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A high-altitude balloon platform for determining exchange of carbon dioxide over agricultural landscapes

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Abstract.

The exchange of carbon dioxide between the terrestrial biosphere and the atmosphere is a key process in the global carbon cycle. Given emissions from fossil fuel combustion and the appropriation of net primary productivity by human activities, understanding the carbon dioxide exchange of cropland agro-ecosystems is critical for evaluating future trajectories of climate change. In addition, human manipulation of agro-ecosystems has been proposed as a technique of removing carbon dioxide from the atmosphere via practices such as no-tillage and cover crops. We propose a novel method of measuring the exchange of carbon dioxide over croplands using a high-altitude balloon (HAB) platform. The HAB methodology measures two sequential vertical profiles of carbon dioxide concentration, and using a mass-balance approach it calculates the surface exchange by difference and application of the ideal gas law. This approach is relatively inexpensive, does not rely on any assumptions besides spatial homogeneity and provides data over a spatial scale between stationary flux towers and satellite-based inversion calculations. The HAB methodology was employed during the 2014 and 2015 growing seasons in central Illinois, and the results are compared to satellite-based NDVI values and a flux tower located relatively near the launch site in Bondville, Illinois. These initial favorable results demonstrate the utility of the methodology for providing carbon dioxide exchange data over a large (10–100 km) spatial area. One drawback is its relatively limited temporal coverage. While recruiting citizen scientists to perform the launches could provide a more extensive dataset, the HAB methodology is not appropriate for providing estimates of net annual carbon dioxide exchange. Instead, a HAB dataset could provide an important check for upscaling flux tower results and verifying satellite-derived exchange estimates.

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1 Introduction

The exchange of carbon dioxide between the atmosphere and the biosphere is a crucial link in the global carbon cycle. Interactions between the biosphere and atmosphere take place in this cycle through the processes of photosynthesis and respiration. Humans perturb this cycle by releasing carbon dioxide through anthropogenic activities. Annually (2000–2009), there was a release of 7.8 PgC as carbon dioxide attributed to the combustion of fossil fuels and cement production (Ciais et al., 2013). Through photosynthesis, the terrestrial biosphere is currently taking in excess carbon dioxide from the atmosphere and therefore increasing its carbon content. Analysis of the annual global carbon cycle has found that approximately half of the anthropogenic carbon dioxide released remains in the atmosphere, while the rest dissolves in ocean water or is incorporated into plant biomass. Another human perturbation in the global carbon cycle is the appropriation of photosynthesis through agriculture and other land management practices. This appropriation is estimated at 14.8 PgC or 25% of global net primary productivity in 2005, and croplands account for about half of total appropriation (Krausmann et al., 2013). Agricultural landscapes also make up a large portion of the biosphere, so the interactions between crops and atmospheric carbon dioxide are key for understanding the global carbon cycle. This has led to an interest in understanding the impact of agricultural practices, such as no-tillage, on the net carbon balance of agricultural systems, but experimental results are often conflicting (Luo et al., 2010) and point to the need for diverse measurement strategies of the carbon balance of agricultural landscapes.

Measuring the net ecosystem exchange (NEE) of carbon dioxide for agro-ecosystems can show whether agricultural practices are an effective way to offset some of the carbon dioxide that was released into the atmosphere through anthropogenic causes. Considering annual crops, agricultural practices that increase soil organic carbon (SOC) remove carbon dioxide from the atmosphere (here defined as negative NEE), neglecting any carbon flows through hydrological systems. While there is debate about the effectiveness of no-tillage farming (Hollinger et al., 2005; Luo et al., 2010), cover crops are another method being considered for increasing SOC (Poeplau and Don, 2015). The effectiveness of these practices can be constrained by measuring the NEE of carbon dioxide between agricultural systems and the atmosphere. Surface-atmosphere exchange measurements complement methodologies that assess the change in SOC to determine agro-ecosystem carbon balance. A variety of strategies have been employed to measure carbon dioxide fluxes in an effort to understand these exchanges.

