolated post-fertilization spikes in N2O emissions (mean increase of 400%) resolving rapidly. CO2 emissions rise during the wet season (from 5 ugNcmˆ2hr to 15 [forest] or 20 [cropland] ugNcmˆ2hr). CH4 uptake rates are slightly negative across seasons and land uses but so low as to rarely be statistically significant. Finally, we find that two important determinants of high GHG fluxes from these intensified crop- lands are row-interrow fertilizer management and the interaction between soil moisture and high soil N availability, suggesting that agricultural management can contribute to balancing agricultural production and landscape emissions in this critical ecosystem undergoing novel agricultural intensification.

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*Keywords:* greenhouse gases, soil profiles, land use change, Amazonia

**Introduction**

* Amazonian soils: not much known about dynamics at depth >5 meters, which is a gap because these soils are very deep and have huge stores of C and nutrients/water
* Not only do we not know much about how Amazonian soils operate, we know very little about how deforestation and agricultural impacts on soil propagate down the soil profile
  + Point to soil metaanaylses that usually max out at 20 cm
* What we do know about deep Amazonian soils indicates that they can have tons of productivity and that the deeper side of things has big implications for plant communities
  + Lots of these plants are deep rooted, getting water from far down, and maybe other stuff – this goes against common wisdom, but in eastern Amazon where there’s marked seasonality the “rapid top soil turnover” thing probably isn’t as dominant as in wet Amazonian forests
* They also matter for global biogeochem cycling because these soils are large reservoirs of C and N
* Let’s look at the literature: do a bar graph or table of studies that have looked below 1 meter and summarize what they say about soil biogeochem and if they had a global change implication, what we know about that, too
* There are a lot of gaps in our understanding of deep Amazonian soils. It’s important to figure out some of them because of the plant community implications and because of the landscape level biogeochem implications
* In this study, we focus on how trace gas emissions change down the soil profile and how those emissions differ between forest and agriculture

**Materials and methods**

***Site description***

Sampling was conducted at Tanguro Ranch, an 32,000 hectare industrial farm located in Mato Grosso, Brazil (Fig. 1). Tanguro Ranch is surrounded by closed-canopy tropical forest (25m height) typical of southeastern Amazonia, a region of transitional forest between cerrado (tropical savanna) to the east and more diverse, high-statured forests to the northwest. This area of Amazonia is also marked by lower precipitation and higher seasonality than central Amazonia. Mean annual precipitation (MAP) at Tanguro Ranch averaged 1900 mm/year between 1987 and 2007 and ranged from 1500 to 2500 mm yr-1 (Tanguro Ranch, unpublished results). The wet season extends from September to April with a dry season between May and August. The dry season in this system features very low rainfall levels; the two seasons from 2012-15 contributed X% and Y% of annual rainfall, respectively. Mean annual temperature (MAT) is 27 C, but temperatures vary between forested areas and cropland areas both diurnially and on average over the year. Tanguro Ranch is located on the Brazilian Shield and the underlying parent material is Precambrian gneisses (Projeto Radambrasil, 1981). Upland soils are ustic Oxisols (55% sand, 2% silt, and 43% clay mean texture, Oliviera et al., 1992, Soil Survey Staff, 1999) with high infiltration rates and little lateral water movement in upper soil horizons (depth to water table estimated to be between 20-40m, (*1*)). The site features little topographic variation and is generally flat plateaus interspersed with stream channels (Nagy et al., *in press*).

Originally deforested to support a pasture ranch (cleared between 1982-83), Fazenda Tanguro now primarily plants soybeans , a nitrogen-fixing legume (conversion from pasture to soy between 2003-8). Highly intensively managed, Tanguro’s croplands receive multiple applications per year of fertilizer (phosphorous [P] and potassium [K]), pesticide, herbicide, fungicide and soil additives (lime) to moderate soil pH (Grupo A. Maggi, pers. comm.). The transition from low intensity pasture to intensive, mechanized cropland is representative of the land use trajectories taking place across eastern Amazonia (*2*, *3*). There have been numerous previous projects in this system, all with the cooperation of farm leadership (*1*, *4*, *5*).

