OUR FOOD IN A CHANGING CLIMATE:

GROWTH, YIELD, AND NUTRIENT CHANGES OF SWEET POTATO GROWN ACROSS THE SPECTRUM OF CO_2 CONCENTRATIONS PROJECTED IN THE NEXT 150 YEARS

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ABSTRACT

The majority of CO_2 fertilization studies have focused on rice, wheat, and soybean; however, climate change is expected to have greatest impact on regions of the world that rely heavily on root crops. This is the first study of its kind to determine how CO_2 fertilization effects *Ipomoea batatas* Lam. (sweet potato) growth and nutrient concentrations across a full trajectory of CO_2 concentrations projected for the next 150 years. A total of 64 sweet potato plants were grown to maturity in a split plot designed study with CO_2 concentration (353, 763, 1,109, and 1,515 ppm) as the whole plot factor and fertilizer (conventional vs. organic) as the split-plot factor. We observed increases in average above-ground dry biomass at 763 ppm (24%, 13%), 1,109 ppm (25%, 41%), and 1,515 ppm (31%, 43%) and average storage root dry biomass increased at 763 ppm (95%, 88%), 1,109 ppm (99%, 62%), and 1,515 ppm (118%, 71%) for both conventional and organic treatments, respectively. Chemical analyses suggest that the increased biomass may be nutrient depleted due to significant ($P < 0.05$) increases in carbohydrates (4.4%, 2.0%) and decreases in protein (-34.6%, -28.6%) and phosphorus (-24.0%, -11.3%) concentrations for both the conventional and organic treatment, respectively. Significant decreases in magnesium (-25.8%) and decreasing trends ($P < 0.1$) were also found for calcium (-46.7%), sodium (-18.4%), iron (-42.1%) and manganese (-70.8%) for the conventional treatment. Decreased nutrient content of *I. batatas* grown under elevated CO_2 could have negative implications globally, especially in developing countries that are already nutrient limited. The storage root biomass response of sweet potato exceeded the extrapolated trajectory of non-root crop experiments by 63 percent at 1520 ppm, indicating sweet potato may be better at utilizing very high atmospheric CO_2 concentrations compared to non-root crop species. Storage root fertilization under very high CO_2 concentrations could dramatically supplement crop production in some of the poorest nations of the world, provided that the response found for sweet potato represents a generalized root-crop response and can be extrapolated to agricultural systems. The dramatically enhanced performance of conventionally (i.e., synthetic) over organically (i.e., manure-based) fertilized plants suggests that optimal nutrient availability will be crucial for support of enhanced crop production at elevated pCO_2.

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ANOVA	Analysis of variance
B	Boron
Ca	Calcium
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTAHR	College of Tropical Agriculture and Human Resources
%DV	Percent daily values
FACE	Free-air CO_2 Enrichment
Fe	Iron
GCM	General Circulation Model
GLM	General Linear Model
HadCM3	Hadley CM3
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
NDS	Nutrient Density Score
NO_3^-	Nitrate
NUE	Nitrogen Use Efficiency
P	Phosphorus
Ppm	Parts Per Million
RCP	Representative Concentration Pathway
R:S	Root to Shoot Ratios
S	Sulfur
SECC	Slightly Elevated CO_2 Concentrations
SRES	Special Report on Emissions Scenarios
TDF	Total Dietary Fiber
TNA	Total Storage Root Nutrients Available
VECC	Very Elevated CO_2 Concentrations
WUE	Water Use Efficiency
Zn	Zinc

CHAPTER 1. INTRODUCTION

Increasing concentration of CO_2 in our atmosphere is the leading example of anthropogenic forced climate change and, unabated, will continue to rise (IPCC, 2001). Effects of climate change on global agriculture are difficult to predict and will differ regionally (Aydinalp & Cresser, 2008), but the better our understanding, the more informed we will be in making sound socio-economic decisions. Sharp changes in temperature and precipitation as well as increased frequency of extreme weather events (e.g., droughts, floods, etc.) are negative consequences climate change will have on agricultural production (Abeygunawardena et al., 2003; Nelson et al., 2009). Conversely, increased plant-tissue production from elevated atmospheric CO_2 concentrations is a positive response (Mikino and Tadahiko, 1999). Models predicting how agricultural production will be influenced by a changing climate are highly dependent on which socio-economic scenario, described in the *Special Report on Emissions Scenarios* (SRES), and general circulation model (GCM) is used and therefore vary significantly from model to model. Tubiello and Fischer (2007) used the A2r SRES scenario and included the CO_2 fertilization response in their model while applying these scenarios to both the Hadley CM3 (HadCM3) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) GCMs. They projected that in the year 2080, cereal production would increase by 2.7 and 9.0 percent in developed countries but decrease 3.3 and 7.2 percent in developing nations for the HadCM3 and CSIRO GCMs, respectively. Nelson et al. (2010) also used the CSIRO GCM and the A2 SRES scenario, but didn’t incorporate the CO_2 fertilization response. The model projected that in the year 2080, both developed and developing countries would result in 21.7 and 23.8 percent decreases in wheat yield, respectively. A number of other studies also show conflicting results, even when focusing on smaller regional scales such as sub-Saharan Africa (Calzadilla et al., 2013; Schlenker, 2010). Modeling the impacts of climate change on agriculture is complex due to wide-ranging processes underlying the working of markets, ecosystems, and human behavior, iterating the importance in widening our understanding of how CO_2 fertilization will impact crops globally.

Current understanding of CO_2 fertilization is based on thousands of two-point closed chamber and free-air CO_2 enrichment (FACE) experiments (Long, 2004) that have grown hundreds of plant species under ambient (i.e., 300-420 ppm) and slightly elevated (i.e., 450-750 ppm) CO_2 concentrations (SECC) but few studies have looked at the response of plants grown under very elevated (i.e., > 750 ppm) CO_2 concentrations (VECC). On average, plants grown under SECC resulted in higher biomass production, primarily due to increased rates of photosynthesis, nitrogen use efficiency (NUE), and water use efficiency (WUE) (Drake et al., 1997; Kimball et al., 1999, 2002; Mandercheid et al., 2014). Plants grown under SECC have also resulted in changes in plant tissue elemental composition and nutrient concentrations. Elevated CO_2 has been shown to increase non-structural carbohydrates (e.g., starch and simple sugars) and decrease nitrogen-containing compounds (e.g., protein) and minerals (e.g., phosphorus, magnesium, and potassium) (Cotrufo et. al, 1998; Hogy, 2009a; Fernando et al., 2014). Poorter and colleagues (1997) reported that the average concentrations of 27 species of plants grown under SECC increased total non-structural carbohydrates by 54 percent and decreased protein and mineral concentrations by 23 and 18 percent, respectively.

Previous CO_2 fertilization experiments based their elevated CO_2 concentrations on early projections, up to the year 2100 (Houghton et al., 1992; Nakicenovic et al., 2000). These projections were modeled using a range of scenarios from worst case “business as usual” to best case “remediation” type, resulting in concentrations from 970 ppm and 549 ppm by the end of the century (Figure 1). Because CO_2 fertilization studies were based on early projections to the year 2100, very few have looked at VECC across the spectrum of possible CO_2 scenarios.

Representative Concentration Pathways (RCPs) were developed for future climate research, which expanded projected atmospheric CO_2 concentrations beyond the year 2300 (Moss et al., 2010; van Vuuren et al., 2011a). In all, four RCPs were created covering the range of emission scenarios from previous studies (van Vuuren et al., 2011b). RCP 8.5 is the upper bound of the four scenarios, corresponding to a high greenhouse gas emissions pathway (Fisher et al., 2007; Moss et al., 2008) where CO_2

concentrations surpass 1500ppm within the next 150 years (Riahi, 2007, 2011) (Figure 1). These results emphasize the importance of understanding the response of VECC on plant growth in a “business as usual” future scenario.

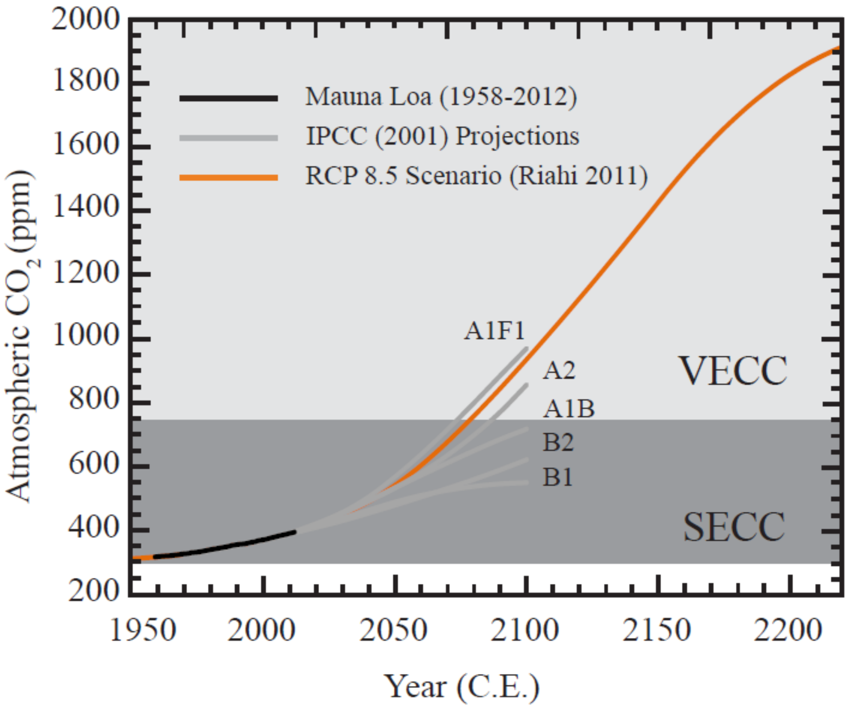


Figure 1: Past, present, and future projections of atmospheric CO_2 with slightly elevated CO_2 concentrations (SECC) vs. very elevated CO_2 concentrations (VECC)

A large majority of previous research focused on global staple food crops (i.e., wheat, rice, and soybean) and found that crops grown in SECC result in increased yield between 20% and 30% (Jablonski et al., 2002; Ainsworth and McGrath, 2010). However, climate change is expected to have greatest impact on regions of the world that rely heavily on tuber and root crops (Mertz et al., 2009), which include some of the most impoverished portions of the globe (Kates and Dasgupta, 2007). Many farmers are highly dependent on root and tuber crops as contributing sources of food, nutrients, and income (Scott et al., 2000). *Ipomoea batatas* Lam. (sweet potato) is an essential root crop, cultivated in more than 100 developing countries, and ranked seventh in production (in tons) throughout Middle Africa (FAO 2010). It remains an important staple food in the diets of the Maori people, Hawaiians, and Papau New Guineans (Cambie & Fergerson, 2003; Saweri, 2001). Sweet potatoes are high yielding, drought tolerant, and have a wide adaptability to various climates and farming systems (Diop, 1998; Jiang et al., 2004). They produce more edible energy per hectare per day than wheat, rice, or cassava with roots rich in carbohydrates and vitamin A and leaves rich in protein (Lebot, 2009; Wolfe, 1992). It has been suggested that increased sweet potato production in African nations, such as Uganda and Kenya, could help meet food requirements, improve nutrient status, enhance food security, and reduce poverty regionally in Africa (Bovell-Benjamin, 2007; Odongo et al., 2004; Oyunga-Ogubi et al,2005).

Studies on SECC on sweet potato have shown 9-21% increases in above-ground dry biomass, 11-40% increases in storage root dry biomass, 24% decreases in leaf N, and a 19% increase in leaf sucrose (Bhattachrya et al., 1989, 1990; Biswas et al., 1996). No study has looked at sweet potato grown across the full trajectory of VECC and its response on both plant biomass and nutrient concentrations. Understanding the full trajectory of sweet potato biomass and nutrient composition of plants grown under VECC will be essential in accurately predicting crop production under future CO_2 scenarios for some of the most impoverished and climate vulnerable nations, globally.

Humans are impacting climate, primarily through the emission of greenhouse gasses, specifically CO_2. CO_2 is not only an important atmospheric gas for its warming potential but also because it is the only source of carbon that plants use during photosynthesis. Previous studies have shown that plants grown under SECC result in increases in plant biomass as well as changes in nutrient concentration. However we don’t know how plants, specifically sweet potato, will respond when grown under VECC for both biomass and nutrient concentrations. Knowing this information is important because it will help us make better-informed socio-economic and agriculture decisions in a changing climate as well as add essential insight into an under researched crop that some of the most impoverished and climate vulnerable nations depend on. Therefore, the aim of this study was to investigate the biomass and nutrient response of sweet potato plants grown across four carbon dioxide concentrations approaching the full range of greenhouse gas estimates for the next 150 years.

CHAPTER 2. MATERIALS AND METHODS

2.1. Experimental design

This study was designed to compare sweet potato plants grown across carbon dioxide concentrations approaching the full range of greenhouse gas estimates for the next 150 years. Plants were subject to two types of fertilizers: organic and conventional. Conventional fertilizer results will be the main focus of the results and discussion, but similarities and differences between the two will be described in detail in section *4.4.*

Sweet potato (*Ipomoea batatas* L. (Lam) 'Waimanalo Red') plants were grown from stem cuttings within positive-pressure chambers under four different CO_2 concentrations at the University of Hawaii's College of Tropical Agriculture and Human Resources (CTAHR) Magoon Research Station. The experiment was designed as a split plot design with CO_2 concentration (352, 763, 1108, and 1515 ppm) as the whole plot factor and fertilizer (conventional vs. organic) as the split-plot factor. A fertile Mollisol (Waialua series; Very-fine, mixed, superactive, isohyperthermic Pachic Haplustolls) was collected from a fallowed field at Hoa Aina o Makaha Farm in Makaha, Hawai'i. Fertilizers were hand-mixed into 12 kg dry soil at recommended rates for optimal sweet potato growth (Valenzuela et al., 1994). 5.82 grams of a 10/10/10 fertilizer and 1.66 grams of 0/0/20 fertilizer was added to each pot of soil for the conventional treatment at the equivalent rate of 80 kg Nitrogen (N)/ha and 112 kg Potassium (K)/ha, a 1:1.4 N:K ratio, which has been shown to result in high quality sweet potato storage roots (Hammett and Miller, 1982). An additional 1.82 grams of 0/0/20 fertilizer was added as a side dressing 6 weeks after planting at the equivalent rate of 50 kg K/ha. Steer manure compost acted as the organic fertilizer and 216.93 grams was applied to each pot at the equivalent rate of 80 kg N/ha and 168 kg K/ha. This rate was determined based on its relatively high C:N ratio (20:1), 1% N, and 2.4% K concentrations. Using the median number of plants harvested in 350 previous elevated-CO_2 experiments (Poorter and Navas, 2003) eight replicates were grown for the two respective fertilizer treatments at each CO_2 concentration across a 90-day period.

Four identical growth chambers (Figure 2) were constructed from a wooden frame (253 cm wide X 97 cm high X 244 cm deep) with the roof sloping down at a 4° angle. Walls were made out of clear 0.15 mm thick polyethylene greenhouse film (AT Films Inc., USA) with two of the walls being removable side panels for maintenance and watering of plants. To elevate the CO_2 concentration in the chambers, pure cylinder CO_2 was bled into an intake pipe where it mixed with ambient air before reaching the chamber interior. The CO_2 flow rate was precisely controlled with an inline needle valve, allowing air enrichment to the desired concentration of CO_2. Air exhausted through a 1 cm gap along the top of the chamber, causing complete air turnover approximately once every 6.3 minutes. Concentrations of CO_2 were continually measured using a WMA-4 CO_2 analyzer (PP Systems, USA) with an accuracy of ±10 ppm (353 and 763 ppm chambers) and ±20 ppm (1108 and 1515 ppm chambers). Temperature (accuracy: ± 0.35 °C) and relative humidity (accuracy: ± 2.5%) were measured using a HOBO U12-012 (Onset Computer Corporation, USA) data logger.

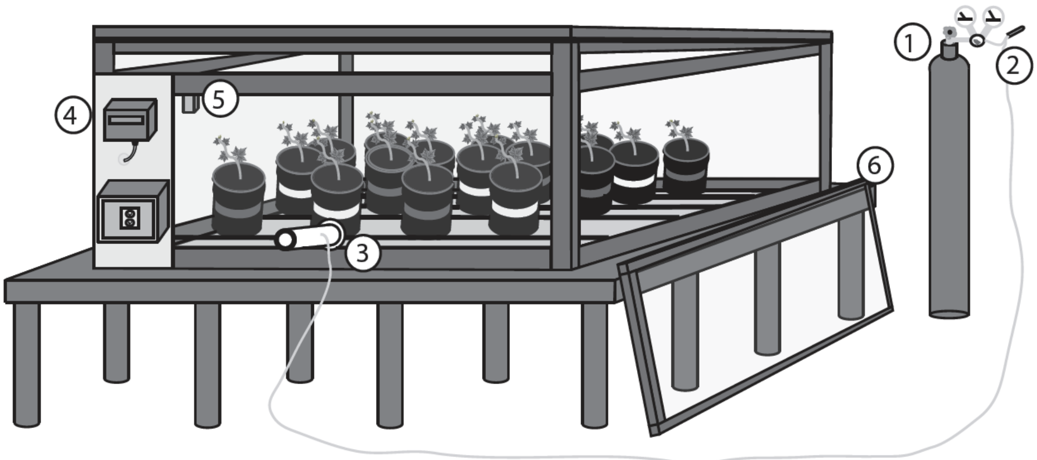


Figure 2: Schematic drawing of climate controlled growth chamber. *1*: CO_2 cylinder; *2*: needle inlet valve; *3*: intake pipe; *4*: WMA-4 CO_2 analyzer; *5*: HOBO data logger; *6*: removable side panel; *grey*: conventional fertilizer; *white*: organic fertilizer.

2.2. Growth and Maintenance

Experiments were designed to ensure that plants were not limited by water, light, or nutrient availability, as these have been shown to mitigate the effect of elevated CO_2 fertilization (Rogers and Dahlman, 1993; Bhattachrya, 1990; Erbs, 2010). Plant and chamber conditions were monitored daily to ensure optimal growing conditions and target CO_2 concentrations. Tensiometers (IRROMETER Company, Inc., USA) were used to monitor soil moisture and plants were hand watered whenever matric potentials were higher than 25 kPa to obtain optimal soil moisture conditions throughout the experiment. To avoid any potential location or chamber influence, plants were rotated within the chamber weekly and between chambers every three weeks. A stringent pest control regime was designed to ensure that pest infestation didn’t impact sweet potato growth. Admire® Pro (Bayer CropScience, USA), a soil-applied systemic, controlled aphids, whiteflies, and other sucking pests. EpiMek® 0.15 EC (Syngenta®, USA), a foliar applied miticide/insecticide, regulated broad and spider mites.

2.3. Biomass assessment

To evaluate the effect of elevated CO_2 on plant growth, a destructive harvest was performed at the end of growth and dry weights were collected. After 12 weeks of growth, the above-ground (stem and leaves) and below-ground (storage root and fine root) material were harvested, separated, dried at 60 ºC for 7 days, and weighed (uncertainty ± 0.01 g) for fresh and dry biomass.

A best-fit CO_2 response curve was used to assess the biomass responses to elevated CO_2. There are many advantages to summarize the data by using best-fit CO_2 response curve over other forms of statistical analysis. It allows interpolation at CO_2 scenarios beyond or in-between actual concentrations plants are grown under and it calculates response variables, making it possible to compare responsiveness to other plant species. Analysis of biomass was completed in terms of a hyperbolic response, as routinely invoked for modeling biological systems. Data was fit to a two-parameter rectangular hyperbola function as used by Hunt et al. (1991, 1993) and Schubert and Jahren (2011) as follows:

$$y = [abx/(a+bx)] \tag{1}$$

where y is the plant-yield variable (i.e., biomass), x is the CO_2 concentration (ppm), a is the asymptote, and b is the slope parameter at $y = x = 100$ ppm, the value used for CO_2 compensation point of dicotyledons (Ludlow and Jarvis, 1971; after Hunt et al., 1991) . The yield variable y was taken as a dry weight basis (g), expressed in natural logarithmic form, as is standard method to ensure homogeneity of variance across treatments (Poorter and Garnier, 1996). The asymptote of the hyperbolic function, variable a, can be thought of as the “maximum yield potential” which would be the highest yield possible under the most optimal level of atmospheric CO_2. Hunt and colleagues (1991, 1993) defined the value b as an overall index of CO_2 responsiveness, measuring the rate at which a plant reaches its asymptote and no longer responds to an increase in CO_2 concentrations. At low b values, the function approaches the asymptote slowly, having continual CO_2 fertilization at VECC. At high b values, the function approaches the asymptote more rapidly, showing reduced CO_2 fertilization at VECC. Plants with low b values would therefore be able to take greater advantage of high CO_2 conditions.

Estimates of a and b were obtained by fitting the model to the observed data, while maximizing the correlation coefficient (r):

$$r = \sqrt{1 - \frac{\sum_{i=1}^{n}(y_i - yf_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2}$$

where y is the average biomass value at each respective CO_2 level, yf is the fitted biomass value given by the hyperbolic model, and $yavg$ is the mean biomass value across all CO_2 levels. Maximized r-values were obtained by using iterative optimization (Solver, Excel), which changed the values of a and b until the model resulted in a best fit. The r-values could then be used to indicate how well the models fit the data.

In discussion section *4.1,* we compare our biomass response data to 24 previous studies looking at the effect of SECC on root crops. Raw data was collected from these studies and changes in percent biomass were calculated in comparison to plants grown under ambient CO_2 concentrations. All percent increases were calculated by normalizing the data to the same ambient concentration of 390ppm. This is essential because every study grows plants under slightly different ambient CO_2 concentrations ranging from 332 to 400ppm. Normalizing all the percent increases to 390ppm allows for better comparison between our study and other root crop studies grown under SECC. (Sources and data used in these calculations can be found in Appendix Table A1)

2.4. Nutrient analysis

To assess the effect elevated CO_2 has on nutrient concentration, sweet potatoes (>100g) were collected from each plant after harvest. Storage roots were blended, freeze-dried, and ball milled before passing through a 150 mesh sieve (0.104 mm). Material < 0.104 mm was then collected for nutrient analysis. Three samples were randomly chosen from each treatment to be analyzed for nutrient content. Soluble and insoluble fiber was determined using AOAC Method 991.43, a sequential enzymatic digestion by heat-stable (alpha)-amylase, protease and amyloglucosidase. Storage roots were sent to Midwest Laboratories, Inc., Omaha, NE USA to be analyzed for protein, fat, carbohydrates, calories, ash (a proximate amount of minerals in a given material), total sugars (glucose, fructose, and sucrose), phosphorus, potassium, magnesium, calcium, sulfur, iron, manganese, boron, and zinc (See Table A2 for methods used at Midwest laboratories and importance of each nutrient in both plant and human metabolism).

Responses of elevated CO_2 on nutrient concentrations will potentially impact the nutrient density score (NDS) of sweet potato storage roots grown under elevated CO_2 conditions. NDS's are built around the concept of comparing different food choices by a comparison of the amounts of key nutrients contained in 100 kcal or 100 g of a given food (Hansen, 1973). There have been multiple approaches to define nutrient density (Drewnowski, 2005; Hansen, 1973; Padberg et al., 1993). However, there is no universally accepted protocol for NDS calculation. All definitions take some combination of “healthier” nutrients to encourage in a diet (e.g., proteins, vitamins, minerals, total dietary fiber) and compare them to “less healthy” nutrients to limit (e.g., calories, unsaturated fat, sodium, carbohydrates, sugars). NDS for this research were calculated using the observed storage root nutrient responses, similar to an approach used by Scheidt and Daniel (2004).

NDS were based on 8 food components, some of which are recommended (i.e., protein, dietary fiber, calcium, iron, magnesium and potassium) and some of which are to be restricted (i.e., calories and sugars). The selection of these nutrients is based off of current regulatory frameworks and dietary guidance (2005 Dietary Guidelines for Americans; U.S. Food and Drug Administration). Percent daily values (%DV) were calculated for each food component based on a 2000-calorie daily diet using the recommended daily values given by the Food and Drug Administration’s specific nutritional labeling requirements and guidelines. NDS were calculated according to the following:

$$NDS = \frac{(\%DV_{protein} + \%DV_{TDF} + \%DV_{Ca} + \%DV_{Fe} + \%DV_{Mg} + \%DV_{K}) / 6}{(\%DV_{calories} + \%DV_{TotalSugars}) / 2} \tag{3}$$

where the numerator is the mean %DV of recommended food components and the denominator is the mean %DV of restricted food components. Therefore, greater NDS values represent a food that is healthier. A NDS greater than 1.0 is considered “healthy” as it suggests a consumption rate of more recommended nutrients than restricted nutrients.

It will also be important to understand the total storage root nutrients available (TNA) for a plant grown under elevated CO_2 concentrations. TNA represent the total amount of nutrients available in the storage roots harvested from an average sized plant grown under varying CO_2 concentrations. We calculated these values by multiplying the nutrient concentrations by the number of servings for an average sized sweet potato plant at each CO_2 concentration.