Data collected with towers, satellites and airplanes have all been used to quantify fluxes of carbon dioxide. The eddy covariance approach employs instruments mounted on towers to measure NEE over areas on the order of 1 km^2 (Monson and Baldocchi, 2014). In combination with chemical tracers, these flux measurements can be used to infer anthropogenic and biogenic influences on carbon dioxide concentrations over wider areas (Potosnak et al., 1999). However, there is not a large amount of data available that measures carbon dioxide exchanges in agricultural areas using this technique (Barcza et al., 2009). Collecting data via satellites and performing inverse models is another way to measure carbon dioxide fluxes over areas of land on the order of 10^7 km^2, but again there is not a large body of data available and there are significant measurement uncertainties (Reuter et al., 2014). Progress is being made at using satellite data to constrain carbon dioxide exchanges at the scale of large urban areas, but efforts currently focus on atmospheric concentration enhancements and not exchanges (Schneising et al., 2013). New approaches using solar-induced fluorescence derived from satellite measurements to predict crop productivity are promising (Guan et al., 2016), but will require validation. An alternative to using towers or satellites involves carbon dioxide sensors flown on high-altitude balloons (HABs). Given assumptions detailed below, HABs can measure surface exchange by comparing concentration profiles between two sequential flights and performing a mass-balance calculation. HABs are able to collect data at an intermediate scale between the small-scale measurements collected by towers and large-scale measurements collected using satellites. The spatial scale is similar to aircraft measurements (Mays et al., 2009), but the cost is much lower. Some drawbacks are limited temporal resolution and the requirement of spatial homogeneity.

Satellite vegetation indices related to the chlorophyll content of plants have been used to interpret and assess NEE surface-exchange measurements in many studies: for example, from tall towers near croplands (Barcza et al., 2009) and multi-site meta-analyses (Churkina et al., 2005). NDVI values are also used as inputs to continental-scale carbon cycle models, because their seasonal variations track the amount of carbon dioxide plants take in through photosynthesis (Sims et al., 2008). Some caution is necessary, because NDVI is not always an accurate predictor of crop yields, and in some cases predictions based on NDVI measurements predict lower crop yields than what was actually grown (Mkhabela et al., 2005). As another example, NDVI values were inferred to point to net carbon sinks in irrigated croplands and temperate forests across the United States (Potter et al., 2007). But Sus et al. (2013) found variations in carbon dioxide uptake depended on land management and sowing field dates. These factors of uncertainty lead to NEE predictions that did not differ significantly from carbon neutrality. In spite of these limitations, there is often a strong temporal correlation between NDVI and NEE that can serve as a constraint for assessing the quality of HAB measurements. During the spring and early summer when crops are growing, NDVI increases as crops leaf out and leaf chlorophyll content increases. In the summer, crops are fully expanded and NDVI reaches a maximum value. In autumn, crops are left in the field to dry, and NDVI decreases throughout this process as leaf chlorophyll content decreases during senescence. In the winter after harvest, NDVI is lowest since bare ground is exposed. These seasonal trends should mirror trends in NEE. Moving from spring to summer, NEE becomes negative because crops are growing and photosynthesis exceeds total respiration. NEE is most negative in the middle of summer when plants are conducting photosynthesis rapidly. When crops are left in the field to dry or are harvested, NEE

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is expected to be positive because crops are not conducting photosynthesis or growing, while the soil is still respiring.

To assess the quality of NEE measured with the HAB platform, two years of growing-season results are compared to the satellite-derived NDVI values from an area representative of the HAB footprint. Based on the argument outlined in the previous paragraph, we hypothesized that the HAB NEE values should follow the same seasonal pattern as NDVI if the method is effective. In addition, the magnitude of the NEE values measured with the HAB platform are compared to publicly available data from a eddy covariance flux site.

