**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 \emph{(Get the updated numbers from Sandro)} (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 dry seasons from 2011-13 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 (Fig 2). 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, Hayhoe 2011). The site features little topographic variation and is generally flat plateaus interspersed with stream channels (number here from Chelsea using her topo thingy).

Originally deforested to support a pasture ranch, Fazenda Tanguro now primarily plants soybeans, a nitrogen-fixing legume. Highly intensively managed, Tanguro’s croplands receive multiple applications per year of fertilizer (phosphorous [P] and potassium [K]), pesticide, herbicide and soil additives (lime) to moderate soil pH (Grupo A. Maggi, pers. comm.). In recent years Tanguro has begun double-cropping (planting a second crop, maize) after the primary soy season, necessitating not only higher gross application rates of P and K, but also the addition of N fertilizer. This shift creates an intensification comparison between the single- and double-cropped fields, both of which can be compared with neighboring native tropical forest. \emph{(Include more pertinent info about management here; point to table 1.)} All fields included in sampling were originally cleared for pasture in 1982 and 1983, conversion to soy in the monitored watersheds took place between 200x and 200y, with some monitored fields becoming double-cropped between 201x and 201y (\ref{tab:sitedescriptions}). There have been numerous previous projects in this system, all with the cooperation of farm leadership (Balch et al., 2008; Hayhoe et al., 2011; Brando et al., 2012).

The transition from intensive, mechanized single-cropping soybean farming to intensive, mechanized double-cropping of soybean/maize on Fazenda Tanguro (see Study System) and the associated increase in chemical inputs (NPK, etc.) is representative of the cropland intensification taking place across Mato Grosso (Galford et al., 2011). The transition has been rapid: at Tanguro, double cropping took place on 10% of their fields in 2011, on over 25% in 2012, and over 50% of fields (18,000 of 32,000 hectares) during the 2013 season, though it has since decreased on the farm while they pursue more permanent storage workflows for the harvested maize (Grupo A. Maggi, pers. comm.).

***Trace gas measurements***

We used a closed chamber method (sensu Venterea 2005) to measure soil-to-atmosphere fluxes of CO2, N2O and CH4. Rectangular stainless steel chamber bases (20 gauge, 53cm long, 32cm wide, 10cm deep) were inserted into the soil with 2-5cm of space between the soil surface and the lip of the chamber. Bases were inserted prior to measurement each day, as farm activity prevented installation of bases for the entirety of the season; we found good agreement in a test comparing fluxes measured using bases that had been installed for 24 hours and fluxes from those that were installed directly prior to measurement (\ref{chamberbase24hr}). Precise base location varied randomly from day to day to ensure that soil and root disturbance artifacts from repeated base removal and reinsertion would not affect trace gas measurements: we took a "random walk" (random number draws for a walk between 20-80 meters in two cardinal directions) from a central GPS point at each sampling location. Five bases were then arranged in a diamond pattern with a central base. At cropland sites, bases were randomly choosen to be inter-row or row chambers. Bases were placed parallel with rows, either centered on the row or centered in between rows. When plants larger than the closed chambers allowed were present in the randomly chosen base location, they were manipulated aboveground until the chamber tops were able to close. Near the end of the corn growing season, the corn stalks were cut in order to close the chamber tops over plants, leaving roots intact.

Chamber tops were also constructed from stainless steel rectangular tubs (20 gauge, 53cm long, 32cm wide, 12cm deep). The chamber edges (2 cm wide) were lined with ethylene propylene diene terpolymer (EPDM) weatherproofing material to provide an airtight seal. Chamber tops were sealed to chamber bottoms using 10 metal clamps arranged around these edges. To prevent large temperature increases inside the chamber, chamber tops were covered with reflective insulating material (find brand). A vent tube (stainless steel) was inserted near the bottom edge of the chamber top to allow pressure to equilibrate within the chamber after each sample. Fluxes were generally measured between 800 and 1200 h local time when soil temperatures were expected to be within one standard deviation of their daily mean values (Figure \ref{fig:dailytempfig}).