2.5 Statistical analysis

General linear model (GLM) analysis of variance (ANOVA) was used in MINITAB16 software to test for significant CO_2 effects on storage root nutrients and biomass responses. Results were determined as follows: highly significant ($P<0.01$), significant ($P<0.05$), trend ($0.1>P>0.05$), and not significant ($P>0.1$). Tukey pairwise comparisons were calculated to obtain confidence intervals allowing for a comparison of the mean values between CO_2 treatments.

CHAPTER 3. RESULTS

3.1 Chamber results

Using a HOBO data logger, relative humidity (%), temperature (°C), and CO_2 (ppm) data were collected every ten minutes throughout the 90-day growth experiment. Experimental and two-day averages were calculated throughout the duration of the experiment (Figure 3) and resulted in a strong correlation between daily average temperature and relative humidity trends between chambers (Table 1). Experimental averages deviated less than ± 0.3 ºC and ± 1.3 %RH between the four chambers, which is less than the accuracy listed for the sensors. Experimental CO_2 averages were maintained within ±10% of the target concentration, a common standard throughout previous studies (Manderscheid, 2010; Franzaring, 2008; Hans-Joachim, 2012). Elevated target concentrations were 760, 1140, and 1520 and experimental averages resulted in concentrations of 763, 1108, and 1518, respectively. The two highest elevated chambers, 1108 ppm and 1518 ppm, had larger CO_2 deviations from the experimental average due to watering and maintenance within the chambers. Chamber CO_2 concentration quickly equilibrated to ambient concentrations after a side panel was removed, but took 30-45 minutes to reach target concentrations after maintenance. This skewed the two-day averages towards lower concentrations during maintenance periods.

Table 1
Chamber conditions throughout twelve-week experiment.[a]

CO_2 (ppm)[b]	Temperature (°C)[b]	Humidity (%)[b]
353 ± 23	29.4 ± 1.6	71.5 ± 7.4
763 ± 72	29.6 ± 1.6	72.2 ± 6.9
1108 ± 127	29.7 ± 1.6	72.4 ± 7.2
1515 ± 168	29.7 ± 1.6	72.8 ± 6.9

[a] Sixteen plants were grown for each set of conditions, with half randomly supplemented with the organic amendment and the other half receiving the conventional fertilizer.
[b] All values are reported as the experimental mean ± 1σ

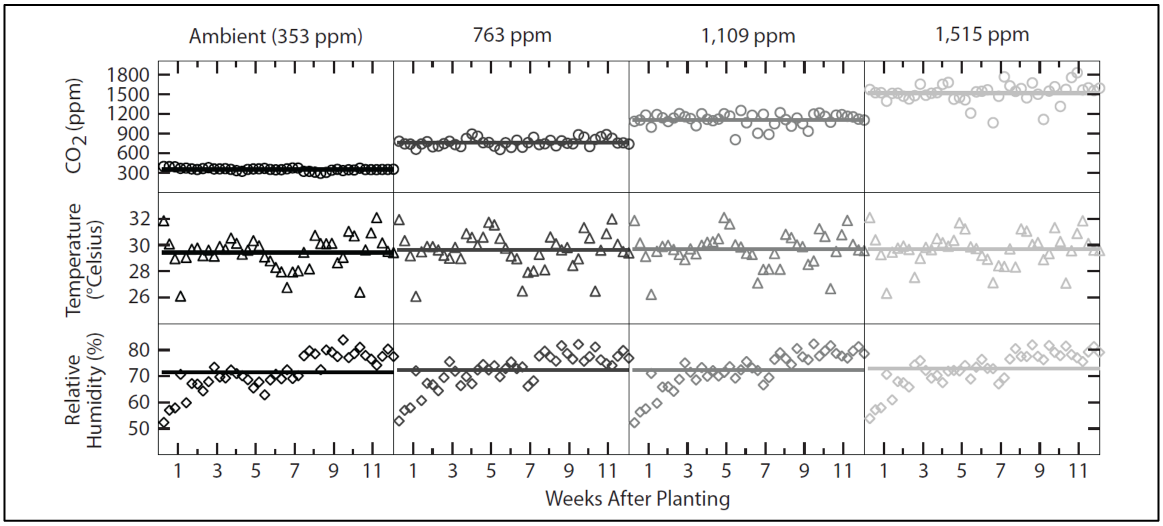


Figure 3: CO_2 and environmental chamber conditions monitored throughout the 12-week growth experiment**.** Open symbols represent two day averages and solid lines represent experimental averages.

3.2 Biomass models and growth responses

Sweet potato grown to maturity under elevated CO_2 levels and in conventional fertilizer amendments resulted in increased above-ground and storage root dry biomass compared with those grown under ambient conditions. Hyperbolic model results described in *section 2.3* (Eq. 1 and 2) indicate that storage roots do not reach its asymptote (lower *b* values) as quickly as above-ground material when grown under elevated CO_2 (Table 2). The hyperbolic models were strongly correlated with above-ground and storage root observations with R^2 values of 0.98 and 0.97, respectively (Table 2). Individual variability is to be expected in all biological experiments. However, within treatment plant-to-plant biomass did not exceed variability observed in previous plant experiments. Measured as the standard deviation of the natural log-transformed dry biomass data, total biomass variability for plants grown at each CO_2 concentration averaged 0.05. This value is much lower than 0.28, the median variability in total biomass determined by Poorter and Navas (2003) for 700 herbaceous species.

The average observed above-ground dry biomass increased by 24%, 25%, and 31% in comparison to the plants grown under ambient conditions for the plants grown under CO_2 concentrations of 763, 1108, and 1515 ppm, respectively (Figure 4). The average observed storage roots showed remarkable increases in dry biomass, increasing by 95%, 99%, and 118% for the plants grown under CO_2 concentrations of 763, 1108, and 1515 ppm, respectively.

Table 2
Conventional fertilizer hyperbolic model (*Eqn. 1 and 2)* results of above and storage root biomass for sweet potato grown under VECC.

	a	b	R^2
Above-ground	3.78	0.16	0.98
Storage root	5.13	0.09	0.97

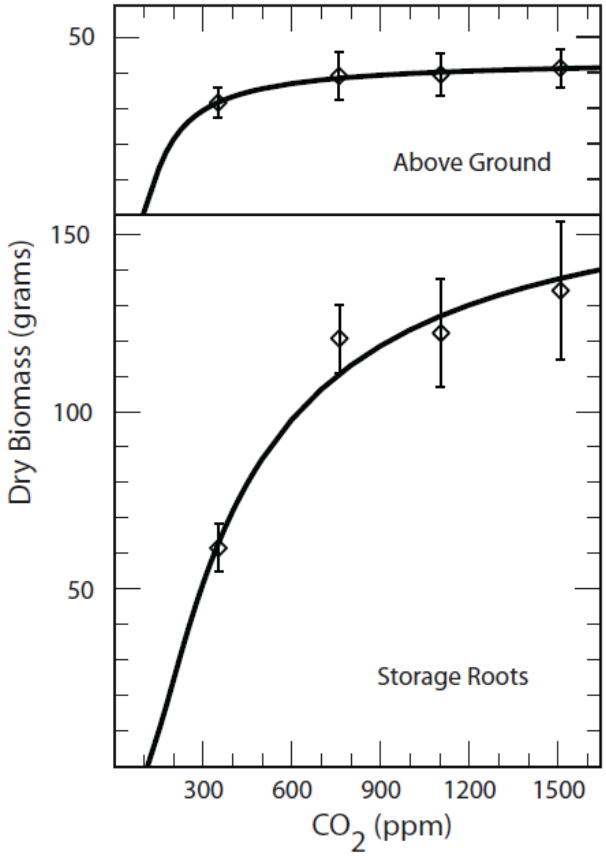


Figure 4: Above-ground and storage root dry biomass for conventional amendments (open diamonds) ± σ (error bars) with hyperbolic model results (black line).

3.3 Storage root nutrient concentration

CO_2 fertilization had positive and negative responses on the nutritional values measured in sweet potato storage roots (Table 3). When the average of the three elevated treatments were compared to those grown under ambient conditions, respective increasing responses were found for the following: carbohydrates, 4.4%; total dietary fiber (TDF), 5.3%; and total sugars, 4.6% (Figure 5a, b, and c). Decreasing responses were found for protein (34.6%) and ash (minerals) (15.7%) (Figure 5d and e). Fat showed negative trends for plants grown under 750 ppm concentration, but then increased similar to ambient concentrations when grown under 1108 and 1515 ppm, with an average 44.5% decrease for the three elevated concentrations in comparison to ambient (Figure 5f).

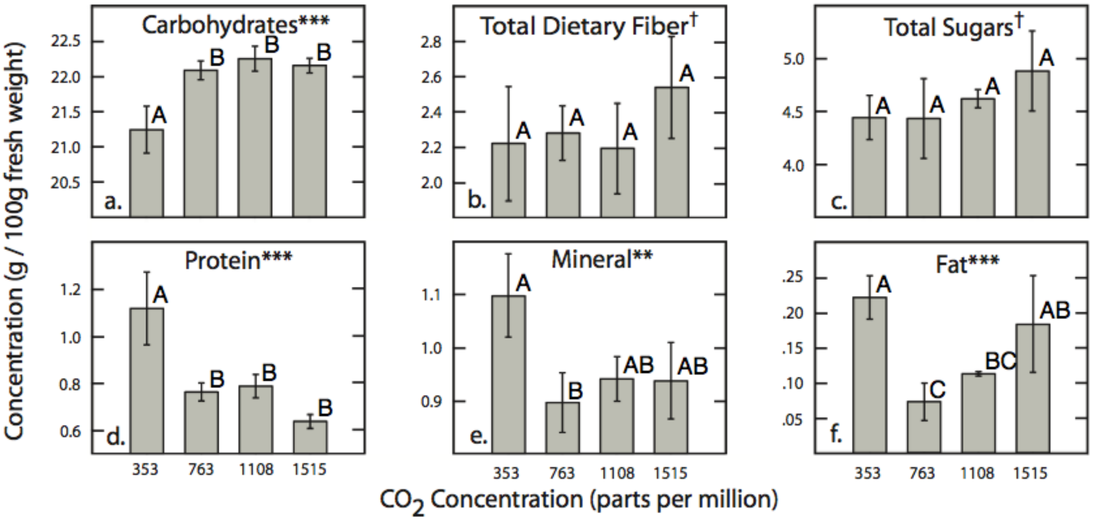


Figure 5: Nutrient concentrations of sweet potato storage roots grown under ambient (353 ppm) and elevated (763, 1108, and 1515 ppm) CO_2 conditions. Statistical significance of elevated CO_2 on nutrients is indicated as *** ($P < 0.01$), ** ($P < 0.05$), *($0.1 > P > 0.05$), or †($P > 0.1$). Concentrations with different capital letters are considered statistically different based on Tukey pairwise comparisons.

Table 3
Average nutrient concentrations of sweet potato grown under ambient and elevated CO_2 concentrations (763, 1108, 1518 ppm) in conventional fertilizer with percent changes in parenthesis and GLM ANOVA p-value results for effect of CO_2 on nutrient concentrations.

		Elevated CO_2 (ppm)						ANOVA p-value
	353	**763**		**1108**		**1518**		
Protien	1.12	0.77	(-31.6)	0.79	(-29.4)	0.64	(-42.7)	0.00
Fat	0.22	0.07	(-67.2)	0.11	(-49.2)	0.18	(-17.2)	0.01
Ash	1.10	0.90	(-18.3)	0.94	(-14.3)	0.94	(-14.6)	0.02
Carbohydrates	21.25	22.09	(4.0)	22.26	(4.8)	22.16	(4.3)	0.00
Calories	74.17	84.49	(13.9)	86.73	(16.9)	82.69	(11.5)	0.18
Sucrose	1.61	2.10	(30.2)	1.72	(6.6)	2.31	(43.4)	0.29
Glucose	1.56	1.30	(-16.5)	1.64	(5.1)	1.50	(-3.7)	0.26
Fructose	1.27	1.03	(-18.9)	1.26	(-0.7)	1.18	(-6.6)	0.17
% Insol. Fiber	1.07	1.07	(0.1)	1.07	(0.5)	1.33	(24.8)	0.38
% Sol. Fiber	1.16	1.21	(5.1)	1.12	(-2.9)	1.21	(4.8)	0.83
% Total Fiber	2.22	2.28	(2.7)	2.19	(-1.3)	2.54	(14.4)	0.41
Total Sugars	4.44	4.43	(-0.2)	4.62	(4.0)	4.89	(10.0)	0.27

3.4 Storage root mineral concentration

CO_2 fertilization resulted in general negative trends for nine mineral concentrations analyzed in sweet potato storage roots (Table 4). When the average of the three elevated treatments were compared to those grown under ambient conditions, decreasing concentrations were found ranging from 6% to 71%. The decreases, from largest to smallest, are as follows: manganese, 71%; calcium, 47%; iron, 42%; magnesium, 26%; phosphorus, 24%; sodium, 18%; boron, 13%; potassium, 6%; and zinc, 6%. Phosphorus and magnesium were the only two minerals that had significant ($P < 0.05$) ANOVA results (Figure 6 a& b) in response to CO_2. However, when grown under elevated CO_2 concentrations, manganese, sodium, calcium, and iron resulted in negative trends (Figure 6c-f). Potassium, zinc, and boron concentrations resulted in non-significant or trending results ($P > 0.1$)

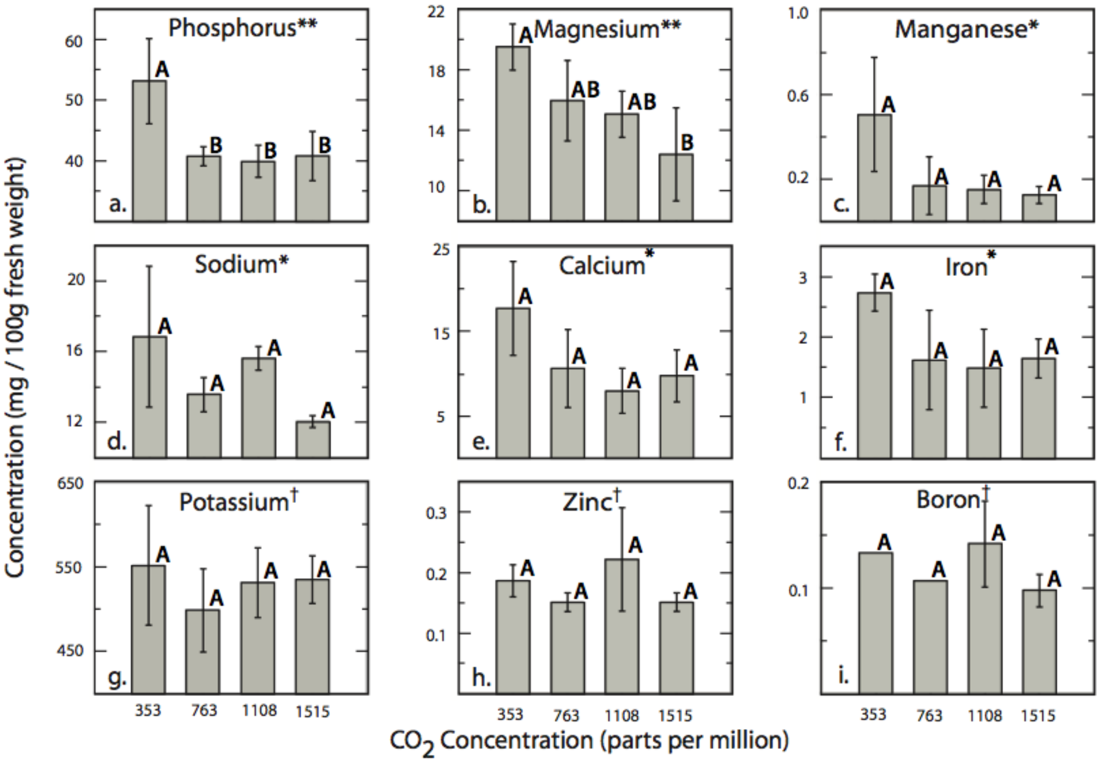


Figure 6: Mineral concentrations of sweet potato storage roots grown under ambient (353 ppm) and elevated (763, 1108, and 1515 ppm) CO_2 conditions. Statistical significance of elevated CO_2 on mineral concentration is indicated as *** ($P < 0.01$), ** ($P < 0.05$), *($0.1 > P > 0.05$), or †($P > 0.1$). Concentrations with different capital letters are considered statistically different based on Tukey pairwise comparisons.

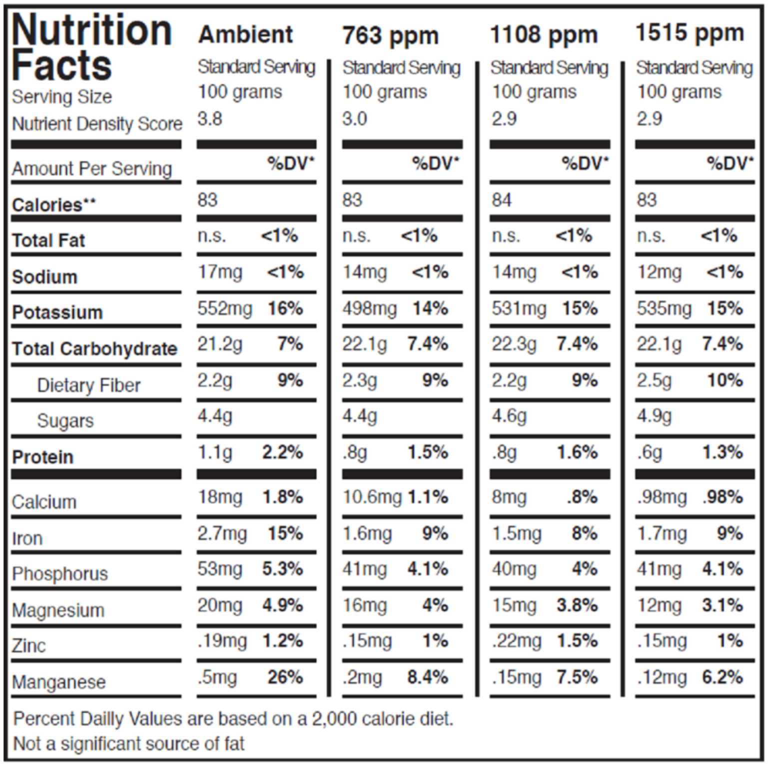
Table 4

Average mineral concentrations of sweet potato grown under ambient and elevated CO_2 concentrations (763, 1108, 1518 ppm) in conventional amended soils with percent changes in parenthesis and ANOVA p-value results for elevated CO_2 on mineral concentrations.

		Elevated CO_2 (ppm)						ANOVA p-value
	353	**763**		**1118**		**1518**		
% Nitrogen	0.68	0.46	(-32.0)	0.48	(-29.6)	0.39	(-32.0)	0.01
% Phosphorus	0.20	0.15	(-23.3)	0.15	(-25.0)	0.15	(-23.3)	0.02
% K	2.07	1.87	(-9.6)	2.00	(-3.7)	2.01	(-9.6)	0.63
% Mg	0.07	0.06	(-18.2)	0.06	(-22.7)	0.05	(-18.2)	0.03
% Ca	0.07	0.04	(-40.0)	0.03	(-55.0)	0.04	(-40.0)	0.08
% S	0.06	0.04	(-33.3)	0.05	(-22.2)	0.04	(-33.3)	0.00
% Na	0.06	0.05	(-19.5)	0.06	(-7.4)	0.05	(-19.5)	0.09
Fe ppm	103.00	61.00	(-40.8)	56.00	(-45.6)	62.00	(-40.8)	0.09
Mn ppm	19.00	6.33	(-66.7)	5.67	(-70.2)	4.67	(-66.7)	0.05
B ppm	5.00	4.00	(-20.0)	5.33	(6.7)	3.67	(-20.0)	0.11
Cu ppm	10.00	10.67	(6.7)	26.33	(163.3)	21.00	(6.7)	0.66
Zn ppm	7.00	5.67	(-19.0)	8.33	(19.0)	5.67	(-19.0)	0.26

3.5 Nutrient density scores

Figure 7 shows the NDS and %DV for plants grown under ambient and elevated CO_2 concentrations (763, 1108, and 1515 ppm), where elevated CO_2 resulted in a negative response of NDS. The largest decrease in NDS is from ambient to 763 ppm, where a decrease in 0.8 in the NDS was observed. From 763 ppm to 1108 ppm, the NDS only decreased by 0.1. From 1108 ppm to 1515 ppm there was no change in NDS. This suggests that most changes in nutrient content will happen in sweet potato grown under SECC and while nutrient content continues to alter at VECC the effects are not as abrupt.



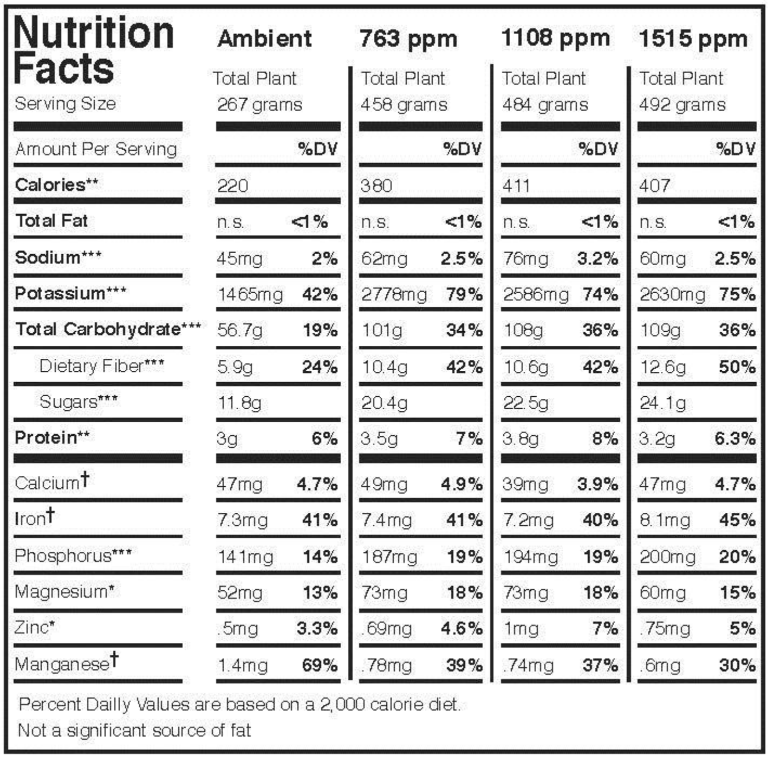
Nutrition Facts	**Ambient**		**763 ppm**		**1108 ppm**		**1515 ppm**	
	Standard Serving		Standard Serving		Standard Serving		Standard Serving	
Serving Size	100 grams		100 grams		100 grams		100 grams	
Nutrient Density Score	3.8		3.0		2.9		2.9	
Amount Per Serving		**%DV***		**%DV***		**%DV***		**%DV***
Calories**	83		83		84		83	
Total Fat	n.s.	**<1%**	n.s.	**<1%**	n.s.	**<1%**	n.s.	**<1%**
Sodium	17mg	**<1%**	14mg	**<1%**	14mg	**<1%**	12mg	**<1%**
Potassium	552mg	**16%**	498mg	**14%**	531mg	**15%**	535mg	**15%**
Total Carbohydrate	21.2g	**7%**	22.1g	**7.4%**	22.3g	**7.4%**	22.1g	**7.4%**
Dietary Fiber	2.2g	**9%**	2.3g	**9%**	2.2g	**9%**	2.5g	**10%**
Sugars	4.4g		4.4g		4.6g		4.9g	
Protein	1.1g	**2.2%**	.8g	**1.5%**	.8g	**1.6%**	.6g	**1.3%**
Calcium	18mg	**1.8%**	10.6mg	**1.1%**	8mg	**.8%**	.98mg	**.98%**
Iron	2.7mg	**15%**	1.6mg	**9%**	1.5mg	**8%**	1.7mg	**9%**
Phosphorus	53mg	**5.3%**	41mg	**4.1%**	40mg	**4%**	41mg	**4.1%**
Magnesium	20mg	**4.9%**	16mg	**4%**	15mg	**3.8%**	12mg	**3.1%**
Zinc	.19mg	**1.2%**	.15mg	**1%**	.22mg	**1.5%**	.15mg	**1%**
Manganese	.5mg	**26%**	.2mg	**8.4%**	.15mg	**7.5%**	.12mg	**6.2%**

Percent Dailly Values are based on a 2,000 calorie diet.
Not a significant source of fat

Figure 7. Nutrient density scores and nutritional label for sweet potato grown under ambient and elevated CO_2 concentrations.

3.5 Total storage root nutrients available

Positive responses were found for calories, protein, carbohydrates, TDF, total sugars, K, Na, and P when grown under elevated CO_2 concentrations (Figure 8). Increasing trends (0.1>p>.05) were observed for Mg and Zn and no strong trends or significance was found for Ca, Fe, Mn, and Cu when grown under elevated CO_2 concentrations. These large increases in TNA, especially in carbohydrates and sugars, suggest that in a CO_2 enriched environment, more total edible energy will come from a single sweet potato plant. For example, 78% more edible carbohydrates exist in a plant grown in 763 ppm CO_2 concentration in comparison to ambient conditions.



