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Angela M. Bouche
DePaul University, angiebouche@yahoo.com

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Faculty Advisor: Dr. Mark Potosnak Department of Environmental Science and Studies and Dr. Bernhard Beck-Winchatz STEM Studies Department Research Completed in Summer 2014 Author Contact: angiebouche@yahoo.com

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A High-Altitude Balloon Platform for Determining Regional Uptake of Carbon Dioxide over Agricultural Landscapes

Angie Bouche*
Department of Environmental Science and Studies

ABSTRACT  Interactions between the biosphere and atmosphere are an important part of the global carbon cycle, and quantifying the carbon dioxide exchanges between them is helpful in predicting the uptake of carbon dioxide from anthropogenic sources by the biosphere in the future. In the Midwestern United States, agricultural systems cover a large part of the landscape, so understanding their role in influencing the global carbon budget is crucial as anthropogenic sources of carbon dioxide grow larger. Carbon dioxide exchanges can be measured by eddy covariance at the ecosystem level (bottom-up approach) or regionally by inversion techniques (top-down approach). Here we describe a novel approach to estimate the exchange at an intermediate spatial scale using weather balloons. Two different techniques were used to collect data. In the first-generation method used from 2012 to 2013 involving a different undergraduate student, a single balloon launch was conducted per launch date and the rate of carbon dioxide uptake between the ascent and descent was compared. In the second-generation method used in the summer of 2014, two launches were conducted in one day and the rate of uptake between the two ascents was calculated. The carbon dioxide concentrations measured during the ascents were converted to a molar difference using the observed temperature and pressure of the atmosphere, and a flux was calculated by summing the molar differences at altitudes under 6,000 m and dividing by the time difference between flights. This value is the Net Ecosystem Exchange (NEE). The first-generation method found that the peak uptake by the biosphere occurred in mid-July highest (the most negative values of NEE were observed). The second-generation method found that uptake was in mid-July as well, with uptake becoming more positive throughout August and September. Only four data points were collected using the second-generation methodology, so significance of this trend is limited. During peak growing season over the summer, uptake rates of -30 µmol m$^{-2}$ s$^{-1}$ were observed, while as fall approached this rate became positive. The methodology established here will be used to explore new hypotheses related to the NEE of crops.

*  Faculty Advisor: Dr. Mark Potosnak
Department of Environmental Science and Studies and Dr. Bernhard Beck-Winchatz
STEM Studies Department
Research Completed in Summer 2014
Author Contact: angiebouche@yahoo.com
INTRODUCTION

Exchanges of carbon dioxide between the biosphere and atmosphere are a vital part of the global carbon cycle. Throughout the world and in the Midwestern United States in particular, agricultural landscapes cover a significant part of the land, so knowledge about the interactions between crops and atmospheric carbon dioxide is important in understanding the carbon balance on a regional scale. Carbon dioxide is a greenhouse gas, commonly released through anthropogenic activity like fossil fuel combustion, which traps solar radiation in the atmosphere and warms the Earth. By quantifying the Net Ecosystem Exchange (NEE) of crops, which is the rate at which carbon dioxide is transferred between the biosphere and atmosphere, it can be determined whether agricultural practices are an effective way to sequester the carbon dioxide that has been released into the atmosphere. Photosynthesis by crops takes in carbon dioxide, defined as a negative value of NEE, while respiration by crops releases carbon dioxide into the atmosphere and gives a positive NEE.

Currently, research on biosphere-atmosphere interactions is being performed using bottom-up eddy covariance techniques that can record measurements over a smaller parcel of land using towers at one location (Gioli et al., 2004). This technique is subject to errors through calculations correcting for the density of air (Serrano-Ortiz et al., 2008), and it is expensive. Also, there is not a large amount of data available that compares carbon dioxide concentrations in agricultural areas using this technique, so conclusions are still preliminary (Barzca et al., 2009). Performing inverse models on data gleaned from satellites is one way to measure carbon dioxide fluxes over large masses of land, but it is difficult to draw firm conclusions from such an analysis due to the sparseness of data available and errors in measurements (Reuter et al., 2014).