Deployment time was 30 minutes (gas measurements collected at minute 0, 10, 20 and 30) between May and August 2012 and 45 minutes (gas measurements collected at minute 0, 15, 30 and 45) for the remainder of the study period. Samples were collected using a 12mL polypropylene syringe (Monoject) that withdrew 12mL of gas from a gauge located at the top of the closed chamber system. Samples were then injected into 9mL glass vials (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. We conducted a set of measurements with evacuated vials and found good agreement after statistical correction for ambient air dilution between the two methods (\ref{unevacmethod}). 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.

Flux measurements were taken intermittently between Date1 and Date2. Planting and harvesting dates for soybeans and corn varied across sites (\ref{tab:sitedescriptions}), but soybean was generally planted around X and harvested around Y. At double-cropped sites, corn was planted with 24 hours of soybean harvest and fertilized "along the row" (direct injections of fertilizer along the row seed line) simultaneously. Corn was fertilized again with broadcast fertilizer application approximately 20-30 days after planting and harvested around Z. Pesticide and herbicide applications were variable and ongoing over the year; lime was applied via X method once a year (?) (pers. communication, Tanguro Ranch; \ref{tab:sitedescriptions}).

Gas samples were analyzed by gas chromatography (GC) using a headspace autosampler at the University of Minnesota (Teledyne Tekmar, Mason, OH). Travel standards were carried from Brazil to Minnesota and used when applicable to correct for travel disruption to samples (travelstandards) 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 (brands). Standard curves and system calibration were done using analytical grade standards (Scott Specialty Gases, Plumsteadville, PA). Gas fluxes were calculated sensu Hutchinson and Mosier (1981) - the rate of change of concentration of each trace gas in the four subsequent vials taken over time at each chamber were used in combination with the chamber volume and soil surface area within the chamber to convert chamber gas concentrations from parts per million (ppm, determined by GC analysis) to mass per volume units (ng N m-3 or ng C m-3). To determine the flux rate, we fit a linear model to these four time points (decide whether we're going to use the instantaneous quad flux method). (Include any formulas here?)

***Soil temperature measurements***

analyzed for DOC using XYZ (brand).

***Soil volumetric water content measurements***

bootstrapping technique with the standard deviations surrounding the regression coefficients.

**Results**

***Trace gas concentrations***

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

***Temperature and moisture results***

Soil properties are really different between land use treatments, too. Bulk density

***Statistical analyses***

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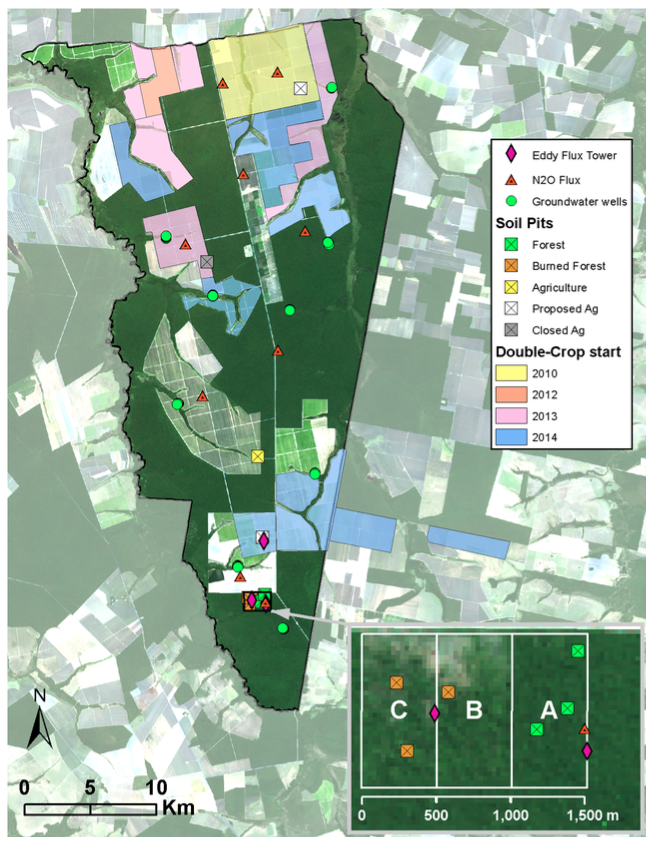
**Discussion**