***Trace gas measurements***

Four 10m soil pits were permanently installed across Tanguro Ranch. C2, K4 and M8 are located in intact forest, while Mutum (MU) pit is located in the center of a soybean field. We installed 7 brass tubes horizontally into the side of each soil pit at depths of 15, 40, 75, 150, 250, 350 and 450 cm. Tubes were between 50 and 200 cm long in order to ensure that gas samples were drawn from soil pore space beyond the zone affected by the exposed pit wall (based on measured temperature and soil moisture, P. Lefebvre, personal communication). Each tube was fitted with a swage and septum for gas sampling. We withdrew between 24 and 96 mL of gas (depending on tube length) which we subsequently discarded a week after installation as a flushing protocol; tubes equilibrated for at least 48 hours before sampling.

At each sampling date, three samples per depth were collected using a 12mL polypropylene syringe (Monoject) that withdrew 12mL of gas which was then injected into into a 9mL glass vial (brand) that had been pre-sealed with butyl rubber septa (brand). We used un-evacuated vials containing “ambient” (lab) air (sensu Venterea 2005). Sets of vials containing ambient air included four replicate vials with ambient air that were later analyzed for concentrations of CO2, N2O and CH4, which were then used to calculate trace concentration without dilution. Un-evacuated vials were preferred over evacuated vials in this study because preliminary lab tests (unpublished results, Venterea, Dolan and O'Connell) indicated that evacuated vials sitting at ambient pressure for several weeks, as they would have been under field conditions in the absence of a reliable means to evacuate vials on site, have a high risk of inward air leakage.

Gas samples were analyzed by gas chromatography using a headspace autosampler at the University of Minnesota (Teledyne Tekmar, Mason, OH). The autosampler was modified to fill multiple sample loops from each vial. Sample loops fed into a flame ionization detector for CH4, an electron capture detector for N2O and a thermal conductivity detector for CO2. Standard curves and system calibration were done using analytical grade standards (Scott Specialty Gases, Plumsteadville, PA).

***Soil temperature measurements***

Thermocouple sensors were installed at soil pit depths of 15, 40, 75, 150, 250, 350 and 450 cm, also buried into the soil pit wall in order to avoid artifact data associated with the exposed soil pit interior. Temperature was recorded every 6 hours and temperature data the result of the average temperature over a short sensor period (variable but ~20 uS). Data was recorded in dataloggers (Campbell Scientific) and downloaded weekly. Temperature and moisture data are reported as averages over a single week in November, December, January and February. These months were chosen to complement gas samples taken during each of these months, which were in turn chosen because soils are more dynamic in this system during the wet season.

***Soil volumetric water content measurements***

Time domain reflectometry (TDR) soil moisture meters were installed at 0, 30, 50, 100, 200, 300, 400, 500, 600, 700, 800 and 900 cm depths in each soil pit. Data was collected in the same datalogger as was used to record thermocouple data (Campbell Scientific) and was downloaded weekly. Data was calibrated and converted to volumetric water content (VWC).

Due to the limited space along soil pit walls, and the need to keep sensors apart, TDR sensors were not placed at the same depths as thermocouple sensors or gas sample tubes. To have fully comparable datasets, we estimated VWC at 15, 40, 75, 150, 250, 350 and 450 cm depth, using the simple assumption that the VWC at the midpoint between two sensors would be the mean of the two.