Here we describe a novel method to take measurements on a scale that is intermediate between eddy-covariance and top-down satellite approaches based on High Altitude Balloon (HAB) flights. HABs are also a more cost-effective solution than eddy covariance techniques or inverse models, meaning that more data can be collected so that more certain conclusions can be drawn. The methodology outlined here has provided some reliable data, but it is still preliminary. New hypotheses will be tested using this methodology, along with more detailed measurements of temperature, to gain more information on the NEE of crops over the coming year. This methodology will be used to test further hypotheses related to the NEE of agricultural landscapes. Possible future projects that could take advantage of this method include a comparison of NEE on different types of land, like forested or residential areas, or a comparison of NEE upwind and downwind from the city of Chicago.

METHODS

In this study, a total of four data points were collected, taking place on four different launch dates. On each date, two launches were conducted approximately 3 hours apart and NEE calculations were performed on the data to find the rate at which carbon dioxide was exchanged from the atmosphere to the biosphere between the ascents of the two flights (Net Ecosystem Exchange). The methodology described in this paper grew out of a first-generation approach used from 2012 to 2013 in which one launch was performed on a given day and the concentration of carbon dioxide between the ascent and descent was measured (Pocs, 2014). In the methodology used in the summer of 2014, two flights were launched on one day and the concentrations of carbon dioxide between the two ascents were compared. This way similar landscapes were being observed, and the extra time between flights allows for a clearer change in flux to be seen. The flights were launched from either a high school athletic field in Pontiac, Illinois or from a grass airstrip (Koenert Aviation) in Kankakee, Illinois. The landscape around these areas was primarily corn and soybean crops. The flight paths were predicted prior to launch using Habhub, which is a software created by UKHAS (UK High Altitude
Society) that uses winds generated by the NOAA GFS (National Oceanic and Atmospheric Administration Global Forecast System) Model. Flight paths typically moved southeast of the launch site, but could vary based on wind conditions.

![Image](https://via.sapientiae.com/)

**Figure 1:** Comparison of actual (top) and predicted (bottom) flight on July 17, 2014. Flights were predicted using NOAA GFS (National Oceanic and Atmospheric Administration Global Forecast System) Models to predict the flight path. The actual flight path was tracked using a Stratostar Command Module. Deviations from the predicted flight path could come from wind and jet stream conditions during the launch.

For example, the flight on July 17, 2014 was predicted to move in a more westerly direction, while on the launch date it moved further south than expected (Figure 1). The flight predictions depend on predictions about the jet stream, which at times can evolve rapidly. Launches using this methodology took place on July 17, 2014, August 14, 2014, August 21, 2014 and September 19, 2014.

The flight package contained five items tied together by common masonry cord (Figure 2). The flight package consisted of a latex balloon filled with industrial grade helium until it obtained around 5 kg of lift, which produced an initial ascent rate of approximately 10 m s\(^{-1}\). The balloon ascended to 12,500 to 17,900 m, where it would burst. The balloon was attached to a parachute via 18 ft lines to slow its descent to approximately 7.5 m s\(^{-1}\) at landing. This was connected to a Stratostar GPS command module (Noblesville, IN) via 6 ft lines. The command module, also known as a Stratostar GPS, was the primary source for tracking data along with pressure, which would be used as a proxy for height in later calculations. These data were relayed via a 900 MHz radio signal that was received by an antenna mounted on the chase vehicle. The Stratostar GPS was connected to a LICOR LI-620 (Lincoln, NE) via 8 ft lines, which measured carbon dioxide concentration by pumping air through the device and was powered by Lithium AA batteries. Data were collected using an Arduino (http://www.arduino.cc/) microcontroller system and a backup analog data logger (HOBO U12, Onset, Bourne, MA). This was connected to a HAM radio (APRS) GPS tracker via 8 ft lines that was used as a secondary tracking device that sent location data out through the internet via a network of amateur ham radio operators (Automatic Packet Reporting System, [http://aprs.fi/](http://aprs.fi/)).
The total package weight was 3.6 kg and was lifted by a 200 g balloon that was filled with industrial-grade helium to provide approximately 5 kg of lift. The balloons ascended to approximately 12,500 to 17,900 m before they burst and traveled about 30 km from the launch site.