Nutrition Facts	Ambient		763 ppm		1108 ppm		1515 ppm	
Serving Size	Total Plant 267 grams		Total Plant 458 grams		Total Plant 484 grams		Total Plant 492 grams	
Amount Per Serving		%DV		%DV		%DV		%DV
Calories**	220		380		411		407	
Total Fat	n.s.	<1%	n.s.	<1%	n.s.	<1%	n.s.	<1%
Sodium***	45mg	2%	62mg	2.5%	76mg	3.2%	60mg	2.5%
Potassium***	1465mg	42%	2778mg	79%	2586mg	74%	2630mg	75%
Total Carbohydrate***	56.7g	19%	101g	34%	108g	36%	109g	36%
Dietary Fiber***	5.9g	24%	10.4g	42%	10.6g	42%	12.6g	50%
Sugars***	11.8g		20.4g		22.5g		24.1g	
Protein**	3g	6%	3.5g	7%	3.8g	8%	3.2g	6.3%
Calcium†	47mg	4.7%	49mg	4.9%	39mg	3.9%	47mg	4.7%
Iron†	7.3mg	41%	7.4mg	41%	7.2mg	40%	8.1mg	45%
Phosphorus***	141mg	14%	187mg	19%	194mg	19%	200mg	20%
Magnesium*	52mg	13%	73mg	18%	73mg	18%	60mg	15%
Zinc*	.5mg	3.3%	.69mg	4.6%	1mg	7%	.75mg	5%
Manganese†	1.4mg	69%	.78mg	39%	.74mg	37%	.6mg	30%

Percent Daily Values are based on a 2,000 calorie diet.
Not a significant source of fat

Figure 8. Total nutrients available for sweet potato grown under ambient and elevated CO_2 concentrations.

CHAPTER 4. DISCUSSION

4.1 Increases in biomass

Percent biomass increases from current atmospheric CO_2 concentration (395 ppm) from the modeled hyperbolic response curve were plotted against the average percent biomass increase curves for 23 herbaceous species taken from Hunt et al. (1991, 1993) and the results of 24 previous studies (Table A2) on five different root crops (Figure 9). When comparing this study's modeled and observed above-ground biomass results at slightly elevated CO_2 concentrations (e.g., 450-750) to previous studies on root crops, similar increases to above-ground biomass in sweet potato are seen (b of Figure 7A), but lower responses than studies on sugar beet, radish, and potato (a, c, d of Figure 7A). Sweet potato above-ground biomass was 5.9 to 13.2 percent less responsive than modeled results of 23 herbacous species (Hunt et al., 1991, 1993) grown under SECC from 600 to 1520 ppm, respectively (Figure 7A). This decreased response in sweet potato above-ground material may be due to late leaf senescence during storage root bulking stage (McLaurin and Kays, 1993; Bourke, 1983). However, this is commonly seen in *Solanum tuberosum* (White potato) at the end of the growing cycle as well (Kolbe and Stephan-Beckmann, 1997a, b) and sweet potato above-ground biomass was less responsive in comparison to white potato (d Figure 7A).

When comparing the modeled storage root biomass results at SECC to previous studies on root crops, similar increases to sugar beet, sweet potato, carrot, and white potato were observed (a,b,d,e of Figure 7B), but responses were lower than those produced by radish (c of Figure 7B). Our results suggest sweet potato below-ground biomass was 22.8 to 62.7 percent more responsive than modeled results of 23 herbacous species (Hunt et al., 1991, 1993) grown under SECC from 600 to 1520 ppm, respectively (Figure 7B). Plant responses to elevated CO_2 have been shown to be species specific (Korner, 2000; Jablonski et al., 2002), but a general response of increased root biomass and root to shoot ratios (R:S) have been observed in previous studies (Madhu and Hatfield, 2013; Idso, 1988). This increase in R:S has been shown to increase 34.9% in sweet potato (Cure, 1985) where most other species R:S ratio ranges from an 8.5% decrease to a 6.4% increase (Madhu and Hatfield, 2013). Rogers and colleagues (1996) reviewed 264 observations from 62 reports of plants grown under SECC indicating 59.5 percent had increased R:S, 37.5 percent had decreased R:S, and 3.0 percent showed no response. Root crops have large below-ground storage organs (e.g., tubers, rhizomes, true roots, etc.) and have been shown to act as a carbon sink when grown under elevated CO_2 (Overdieck et al., 1988; Miglietta et al., 2000; Hogy and Fangmeier 2009b) which could explain the enhanced response when compared to herbaceous species. On average there was a 62 percent increase in R:S ratio when compared to plants grown under ambient concentrations and a large portion of the net increase (40% of the above-ground and 47% of the storage root biomass) occurred above 700 ppm, approximately the average atmospheric CO_2 level expected by the year 2100 (IPCC, 2001). These results suggest that CO_2 fertilization will continue to supplement storage root biomass of sweet potato grown under VECC due to increased R:S ratios and utilization of the below ground storage organ as a carbon sink.

Only seven, non two-point experiments, of the 24 previous root crop studies could be extrapolated using the hyperbolic model, and only one where plants were grown at elevated concentrations greater than 750 ppm (Schubert and Jahren, 2011). Schubert and Jahren (2011) grew *Raphaus sativus* (common radish) at CO_2 concentrations up to 1791 ppm and had similar *b* values (responsiveness: See section 2.3) compared to this study. The studies that grew plants at SECC included two growing sweet potato and four growing white poatato. Storage root modeled projections for sweet potato and white potato averaged 50.0% and 45.8% increases at 1520 ppm, respectively (Table 5). Only one study, Bhattachrya et al. (1999), resulted in similar *b*-values to this study for the storage root biomass, all others were much greater (Table 5). Therefore, using the hyperbolic model on SECC data may underestimate the fertilization response of below-ground biomass of crops grown at VECC.

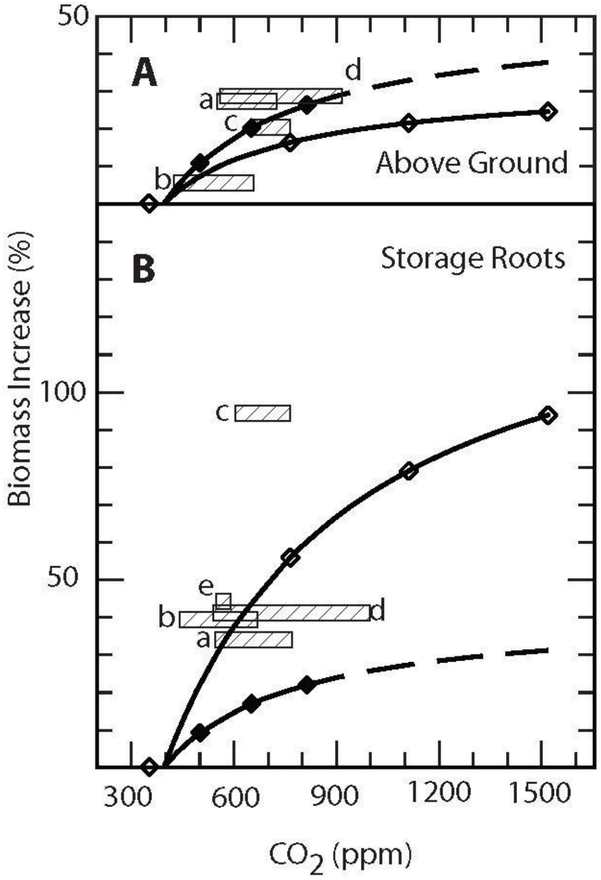


Figure 9: Projected percent biomass increase for above-ground and storage root dry biomass (open diamonds) of sweet potato across atmospheric CO_2 concentrations estimated for the next 150 years (353-1515 ppm) compared with previous results on root crops (Shaded bars; a. *Beta vulgaris*, sugar beet; b. *Ipomoea batatas Lam.*, sweet potato; c. *Raphanus sativus,* radish; d. *Solanum tuberosum,* potato; e. *Daucus carota*, carrot) and the percent increase of 23 responsive ($b<1$) herbaceous species, using the hyperbolic model results from Hunt et al. 1991, 1993. Open diamonds (this study) and closed diamonds (Hunt et al. 1991, 1993) mark the CO_2 concentrations plants were grown under with the dashed line representing extrapolated data from Hunt et al. 1991, 1993. Shaded bars represent the average percent increase calculated for each root crop (y-axis) with the range of CO_2 concentrations the crop was grown under (x-axis).

Table 5
Model results of non two-point studies with projected percent increases calculated from extrapolation of hyperbolic model for crops grown to CO_2 concentrations up to 1520 ppm.

		Model Results		Percent increase from Ambient[1] at each CO_2 concentration (ppm)				% Net increase at high CO_2
	a	b	r	600	760	1140	1520	
Sweet Potato								
This Study								
Above	3.78	.16	.99	11.6	16.1	21.7	24.4	52.5
Below	5.13	.09	.99	37.5	55.4	80.3	93.8	60.0
Bhattacharya et al. (1990)								
Above	3.40	.25	.99	6.2	8.5	11.3	12.6	50.7
Below	4.95	.09	.84	32.2	46.9	66.9	77.6	58.5
Biswas et al. (1996)								
Above	4.35	.18	.60	13.97	19.5	26.4	29.8	53.1
Below	4.35	.22	.51	16.42	15.9	21.3	24.0	31.6
Potato								
Donnelly et al. (2001)								
Above	6.99	.30	.99	22.1	31.2	42.8	48.7	54.6
Below	8.37	.34	.964	29.1	41.68	58	66.4	56.2
Conn and Cochran (2006)								
Above	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Below	8.79	.52	.95	21	29.5	40.3	45.6	53.9
Miglietta et al. (1998)								
Above	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Below	5.72	.22	.85	19.5	27.6	37.7	42.8	54.4
Heagle et al. (2003)								
Above [2]	4.09	.58	.99	4.0	5.4	7.1	7.9	49.4
Below[2]	7.80	.38	.97	22.2	31.4	42.9	48.8	54.5
Above[2]	4.54	.54	.81	5.2	7.1	9.4	10.5	50.5
Below[2]	7.90	.70	.99	12.3	17.0	22.8	25.5	51.8
Radish								
Schubert and Jahren (2011)								
Above	5.89	.23	.88	20.1	28.5	38.9	44.2	54.5
Below	6.18	.07	.82	64.2	100.2	156.0	189.1	66.0
23 Herbaceous Species								
Hunt et al. (1991, 1993)								
Above	6.97	.38	-	17.5	24.5	33.3	37.6	53.5
Below	6.40	.38	-	14.7	20.5	27.6	31.1	52.7

[1] Percent changes were calculated as increases from 395ppm.

[2] Two different cultivars were recorded for this study and modeled separately.

4.2 Elevated CO_2 on nutrient concentrations

Increased rates of photosynthesis, WUE, and NUE on plants grown at elevated CO_2 concentrations not only alter biomass, but also change the plants elemental composition. The majority of studies looking at these effects have focused on the foliar portion of crops, or the seed or grain of major global crops and resulted in increased carbohydrate concentration and decreased protein and mineral concentration (Seneweer and Conroy, 1997; Fangmeier et al., 1999; Prior et al., 1998). Loladze (2002) reviewed 25 studies that looked at changes in mineral concentration of plants grown under slightly elevated (twice ambient) CO_2 concentrations. He found average percent decreases in N, P, K, Ca, S, Mg, Fe, Zn, Mn, and Cu for all foliar plants, and decreases for all minerals except K (.86% increase) and Cu (no data) for wheat showing the same trends found for wheat mineral concentration in another study (Hogy et al., 2009a). Studies focused on the storage organs of root crops are primarily focused on *S. tuberosum* (white potato) and show similar decreasing mineral concentration trends when grown under slightly elevated CO_2 concentrations (Table 6) (Fangemeier, 2002; Heagle, 2003; Hogy and Fangmeier, 2009b) Decreases in mineral concentration has been shown to be a result of dilution from greater incorporation of carbon-rich molecules (i.e., carbohydrates) instead of mineral incorporation (Porter et al., 1997; Fangmeier et al., 1997) and some minerals may also show decreased uptake due to lower transpiration under SECC (23% on average Kimball et al., 2002; Cure and Acock, 1986; Rogers and Dahlman, 1993) resulting in partial stomatal closure and lower rates of mass flow (Conroy and Hockling, 1993; Conn and Cochran, 2006). This study was the first of its kind to look at the changes in nutrient concentration from VECC on sweet potato storage roots.

Table 6

Percent change in Mineral Concentration for a doubling of ambient CO_2 concentration taken from this study as well as other studies looking at CO_2 on mineral concentration.

	Sweet Potato	White Potato	White Potato	Foliar	Wheat Grain	Wheat
	This Study	Hogy and Fangmeier (2009b)	Heagle et al., (2003)	Loladze (2002)		Hogy et al., (2009a)
% Nitrogen	-32.02	n.a.	-20.71	-15.54	-19.77	n.a.
% Phosphorus	-23.33	5.60	-3.39	-7.82	-2.34	-0.20
% K	-9.65	-3.20	2.17	-9.87	1.64	1.00
% Mg	-18.18	-1.20	2.08	-9.87	-10.88	1.30
% Ca	-40.00	-6.10	-4.12	-7.84	-14.84	-1.10
% S	-33.33	1.00	n.a.	-1.88	-19.77	-1.60
% Na	-19.47	n.a.	n.a.	n.a.	n.a.	-4.10
Fe ppm	-40.78	4.80	-1.37	-0.93	-15.32	-3.40
Mn ppm	-66.67	0.07	0.24	-0.48	-6.74	-3.40
B ppm	-20.00	-6.40	n.a.	n.a	n.a	n.a
Cu ppm	6.67	n.a.	7.08	-14.54	0.00	-2.80
Zn ppm	-19.05	-22.80	-10.13	-12.50	-20.74	-0.60

4.3. Nutrient density scores and total storage root nutrients available

Although there are increases in TNA for proteins and a number of minerals, the decreasing NDS suggest that it will be necessary to eat larger amounts of storage roots to get the same %DV of proteins and minerals, while getting an excess amount of carbohydrates and sugars. This trend could impact the approach to a balanced diet in an elevated CO_2 world with most of the nutrient changes happening under SECC.

4.4 Organic vs. conventional responses

All previously discussed results were for sweet potato grown in conventional fertilizer amendments. To compare the influence of nutrient availability, sweet potato plants were also grown under organic fertilizer amendments and biomass and nutrient responses were analyzed. Similar to the conventional amendment, chemical analyses suggest that the increased biomass may be nutrient depleted in organic amended soils. Significant ($P < 0.05$) increases in carbohydrates (2.0%) and decreases in protein (-28.6%) and phosphorus (-11.3%) concentrations were found in the organic treatments. The conventional amendments resulted in significant decreases in magnesium (-25.8%) and decreasing trends ($P < 0.1$) were also found for calcium (-46.7%), sodium (-18.4%), iron (-42.1%) and manganese (-70.8%) that weren't found in the organic treatments.

Organic amendments showed similar response to elevated CO_2 in above-ground dry biomass, but were less responsive for storage root dry biomass (Figure 10). The impact of amendment type may be due to the immediate access plants have to nutrients and its impact on plant growth. Conventionally bound nutrients, especially N, are readily available and much more soluble, whereas organically bound nutrients interact with soil microbes in the soil to convert organically bound N to forms available to plants in the form of nitrate (NO_3^-).

Both above-ground and storage root dry biomass hyperbolic response curves for the organic treatment resulted in weaker correlations to the observed values, as shown by their lower R^2 values (Table 7). These weaker correlations are primarily due to the large residual caused by the data point at CO_2 concentration 763 ppm. The 763 ppm treatment had a lower amount of fine root allocation by 40 percent in comparison to all other organic CO_2 treatments. Increased fine root allocation is often associated with a plant looking to tap new sources of nutrients through absorption by increasing its surface area (Tester and Leigh, 2001). It also had a greater response in storage root allocation (13%) and decreased response in above-ground material (-20%) in comparison to the VECC. One possibility is that organic plants grown in the SECC were further along in the final phase of sweet potato development. The final phase includes rapid rates of storage root bulking, reduced growth of vines and fine root material, and senescing leaf material (Lebot, 2004). This may explain why storage roots observations were much greater than the plants grown in VECC and above-ground material was less than the plants grown under VECC. However, no evidence suggests that plants grown under SECC mature more rapidly than plants grown under VECC and conventional amended treatments showed no similar response. The dramatically enhanced performance of conventionally (i.e., synthetic) over organically (i.e., manure-based) fertilized plants suggests that optimal nutrient availability will be crucial for support of enhanced crop production at elevated pCO_2.

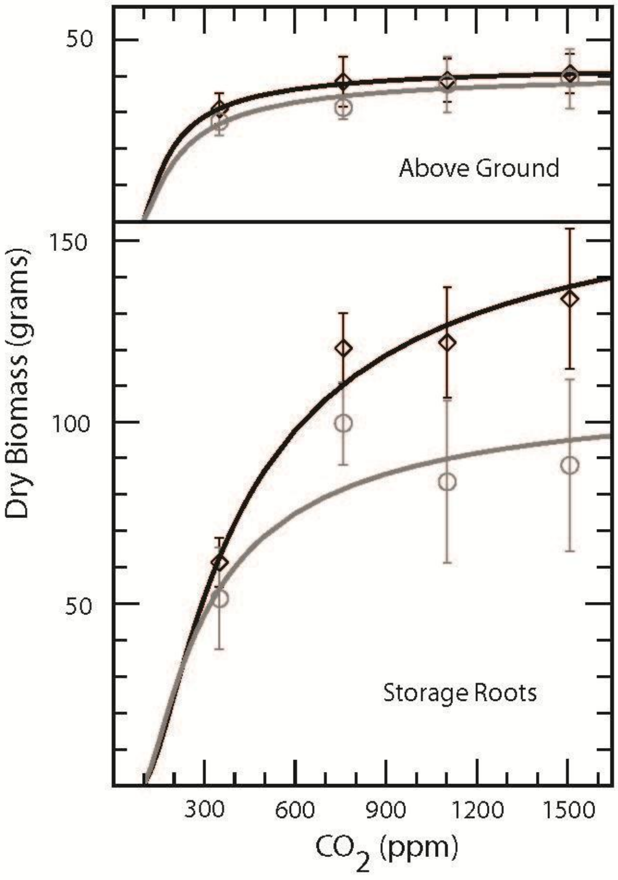


Figure 10. Organic (grey) vs. conventional (black) above-ground and storage root biomass response curves and observations with error bars representing ± one standard deviation.

Table 7.

Biomass and hyperbolic model results of Sweet potato grown under VECC for both organic and conventional fertilizer amendments. Concentrations with different capital letters are considered statistically different based on Tukey pairwise comparisons.

					Model Results		
	Ambient	763 ppm	1108 ppm	1515 ppm	a	b	R^2
Conventional							
Leaves	15.7 ± 2.6	20.3 ± 4.4	20.5 ± 3.3	21.2 ± 3.1	3.12	0.09	0.99
	A	AB	AB	B			
Stems	16.1 ± 2.0	19.3 ± 2.8	19.3 ± 2.6	20.4 ± 2.3	3.05	0.12	0.97
	A	AB	AB	B			
Total Above	31.8 ± 4.2	39.6 ± 6.8	39.8± 5.9	41.6 ± 5.3	3.78	0.16	0.98
	A	B	B	B			
Storage Root	61.8 ± 6.7	120.6 ± 9.6	122.7 ± 15.2	134.9 ± 18.0	5.13	0.09	0.97
	A	B	B	B			
Fine Root	3.5 ± 2.4	3.8 ± 2.2	3.7 ± 1.6	4.6 ± 4.0	-	-	-
	A	A	A	A			
Total Plant	97.1 ± 3.7	164.0 ± 4.0	166.2 ± 10.6	181.1 ± 10.4	5.37	0.13	0.98
Organic							
Leaves	14.7 ± 1.7	17.3 ± 1.9	21.1 ± 4.3	21.8 ± 4.1	3.13	0.07	0.89
	A	AB	BC	C			
Stems	13.6 ± 2.4	14.8 ± 1.6	17.9 ± 3.6	18.8 ± 4.1	2.94	0.08	0.79
	A	AB	B	B			
Total Above	28.4 ± 3.9	32.1 ± 3.2	40.0 ± 7.7	40.6 ± 8.2	3.73	0.12	0.85
	A	AB	BC	C			
Storage Root	53.3 ± 13.9	100.3 ± 11.4	86.2 ± 22.3	91.0 ± 23.5	4.7	0.11	0.79
	A	B	B	B			
Fine Root	7.2 ± 7.1	4.7 ± 3.1	8.2 ± 6.4	8.2 ± 6.2	-	-	-
	A	A	A	A			
Total Plant	88.9 ± 7.1	137.0 ± 7.7	133.4 ± 12.8	139.8 ± 10.2	5.09	0.16	0.95
	A	B	B	B			

CHAPTER 5. CONCLUSION

This experiment showed that sweet potato biomass and nutrient concentrations under SECC responded similarly to previous studies on a wide range of crop and non-crop species. However, sweet potato grown under VECC projected for the next 150 years showed continued storage root biomass fertilization. Fitting the hyperbolic model to other root-crop species grown under SECC resulted in high r values, but generally had lower *b*-values, suggesting that in order to get accurate projections crops should be grown in VECC instead of using extrapolation. Although crop production under VECC could see increases in biomass production, changes to nutrition could raise a new set of concerns in a high CO_2 world. Decreasing concentrations of protein and minerals in sweet potato grown under elevated CO_2 lower nutrient density scores but most of the nutritional changes occur in plants grown under SECC. Decreasing NDS will impact developing countries more severely because they have less access to different types of foods and often eat seasonal crops. Therefore, small decreases in proteins and minerals would increase rates of malnourishment and diet related illnesses in areas of the world that are already suffering from malnourishment and will be most affected by future climate change. If nutrient changes can be managed fertilization response under VECC levels could improve crop production in some of the poorest nations of the world, providing that nutrient (i.e., nitrogen, phosphorus, potassium, etc.) and water resources are sufficient and sustainable.

REFERENCES

Abeygunawardena, P., Vyas, Y., Knill, P., Foy, T., Harrold, M., Steele, P., Tanner, T., Hirsch, D., Oosterman, M., Rooimans, J., Debois, M., Lamin, M., Liptow, H., Mausolf, E., Verheyen, R., Agrawala, S., Caspary, G., Paris, R., Kashyap, A., Sharma, R., Mathur, A., Sharma, M., and Sperling, F. 2003. Poverty and climate change: Reducing the vulnerability of the poor. United Nations Environment Programme, World Bank: 43 pp.

Aydinalp C. and Cresser M. S. (2008). The effects of global climate change on agriculture. American-Eurasian Journal Agricultural and Environmental Science, 3(5):672-676.

AOAC Method 991.43 (http://www.food.gov.uk/multimedia/pdfs/annexg.pdf)

Ainsworth, E., and J. M. McGrath, 2010: Direct effects of rising atmospheric carbon dioxide and ozone of crop yields. *Global Change Research,* **37**, 109-130. DOI: 10.1007/978-90-481-2953-9_7

Bhattacharya et al., 1985. Growth and Yield Response of Sweet Potato to Atmospheric CO_2 enrichment. Crop Science. 25, 975-981.

Bhattacharya et. al., 1989. Biochemical changes in carbohydrates and proteins of sweet potato plants (*Ipomoea batatas [L.] Lam.)* in response to enriched CO_2 environment at different stages of growth and development. J. Plant Physiol. 135. 261-266.

Bhattacharya, N.C., et. al, 1990. Interaction of Enriched CO_2 and Water Stress on the Physiology of and Biomass Production in Sweet Potato Grown in Open-Top Chambers. Plant, Cell and Environment. 13, 933-940.

Biswas, P.K., et. al, 1996. Growth and Yield Responses of Field-Grown Sweetpotato to Elevated Carbon Dioxide. Crop Sci. 36, 1234-1239.

Bourke, R.M. 1984. Growth analysis of four sweet potato (Ipomoea batatas) cultivars in Papua New Guinea. Trop. Agr. (Trinidad) 61. 177–188.

Bovell-Benjamin, A.C. 2007. Sweet Potato: A Review of its past, present, and future role in human nutrition. Advances in food and nutrition research 52, 1-59.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R., Ringler, C., 2013. Economywide impacts of climate change on agriculture in Sub-Saharan Africa. Ecological Economics 93, 150-165.

Cambie, R.C. and Ferguson, L.R. 2003. Potential functional foods in the traditional Maori diet. Mutation Research 523-524, 109-117.

Conn, J.S. and Cochran, V.L. 2006. Response of potato (Solanum tuberosum L.) to elevated atmospheric CO_2 in the North American Subarctic. Agriculture, Ecosystems and Environment **112**: 49-57.

Conroy, J., and Hocking, P., 1993. Nitrogen nutrition of C3 plants at elevated atmospheric CO_2 concentrations. Physiologia Plantarum, 89, 570-576.

Cotrufo, M.F., Ineson, P., and Scott, A. 1998. Elevated CO_2 reduces the nitrogen concentration of plant tissue. Global Change Biology 4, 43–54.

Cubasch, U., et al. (2001), Projections of future climate change, in Climate Change 2001: The Scientific Basis, edited by J. T. Houghton et al., 525– 582, Cambridge Univ. Press, New York.