2 Materials and methods

Measuring NEE can be accomplished by comparing vertical profiles of carbon dioxide concentration from two HAB launches 3–4 hours apart. The difference in the molar volumetric densities of carbon dioxide determined with the ideal gas law can be summed over a specified altitude range to calculate NEE. When carbon dioxide concentration is higher for the first flight than the second, carbon dioxide is being removed from the atmosphere (defined as negative NEE and corresponding to photosynthesis exceeding respiration). The details of the calculation are provided below (Equation 1). Similar to the eddy covariance technique, this method assumes that net horizontal advection is negligible and therefore requires spatial homogeneity across the area being studied. To put a practical limit on the assumption of horizontal homogeneity, the relevant changes in carbon dioxide are assumed to be in the boundary layer, which is defined as the layer of the troposphere affected by surface exchanges within a timescale of one hour or less (Stull, 1988). The HAB method does not explicitly rely on a knowledge of the boundary layer height, as long as the vertical profile considered exceeds that height and the condition of horizontal homogeneity is met. But knowledge of the boundary layer height can be used to reject carbon dioxide changes due to changing winds in the free atmosphere unrelated to local surface exchange. During the daytime in the summer, the atmosphere is approximately homogeneous in its carbon dioxide concentration within the boundary layer because it is mixed by convection and turbulence (the mixed layer, Stull, 1988). Above the mixed layer, at an altitude of approximately 1000–2000 m there is a large increase in carbon dioxide concentration over a relatively short change in altitude (the entrainment zone). The mixed layer height should increase for the second flight due to increased vertical mixing driven by additional solar heating at the surface (Figure 1). Above the mixed layer height, the two carbon dioxide profiles should be similar, and differences would be due to changes in large-scale horizontal advection.

The current procedure is a modification on a previous method (Pocs, 2014), where one balloon launch was conducted per day and NEE was calculated based on the difference in carbon dioxide values recorded during the ascent and descent of a single flight. In the previous methodology, the launch site and retrieval site could have different surface characteristics that could affect carbon dioxide concentrations in the surface layer. Therefore, using two ascents for comparison removed an aspect of spatial heterogeneity. The additional time between flights, when compared to the time between ascent and descent of a single flight (less than one hour), also allowed for a larger difference in carbon dioxide concentration and a greater increase in the boundary layer height.

Throughout the summers of 2014 and 2015, a total of ten launches were performed. Four of these launches took place from July to September 2014, and six took place from June to September 2015 (Table 1). As the balloon ascended, burst and descended, it was followed by a chase vehicle using GPS location data received from the tracking devices. Once the balloon was retrieved, the process was repeated approximately 3 hours later. The launches took place at an athletic field at Pontiac Township High School in Pontiac, IL (40.886° N, 88.616° W) with the exception of the flight on 17 July 2014, which took place at Koerner Aviation in Kankakee, IL (41.096° N, 87.913° W). Both of these locations were small towns surrounded by agricultural fields of soy and corn crops, broken into the typical pattern of 2.6 km^2 sections.

The equipment launched during each flight (Figure 2) consisted of a latex balloon filled with helium, a parachute, two GPS tracking devices, a carbon dioxide sensor and an ozone sensor (2015 flights only). The ozone data were collected for another project to measure surface ozone exchange. The parachute (Rocketman Enterprise, Inc., Bloomington, Minnesota, USA) had a spreader (wooden ring) and was above the Stratostar GPS command module (Noblesville, Indiana, USA). The command module was the primary source for tracking the location of the balloon, including the altitude provided by GPS. It also collected data on pressure, which was used as a proxy for height to align the carbon dioxide data to the Stratostar data. These data were relayed in real time to the chase vehicle via a 900 MHz radio signal. Carbon dioxide molar concentrations (ppmv) were obtained with a LICOR LI-620 (Lincoln, NE, USA). Ambient air was pumped through an air filter and then the carbon dioxide measuring device. The instrument was powered by ten lithium AA disposable batteries. The instrument also reported cell pressure and temperature (controlled to 50° C). Because of the relatively slow flow rate (< 1 l min^{-1}) and lack of restriction on the instrument outlet, cell pressure was assumed to be equal to ambient pressure. On the 19 June 2015, 2 July 2015 and 15 July 2015 flights, a LICOR LI-640 was used. This instrument enabled us to also measure water vapor concentrations, which were used to understand the structure of the boundary layer. The data were collected from the LICOR instrument serial output using an Arduino (http://www.arduino.cc/) microcontroller system and a memory card. A backup analog data logger (HOBO U12, Onset, Bourne, MA, USA) that recorded only carbon dioxide and pressure from the LICOR was also used. Finally, another GPS tracker (BigRedBee, Lake Oswego, Oregon, USA) was attached to the LICOR flight package and was used as a secondary tracking device that sent location data via a network of amateur ham radio operators to a website (Automatic Packet Reporting System, http://aprs.org/).