**Results**

***Trace gas concentrations***

We find that dry season N2O emissions in single-cropped (soybean only) fields,

***Temperature and moisture results***

In two forest soil pits (K4 and M8), soil temperature at depth follows a consistent pattern, increasing between 15cm and 1m depth, before remaining steady at lower depths. Forest pit C2 also has higher temperatures at depth, but the increase continues after 1m depth and the temperature pattern is more variable, decreasing at 45cm (equipment error?), increasing at 75cm depth, before decreasing at 1.5m, after which temperatures continue to rise down the soil column. Mutum pit (soybean) has soil temperatures that have larger standard error values at each depth – the forest pits, by contrast, have variable surface soil temperatures, but relatively small standard errors for deeper temperatures. Further, Mutum’s soil temperatures are significantly different than the soil temperatures in other pits (p < 0.001, Table 1), and are similar across sampling month and depth, remaining between 25.5 and 27.5 °C, higher than all but 3 weekly average temperatures in any of the forest pit sites or depths. While month was not a significant predictor of temperature in this case (Table 1), it is notable that all four months considered (November-February) are similar climatically.

***Statistical analyses***

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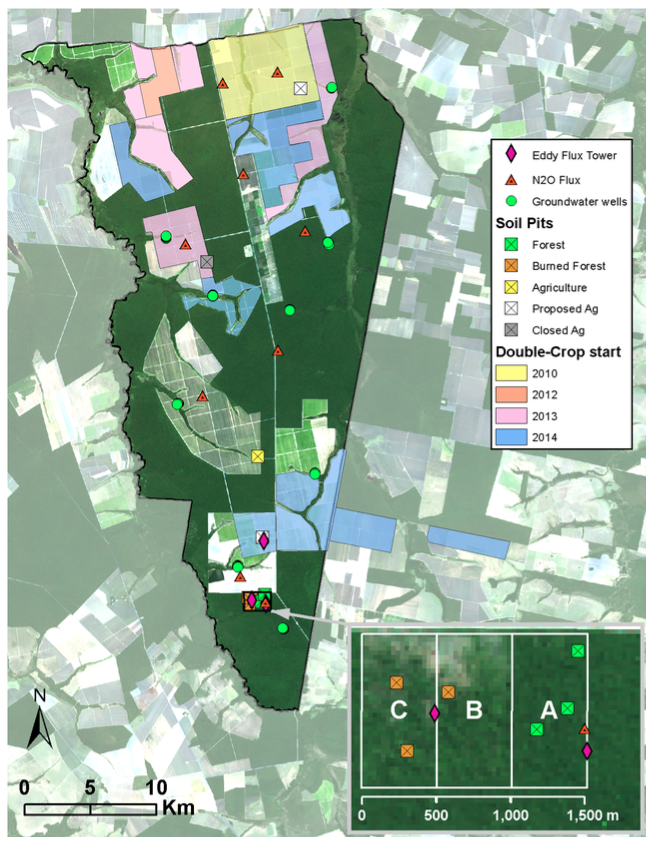
**Discussion**