Cure, J.D. 1985. Carbon dioxide doubling responses: A crop survey. In: B.R. Strain and J.D. Cure, editors, Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238. U.S. Dep. of Energy, Washington, DC. p. 99–116.

Cure, J.D. and Acock, B. 1986. Crop responses to carbon dioxide doubling: A literature survey. Agric. For. Meteorol. 38. 127-145

Diop, A.,1998. Storage and processing of roots and tubers in the tropics. In “Food and Agriculture Organization of the United Nations, Agro-Industries and Post-Harvest Management Service” (D.J.B. Calverley, ed.) pp. 38-50. Agricultural Support Systems Division. Food and Agriculture Organization. Rome, Italy.

Drake B.J., Gonza`lez-Meler M.A., Long S.P., 1997. More efficient plants: a consequence of rising atmospheric CO_2? Annu Rev Plant Physiol Plant Mol Biol 48, 609–639

Drewnowski, A., 2005. Concept of a nutritious food: toward a nutrient density score. Am. J. Clin. Nutr. 82(4), 721-732

Ehleringer, J.R., Field, C.B., Lin, Z.-F., Kuo, C.-Y., 1986. Leaf carbon isotope and mineral composition in subtropical plants along an irradiance cline. Oecologia 70, 520–526.

Erbs, M.R., Manderschied, R., Jansen, G., Seddig, S., Pacholski, A., and Weigel, H.J. 2010 Effects of of free-air CO_2 enrichment and nitrogen supply on grain quality parameters of wheat and barley grown in a crop rotation. *Agric. Ecosyst. Environ.* 136, 59–68

Fangmeier, A., Gruters, U., Hogy, P., Vermehren, B., Jager,H.J., 1997. Effects of elevated CO_2, nitrogen supply and tropospheric ozone on spring wheat — II. Nutrients (N, P, K, S, Ca, Mg, Fe, Mn, Zn). Environ. Pollut. 96, 43–59.

Fangmeier, A., D. Teemerman M L. Montensen. ,K. Kemp, J. Bunke, M. Mitchell, V. oijen and H. J. Weighel. 1999. Effects on nutrients and on grain quality in spring wheat crops grown under elevated CO_2 concentrations and stress conditions in the European multiple site experiment. ESPACE Wheat . Eur. *J. Agron.* 10, 215-229.

Fernando, N., Panozzo, J., Tausz, M., Norton, R.M., Neumann, N., Fitzgerald, G.J., and Seneweera, S. 2014. Elevated CO_2 alters grain quality of two bread wheat cultivars grown under different environmental conditions. Agriculture, Ecosystems and Environment. 185, 24-33.

Fisher B, Nakicenovic N, Alfsen K, Corfee Morlot J, De la Chesnaye F, Hourcade J.-C, Jiang K, Kainuma M, La Rovere E, Matysek A, Rana A, Riahi K, Richels R, Rose S, van Vuuren DP, Warren R, 2007. Chapter 3: Issues related to mitigation in the long-term context. In: Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Franzaring, J., Hogy, P., Fangmeier, A., 2008. Effects of free air CO_2 enrichment on the growth of summer oilseed rape (Brassica napus cv. Campino). Agriculture, Ecosystems and Environment 128, 134–137.

Hansen R.G. 1973. An index of food quality. Nutr Rev 31,1-7.

Hans-Joachim, W., Manderscheid, R., 2012. Crop growth responses to free air CO_2 enrichment and nitrogen fertilization: Rotating barley, ryegrass, sugar beet and wheat. Europ. J. Agronomy 43, 97-107.

Hammett, L.E., and Miller, C.H. 1982. Influence of mineral nutrition and storage on quality factors of 'Jewel' sweet potatoes. J. Am. Soc. Hortic. Sci. 107, 972-975.

Hogy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Franzaring, J., Muntifering, R., Fangmeier, A., 2009a. Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment. Plant Biology 11, 60–69.

Hogy, P., Fangmeier, A., 2009b. Atmospheric CO_2 enrichment affects potatoes Tuber quality traits. European Journal of Agronomy. 30, 85-94

Houghton, J.T., Callander, B.A., Varney, S.K. 1992. Climate Change 1992: The Supplemantary Report to the IPCC Scientific Assessment. Cambridge University Press, Cambridge.

Hunt, R., Hand, D.W., Hannah, M.A., Neal, A.M., 1991. Response to CO_2 enrichment in 27 herbaceous species. Funct. Ecol. 5, 410–421.

Hunt, R., Hand, D.W., Hannah, M.A., Neal, A.M., 1993. Further responses to CO_2 enrichment in British herbaceous species. Funct. Ecol. 7, 661–668.

Idso, S.B. 1988. Three phases of plant response to atmospheric CO_2 enrichment. Plant Physiology 87, 5-7.

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Jablonski, L.M., Wang, X.Z,, and Curtis, P.S. 2002. Plant reproduction under elevated CO_2 conditions: a meta-analysis of reports on 79 crop and wild species. New Phytologist, 156, 9–26.

Jiang, X., Jianjun, H., and Wang, Y., 2004. Sweetpotato processing and product research and development at the Sichuan Academy of Agricultural Sciences. In “Sweetpotato Post-Harvest Research and Development in China” (K.O. Fuglie and M. Herman, eds), Proceedings of an Internationa Workshop held in Chengdu, Sichuan, PR China, November 7-8, 2001, International Potato Center (CIP), Bogor, Indonesia.

Kates, R.W., Dasgupta, P. 2007. African poverty: a grand challenge for sustainability science. Proc. Natl. Acad. Sci. U.S.A. 104, 16747–16750.

Kimball, B.A., LaMorte, R.L., Pinter Jr., P.J., Wall., G.W., Hunsaker, D.J., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D., and Brooks, T.J. 1999. Effects of free-air CO_2 enrichment on the energy balance and evapotranspiration of wheat. Water Resources Research 35, 1179-1190.

Kimball, B.A., Kobayashi, K. and Bindi, M. 2002. Responses of agricultural crops to free-air CO_2 enrichment. Advances in Agronomy **77**: 293-368.

Kolbe, H., Stephan-Beckmann, S., 1997a. Development, growth and chemical composition of the potato crop (Solanum tuberosum L.). I. Leaf and stem. Potato Res. 40, 111-129.

Kolbe, H., Stephan-Beckmann, S., 1997b. Development, growth and chemical composition of the potato crop (Solanum tuberosum L.). II. Tuber and whole plant. Potato Res. 40, 135-153.

Korner, C., 2000. Biosphere responses to CO_2-enrichment. Ecological Applications, 10, 1590-1619.

Loladze, I. 2002. Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry?. Trends in Ecology & Evolution 17, 457-461.

Lebot, V. 2009. Crop Production Science and Horticulture, Volume 17: Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams and Aroids. CABI Publishing. Wallingford, Oxon, GBR. 109-199.

Long S.P., Ainsworth E.A., Rogers, A., and Ort D.R. 2004. Rising atmospheric carbon dioxide: plants FACE the future. Annual Review of Plant Biology, 55, 591–628.

Ludlow, M.M., Jarvis, P.G., 1971. Methods for measuring photorespiration in leaves. In: Sestak, Z., Catsky, J., Jarvis, P.G. (Eds.) , Plant Photosynthetic Production: Manual of Methods. Dr W. Junk N.V. Publishers, The Hague, pp. 294–315.

Madhu, M., Hatfield, J.L., 2013. Dynamics of plant root growth under increased atmospheric carbon dioxide. Agron. J. 105, 657-669.

Makino, A., Mae, T. 1999. Photosynthesis and plant growth at elevated levels of CO_2. Plant Cell Physol. 40, 999-1006.

Manderscheid R, Pacholski A, Weigel HJ., 2010. Effect of free air carbon dioxide enrichment combined with two nitrogen levels on growth, yield and yield quality of sugar beet: Evidence for a sink limitation of beet growth under elevated CO_2. Europ J Agronom 32, 228–39.

Manderscheid, R., Erbs, M., Weigel, H.J., 2014. Interactive effects of free-air CO_2 enrichment and drought stress on maize growth . European Journal of Agronomy 52, 11-21.

McLaurin, W.J., Kays, S.J. 1993. Substantial leaf shedding – A consistent phenomenon among high-yielding sweetpotato cultivars. HortScience 28(8), 826-827

Mertz, O., Halsnaes, K., Olesen, J., & Rasmussen, K., 2009. Adaptation to climate change in developing countries. Environmental Management, 43, 743–752.

Miglietta, F., Bindi, M., Vaccai, F.P., Schapendonk, A.H.C.M., Wolf, J., Butterfield, R.E., 2000. Crop ecosystem responses to climatic change: root and tuberous crops. In: Reddy, K.R., Hodges, H.F. (Eds.), Climate Change and Global Crop Productivity. CABI Publishing, Wallingford, UK. 189–212.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl., G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., and Wilbanks, T.J. 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J.P., and Zurek, M. 2008. Towards New Scenarios for Analysis of Emissions,Climate Change, Impacts, and Response Strategies. Intergovernmental Panel on Climate Change, Geneva, 132 pp.

Nakicenovic, N., Davidson, O., Davis, G., Grubler, A., Kram, T., Rovere, E.L.L., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., and Dadi, Z. 2000. IPCC Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi, S., and You, L., 2010. Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. Washington, DC: International Food Policy Research Institute.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M., and Lee, D. 2009. Climate change: impact on agriculture and cost adaption. Washington, DC: International Food Policy Research Institute.

Odongo, B., Mwanga, R.O.M., and Niringiye, N. 2004. Promoting improved sweet potato varieties and processing technologies in Lira, Pallisa, and Soroti Districts. Final Technical Report, October 2004-12-09. NAARI, Kampala, Uganda.

Overdieck, D., Reid, C., and Strain, B.R. 1988. The effects of preindustrial and future CO_2 concentrations on growth, dry matter production and the C/N relationship in plants at low nutrient supply: Vignaunguiculata (cowpea), Abelmoschus esculentus (okra) and Raphanus sativus (radish). Botanik 62:119--134.

Oyunga-Ogubi M.A., Ng'ang'a, N.M., and Olayo, J.A., 2005. Sweetpotato processing for improved vitimin A intake: Gender implications and potential for sustainable technology adaption in Siaya District, Kenya. (http:/www.asareca.org)

Padberg DI, Kubena KS, Ozuna T, Kim H, Osborn L. The nutritional quality index: an Instrument for communicating nutrition information to consumers. College Station, TX: Agricultural and Food Policy Cen- ter, Texas A&M University, 1993. (AFPC Policy Research Report 93-10.)

Poorter, H., Garnier, E., 1996. Plant growth analysis: an evaluation of experimental design and computational methods. J. Exp. Bot. 47, 1343–1351

Poorter, H., Berkel, Y.V., Baxter, R., Hertog, J.D., Dijkstra, P., Gifford, R.M., Griffin, K.L., Roumet, C., Roy, J., and Wong, S.C. 1997. The effect of elevated CO_2 on the chemical composition and construction costs of leaves of 27 C_3 species. Plant, Cell and Environment. 20, 472-482.

Poorter, H., Navas, M.L., 2003. Plant growth and competition at elevated CO_2: on winners, losers and functional groups. New Phytol. 157, 175–198.

Prior, S.A., Torbert, H.A., Runion, G.B., Mullins, G.L., Rogers, H.H., Mauney, J.R., 1998. Effects of CO_2 enrichment on cotton nutrient dynamics. J. Plant Nutr. 21, 1407–1426.

Rogers, H.H., Prior, S.A., Runion, G.B., Mitchell, R.J., 1996. Root to shoot ratio of crops as influenced by CO_2. Plant Soil 187:229–248. doi:10.1007/ BF00017090

Rogers, H.H., Dahlman, R.C., 1993. Crop responses to CO_2 enrichment. Vegetatio. 104, 117-131.

Roumet, C., Bel, M.P., Sonie, L., Jardon, F., Roy, J., 1996. Growth response of grasses to elevated CO_2: a physiological plurispecific analysis. New Phytol 113: 595-603 Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. U.S.A. 104, 19703–19708.

Riahi, K., Gruebler, A., Nakicenovic, N. 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Chang 74(7), 887–935.

Riahi K, Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P. 2011. RCP 8.5 – A scenario of comparatively high greenhouse gas emissions. Climatic Change 109, 33-57.

Saweri, W., 2001. The rocky road from roots to rice: A review of changing food and nutrition situation in Papau New Guinea. P.N.G. Med. J. 44, 151-163.

Scheidt, D.M., Daniel, E., 2004. Composite index for aggregating nutrient density using food labels: Ratio of recommended to restricted food components. Journal of Nutrition Education and Behavior 36, 35-39.

Schlenker, W., Lobel, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 1-8.

Schubert , B.A., and Jahren, A.H., 2011. Fertilization trajectory of the root crop *Raphinus sativus* across atmospheric $p\mathrm{CO}_2$ estimates for the next 300 years. Agriculture, Ecosystems and Environment. 140, 174-181.

Scott, G, Best, R, Rosegrant, M.W., and Bokanga, M. 2000. Roots and Tubers in the Global Food System: A vision statement to the year 2020. CIP, CIAT, IFPRI, IITA, IPGRI. Printed in Lima, Peru: International Potato Center.

Seneweer, S.P., and Conroy, J.P., 1997. Growth, grain yield and quality of rice (*Oryza sative* L) in response to elevated CO_2 and phosphorus nutrition. Soil Science and Plant Nutrition. 43, 1131-1136.

Tester, M., Leigh, R.A., 2001. Partitioning of nutrient transport processes in roots. Journal of Experimental Botany. 52, 445-457.

Tubiello, F.N. and Fischer, G. 2007. Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000-2080. Technology Forecasting & Social Change 74, 1030-1056.

Van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Weyant, J. 2011a. A special issue on the RCPs. Climatic Change 109, 1-4.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. 2011b. The representative concentration pathways: an overview. Climatic Change 109, 5-31.

Valenzuela, H., S Fukuda, and A. Arakaki. 1994. Sweetpotato production guides for Hawaii. Hawaii Agr. Expt. Ata. Res. Ext. Ser. 146.

Wolfe, J.A., 1992. Sweetpotato: An Untapped Food Resource. 44-117. Cambridge University Press, New York, NY

APPENDIX

Table A1

Methods used in determining nutritive concentration and their respective human and plant benefits

What Was Analyzed	How Plants Use It	How Humans Use It	Method Used to Analyze
Protein	• Used in growth, development and reproduction by providing carbon, nitrogen, and sulfur resources.	• Proteins provide essential amino acids which each have a specialized function in the human body. Of the 20 amino acids that exist, 9 must be obtained through diet.	AOAC 992.15
Fat	• Commonly found in seeds and used as a dense source of energy for plants.	• Provides energy, protects organs, and allows the body to absorb necessary nutrients such as vitamins A, D, E, and K	AOAC 922.06
Ash (Mineral L.O.I.)	• Plants need a number of different minerals for growth, maintenance, and reproduction.	• Humans need a number of minerals for proper bodily functions.	AOAC 900.02
Carbohydrates	• Plants use carbohydrates for energy or as building blocks to make more complex molecules.	• Carbohydrates provide energy for working muscles, fuel for the central nervous system, enable fat metabolism, and prevent protein from being used as energy.	Calculation
Calories	• Calories provide energy to a plant because they are directly related to the amount of fat, protein, and carbohydrate concentrations.	• Calories are a measurement of the energy given off by the concentration of fat, protein, and carbohydrates in a given food.	21 CFR Part 101.9 (Calculation)
Total Sugars	• Sugars are essential in providing energy to plants during respiration and can be used to create more complex molecules essential to	• The main sugars in fruits and vegetables are glucose, fructose, and sucrose, which play an essential role in cellular energy	AOAC 982.14 HPLC/RI-Hot water extraction

	plant functions.	in our body.	
Insoluble Fiber	• Insoluble fiber is primarily made up of cellulose, hemicellulose and lignin. These are used primarily in growth to support structural integrity of cell walls.	• Both sources of fiber increase food volume without increasing caloric intake and aid in digestion. • Insoluble fiber regulates blood sugar, lowering risk in diabetes and can add bulk to the stool, alleviating constipation.	AOAC 991.43
Soluble Fiber	• Soluble fiber is made up of water-soluble saccharides which function as long-term storage sources of sugars, and therefore energy.	• Soluble fiber can lower the LDL Cholesterol and the absorption of glucose into the blood stream lowering risk to cardiovascular disease and helps stabilize blood sugar levels.	AOAC 991.43
Nitrogen	• Nitrogen is a part of all living cells and is a necessary part of all proteins, enzymes and metabolic processes involved in the synthesis and transfer of energy.	• Nitrogen is the building block for amino acids, which are the building blocks of proteins, and are essential for human nutrition.	ICP-AES
Phosphorus	• Phosphorus is an essential part of the process of photosynthesis.	• The main function of phosphorus is in the formation of bones and teeth. It also helps with kidney function, muscle contractions, normal heartbeat, and nerve signaling.	ICP-AES
Potassium	• Potassium aids in the building of protein, photosynthesis, fruit quality and reduction of diseases.	• Your body needs potassium to build proteins, break down and use carbohydrates, and control the electrical activity of the heart.	ICP-AES
Magnesium	• Magnesium is part of the chlorophyll in all green plants and essential for photosynthesis and also helps activate many plant enzymes needed for growth.	• Magnesium helps in the contraction and relaxation of muscles, function of certain enzymes in the body, production and transport of energy, and production of	ICP-AES

		protein.	
Calcium	Calcium is an essential part of plant cell wall structure and provides for normal transport and retention of other elements in the plant.	Calcium aids in building strong bones and teeth, clotting blood, sending and receiving nerve signals, squeezing and relaxing muscles, releasing hormones, and keeping a normal heartbeat.	ICP-AES
Sulfur	Sulfur is essential for the production of protein and improves root growth and seed production.	Sulfur is essential for building of numerous amino acids, which are essential in human nutrition.	ICP-AES
Sodium	Sodium is generally a toxin for most plants, inhibiting growth, but is also a desirable way to build osmotic potential and aid in water uptake.	The body uses sodium to control blood pressure and blood volume. Sodium is also needed for your muscles and nerves to work properly.	ICP-AES
Iron	Essential for formation of chlorophyll.	The human body needs iron to make the oxygen-carrying proteins hemoglobin and myoglobin. Hemoglobin is found in red blood cells and myoglobin is found in muscles.	ICP-AES
Manganese	Functions with enzyme systems involved in breakdown of carbohydrates, and nitrogen metabolism.	Essential for enzymes needed in the use of biotin, B-1, and vitamin C. It also helps with metabolization of proteins and digestion.	ICP-AES
Boron	Aids in the use of nutrients and regulation of other nutrients and is essential for seed and fruit development.	Boron has been found to help bones utilize calcium and help regulate the magnesium and phosphorus balance in the body.	ICP-AES
Copper	Important for reproductive growth.	Copper works with iron to help the body form red blood cells. It also helps keep	ICP-AES

		the blood vessels, nerves, immune system, and bones healthy.	
Zinc	- Essential for the transformation of carbohydrates and is part of the enzyme systems which regulate plant growth.	- Zinc is needed for the body's defensive (immune) system to properly work and plays a role in cell division, cell growth, wound healing, and the breakdown of carbohydrates.	ICP-AES

Table A2

Previous literature results for other root crop species with both above and below ground biomass response.

Species	Common Name	Biomass Part	Control CO_2 (ppmv)	Elevated CO_2 (ppmv)	% Biomass Change	Reference
Beta vulgaris	sugar beet	AG	332	725	49	Ziska et al. 1995
Beta vulgaris	sugar beet	AG	332	725	153	Ziska et al. 1995
Beta vulgaris	sugar beet	AG	332	725	28	Ziska et al. 1995
Beta vulgaris	sugar beet	AG	375	550	-11	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	5	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	32	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	20	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	5	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	4	Mandersched et al, 2010
Beta vulgaris	sugar beet	AG	375	550	21	Mandersched et al, 2010
Ipomoea batatas	sweet potato	AG	364	438	6	(Bhattacharya et al., 1990)
Ipomoea batatas	sweet potato	AG	364	666	9	(Bhattacharya et al., 1990)
Ipomoea batatas	sweet potato	AG	354	431	22	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	AG	354	506	23	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	AG	354	659	12	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	AG	361	438	-15	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	AG	361	514	-2	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	AG	361	665	19	(Biswas et al., 1996)
Raphanus sativus	radish	AG	386	761	7	(Barnes and Pfirrmann, 1992)
Raphanus sativus	radish	AG	330	600	25	(Chu et al., 1992)
Raphanus sativus	radish	AG	350	700	8	(Wong, 1993)
Raphanus sativus	radish	AG	350	700	52	(Wong, 1993)
Raphanus sativus	radish	AG	350	650	22	(Overdieck et al., 1988)
Raphanus sativus	radish	AG	300	700	39.6	Romanova et al, 2002
Solanum tuberosum	potato	AG	398	543	23	(Donnelly et al., 2001)
Solanum tuberosum	potato	AG	398	694	28	(Donnelly et al., 2001)
Solanum tuberosum	potato	AG	360	900	17	Tao (2010)
Solanum tuberosum	potato	AG	360	900	48	Tao (2010)
Beta vulgaris	sugar beet	BG	332	775	29	Ziska et al. 1995
Beta vulgaris	sugar beet	BG	332	775	178	Ziska et al. 1995
Beta vulgaris	sugar beet	BG	332	775	87	Ziska et al. 1995
Beta vulgaris	sugar beet	BG	375	550	14	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	375	550	10	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	375	550	17	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	375	550	8	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	375	550	36	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	375	550	18	Mandersched et al, 2010
Beta vulgaris	sugar beet	BG	378	668	26	(Demmers-Derks et al., 1998)
Daucus carota	carrot	BG	348	551	31	(Wheeler et al., 1994)
Daucus carota	carrot	BG	348	551	80	(Wheeler et al., 1994)

Ipomoea batatas	sweet potato	BG	364	438	63	(Bhattacharya et al., 1990)
Ipomoea batatas	sweet potato	BG	364	666	40	(Bhattacharya et al., 1990)
Ipomoea batatas	sweet potato	BG	361	438	26	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	BG	361	514	43	(Biswas et al., 1996)
Ipomoea batatas	sweet potato	BG	361	665	69	(Biswas et al., 1996)
Raphanus sativus	radish	BG	350	650	70	(Jablonski, 1997)
Raphanus sativus	radish	BG	330	600	40	(Chu et al., 1992)
Raphanus sativus	radish	BG	386	761	43	(Barnes and Pfirrmann, 1992)
Raphanus sativus	radish	BG	350	700	289	(Wong, 1993)
Raphanus sativus	radish	BG	350	700	113	(Wong, 1993)
Raphanus sativus	radish	BG	350	650	78	(Overdieck et al., 1988)
Solanum tuberosum	potato	BG	360	900	107	Tao (2010)
Solanum tuberosum	potato	BG	360	900	142	Tao (2010)
Solanum curtilobum	potato	BG	360	720	85	olivo (2002)
Solanum tuberosum	potato	BG	360	720	40	olivo (2002)
Solanum tuberosum	potato	BG	365	550	34	Magliulo
Solanum tuberosum	potato	BG	365	550	53	Magliulo
Solanum tuberosum	potato	BG	400	1000	100	Ludewig et al. (1998)
Solanum tuberosum	potato	BG	400	720	25	Katny et al. (2005)
Solanum tuberosum	potato	BG	350	750	27	Schapendonk et al., 2000
Solanum tuberosum	potato	BG	350	750	49	Schapendonk et al., 2000
Solanum tuberosum	potato	BG	350	700	33	(Chen et al., 2003)
Solanum tuberosum	potato	BG	380	550	6	(Högy and Fangmeier, 2009)
Solanum tuberosum	potato	BG	370	715	29	(Heagle et al., 2003)
Solanum tuberosum	potato	BG	370	540	20	(Heagle et al., 2003)
Solanum tuberosum	potato	BG	370	715	22	(Heagle et al., 2003)
Solanum tuberosum	potato	BG	398	543	26	(Donnelly et al., 2001)
Solanum tuberosum	potato	BG	398	694	41	(Donnelly et al., 2001)
Solanum tuberosum	potato	BG	369	543	20	(Conn and Cochran, 2006)
Solanum tuberosum	potato	BG	369	707	36	(Conn and Cochran, 2006)

Barnes, J.D., Pfirrmann, T., 1992. The influence of CO_2 and O_3, singly and in combination, on gas exchange, growth and nutrient status of radish (*Raphanus sativus* L.). New Phytol. 121, 403-412.

Bhattacharya, N.C., Hileman, D.R., Ghosh, P.P., Musser, R.L., Bhattacharya, S., Biswas, P.K., 1990. Interaction of enriched CO_2 and water stress on the physiology of and biomass production in sweet potato grown in open-top chambers. Plant, Cell Environ. 13, 933-940.

Biswas, P.K., Hileman, D.R., Ghosh, P.P., Bhattacharya, N.C., McCrimmon, J.N., 1996. Growth and yield responses of field-grown sweetpotato to elevated carbon dioxide. Crop. Sci. 36, 1234-1239.