Prior to each launch date, the flight paths were predicted using the Cambridge University Spaceflight Landing Predictor (http://predict.habhub.org/), which uses winds generated by the NOAA GFS

(National Oceanic and Atmospheric Administration Global Forecast System) Model (Figure 3). For 2014 launches, a 200-g latex balloon (Kaymont Consolidated Industries, Deer Park, New York, USA) was filled with industrial grade helium until it obtained approximately 5 kg of lift, which produced an initial ascent rate of approximately 5–6 m s^{-1} for our payload weight of 3.6 kg. In 2015, the balloon was filled until it obtained 7–8 kg of lift. It was necessary to obtain more lift on 2015 launches because an extra ozone sensor (1.8 kg) was attached to the flight package, giving a total weight of 5.4 kg. On the 12 September 2015 flight, a 150-g balloon was used. Typically the balloons reached an altitude of around 13000–15000 m before bursting, but by using the smaller 150-g balloon on the 12 September 2015 flight, the burst altitude was reduced to approximately 9000 m (Table 1).

The data were analyzed using R (version 3.2.3, R Core Team, 2015) and a mass-balance approach was employed (Equation 1). First, all data were averaged by altitude into 100-m bins (denoted by i) with the first bin at 300–400 m (the launch sites were at an elevation of approximately 230 m; everything referenced to sea level) and the last bin at 5900–6000 m. A single ambient temperature was calculated by applying the hydrostatic equation to the vertical profile of measured pressure under 6000 m recorded by the Stratostar GPS and assuming that temperature did not change with altitude. Using this temperature and the average measured pressure, the density of air was found using the ideal gas law for each altitude bin. This molar density of air (ρ_i, mol m^{-3}) was multiplied by the difference in the concentration of carbon dioxide ($C_{2,i} - C_{1,i}$) in μmol of carbon dioxide per mol of air measured between the two flights. This value is the molar difference of carbon dioxide per cubic meter between flights. This was divided by the time that passed between the two launches (Δt, s) and multiplied by the bin height to get the NEE rate for each altitude bin. Finally, a summation across the altitudes resulted in the net NEE. The sign convention for the exchange was relative to the atmosphere, so net uptake by the crops (photosynthesis exceeds respiration) was negative.

$$\mathrm{NEE} = \sum_{i=3}^{59} \frac{\rho_i (C_{2,i} - C_{1,i})}{\Delta t} \times 100\ \mathrm{m} \quad (1)$$

The time series of NEE measurements was then compared to NDVI values obtained from the Terra MODIS satellite. The NDVI values (Vegetation Indices 16-Day L3 Global 1km, MOD13A2) were retrieved from Reverb/ECHO, courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, [http://reverb.echo.nasa.gov/]. The online version of the HDF-EOS To GeoTIFF Conversion Tool (HEG) was used to retrieve a subset (upper-left corner: 41.084° N, 88.977° W; lower-right corner: 40.770° N, 88.121° W) of NDVI values as a GEOTiff file, which were then averaged with R to produce one NDVI value for the area per 16-day period. This provided one NDVI value for each 16-day period from April 2014 to December 2015. The seasonal trends in NDVI and NEE were then compared.

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NEE values from the HAB methodology were also compared to data from an eddy covariance tower site located in Bondville, Illinois (Meyers and Hollinger, 2004) that is part of the Ameriflux network (http://ameriflux.ornl.gov/fullsiteinfo.php?sid=44, Baldocchi et al., 2001). Previous studies at this site have assessed how agricultural systems contribute to atmospheric carbon balance (Hollinger et al., 2005; West et al., 2010). Half-hour flux data from 1996–2008 were averaged for daytime values between 11:00 and 15:00 (Central Standard Time) to correspond to HAB launch times. The data from within these times were grouped into 10-day bins based on day of year, and averages and standard deviations were calculated across the entire 13-year data set to produce a composite seasonal cycle.