A mass-balance approach was used to calculate the Net Ecosystem Exchange (NEE) from the carbon dioxide concentration profiles. Using the ideal gas law and the CO$_2$ relative concentration measurements, the moles of CO$_2$ were calculated for each flight per unit of surface area. The difference in the molar amount of carbon dioxide was divided by the time between flights to derive the surface flux. Pressure as measured by the LICOR LI-620 was used as a proxy for altitude, as determined from the Stratostar measurements. On an ideal flight, the carbon dioxide concentration for the first flight of the day would increase when the balloon is still low in the atmosphere, plateau, and then increase steadily with altitude. During the second flight of the day, carbon dioxide concentration would follow this same pattern, but the plateau of uptake would occur at a higher altitude (Figure 3). This is considered ideal because it shows a clear growth in the height of the boundary layer and a corresponding uptake of carbon dioxide by crops.

Near the ground surface, the atmosphere is homogenous in its concentration of carbon dioxide due to convection cells mixing the air. However, at an altitude of around 1,000 m there is a large increase in carbon dioxide concentration over a relatively short altitude interval because convection cells are no longer present to mix the air. This sharp change occurs at what is known as the boundary layer. The negative values of NEE correspond with a growth in the altitude of the boundary layer during the time between flights, which occurs as the day goes on because solar radiation and photosynthesis by crops increase the height of the well-mixed layer of atmosphere present near the ground.

In the summation that was preformed to calculate NEE, data was broken into bins in intervals of 100 m with the first group of data starting at 300 m and the last ending at 6,000 m. The term $i$ below the sigma represents this starting value and the number above the sigma represents this endpoint, divided by 100. The ambient temperature was calculated by applying the hydrostatic equation to the observed change in pressure by altitude and assuming that temperature did not change with altitude within the 100 m interval. The average density of air was found using the ideal gas law. The density of air ($\rho_a/V$) where $n_a$ is the moles of air and $V$ is a unit volume of air in m$^3$. The density was multiplied by the difference in the concentration of carbon dioxide ($C_2 - C_1$) in µmol measured between the two flights to find the molar difference. This was divided by the time that passed between the two launches ($\Delta t$, s) to turn the measurement into a flux:

$$NEE = \sum_{i=3}^{60} \frac{n_a}{V} \frac{(C_2 - C_1)}{\Delta t} \times 100$$

The per unit volume fluxes were transformed from surface area by multiplying by the height of the averaging bin (100 m). These fluxes were summed over the first 6,000 m closest to the surface to determine one NEE per launch date. During flights, NEE could be seen graphically as
in the area between the lines representing carbon dioxide concentrations of the first and second flights (Figure 3).

**Figure 3:** Graph of an idealized flight that shows a well-mixed, homogenous concentration of carbon dioxide near ground level, then a decrease in carbon dioxide concentration from the first launch (blue) to second launch (red). This corresponds with a growth in the boundary layer during the day from 900 m to 1400 m (see text for further details). Above a certain altitude concentrations between the flights would match again, because ground-level photosynthetic activity does not affect carbon dioxide concentrations above this altitude.

**RESULTS AND DISCUSSION**

The first three flights over the summer of 2014 showed uptake of carbon dioxide by crops, with less carbon dioxide being taken up as the summer went on, and a release of carbon dioxide by the crops in the fall during the last flight. The flight with the greatest uptake was on July 17, 2014 where the NEE over the first 6,000 m was -25.62 µmol m⁻² s⁻¹. On August 14, 2014 the NEE was -9.74 µmol m⁻² s⁻¹, on August 21, 2014 the NEE was -9.23 µmol m⁻² s⁻¹, and on September 19, 2014 the NEE was 5.97 µmol m⁻² s⁻¹. This means that a release of carbon dioxide by the crops was observed on September 19. Thus, between July 17 and September 19 2014, the NEE became more positive and eventually a release in carbon dioxide was observed (Figure 4). This data is consistent with trends observed in data collected using the first-generation approach from 2012 to 2013 (Pocs, 2014). However, it should be noted that data collected during the second generation approach follows a seasonal pattern more consistently than data collected using the first-generation approach (Figure 5). This shows that the methodology outlined in this paper is an improvement upon previous methods when it comes to producing reliable data.