Chen, C.T. and Setter, T.L. 2003. Response of potato tuber cell division and growth to shade and elevated CO_2. Annals of Botany 91: 373-381.

Chu, C.C., Coleman, J.S., Mooney, H.A., 1992. Controls of biomass partitioning between roots and shoots: Atmospheric CO_2 enrichment and the acquisition and allocation of carbon and nitrogen in wild radish. Oecol. 89, 580-587.

Conn, J.S., Cochran, V.L., 2006. Response of potato (*Solanum tuberosum* L.) to elevated atmospheric CO_2 in the North American subarctic. Agric., Ecosyst. Environ. 112, 49-57.

Demmers-Derks, H., Mitchell, R.A.C., Mitchell, V.J., Lawlor, D.W., 1998. Response of sugar beet (*Beta vulgaris* L.) yield and biochemical composition to elevated CO_2 and temperature at two nitrogen applications. Plant Cell. Environ. 21, 829-836.

Donnelly, A., Craigon, J., Black, C.R., Colls, J.J., Landon, G., 2001. Elevated CO_2 increases biomass and tuber yield in potato even at high ozone concentrations. New Phytol. 149, 265-274.

Heagle, A.S., Miller, J.E., Pursley, W.A., 2003. Growth and yield responses of potato to mixtures of carbon dioxide and ozone. J. Environ. Qual. 32, 1603-1610.

Högy, P., Fangmeier, A., 2009. Atmospheric CO_2 enrichment affects potatoes: 1. Aboveground biomass production and tuber yield. Eur. J. Agron. 30, 78-84.

Jablonski, L.M., 1997. Responses of vegetative and reproductive traits to elevated CO_2 and nitrogen in *Raphanus* varieties. Can. J. Bot. 75, 533-545.

Katny, M.A.C., Hoffmann-Thoma, G., Schrier, A.A., Fangmeier, A., Jager, H.J., van Bel, A.J.E., 2005. Increase of photosynthesis and starch in potato under elevated CO_2 is dependent on leaf age. Journal of Plant Physiology. 162, 429-438.

Ludewig, F., Sonnewald, U., Friedrich, K., Heineke, D., Geiger, M., Stitt, M., Muller-Rober, B.T., Gillissen, B., Kuhn, C., Frommer, W.B., 1998. The role of transient starch in acclimation to elevated atmospheric CO_2. FEBS Letters. 429, 147-151.

Manderscheid, R., Pacholski, A., Weigel, H.-J., 2010. Effect of free air carbon dioxide enrichment combined with two nitrogen levels on growth, yield and yield quality of sugar beet: Evidence for a sink limitation of beet growth under elevated CO_2. Eur. J. Agron. 32, 228-239.

Magliulo, V., Bindi, M., Rana, G., 2003. Water use of irrigated potato (*Solanum tuberosum L.*) grown under free air carbon dioxie enrichment in central Italy. Agriculture, Ecosystems and Environment. 97, 65-80.

Olivo, N., Martinez, C.A., Oliva, M.A., 2002. The photosynthetic response to elevated CO_2 in high altitude potato species (*Solanum curilobum*). Photosynthetica. 40 (2), 309-313.

Overdieck, D., Reid, C., Strain, B.R., 1988. The effects of preindustrial and future CO_2 concentrations on growth, dry matter production and the C/N relationship in plants at low nutrient supply: *Vigna unguiculata* (cowpea), *Abelmoschus esculentus* (okra) and *Raphanus sativus* (radish). Angew. Bot. 62, 119-134.

Romanova, A.K., Mudrik, V.A., Novichkova, R.N., Demidova, R.N., Polyakova, V.A., 2002. Physiological and biochemical characteristics of sugar beet plants grown at an increased carbon dioxide concentration at various nitrate doses. Russian Journal of Plant Physiology. 49 (2), 204-210.

Schapendonk, H.C.M., Oijen, M.V., Dijkstra, P., Pot, C.S., Jordi, W.J.R.M., Stoopen, G.M., 2000. Effects of elevated CO_2 concentration on photosynthetic acclimation and productivity of two potato cultivars grown in open-top chambers. Aust. J. Plant. Physiol. 27, 1119-1130.

Tao, G., Letham, D.S., Yong, J.W.H., Zhang, K., John, P.C.L., Schwartz, O., Wong, S.C., Farquhar, G.D., 2010. Promotion of shoot development and tuberisation in potato by expression of a chimaeric cytokinin synthesis gene at normal and elevated CO_2 levels. Functional Plant Biology. 37, 43-54.

Wheeler, T.R., Morison, J.I.L., Ellis, R.H., Hadley, P., 1994. The effects of CO_2, temperature and their interaction on the growth and yield of carrot (*Daucus carota* L.). Plant Cell. Environ. 17, 1275-1284.

Wong, S.-C., 1993. Interaction between elevated atmospheric concentration of CO_2 and humidity on plant growth: comparison between cotton and radish. Vegetatio 104/105, 211-221.

Ziska, L.H., Sicher, R.C., Kremer, D.F., 1995. Reversibility of photosynthetic acclimation of swiss chard and sugarbeet grown at elevated concentrations of CO_2. Physiol. Plant. 95, 355-364.

Table A3
Pre incubation soil fertility measurements taken before the addition of organic and conventional fertilizers. All samples processed at the Agricultural Diagnostics Service Center at the University of Hawaii at Manoa.

	mmhos/cm		Parts per million				Percent		mg/dm^3			
	pH	EC	P	K	Ca	Mg	N	TC	Mn	Fe	Cu	Zn
Mollisol #1	6.6	0.42	470	840	2726	1551	0.09	1.2	267	23	7.7	8.6
Mollisol #2	6.7	0.42	535	844	2732	1572	0.13	1.2	222	23	7.2	8.4
Mollisol #3	6.6	0.42	553	834	2752	1554	0.15	1.2	219	24	7.0	8.4

Table A4.
Steer manure compost elemental composition used in calculation of applicable rates to amend into soils. All samples were processed at the Agricultural Diagnostics Service Center at the University of Hawaii at Manoa.

	Percent							Part per million				
	N	C	P	K	Ca	Mg	Na	Fe	Mn	Zn	Cu	B
Compost #1	1.09	19.28	0.41	2.26	2.33	0.74	0.51	10841	410	58	25	49
Compost #2	1.25	19.79	0.49	2.44	2.21	0.82	0.56	8701	251	78	28	51
Compost #3	1.12	18.97	0.51	2.56	2.17	0.86	0.58	8176	258	83	29	57

Table A5

Post incubation soil fertility measurements taken after the addition of organic and conventional fertilizers. All samples processed at the Agricultural Diagnostics Service Center at the University of Hawaii at Manoa.

			mmhos/cm	ppm				%		mg/dm^3			
CO_2 (ppm)	Ammendment	pH	EC	P	K	Ca	Mg	N	TC	Mn	Fe	Cu	Zn
352	Organic	7	0.76	568	656	1953	895	0.09	1.4	244	20	8.3	8.5
763	Organic	7	0.77	625	666	1959	895	0.28	1.4	258	20	8.3	8.3
1108	Organic	7	0.75	659	664	1933	898	0.36	1.4	255	18	8.2	8.2
1515	Organic	7	0.7	663	655	1957	895	0.18	1.5	250	20	8.4	9.3
352	Conventional	6.6	0.68	551	512	1802	893	0.14	1.2	258	18	8.1	7.8
763	Conventional	6.6	0.68	592	515	1809	890	0.19	1.2	265	18	8.2	8.2
1108	Conventional	6.5	0.68	647	508	1847	873	0.08	1.2	258	19	8	7.9
1515	Conventional	6.5	0.67	551	507	1829	886	0.28	1.2	245	19	8.1	8.7

Table A6

Post experiment soil fertility measurements taken as the average of the three replicates per treatment. The soils were collected from the same plants that were used in nutrient analysis. All soil measurements were taken at Midwest Laboratories.

			Phosphorus			Neutral Ammonium Acetate (Exchangeable)						% Base Saturation (Computed)						DTPA Extraction					
		OM (LOI)	P1[a]	P2[b]	Olsen[c]	K	Mg	Ca	Na	pH	C.E.C	K	Mg	Ca	Na	Nitrate-N (FIA)		S	Zn	Mn	Fe	Cu	B
Fertilizer	CO2	%	ppm			ppm					meq/ 100g	%				ppm	lbs/A	ppm					
Conventional	352	3.6	64	132	128	499	1187	2183	307	6.6	24.9	5.1	40	44	5.3	12	22	112	11	31	47	3.3	1.2
Conventional	763	3.6	56	123	113	504	1238	2238	289	6.7	24.6	5.3	42	46	5.1	13	24	97	11	33	41	3.5	1.2
Conventional	1108	3.6	56	132	131	519	1335	2399	305	6.7	25.8	5.2	43	47	5.1	11	20	103	11	35	40	3.5	1.2
Conventional	1515	3.6	68	121	127	436	1195	2185	286	6.7	24.2	4.6	41	45	5.1	12	22	102	11	34	39	3.4	1.1
Organic	352	3.7	56	133	122	779	1213	2248	316	6.9	24.7	8.1	41	46	5.6	28	51	92	11	30	38	3.4	1.4
Organic	763	3.8	59	118	125	717	1205	2237	314	6.9	24.4	7.5	41	46	5.6	21	37	91	11	30	38	3.3	1.4
Organic	1108	3.7	62	139	127	692	1234	2340	315	7.0	25.1	7.1	41	47	5.4	22	40	102	12	33	38	3.4	1.3
Organic	1515	3.8	67	145	133	667	1210	2305	310	6.9	24.7	6.9	41	47	5.5	24	44	100	12	33	39	3.5	1.3

[a] Weak Bray (1:7)
[b] Strong Bray (1:7)
[c] Bicarbobate P

Table A7
Weeks 1-3 stem length, leaf number and leaf area measurements for ambient chamber.

			Week 1			Week 2			Week 3		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	Ambient	Inorganic	11	6	-	24.5	15	-	93.5	27	34.7
2	Ambient	Inorganic	11.5	4	-	22	13	-	69.5	21	26.0
3	Ambient	Inorganic	9.5	5	-	49	23	-	152.5	43	29.5
4	Ambient	Inorganic	14.5	6	-	40	27	-	166	44	29.5
5	Ambient	Inorganic	14	7	-	31	16	-	82	27	33.0
6	Ambient	Inorganic	9.5	7	-	39.5	19	-	171.5	42	34.7
7	Ambient	Inorganic	12.5	5	-	49	19	-	224	46	34.7
8	Ambient	Inorganic	10.5	6	-	48.5	22	-	187	41	29.5
9	Ambient	Organic	11.5	9	-	47.5	28	-	189	48	27.8
10	Ambient	Organic	10.5	5	-	24.5	14	-	71.5	22	31.2
11	Ambient	Organic	9	5	-	35.5	24	-	180.5	49	31.2
12	Ambient	Organic	12.5	8	-	43	25	-	118	38	29.5
13	Ambient	Organic	9.5	6	-	23	17	-	113.5	34	33.0
14	Ambient	Organic	12	3	-	30	13	-	122	31	27.8
15	Ambient	Organic	11.5	6	-	34	16	-	117.5	35	34.7
16	Ambient	Organic	12	6	-	43.5	18	-	168.5	45	33.0

Table A8

Weeks 4-6 stem length, leaf number and leaf area measurements for ambient chamber

			Week 4			Week 5			Week 6		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	Ambient	Inorganic	293	49	34.7	488	103	33.0	439	112	29.5
2	Ambient	Inorganic	248	40	31.2	521	99	31.2	531.5	107	33.0
3	Ambient	Inorganic	265.5	58	31.2	353	83	31.2	406	96	24.3
4	Ambient	Inorganic	353	60	31.2	450	108	36.5	508	114	31.2
5	Ambient	Inorganic	180	41	34.7	261	71	29.5	218.5	77	29.5
6	Ambient	Inorganic	328.5	56	36.5	403.5	98	33.0	441	110	31.2
7	Ambient	Inorganic	408.5	67	34.7	518.5	104	34.7	595	109	26.0
8	Ambient	Inorganic	293	56	31.2	397	82	31.2	414	91	27.8
9	Ambient	Organic	264	58	31.2	390.5	82	26.0	468	98	22.6
10	Ambient	Organic	266	48	31.2	384.5	75	34.7	415.5	89	26.0
11	Ambient	Organic	240	56	34.7	378.5	98	31.2	411	108	20.8
12	Ambient	Organic	205.5	44	27.8	285	73	24.3	319	85	26.0
13	Ambient	Organic	200	45	34.7	409.5	78	29.5	473.5	91	27.8
14	Ambient	Organic	166.5	44	27.8	399.5	86	31.2	472.25	100	26.0
15	Ambient	Organic	188	45	34.7	312.5	88	34.7	442	113	36.5
16	Ambient	Organic	182	50	33.0	321	89	33.0	359	92	27.8

Table A9
Weeks 8-12 stem length, leaf number and leaf area measurements for ambient chamber

			Week 8			Week 10			Week 12		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	Ambient	Inorganic	680	151	29.5	822	152	24.3	734	140	29.5
2	Ambient	Inorganic	789	164	33.0	1105	176	24.3	1119	168	27.8
3	Ambient	Inorganic	624	139	26.0	867	212	38.2	972	199	24.3
4	Ambient	Inorganic	633	148	31.2	942	211	36.5	1017	185	27.8
5	Ambient	Inorganic	550	139	36.5	778	203	34.7	892	198	27.8
6	Ambient	Inorganic	579	178	31.2	931.5	210	34.7	1069	218	31.2
7	Ambient	Inorganic	813	172	27.8	1072	185	24.3	1173	199	34.7
8	Ambient	Inorganic	597.5	148	33.0	879	204	34.7	954	180	27.8
9	Ambient	Organic	754	128	27.8	1116	173	34.7	1053	192	27.8
10	Ambient	Organic	609	143	26.0	746	188	26.0	870	182	24.3
11	Ambient	Organic	596	179	31.2	842.5	204	31.2	1033	209	20.8
12	Ambient	Organic	510	142	26.0	716	186	27.8	869	212	27.8
13	Ambient	Organic	660	164	33.0	785	198	31.2	783	172	29.5
14	Ambient	Organic	654	167	34.7	862	209	27.8	1036	201	26.0
15	Ambient	Organic	620	163	39.9	798	220	38.2	1153	214	27.8
16	Ambient	Organic	557	158	29.5	791	192	27.8	874	188	24.3

Table A10

Weeks 1-3 stem length, leaf number and leaf area measurements for 763 ppm chamber.

				Week 1			Week 2			Week 3	
Pot	CO_2	Fertilizer	Stem	# of	Leaf	Stem	# of	Leaf	Stem	# of	Leaf

#			Length (cm)	Leaves	Area (cm^2)	Length (cm)	Leaves	Area (cm^2)	Length (cm)	Leaves	Area (cm^2)
1	763 ppm	Inorganic	12	7	-	48	30	-	246.5	45	33.0
2	763 ppm	Inorganic	14	8	-	46	22	-	176	36	34.7
3	763 ppm	Inorganic	18.5	7	-	73.5	32	-	217	48	33.0
4	763 ppm	Inorganic	15.5	8	-	83.5	29	-	213	38	27.8
5	763 ppm	Inorganic	18.5	8	-	84	32	-	171	34	27.8
6	763 ppm	Inorganic	12	7	-	59	27	-	263	47	29.5
7	763 ppm	Inorganic	12.5	5	-	70	24	-	214	32	38.2
8	763 ppm	Inorganic	15	7	-	49.5	34	-	268	43	31.2
9	763 ppm	Organic	12.5	5	-	43	27	-	189.5	30	27.8
10	763 ppm	Organic	14	5	-	70	28	-	251.5	44	24.3
11	763 ppm	Organic	15.5	5	-	73.5	34	-	226	47	29.5
12	763 ppm	Organic	16	6	-	45.5	26	-	167	31	27.8
13	763 ppm	Organic	11	5	-	51	20	-	179.5	45	29.5
14	763 ppm	Organic	14	6	-	51	25	-	222	33	29.5
15	763 ppm	Organic	14	8	-	95	36	-	264	47	31.2
16	763 ppm	Organic	13	8	-	76	39	-	240.5	38	31.2

Table A11

Weeks 4-6 stem length, leaf number and leaf area measurements for 763 ppm chamber.

			Week 4			Week 5			Week 6		
Pot #	CO_2	Fertilizer	Stem Length	# of Leaves	Leaf Area	Stem Length	# of Leaves	Leaf Area	Stem Length	# of Leaves	Leaf Area

			(cm)		(cm^2)	(cm)		(cm^2)	(cm)		(cm^2)
1	763 ppm	Inorganic	337	58	33.0	492.5	103	34.7	637	132	24.3
2	763 ppm	Inorganic	229	47	34.7	389	115	36.5	467.5	134	31.2
3	763 ppm	Inorganic	276	54	33.0	397	78	34.7	564.5	101	27.8
4	763 ppm	Inorganic	272	43	27.8	431	69	34.7	450	91	29.5
5	763 ppm	Inorganic	223.5	41	36.5	333	58	31.2	400	99	27.8
6	763 ppm	Inorganic	341	56	34.7	555.5	104	38.2	591.5	125	29.5
7	763 ppm	Inorganic	325.5	44	31.2	557	90	36.5	583	118	31.2
8	763 ppm	Inorganic	373	65	31.2	428	114	33.0	572	120	22.6
9	763 ppm	Organic	257	40	31.2	416.5	86	34.7	458	122	29.5
10	763 ppm	Organic	272.5	49	24.3	391	81	34.7	410	98	26.0
11	763 ppm	Organic	246	51	31.2	388	79	33.0	470	106	33.0
12	763 ppm	Organic	192	47	31.2	375.5	88	34.7	456	96	24.3
13	763 ppm	Organic	208	53	24.3	387	75	34.7	463	102	24.3
14	763 ppm	Organic	253.5	47	27.8	367	70	34.7	421.5	93	26.0
15	763 ppm	Organic	273	56	27.8	378	84	33.0	285.5	109	27.8
16	763 ppm	Organic	285	45	31.2	385	84	33.0	431.5	99	27.8

Table A12
Weeks 8-12 stem length, leaf number and leaf area measurements for 763 ppm chamber.

				Week 8			Week 10			Week 12	
Pot	CO_2	Fertilizer	Stem	# of	Leaf	Stem	# of	Leaf	Stem	# of	Leaf

#			Length (cm)	Leaves	Area (cm^2)	Length (cm)	Leaves	Area (cm^2)	Length (cm)	Leaves	Area (cm^2)
1	763 ppm	Inorganic	823	187	29.5	992	216	24.3	1096	215	20.8
2	763 ppm	Inorganic	593	173	33.0	725	240	38.2	835	222	34.7
3	763 ppm	Inorganic	596	132	29.5	691	183	31.2	804	193	27.8
4	763 ppm	Inorganic	803	189	33.0	997	206	34.7	1384	219	19.1
5	763 ppm	Inorganic	1024	179	29.5	987	216	31.2	1089	192	31.2
6	763 ppm	Inorganic	794	202	36.5	1069	231	38.2	1270	207	27.8
7	763 ppm	Inorganic	1038	282	38.2	1064	245	41.7	1489	263	34.7
8	763 ppm	Inorganic	745	169	34.7	898	229	34.7	1094	215	26.0
9	763 ppm	Organic	595	278	31.2	695	248	31.2	900	221	27.8
10	763 ppm	Organic	543	165	36.5	825	166	24.3	960	201	24.3
11	763 ppm	Organic	597	162	36.5	720	161	27.8	909	194	24.3
12	763 ppm	Organic	687	175	36.5	949	212	22.6	1097	238	22.6
13	763 ppm	Organic	712	149	29.5	899	198	24.3	972.5	232	33.0
14	763 ppm	Organic	582	154	31.2	864.5	186	27.8	993	172	31.2
15	763 ppm	Organic	586	164	34.7	576.5	195	27.8	934	211	27.8
16	763 ppm	Organic	621	175	33.0	828	183	27.8	960.5	193	22.6

Table A13

Weeks 1-3 stem length, leaf number and leaf area measurements for 1108 ppm chamber.

			Week 1			Week 2			Week 3		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	1108 ppm	Inorganic	10	5	-	32.5	20	-	232	42	34.7
2	1108 ppm	Inorganic	12.5	6	-	63	26	-	159.5	39	38.2
3	1108 ppm	Inorganic	12	4	-	29.5	16	-	104.5	28	29.5
4	1108 ppm	Inorganic	12.5	6	-	50	25	-	176.5	45	34.7
5	1108 ppm	Inorganic	10.5	5	-	36	20	-	171.5	45	34.7
6	1108 ppm	Inorganic	11	6	-	96	31	-	279	51	31.2
7	1108 ppm	Inorganic	15.5	6	-	78	34	-	286	59	46.9
8	1108 ppm	Inorganic	15	7	-	75	30	-	263	57	38.2
9	1108 ppm	Organic	16.5	7	-	79	29	-	224	50	43.4
10	1108 ppm	Organic	15.5	9	-	97	40	-	256	59	46.9
11	1108 ppm	Organic	13	6	-	36	21	-	201.5	30	45.1
12	1108 ppm	Organic	9	3	-	42	24	-	185	37	29.5
13	1108 ppm	Organic	12	7	-	46	20	-	118	33	46.9
14	1108 ppm	Organic	12	6	-	53	24	-	174.5	43	41.7
15	1108 ppm	Organic	15.5	6	-	69	37	-	241.5	47	31.2
16	1108 ppm	Organic	9	4	-	23	14	-	107	24	31.2

Table A14

Weeks 4-6 stem length, leaf number and leaf area measurements for 1108 ppm chamber.

			Week 4			Week 5			Week 6		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	1108 ppm	Inorganic	287	69	36.5	592.2	144	33.0	693.5	137	27.8
2	1108 ppm	Inorganic	203.5	46	38.2	468	76	34.7	497	119	26.0
3	1108 ppm	Inorganic	224.5	48	31.2	655.5	118	33.0	655.5	137	34.7
4	1108 ppm	Inorganic	234	62	27.8	426.5	103	29.5	468	96	33.0
5	1108 ppm	Inorganic	217	63	36.5	431	108	34.7	498.5	96	31.2
6	1108 ppm	Inorganic	326.5	59	34.7	566	96	36.5	601	105	29.5
7	1108 ppm	Inorganic	336	66	46.9	425	97	31.2	492.5	93	24.3
8	1108 ppm	Inorganic	291.5	71	38.2	467	104	33.0	486	96	27.8
9	1108 ppm	Organic	263	55	43.4	276	55	31.2	314	66	29.5
10	1108 ppm	Organic	277	63	27.8	413.5	70	27.8	488	90	31.2
11	1108 ppm	Organic	226.5	44	36.5	271.5	79	29.5	319.5	98	34.7
12	1108 ppm	Organic	229	55	34.7	384.5	101	26.0	448.5	128	27.8
13	1108 ppm	Organic	215	50	46.9	330.5	74	33.0	411	96	29.5
14	1108 ppm	Organic	239	52	41.7	470.1	93	31.2	545.6	122	29.5
15	1108 ppm	Organic	261	51	31.2	407.5	89	38.2	469	133	31.2
16	1108 ppm	Organic	198	44	36.5	521.8	112	31.2	586.5	136	27.8

Table A15

Weeks 8-12 stem length, leaf number and leaf area measurements for 1108 ppm chamber.

			Week 8			Week 10			Week 12		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	1108 ppm	Inorganic	844	178	31.2	1149	275	22.6	1114	231	27.8
2	1108 ppm	Inorganic	746	149	24.3	668.5	254	24.3	1046	257	27.8
3	1108 ppm	Inorganic	1042	165	31.2	1129	252	20.8	1612	253	29.5
4	1108 ppm	Inorganic	667	218	31.2	802	225	22.6	950	217	24.3
5	1108 ppm	Inorganic	764	165	29.5	1039.5	242	27.8	1170	224	26.0
6	1108 ppm	Inorganic	786	194	31.2	997	206	34.7	1137	201	26.0
7	1108 ppm	Inorganic	829	202	24.3	898	228	22.6	1029	205	31.2
8	1108 ppm	Inorganic	855	194	26.0	1213	240	31.2	948	220	31.2
9	1108 ppm	Organic	576	128	31.2	802	182	27.8	914	181	27.8
10	1108 ppm	Organic	547	160	31.2	753	181	24.3	741	197	24.3
11	1108 ppm	Organic	629	153	31.2	907.5	197	20.8	1167	205	26.0
12	1108 ppm	Organic	673.5	90	24.3	879	201	20.8	970.5	212	26.0
13	1108 ppm	Organic	560	159	24.3	936	195	31.2	858	216	26.0
14	1108 ppm	Organic	897	164	29.5	1028	220	26.0	1379	228	24.3
15	1108 ppm	Organic	830	116	27.8	1105	234	24.3	1379	247	20.8
16	1108 ppm	Organic	737	197	27.8	906	212	27.8	994	212	27.8

Table A16

Weeks 1-3 stem length, leaf number and leaf area measurements for 1515 ppm chamber.