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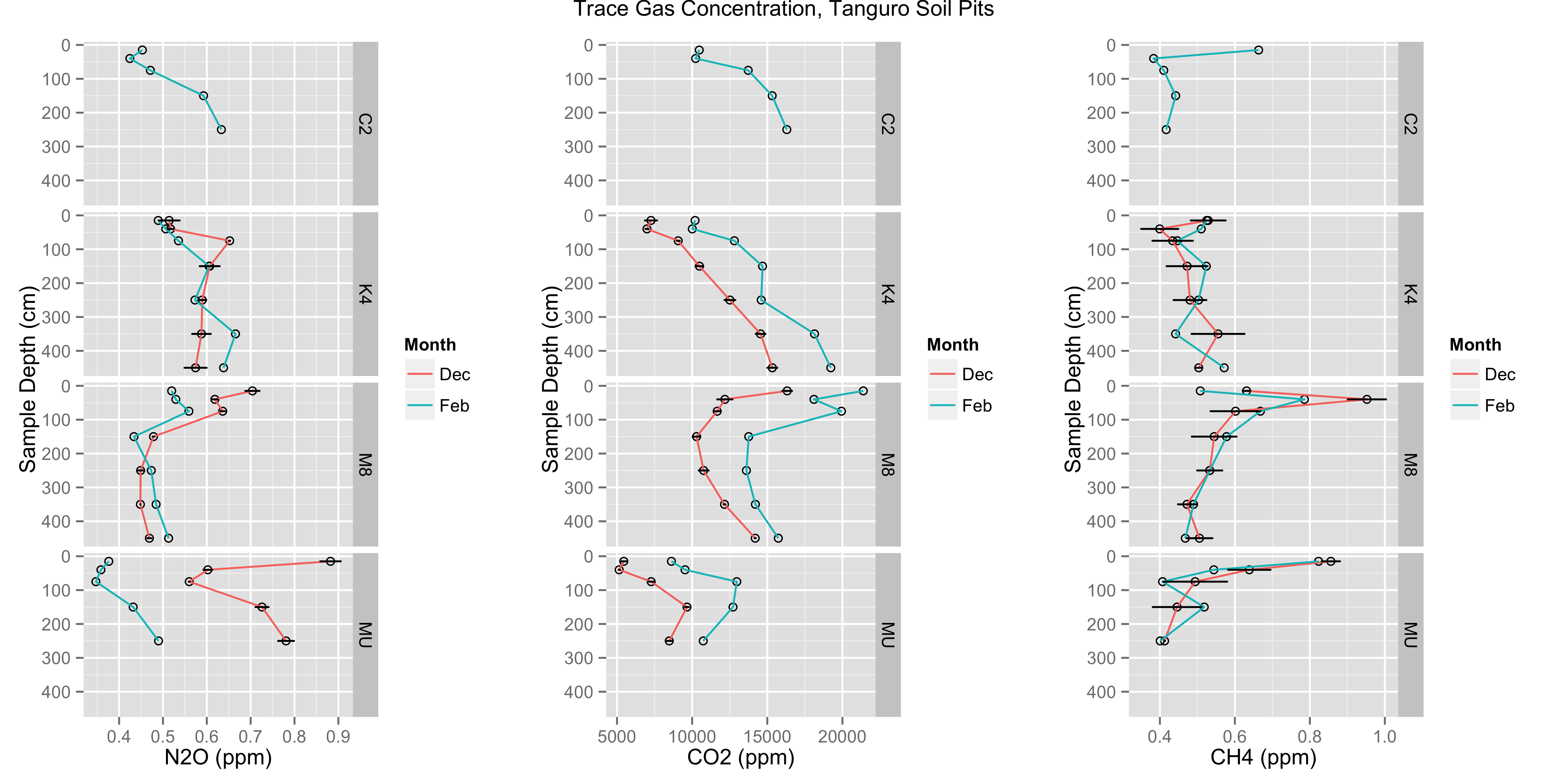
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Note that subsections are ok here later in the discussion if needed.