3 Results and discussion

The observed vertical profiles of carbon dioxide and associated NEE values (Figure 4) often exhibited characteristics of the ideal flight (Figure 1), but there was more variation and some flights exhibited more complexity. Many flights had a sharp decrease in carbon dioxide concentrations that corresponded to a well defined boundary layer height. For example, the second flight on 14 August 2014 had a boundary layer height that increased by approximately 200 m compared to the first flight (Figure 4, top-left panel). This is consistent with the growth in the boundary layer over a 3-hour period (Stull, 1988, Figure 1.7). Above around 1800 m, carbon dioxide concentrations between the two flights approximately matched, as expected. For the flights on 13 Aug 2015, the carbon dioxide concentrations observed within the mixed layer showed near-ideal behavior (Figure 4, top-right panel). In this case, both a decrease in carbon dioxide concentration within the mixed layer and an increase in the boundary layer height were observed. But above the transition, there is a difference in concentrations that cannot be unequivocally assigned to local surface exchange. The calculated positive contribution to NEE from approximately 1400–2400 m could be attributed to entrainment processes and therefore would be considered as part of the surface exchange. Alternatively, the increase in carbon dioxide concentrations could be due to long-range transport and changes in the source regions of the free-atmosphere winds. This would be a violation of our assumption of spatial homogeneity, and should not be included in the surface NEE summation. Our current analysis includes this contribution, but additional information about boundary layer structure (for example, profiles of temperature and humidity) could resolve this question.

There was an instrumentation issue with a different carbon dioxide sensor used on three flights: 19 June, 2 July and 15 July 2015. Instead of the LI-820 sensor which only measured carbon dioxide, the LI-840 was deployed that measured both carbon dioxide and water vapor. The intent was to gain additional information about the boundary layer structure from the water vapor profile. But with this new instrument, carbon dioxide concentrations in the free atmosphere systematically differed between flights, unlike all the other flights where they were closely matched. Concentrations of carbon dioxide for the second flight were consistently 4 ppmv higher than the first flight, which is a factor of approximately 1% of the total concentration. Given this empirical observation, the data were adjusted by reducing both the recorded carbon dioxide concentration and pressure values by 1% for the second flight (Figure 4, bottom two panels). After the adjustment, the data matched the conceptual model, which has equivalent carbon dioxide concentrations in the free atmosphere. This procedure was applied to all three dates that used the LI-840 instrument. With the adjustment, the profile from 15 July 2015 could be interpreted as having a residual boundary layer at 1000–1300 m (Figure 4, bottom-right panel).

3.1 Comparison of HAB results with other data sources

Our observations of NEE seasonal trends matched our expectations derived from NDVI satellite values and a nearby eddy covariance (EC) site in Bondville, Illinois. In 2014, HAB NEE values were most negative in mid July (-24.4 μmol m^{-2} s^{-1}) and became more positive as the summer went on (Figure 5). In 2015, there was a minimum on 19 June 2015 (day of year 170) at -30.8 μmol m^{-2} s^{-1} and a maximum on 12 September 2015 (day of year 255) of 6.50 μmol m^{-2} s^{-1}, but there was more variability compared to 2014. For the near-zero NEE observed on 23 July 2015 (day of year 204), there is the possibility that local sources of carbon dioxide near the launch location of Pontiac offset crop NEE. This flight had near-surface (< 800 m) positive NEE values, similar to 14 August 2014 (top-left panel, Figure 4), which are consistent with local carbon dioxide emissions from the urban area of Pontiac. For 2014, there are only four HAB measurements, but the timing of their minimum and maximum match within the 10-day averaging window of the EC values (Figure 5). While the HAB maximum for 2015 is consistent with the EC trend, the HAB minimum occurs much earlier (day of year 170 versus 205). Further research with more measurement dates is necessary to determine if the variability observed in 2015 was due to experimental imprecision or intrinsic variability in NEE. One possibility is that the sensor correction used for three flights in 2015 introduced experimental error that obscured the seasonal trend in HAB NEE. While the empirical correction produced free-atmosphere carbon dioxide concentrations that matched between the two flights, we do not understand the nature of the instrument malfunction and therefore we cannot assess its potential impact on the corrected NEE values.

An inspection of NDVI values (Figure 5) does not reveal any obvious differences between 2014 and 2015 that would account for increased variability in 2015. Lower NDVI values in 2015 could reflect increased plant stress, but this is speculative. NDVI values reach their fall minimum later than the HAB NEE become positive (net respiration), but this is also true for the comparison with the long-term EC NEE values from Bondville. The timing of the fall decrease in our NDVI values is roughly consistent with seasonal NDVI trends from an agricultural area of Nebraska (Eastman et al., 2013). The lag between NEE and NDVI decreases could be due to the time that crops spend in the field before harvest. In late summer and autumn, crops do not have a positive net photosynthesis, but

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agricultural practice is to leave crops in place to dry out. NDVI might continue to sense vegetation when crops are present in the field even if they are not undergoing photosynthesis due to senescence.