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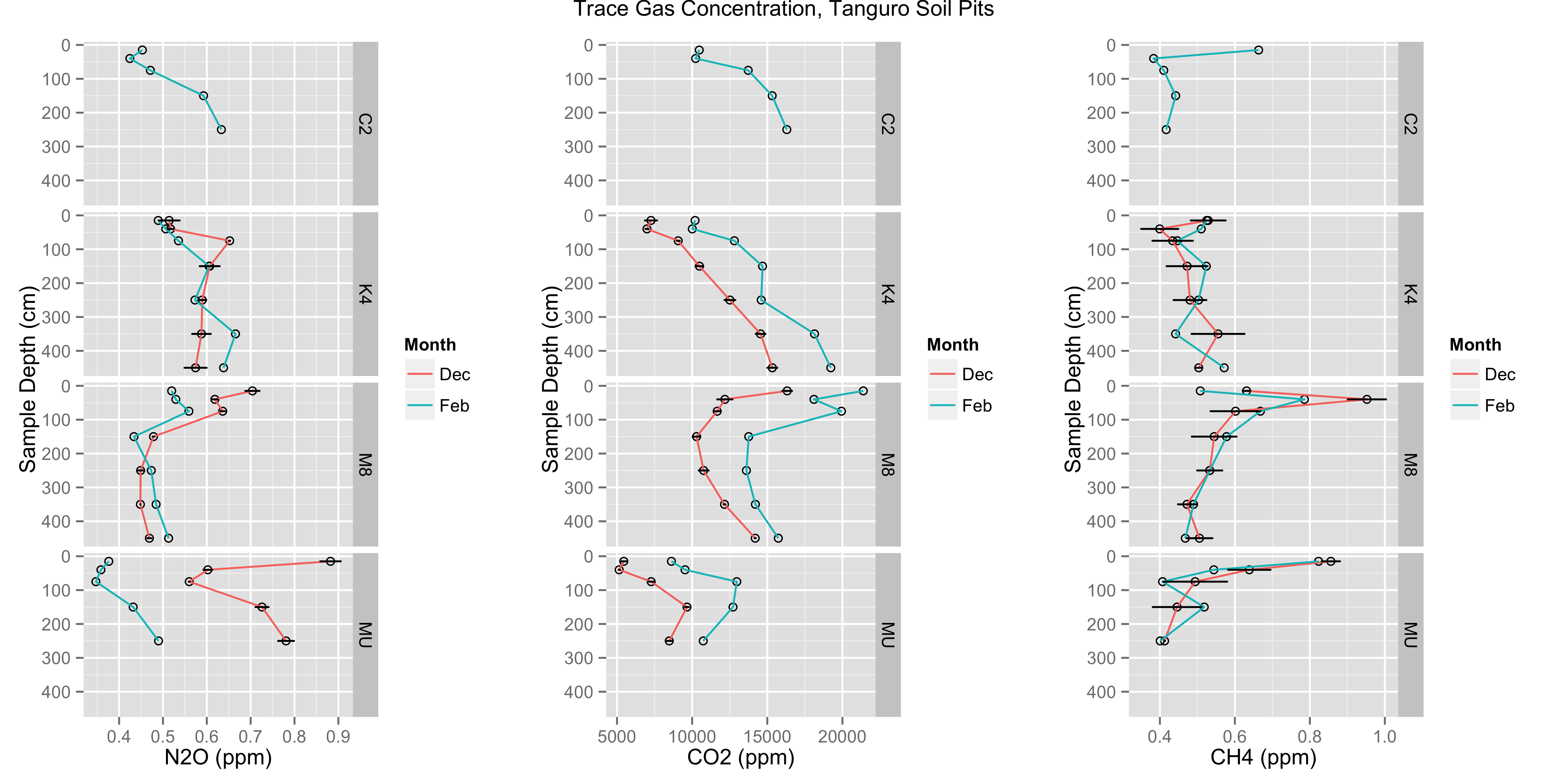
Any subsections

Note that subsections are ok here later in the discussion if needed.