			Week 1			Week 2			Week 3		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)	Stem Length (cm)	# of Leaves	Leaf Area (cm^2)
1	1515 ppm	Inorganic	14	7	-	68.5	27	-	397	65	39.9
2	1515 ppm	Inorganic	15.5	6	-	45	17	-	102	26	31.2
3	1515 ppm	Inorganic	11	5	-	44	24	-	175.5	43	36.5
4	1515 ppm	Inorganic	18.5	10	-	111	42	-	351	50	31.2
5	1515 ppm	Inorganic	15	8	-	110.5	43	-	350	80	34.7
6	1515 ppm	Inorganic	13	7	-	69	31	-	334	80	34.7
7	1515 ppm	Inorganic	17	11	-	98	41	-	230	50	34.7
8	1515 ppm	Inorganic	20	8	-	81	33	-	285.5	58	34.7
9	1515 ppm	Organic	5	7	-	126.5	42	-	310.5	69	31.2
10	1515 ppm	Organic	8.5	5	-	33	23	-	124	33	33.0
11	1515 ppm	Organic	15	8	-	61	30	-	188	39	33.0
12	1515 ppm	Organic	14.5	5	-	52.5	30	-	200.5	42	31.2
13	1515 ppm	Organic	13.5	5	-	31	21	-	177.5	31	24.3
14	1515 ppm	Organic	16.5	7	-	55	20	-	154	38	38.2
15	1515 ppm	Organic	12	8	-	82	40	-	248	41	31.2
16	1515 ppm	Organic	12	5	-	57.5	27	-	201.5	46	31.2

Table A17

Weeks 4-6 stem length, leaf number and leaf area measurements for 1515 ppm chamber.

			Week 4			Week 5			Week 6		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area	Stem Length (cm)	# of Leaves	Leaf Area	Stem Length (cm)	# of Leaves	Leaf Area
1	1515 ppm	Inorganic	465	72	46.9	621	97	38.2	748	157	29.5
2	1515 ppm	Inorganic	209.5	44	38.2	433	87	33.0	550	124	27.8
3	1515 ppm	Inorganic	251	57	36.5	472	90	34.7	483.5	122	27.8
4	1515 ppm	Inorganic	376.5	73	31.2	495	151	34.7	595	131	31.2
5	1515 ppm	Inorganic	408	86	34.7	590	99	31.2	604	114	27.8
6	1515 ppm	Inorganic	423.5	88	34.7	519.5	97	34.7	570	121	27.8
7	1515 ppm	Inorganic	309.5	63	31.2	421.5	80	31.2	354	103	27.8
8	1515 ppm	Inorganic	331	64	33.0	424	79	34.7	477.5	110	26.0
9	1515 ppm	Organic	278	73	33.0	388.55	90	24.3	524.5	123	22.6
10	1515 ppm	Organic	204.5	47	33.0	457	86	33.0	586.5	117	27.8
11	1515 ppm	Organic	226.5	47	33.0	338	61	33.0	393.5	81	26.0
12	1515 ppm	Organic	237.5	51	31.2	331.5	70	34.7	491.5	101	26.0
13	1515 ppm	Organic	222	50	24.3	429.5	82	24.3	623	96	27.8
14	1515 ppm	Organic	216	49	38.2	422	80	33.0	503	114	27.8
15	1515 ppm	Organic	300	52	31.2	402	80	31.2	468.5	104	27.8
16	1515 ppm	Organic	272.5	58	31.2	451	75	31.2	444.5	101	29.5

Table A18

Weeks 8-12 stem length, leaf number and leaf area measurements for 1515 ppm chamber.

			Week 8			Week 10			Week 12		
Pot #	CO_2	Fertilizer	Stem Length (cm)	# of Leaves	Leaf Area	Stem Length (cm)	# of Leaves	Leaf Area	Stem Length (cm)	# of Leaves	Leaf Area
1	1515 ppm	Inorganic	935	229	24.3	1021	235	39.9	1086	250	31.2
2	1515 ppm	Inorganic	825	163	26.0	1070	249	29.5	1356	231	19.1
3	1515 ppm	Inorganic	860	183	26.0	884.6	226	29.5	1012	212	31.2
4	1515 ppm	Inorganic	791	204	24.3	910	227	31.2	1104	229	22.6
5	1515 ppm	Inorganic	752.5	192	27.8	848	215	27.8	975.5	235	22.6
6	1515 ppm	Inorganic	791	176	27.8	938	221	31.2	1211	254	34.7
7	1515 ppm	Inorganic	576	164	30.4	769	192	27.8	874	208	26.0
8	1515 ppm	Inorganic	529	181	20.8	894	202	36.5	991	198	31.2
9	1515 ppm	Organic	707	83	27.8	886	209	24.3	1038	225	20.8
10	1515 ppm	Organic	639	174	27.8	1022	232	20.8	1339	248	22.6
11	1515 ppm	Organic	641.5	156	29.5	858	171	29.5	988.5	173	22.6
12	1515 ppm	Organic	732	197	27.8	927	197	26.0	1027	232	22.6
13	1515 ppm	Organic	742	105	24.3	1106	224	20.8	1084.5	254	19.1
14	1515 ppm	Organic	801	186	24.3	971.5	226	27.8	1215	239	36.5
15	1515 ppm	Organic	678	182	24.3	890	190	22.6	1008	191	22.6
16	1515 ppm	Organic	683	194	24.3	791	179	26.0	795	182	27.8

Table A19

Average elemental leaf concentrations in dried sweet potato leaf material at varying levels of CO_2 and fertilizer amendment.

Fertilizer	CO_2	%							ppm				
		N	P	K	Mg	Ca	S	Na	Fe	Mn	B	Cu	Zn
Conventional	352	2.99	0.26	4.11	0.75	0.92	0.31	0.57	267	132	855	6.67	25.7
Conventional	763	2.29	0.22	3.42	0.65	0.93	0.25	0.56	242	115	766	5.33	21.0
Conventional	1108	2.00	0.20	3.57	0.58	0.92	0.23	0.56	281	114	704	6.33	17.7
Conventional	1515	1.73	0.19	3.26	0.67	1.05	0.23	0.63	258	109	793	4.33	15.7
Organic	352	2.83	0.30	4.10	0.78	1.07	0.36	0.71	231	118	982	9.67	29.3
Organic	763	2.09	0.23	3.20	0.70	1.08	0.29	0.71	332	98	857	7.00	20.7
Organic	1108	1.88	0.21	2.70	0.72	1.20	0.27	0.74	170	104	913	6.00	19.3
Organic	1515	1.74	0.23	3.10	0.67	1.08	0.29	0.73	202	78	855	6.00	19.0

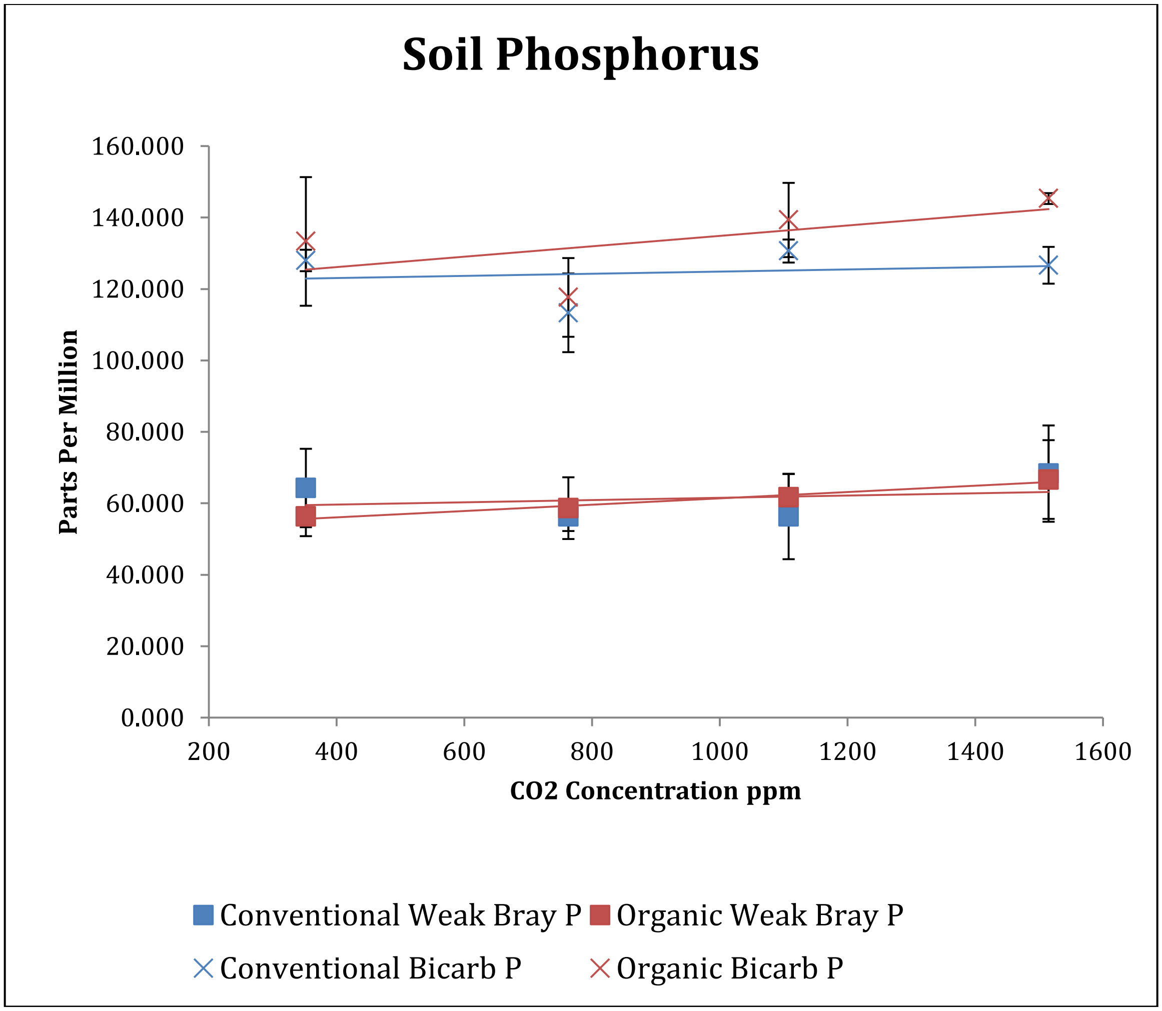


Figure A1
Post experiment soil phosphorus vs. CO$_2$ concentration from values in Table A6. Error bars represent ± 1 standard deviation.

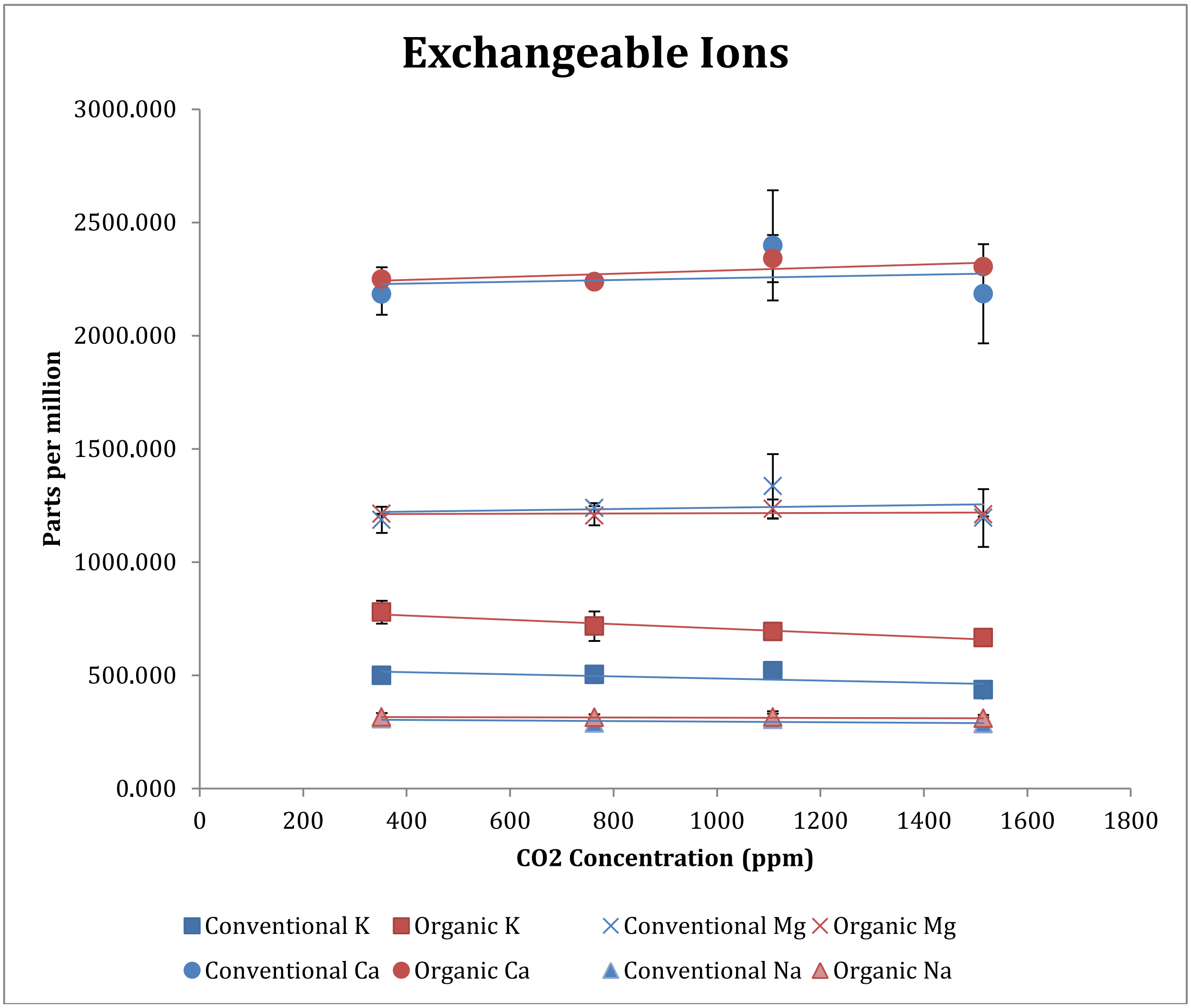


Figure A2
Post experiment soil exchangeable ions vs. CO_2 concentration from values in Table A6. Error bars represent ± 1 standard deviation.

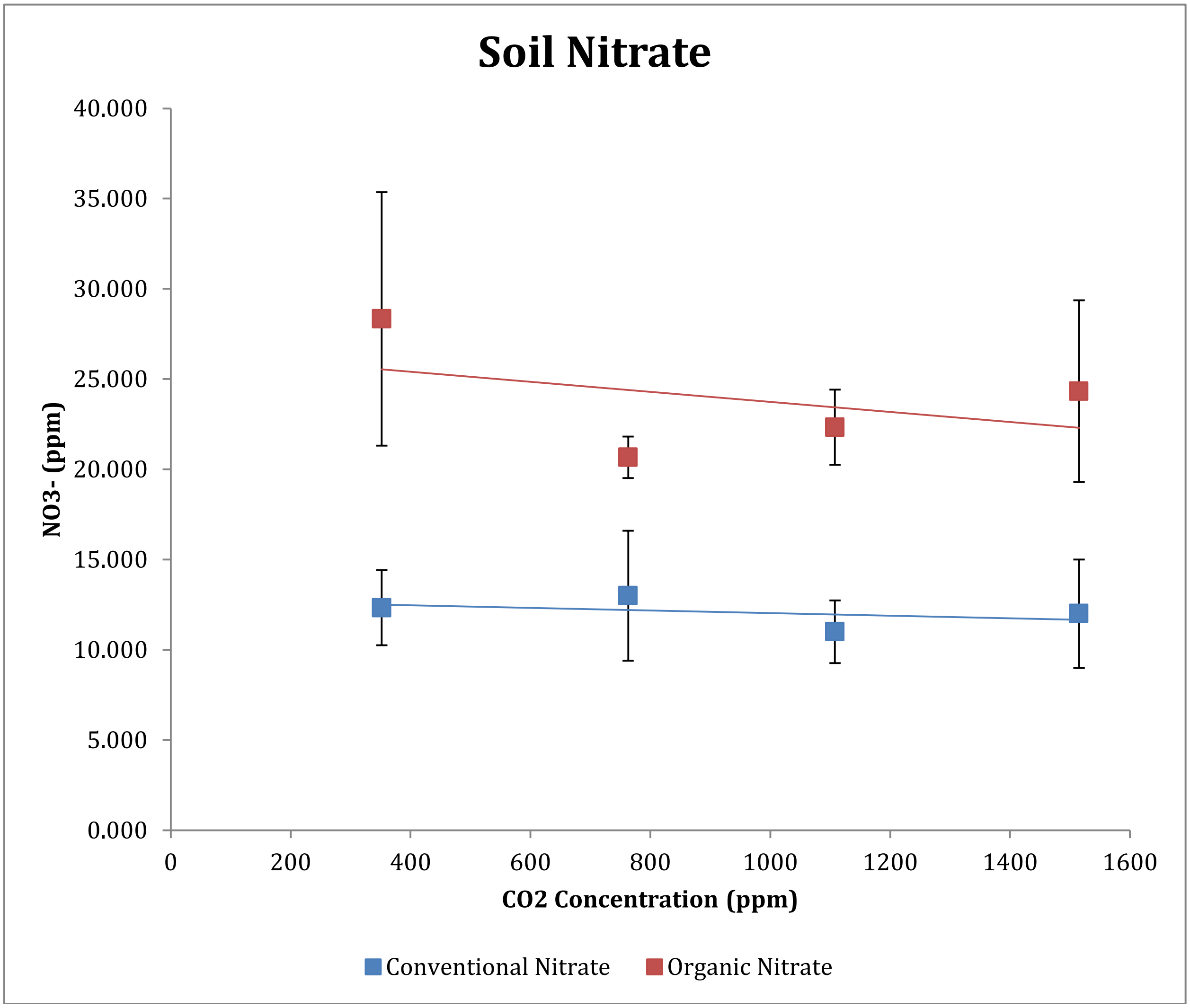


Figure A3
Post experiment soil nitrate vs. CO_2 concentration taken from values in table A6. Error bars represent ± 1 standard deviation.

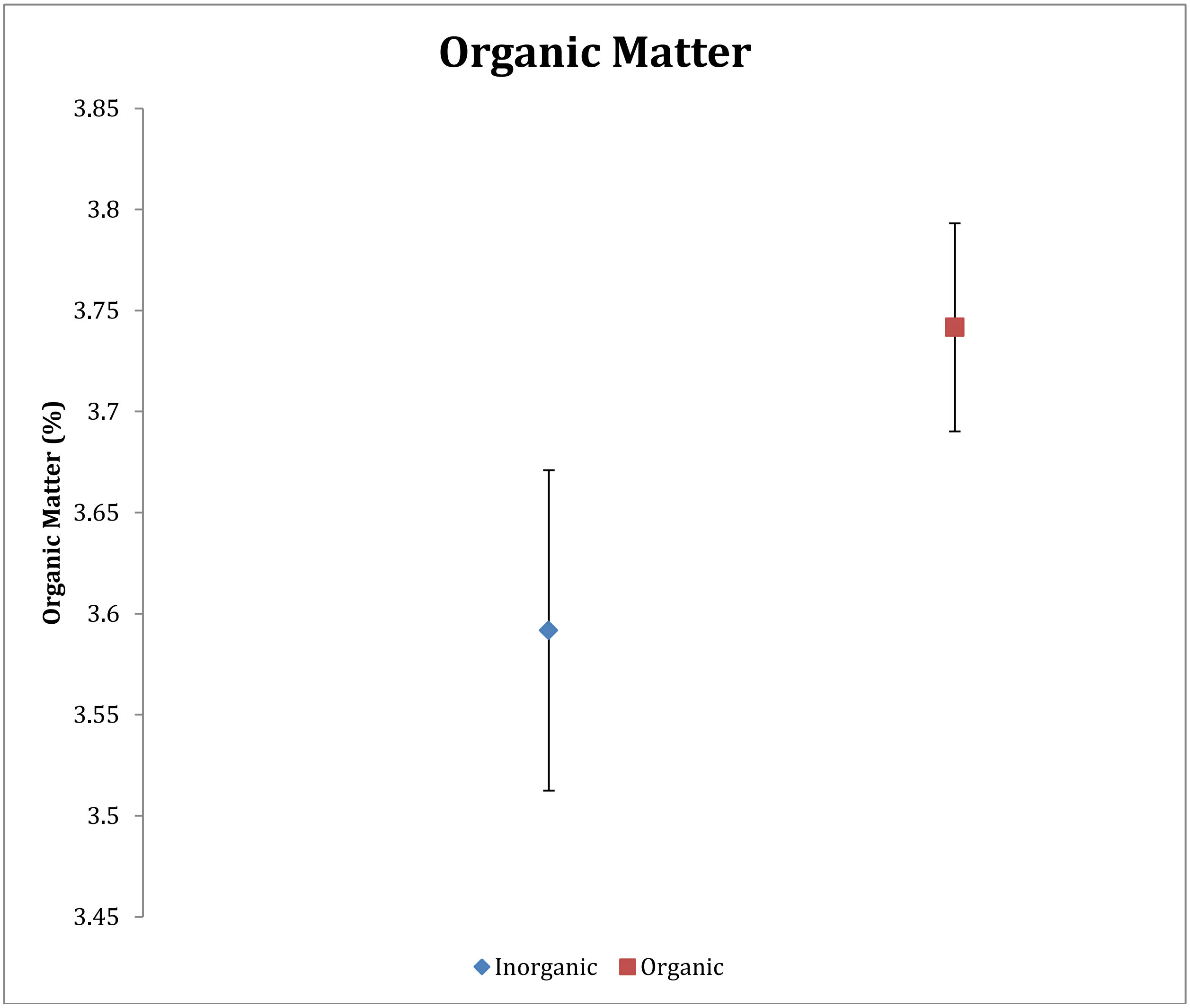


Figure A4
Post experiment soil organic matter (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

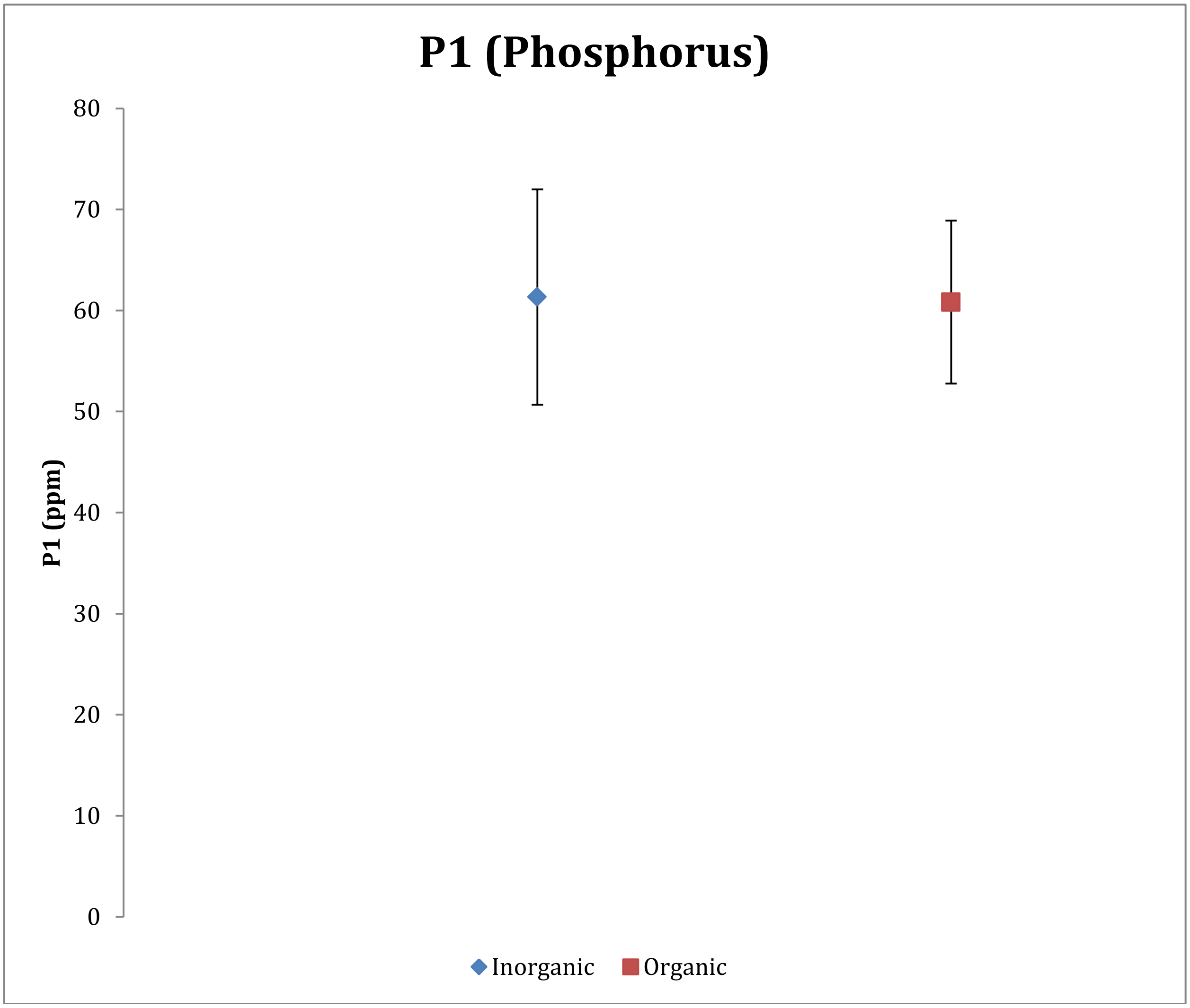


Figure A5
Post experiment soil weak bray phosphorus (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