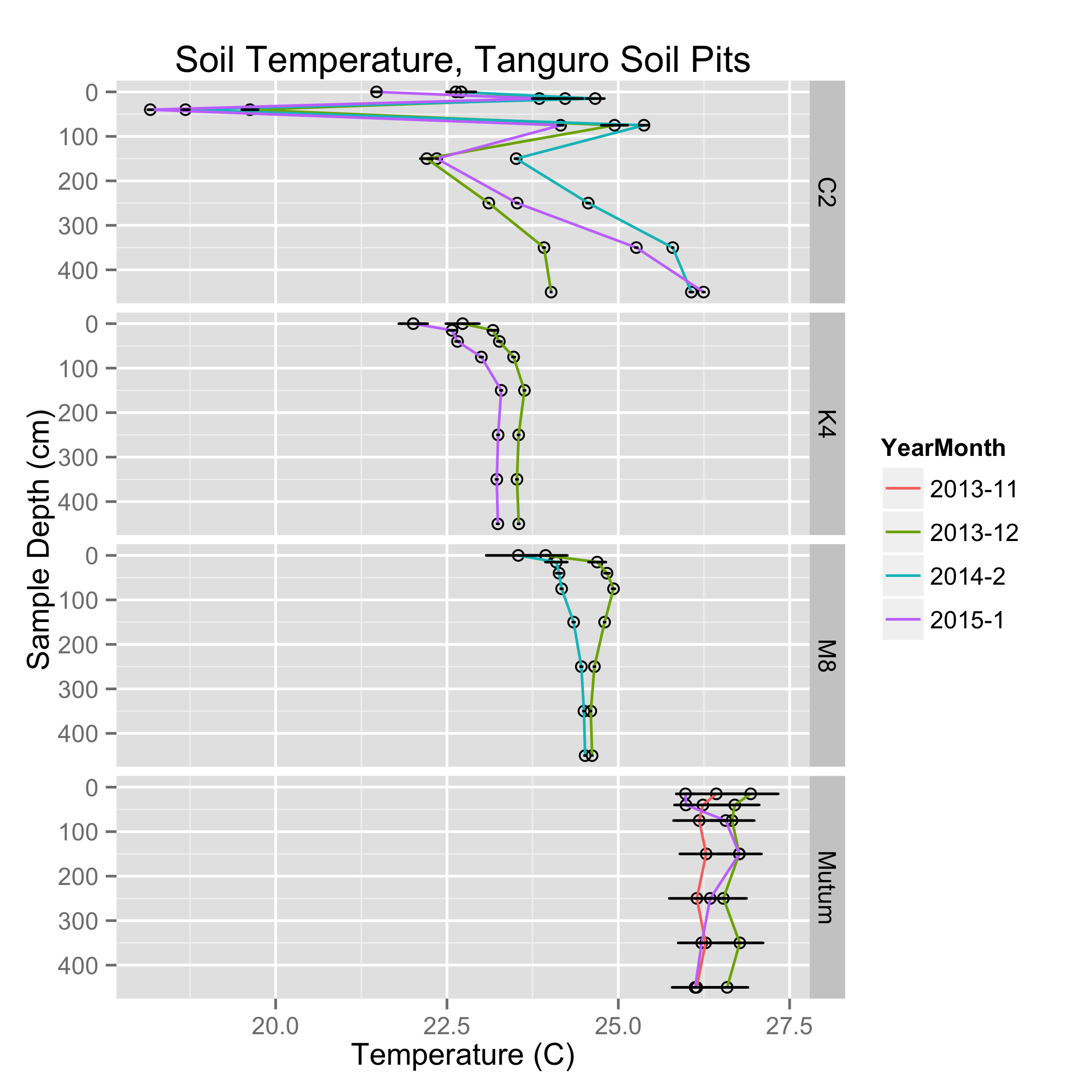
**Figures:**



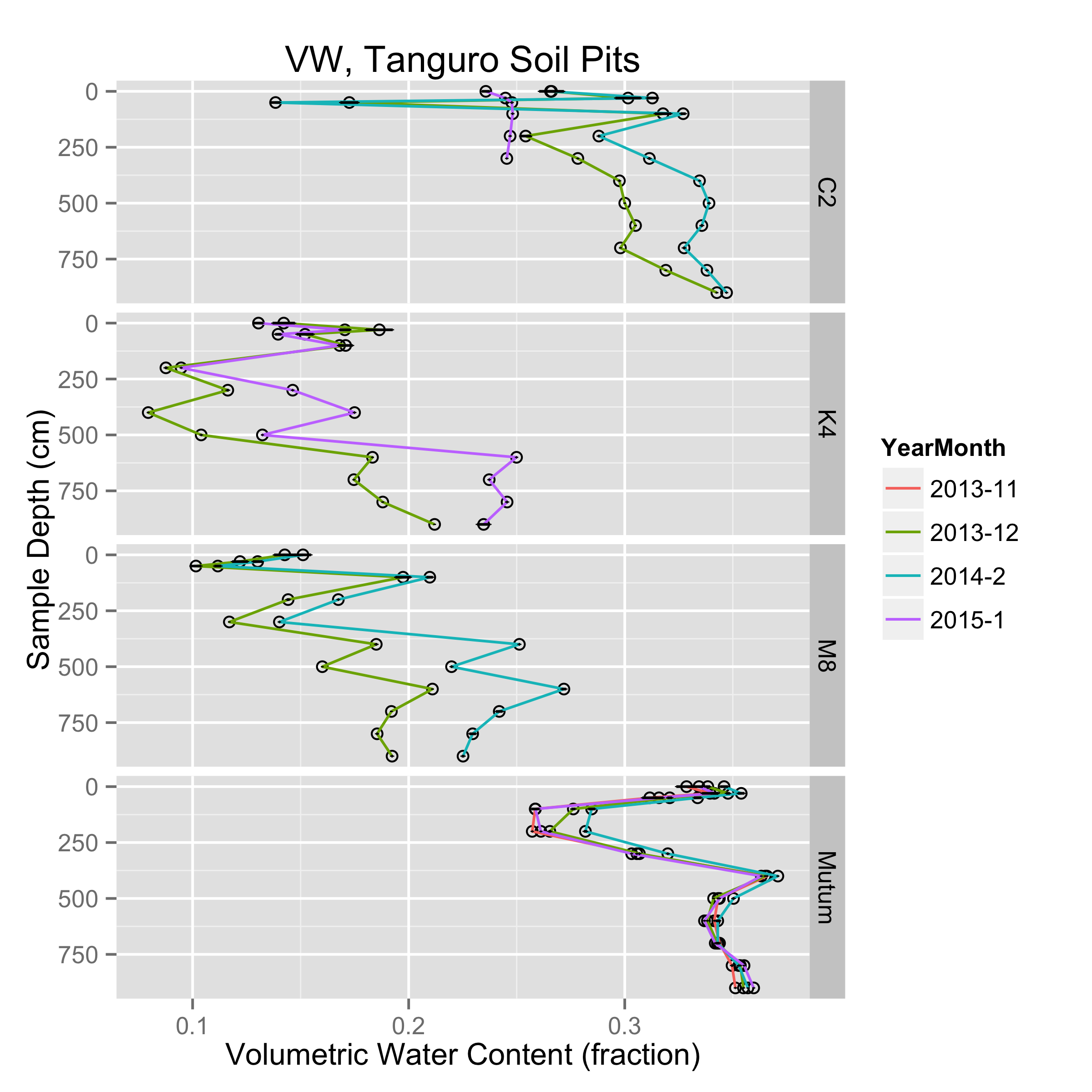
**Figure 1.** Map of study site Tanguro Ranch (courtesy Paul Leferve). Dark areas are forested parcels; light areas are agricultural fields. Soil pits (squares) sampled in this investigation include the southern three forest pits (green squares within forest block “A” in inset) and an agricultural forest 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.

**References and Notes:**

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**Supplemental Figures:**