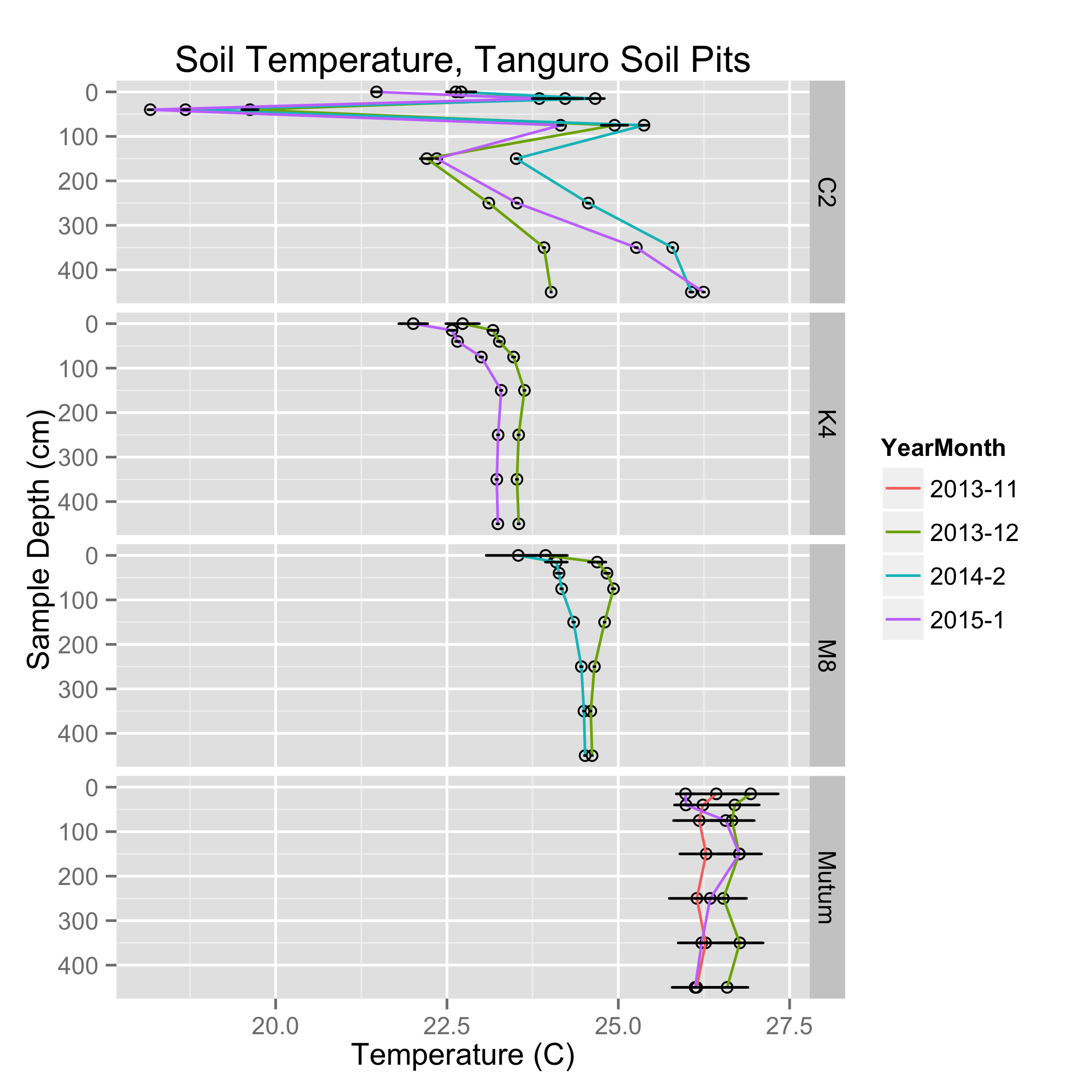
**Figures:**



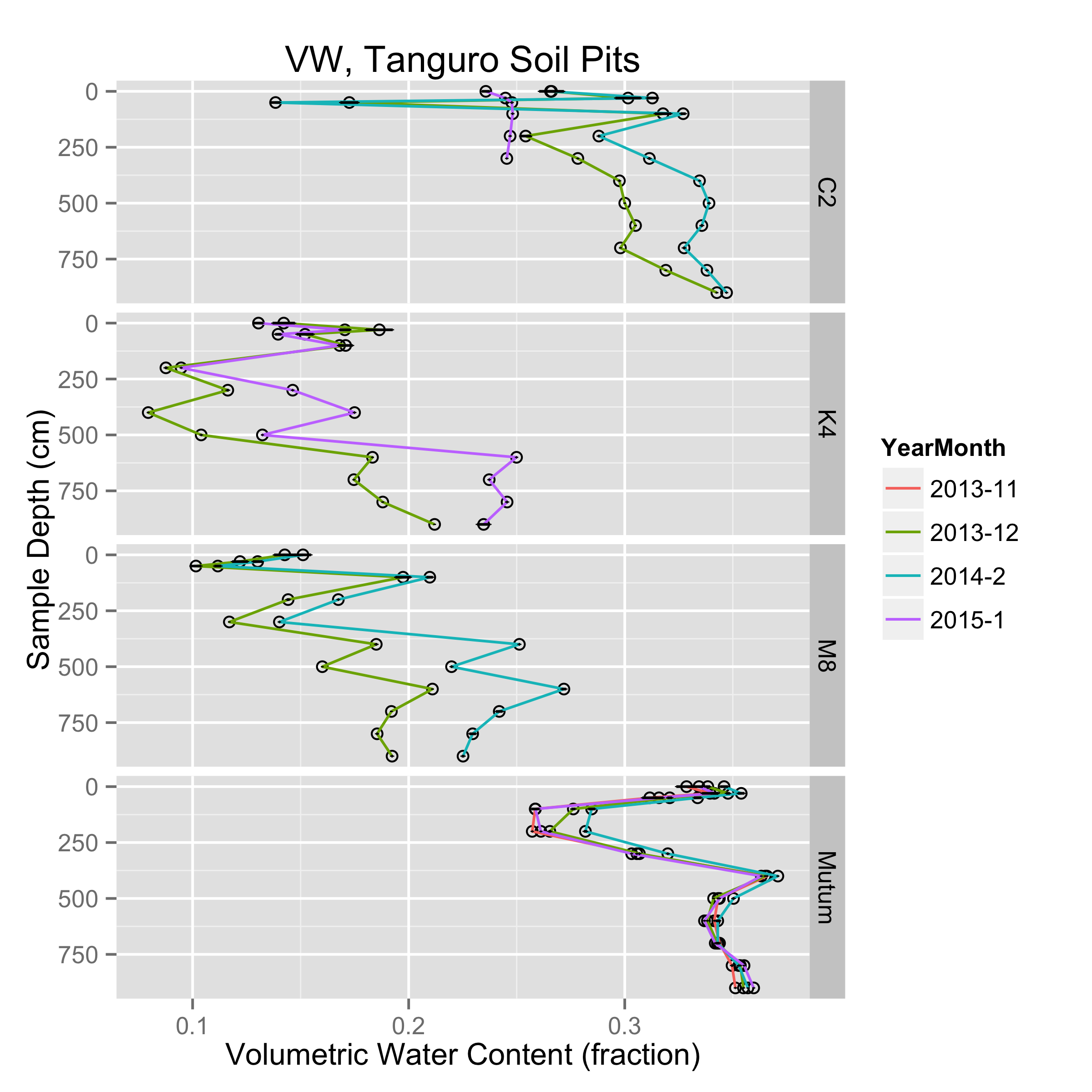
**Figure 1.** Map of study site Tanguro Ranch (courtesy Paul Leferve). Dark areas are forested parcels; light areas are agricultural fields. Soil pits (squares) sampled in this investigation include the southern three forest pits (green squares within forest block “A” in inset) and an agricultural forest pit (yellow square) in the southern half of the farm. Color overlay indicates what year soy/maize double cropping began, where applicable.



**Figure 2.** Standing presence (ppm) of trace gases in soil pore space in soil pits at Tanguro Ranch. Sampling was conducted in December 2013 and February 2014. C2, K4 and M8 are located within intact forest, while MU is located within cultivated soybean. Error bars represent the standard error.



**Figure 3.** Soil temperature (C) in soil pits at Tanguro Ranch. Data is the mean and standard error of a week of thermocouple readings (taken every 6 hours) for the sampling months and a representative week earlier in the wet season (November) and later in the wet season (February) than when gas samples were collected.