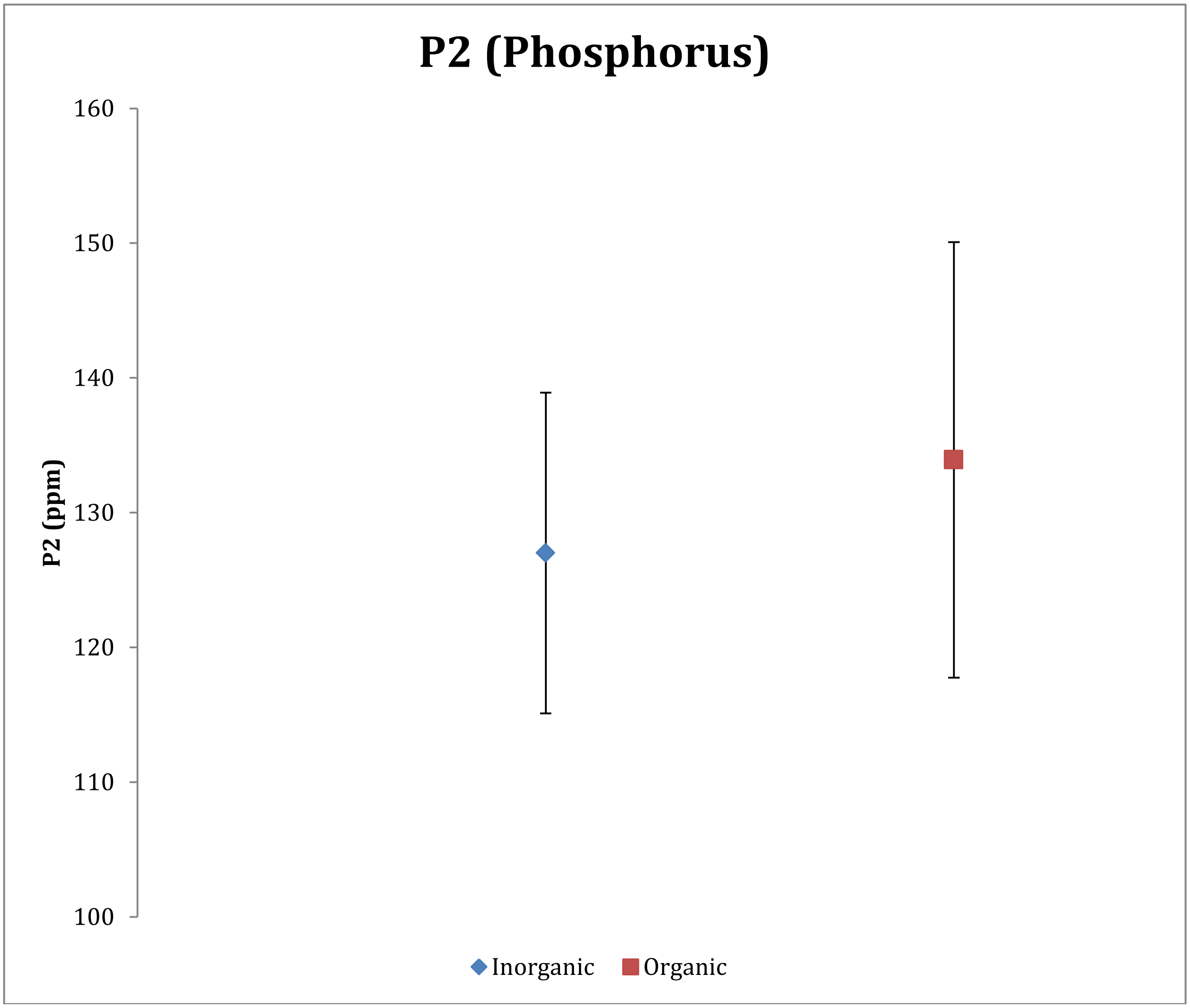


Figure A6
Post experiment soil strong bray phosphorus (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

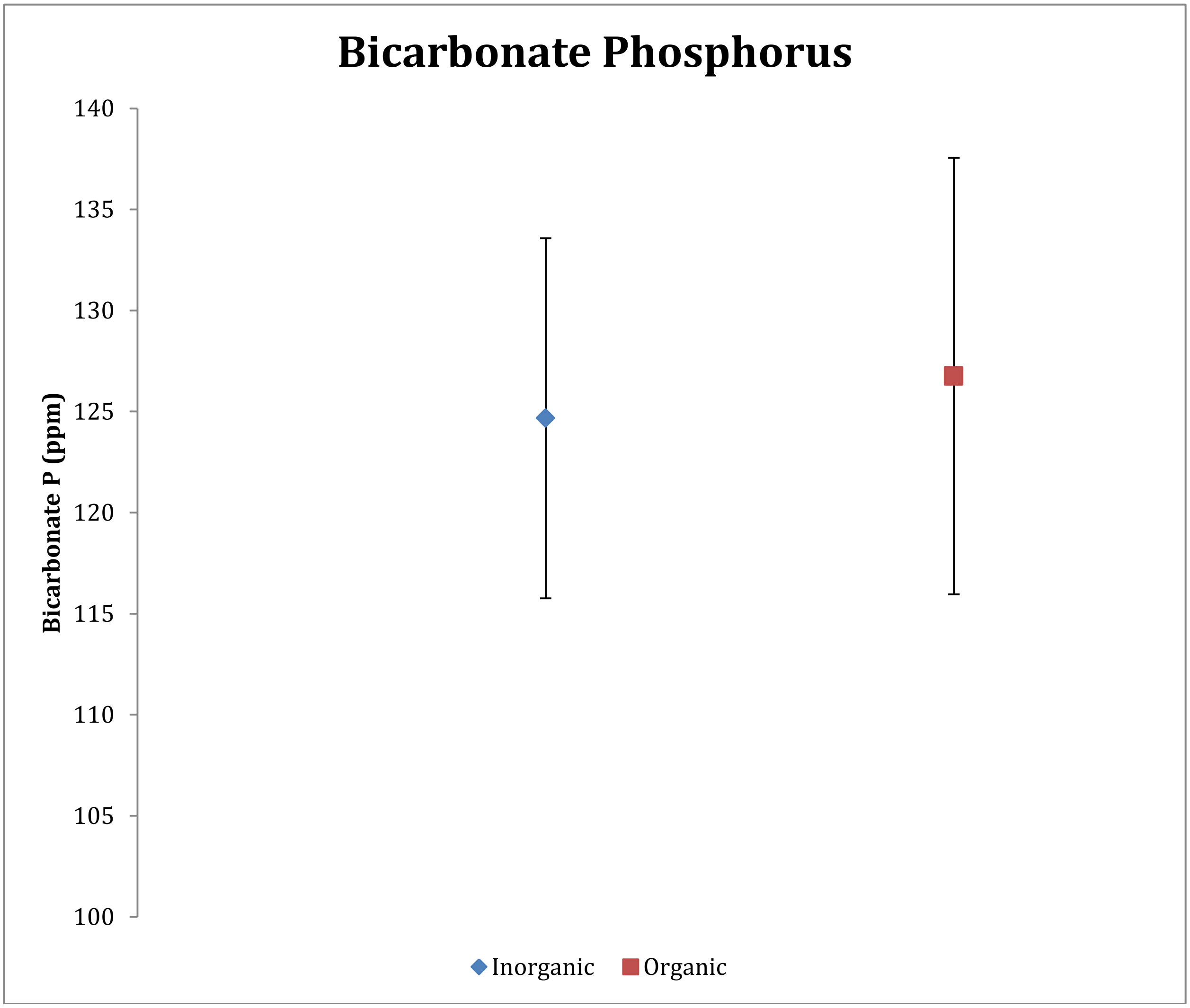


Figure A7
Post experiment soil bicarbonate phosphorus (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

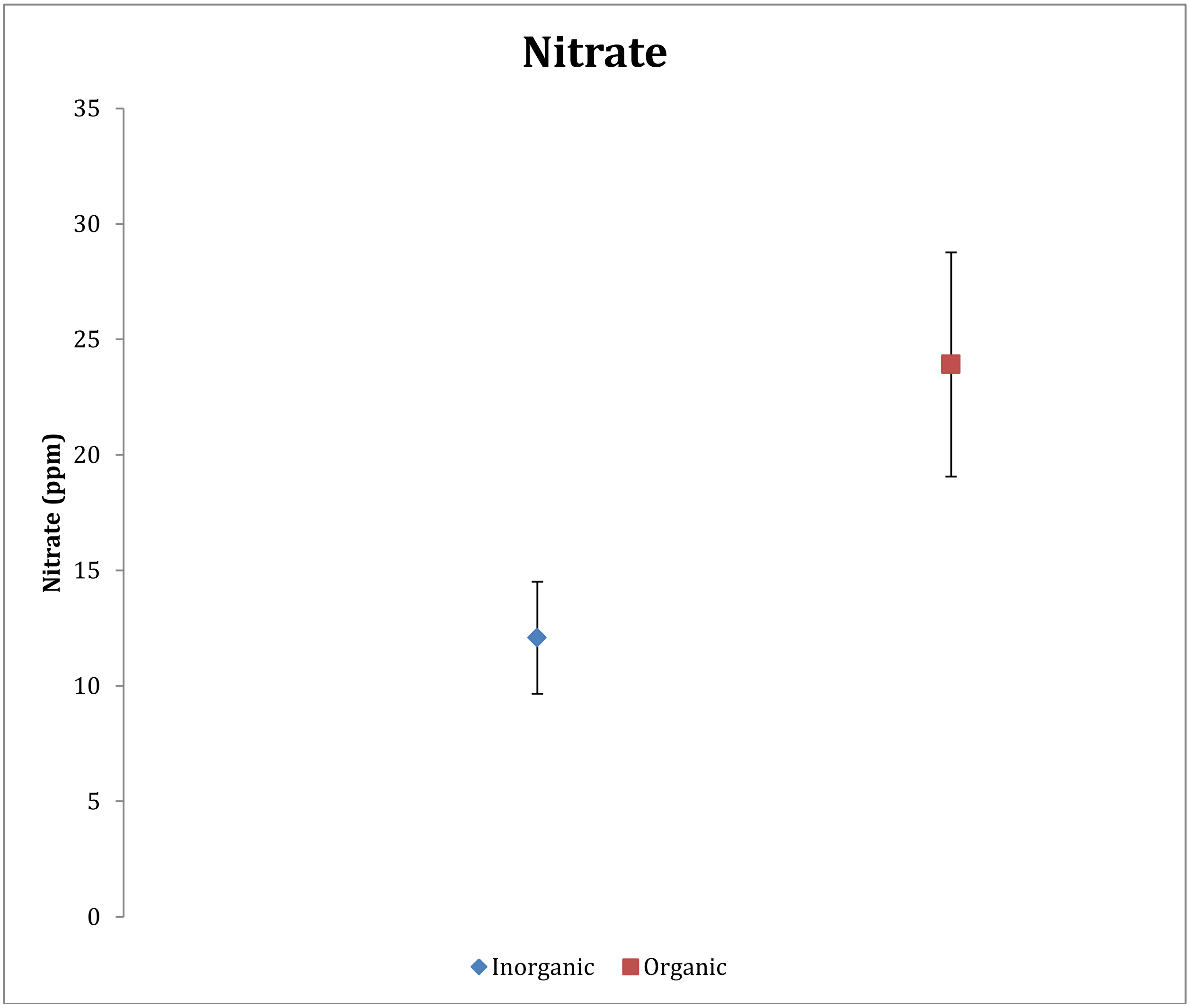


Figure A8
Post experiment soil nitrate (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

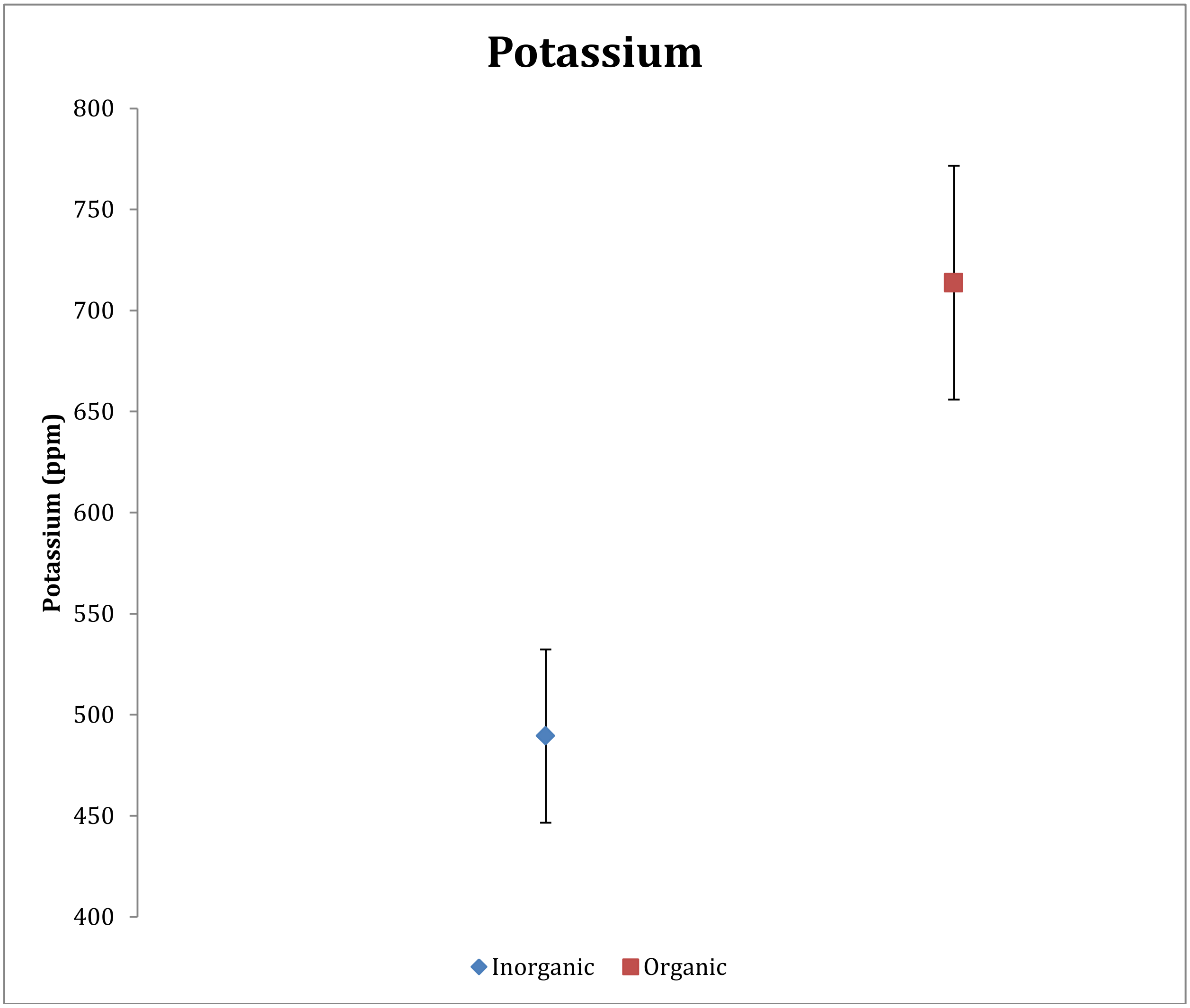


Figure A9
Post experiment soil potassium (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

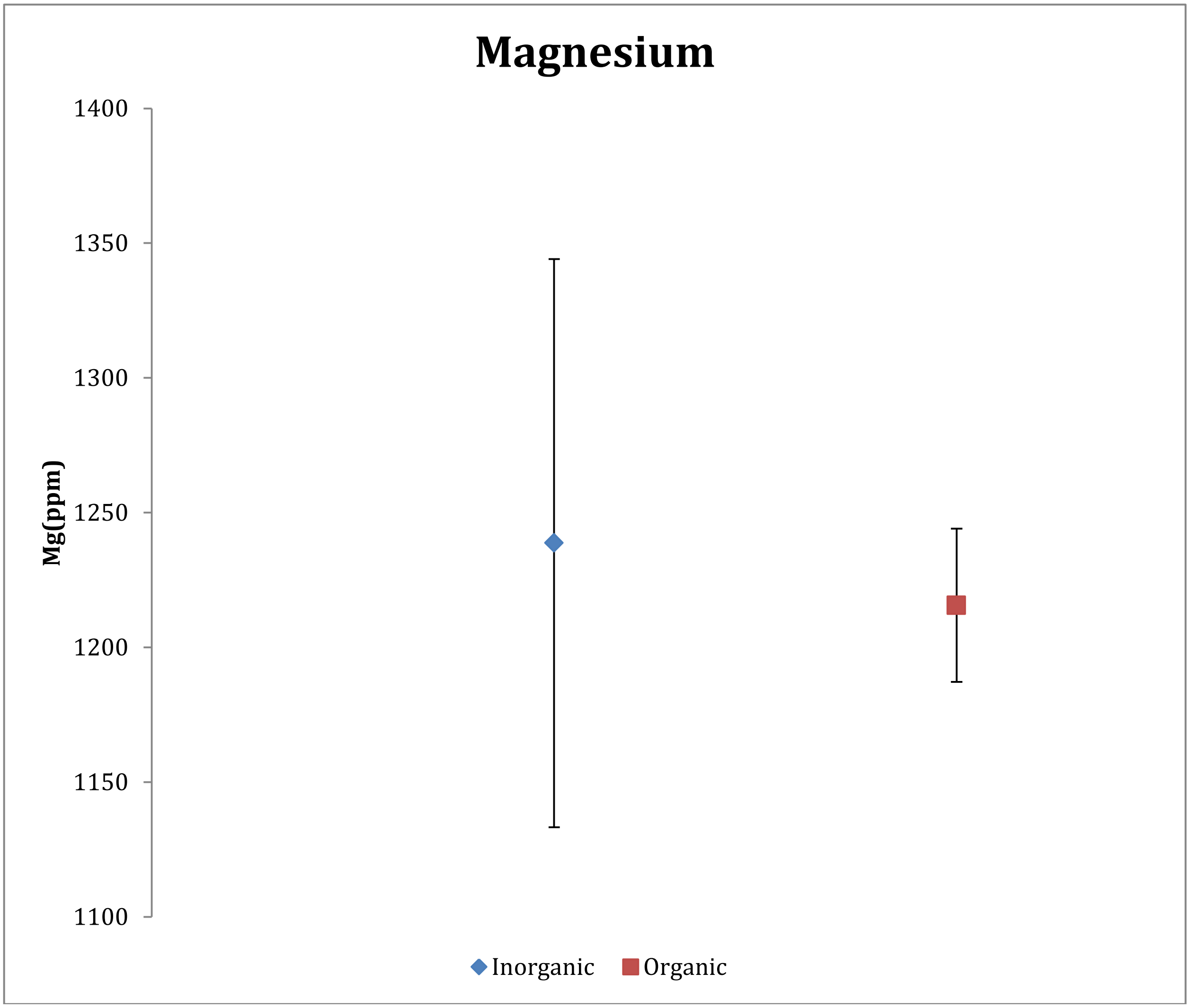


Figure A10
Post experiment soil magnesium (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

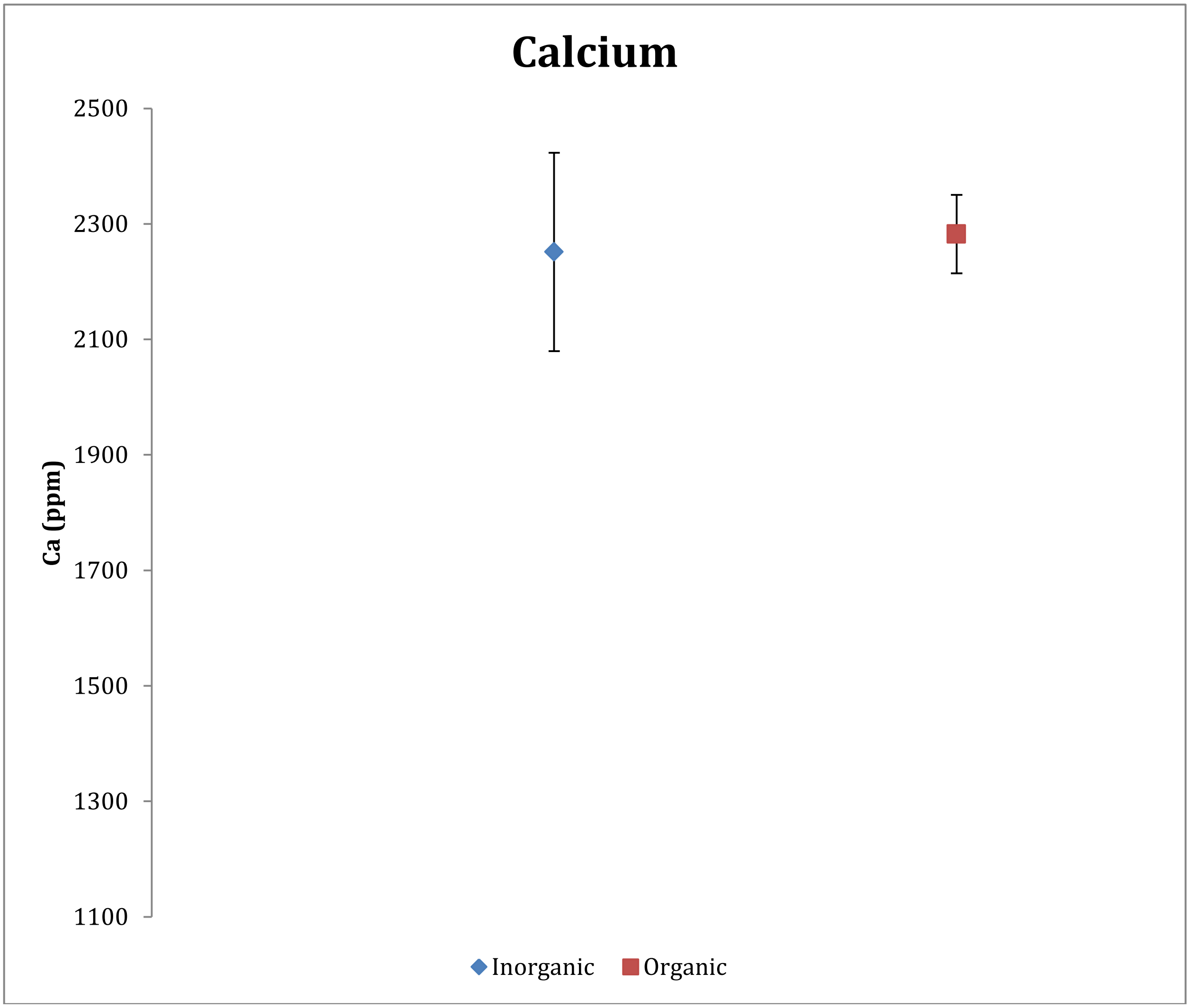


Figure A11
Post experiment soil calcium (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

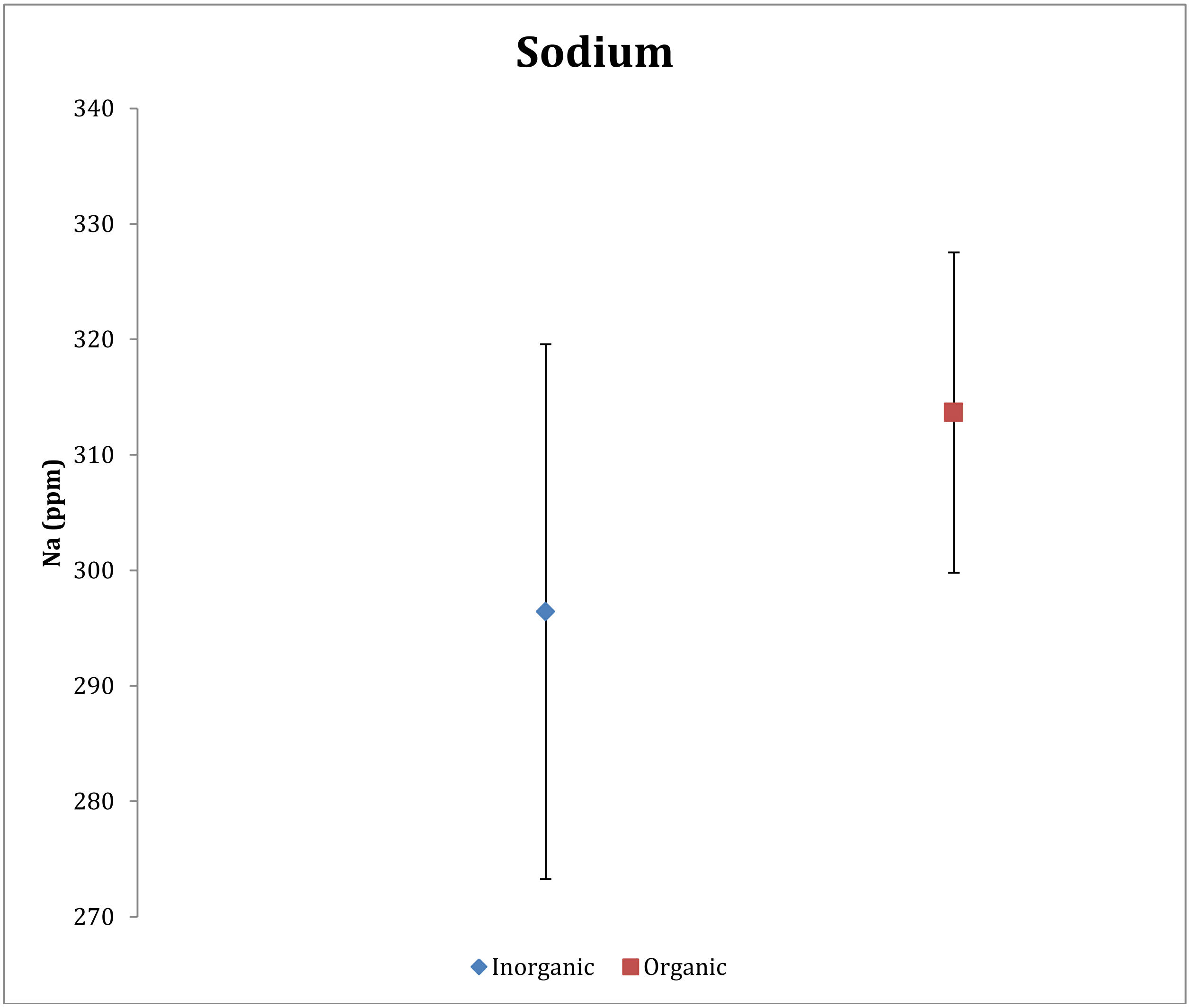


Figure A12
Post experiment soil sodium (organic vs. conventional) from values taken from table A6.
Error bars represent ± 1 standard deviation.