The magnitudes of NEE observed with the HAB methodology are consistent with other estimates of NEE. An ensemble of models estimated net primary productivity to be 600–800 gC m^{-2} annually for this region of Illinois (Cramer et al., 1999). Assuming a growing season of a 100 days (Figure 5) and 12 hours of carbon dioxide uptake occurring per day, an annual uptake of 650 gC m^{-2} infers an instantaneous uptake rate of 12.5 μmol m^{-2} s^{-1}, which is within the range of our measured values. Our results are also consistent with smaller-scale measurements from the Bondville flux site. Except for the HAB NEE flight that is hypothesized to be contaminated by local sources (23 July 2015), all the other HAB NEE measurements are either within or very close to within one standard deviation of the long-term (13 year) mean of the EC data (Figure 5). Finally, the overall seasonal trends from both 2014 and 2015 and the magnitude of the values are consistent with the trends and the range of observed data collected using the first-generation approach from 2012 to 2013 (Pocs, 2014).

3.2 Advantages and limitations of the HAB methodology

The HAB methodology has numerous advantages. (1) It is a direct mass-balance approach. There are no assumptions necessary to calculate the surface exchange: the equations rely only on the ideal gas law. (2) Using a single instrument to measure both carbon dioxide vertical profiles reduces errors inherent in difference measurements. By comparing the two carbon dioxide profiles retrieved above the mixed layer, issues associated with sensor imprecision between flights can be assessed. This allowed us to spot problems with the LI-840 instrument compared to the more stable LI-820. (3) The HAB methodology measures NEE at an intermediate scale between stationary eddy flux sites and regional-scale measurements derived from satellite inversions of remotely-sensed carbon dioxide concentrations. (4) The costs associated with HAB are modest compared to aircraft flux measurements. This lowers the barrier for entry and opens the possibility for citizen science groups to contribute measurements. For example, high school students have observed and assisted our launches.

There are some drawbacks. Most importantly, conducting balloon launches is time-intensive and measurements are episodic. Unlike the continuous half-hour data stream from an eddy covariance tower, measurements need to be acquired by hand. Because of this, the method is useful for temporally limited comparisons to other data sources as done in the current study, but is not appropriate for calculating annual net NEE values by itself.

Like the eddy covariance method of determining surface fluxes (Horst and Weil, 1992), another issue is determining the spatial extent of the surface area (footprint) that influences the NEE calculated by the HAB methodology. A simple scaling analysis gives an approximate upwind footprint distance based on vertical mixing times and horizontal wind speeds throughout the mixed layer. Using the definition of the mixed layer of Stull (1988) as the region of the atmosphere in contact with the surface within the times scale of one hour, a typical upper-end horizontal wind speed (16 km hour^{-1})

gives a upwind length scale of 16 km. An upper limit for the upwind footprint distance that does not rely on this definition would use the time between flights (4 hours maximum) and the same wind speed to get a distance of 64 km. A more detailed study of turbulent mixing would be necessary to assess the footprint extent perpendicular to the horizontal wind direction. The necessity for a spatially homogeneous landscape limits the locations for deployment. Even if this condition is met, forested landscapes, urban areas and private property pose an issue for instrument retrieval. A tethered balloon system would address this problem, but increase the complexity of the experiment.

4 Conclusions

Further research with the HAB methodology could be done to extend the validity of the method. Multiple launches could be conducted on the same day in different locations, which would help assess the spatial footprint of the HAB methodology. A series of more than two launches performed on one day at the same location would allow diurnal cycles in NEE to be considered. Both of these improvements require multiple launch teams, which could be used as an opportunity to recruit citizen scientists into the process. The launch site could be moved to a more agricultural landscape, which would minimize the influence of local anthropogenic sources encountered in Pontiac.