**Figure 4.** Soil volumetric water content (fraction) in soil pits at Tanguro Ranch. Data is the mean and standard error of a week of TDR readings (taken every 6 hours) for the sampling months and a representative week earlier in the wet season (November) and later in the wet season (February) than when gas samples were collected.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| (Intercept) | 22.99158857 | 0.342607556 | 67.1076517 | < 0.001\*\* |
| PitIDK4 | -0.124926073 | 0.404484936 | -0.3088522 | 0.758 |
| PitIDM8 | 0.894940007 | 0.39996541 | 2.2375435 | 0.028\* |
| PitIDMutum | 3.172768309 | 0.420204216 | 7.550539 | < 0.001\*\* |
| MonthFeb | 0.172198935 | 0.39996541 | 0.4305346 | 0.668 |
| MonthJan | -0.376660572 | 0.341091648 | -1.1042797 | 0.273 |
| MonthNov | -0.441827998 | 0.574487317 | -0.7690822 | 0.444 |
| sampledepth | 0.002732436 | 0.000866944 | 3.1518041 | < 0.01\* |
| *Model: meanTemperature ~ PitID + Month + sampledepth*  *Multiple R-squared: 0.6112*  *F-statistic: 15.49 on 7 and 69 DF, p-value: 5.1e-12* | | | | |