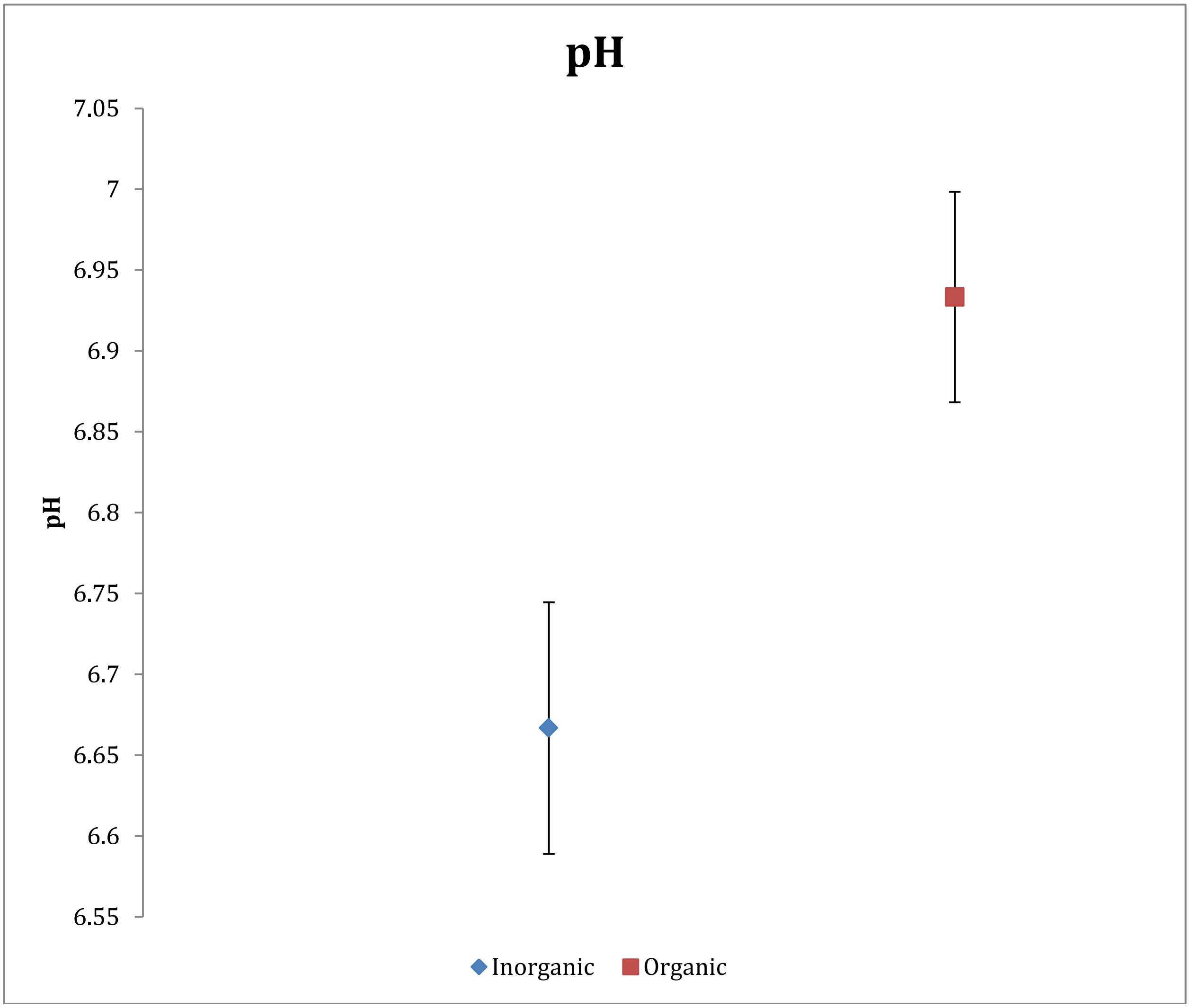


Figure A13
Post experiment soil pH (organic vs. conventional) from values taken from table A6.
Error bars represent ± 1 standard deviation.

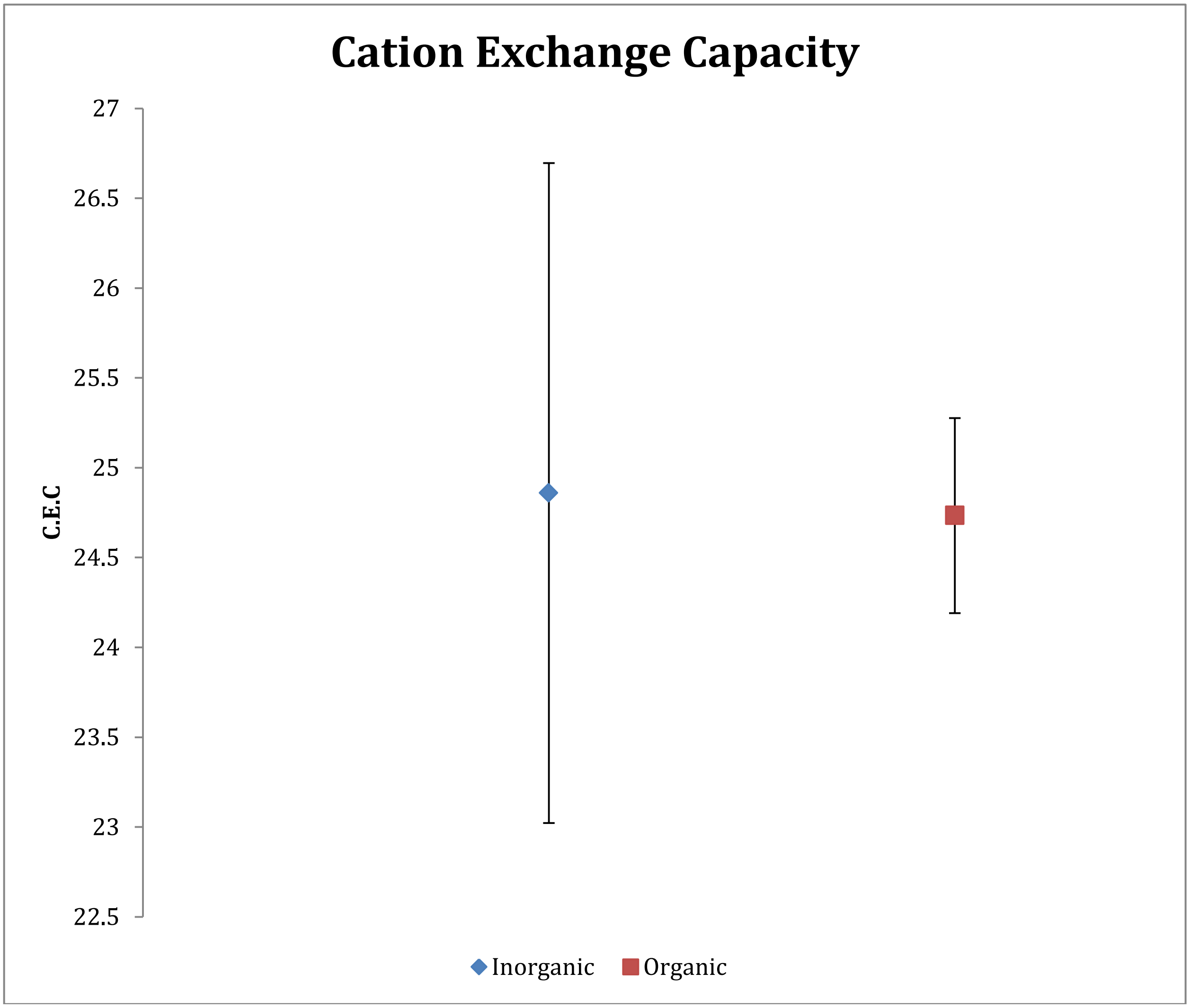


Figure A14
Post experiment soil cation exchange capacity (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

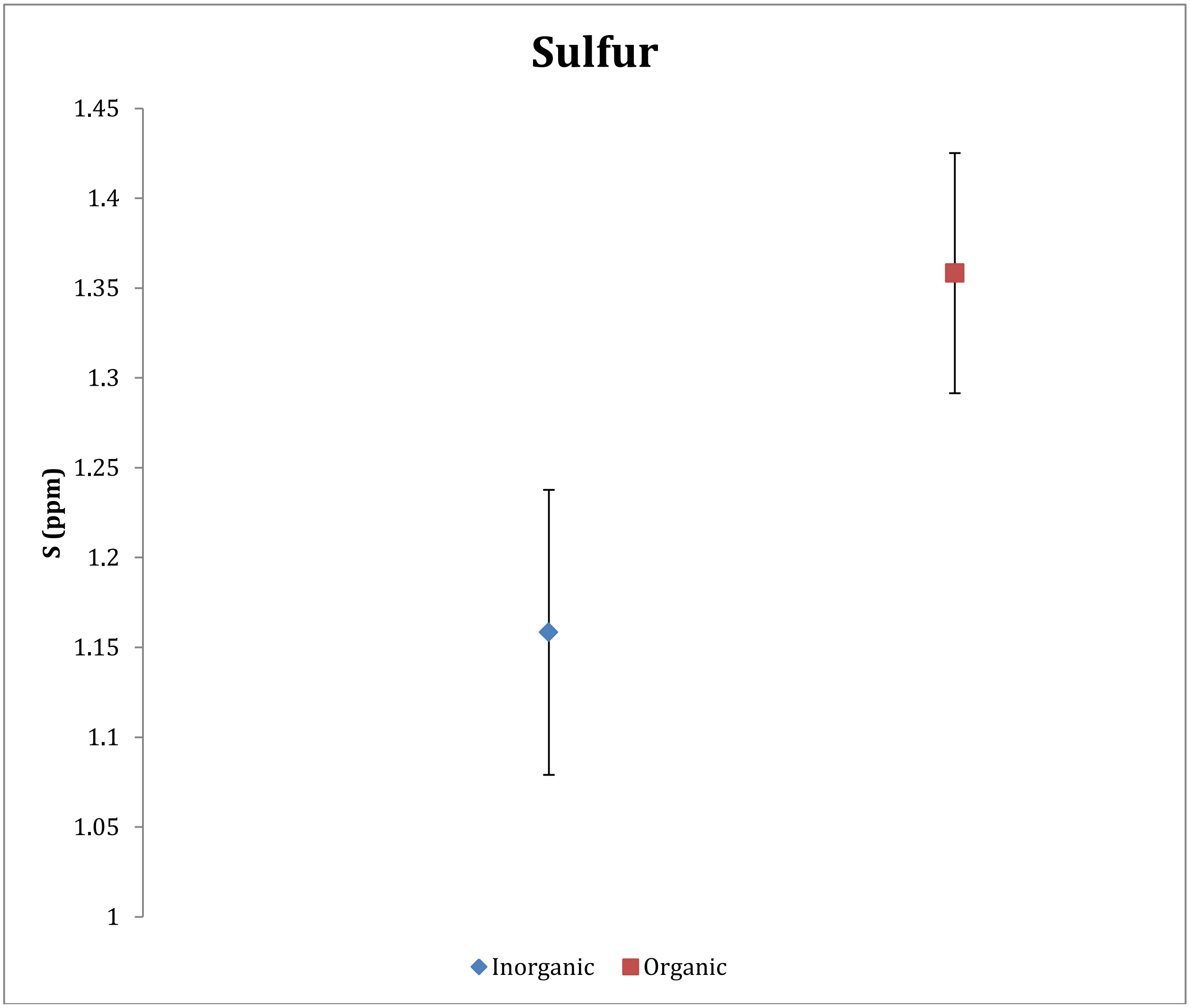


Figure A15
Post experiment soil sulfur (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

Figure A16
Post experiment soil zinc (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

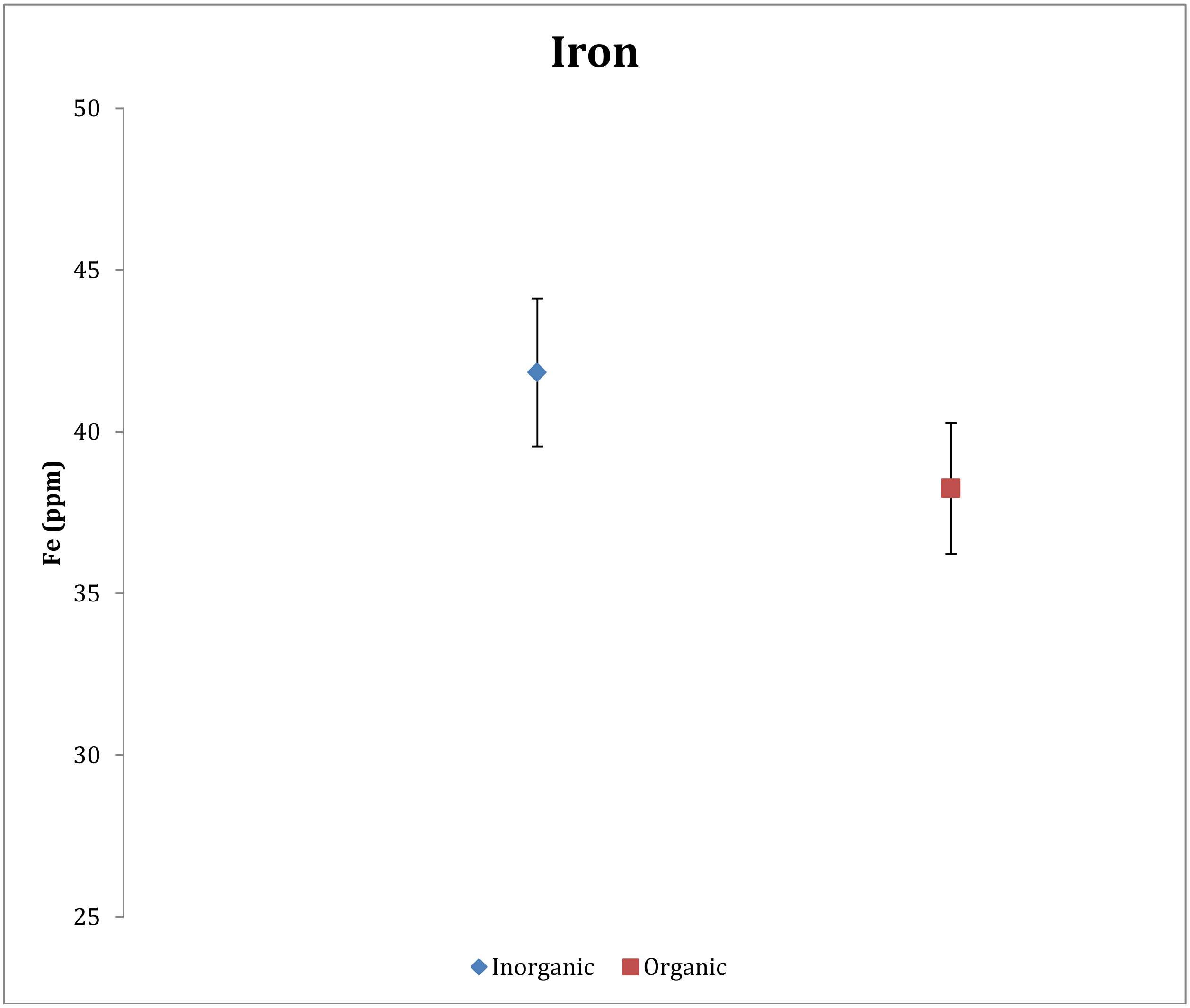


Figure A17
Post experiment soil iron (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

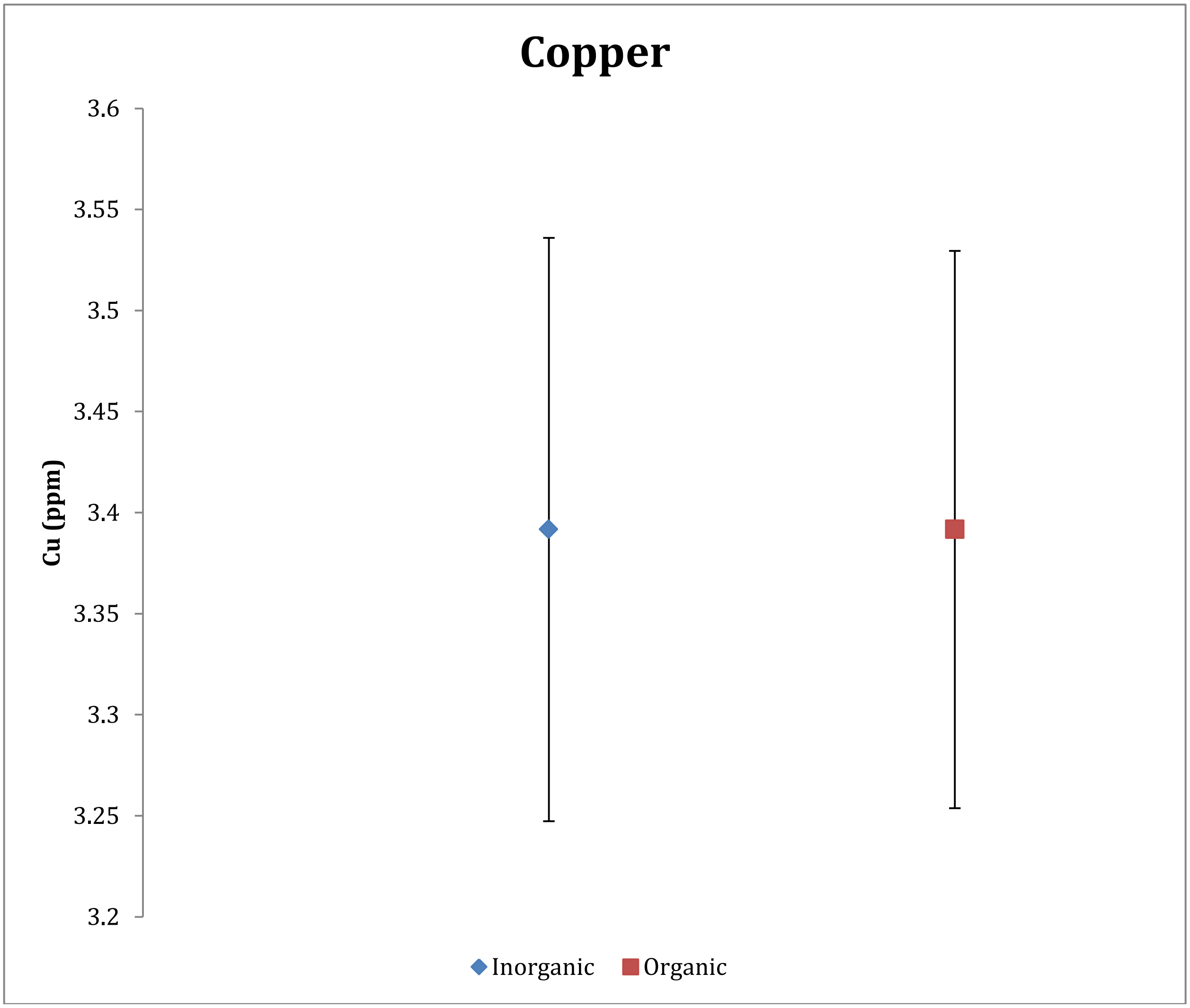


Figure A18
Post experiment soil copper (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.

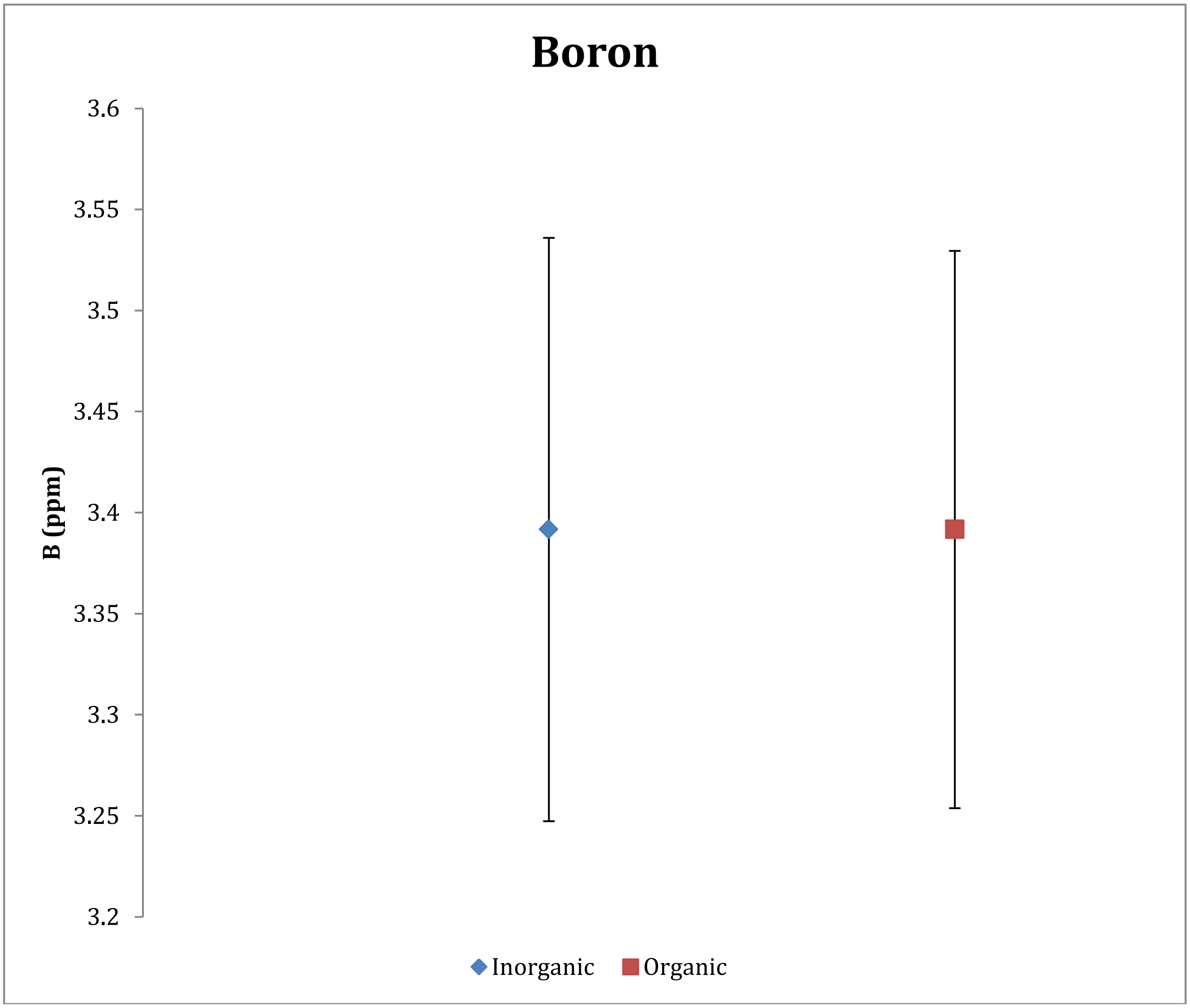


Figure A19
Post experiment soil boron (organic vs. conventional) from values taken from table A6. Error bars represent ± 1 standard deviation.