Only four flights have been performed using the methodology described here, so any conclusions found from the data described are still preliminary.

There were some discrepancies in the vertical profiles of carbon dioxide during certain flights that raise uncertainties in whether the difference in NEE observed is due to uptake by the plants or horizontal advection. Horizontal advection is the change in atmospheric conditions due to wind transporting air with a different carbon dioxide concentration. Determining whether changes in flux are due to horizontal advection or uptake by crops is difficult, but measurements of temperature or humidity can help show the location of the boundary layer so that...
assumptions about the reason for any differences can be made.

On the graph of August 21 (Figure 6), there is what appears to be a release of approximately 1.5 $\mu$mol m$^{-2}$ s$^{-1}$ of carbon dioxide at two separate altitudes of around 700 and 1200 m. It is not clear why this release of carbon dioxide would happen. One possibility is that air at that altitude was coming from a source region like a city or a power plant. On the launches conducted on July 17 and August 14 there is an increase in the height of the boundary layer and decrease in the concentration of carbon dioxide from 1100 to 1800 m and 1200 to 1600 m respectively (Figure 6).

![Figure 5: Combining data from the first generation approach, shown in blue, (Pocs, 2014) and second generation approach, shown in green, it can be noted that data collected using the second generation approach follows seasonal patterns of NEE more consistantly.](image)

CONCLUSIONS

The conclusion that NEE would be negative during the peak growing season and increase during the summer is one that is supported by the literature as well a first-generation approach that was used previously with a similar methodology. In the first generation approach, the most negative NEE values were found during flights from mid-July, and with the current methodology, the July 17 flight showed the most negative NEE.

In various literature references, experiments have used top-down approaches using satellites over a larger expanse of land, or bottom-up surface eddy covariance fluxes over smaller areas and have found similar trends to those seen using this methodology. Eddy covariance approaches have shown that fluxes of carbon dioxide at surface levels vary seasonally, with uptake rates being highest in the summer, which is consistent with the results found here (Hou et al., 2013). SCIAMACHY satellites that can measure carbon dioxide fluxes at a regional scale have detected that seasonal variations of carbon dioxide fluxes in the northern hemisphere were at a minimum in the summer and at a maximum in the spring (Schneising et al., 2013).

Crops should take up the most carbon dioxide during flights conducted in the middle of the summer, because that is the peak growing season for crops. While plants are growing, they are photosynthesizing, which assimilates carbon dioxide from the atmosphere. In August, crops are not growing as quickly, so they take in less carbon dioxide. When the crops are drying out in the fall there is a release of carbon dioxide into the atmosphere, because the crops are no longer conducting photosynthesis. Certain farming practices, such as no till farming, can minimize the flux of carbon dioxide into the atmosphere, and the methodology used here could be employed to quantify the effectiveness of these efforts. In future experiments, measurements of temperature and humidity could help determine transitions that are present in the boundary layer independent of carbon dioxide concentration. This would make it easier to decide when differences in NEE are arising from uptake by crops versus horizontal advection. When the amount of carbon dioxide taken out of the atmosphere by plants is quantified, that allows us to know how effective agricultural land is at taking carbon dioxide out of the atmosphere, where it has important consequences for the greenhouse effect and climate change.
Figure 6: Panel A (on left) shows the concentration of carbon dioxide in ppm over the first 6,000 m of the two flights. The first flight of the day, shown in blue, tends to have a clear increase in the higher concentration of carbon dioxide at what is known as the boundary layer than the second flight, shown in red. This difference in concentration is shown as a negative NEE in panel B (on right). If the concentration of carbon dioxide was higher at a given altitude in the second flight, then panel b would show NEE as positive.
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