**Table 1.** Regression table with mean temperature as the response variable and pit, month and depth as the predictor variables.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| (Intercept) | 2.50E-01 | 6.01E-03 | 41.59680003 | < 0.001\*\* |
| PitIDK4 | -1.18E-01 | 7.33E-03 | -16.0901418 | < 0.001\*\* |
| PitIDM8 | -1.18E-01 | 7.14E-03 | -16.54334816 | < 0.001\*\* |
| PitIDMutum | 4.27E-02 | 6.30E-03 | 6.775752323 | < 0.001\*\* |
| MonthFeb | 2.08E-02 | 5.93E-03 | 3.50306348 | < 0.001\*\* |
| MonthJan | 1.77E-05 | 6.14E-03 | 0.002878346 | 0.998 |
| MonthNov | -1.72E-04 | 9.23E-03 | -0.018660816 | 0.985 |
| sampledepth | 7.38E-05 | 8.48E-06 | 8.704220879 | < 0.001\*\* |
| *Model: meanVWC ~ PitID + Month + sampledepth*  *Multiple R-squared: 0.8459*  *F-statistic: 152.9 on 7 and 195 DF, p-value: < 2.2e-16* | | | | |

**Table 2.** Regression table with mean VWC as the response variable and pit, month and depth as the predictor variables.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| (Intercept) | 0.06597981 | 0.27932511 | 0.2362115 | 0.815 |
| meandegC | 0.01622592 | 0.01216652 | 1.3336534 | 0.193 |
| meanVW | 0.48671002 | 0.23395342 | 2.0803714 | 0.047 |
| Month.L | 0.06237414 | 0.02439825 | 2.5565007 | 0.017\* |
| lm(formula = meanN2Oppm ~ meandegC + meanVW + Month)  Multiple R-squared: 0.4172  F-statistic: 6.441 on 3 and 27 DF, p-value: 0.001969 | | | | |

**Table 3.** Regression table with ppm N2O as the response variable.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| (Intercept) | 4800.0376 | 7965.0302 | 0.602639 | 0.552 |
| meandegC | 592.3057 | 346.9315 | 1.70727 | 0.099 |
| meanVW | -33413.1137 | 6671.2444 | -5.008528 | < 0.001\*\* |
| Month.L | -4170.4722 | 695.7226 | -5.994447 | < 0.001\*\* |
| lm(formula = meanCO2ppm ~ meandegC + meanVW + Month)  Multiple R-squared: 0.6605  F-statistic: 17.51 on 3 and 27 DF, p-value: 1.636e-06 | | | | |

**Table 4.** Regression table with ppm CO2 as the response variable.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| (Intercept) | -0.225775961 | 0.350135376 | -0.6448248 | 0.524 |
| meandegC | 0.039935938 | 0.015234043 | 2.621493 | 0.014 |
| meanVW | -0.705298271 | 0.323965176 | -2.1770805 | 0.038 |
| sampledepth | -0.000466753 | 0.000158573 | -2.9434588 | < 0.01\* |
| lm(formula = meanCH4ppm ~ meandegC + meanVW + sampledepth)  Multiple R-squared: 0.3338  F-statistic: 4.509 on 3 and 27 DF, p-value: 0.0109 | | | | |

**Table 5.** Regression table with ppm CH4 as the response variable.

**References and Notes:**

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**Supplemental Figures:**