Because of the massive human perturbation of the natural carbon cycle due to agriculture, landscape-scale measurements are necessary to understand the fully integrated surface exchanges. While small-scale eddy flux measurements are a good tool for assessing particular agricultural practices at the plot scale, the HAB methodology can be used to verify carbon dioxide exchanges over much larger spatial scales. Agriculture occupies a vast amount of land, so understanding its ability to take up or release carbon dioxide is crucial for understanding the global carbon cycle as a whole.

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Table 1. Flight data from all flights conducted during the summers of 2014 and 2015. Each date had two separate flights to produce one estimate of NEE.

Date	Burst Height 1 (m)	Ascent Rate 1 (m s^{-1})	Burst Height 2 (m)	Ascent Rate 2 (m s^{-1})
17 Jul 2014	14770	4.74	13480	6.21
14 Aug 2014	15000	5.35	14810	5.60
21 Aug 2014	14760	6.01	15530	6.23
19 Sep 2014	13290	6.24	13850	5.56
19 Jun 2015	14200	4.70	13060	4.84
02 Jul 2015	13030	5.29	13730	4.85
15 Jul 2015	12340	6.07	13450	5.80
23 Jul 2015	12930	5.96	12490	6.39
13 Aug 2015	13810	6.40	13200	6.37
12 Sep 2015	9040	6.55	9400	5.76

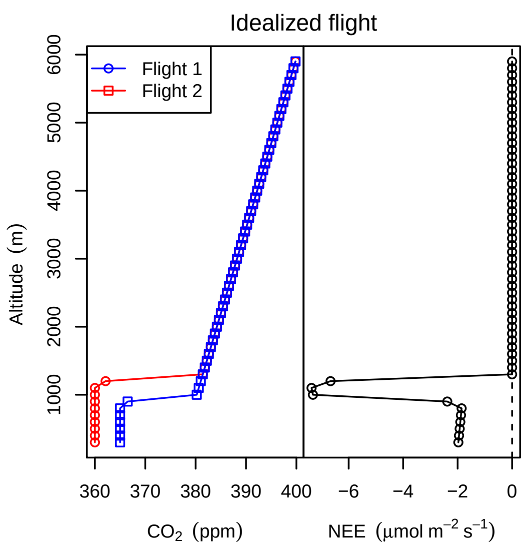

Figure 1. An idealized flight that includes a well-mixed, homogeneous concentration of carbon dioxide near ground level, then a decrease in carbon dioxide concentration from the first launch (blue) to second launch (red) corresponding with an increase in the boundary layer height. Above the boundary layer height of the second flight concentrations between the flights should match again, because ground-level photosynthetic activity does not affect carbon dioxide concentrations above this altitude (left panel). Both the decrease in the mixed layer carbon dioxide concentration and the increase in the boundary layer height contribute to surface exchange (right panel). The molar differences with altitude are summed to find the total NEE.

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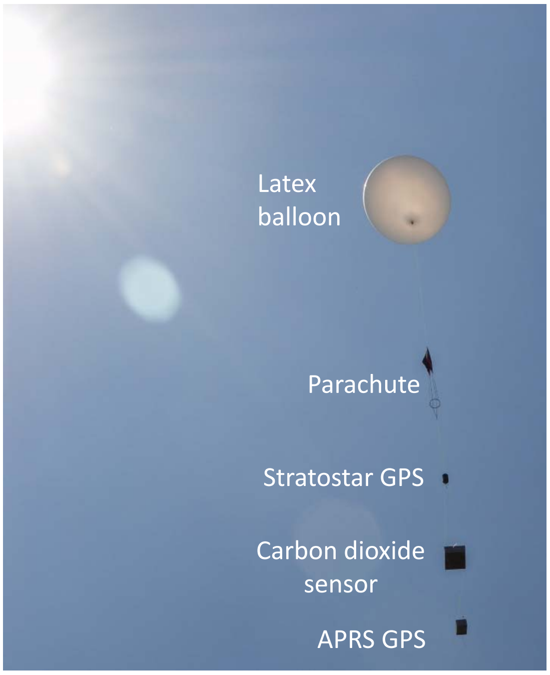

Figure 2. Picture of flight train of packages. The total package weight of 5.4 kg was lifted by a 200-g latex balloon that was filled with industrial-grade helium. The packages were all connected with 1.8-m lines (mason's string), except for 5.5-m lines for the balloon to parachute connection.

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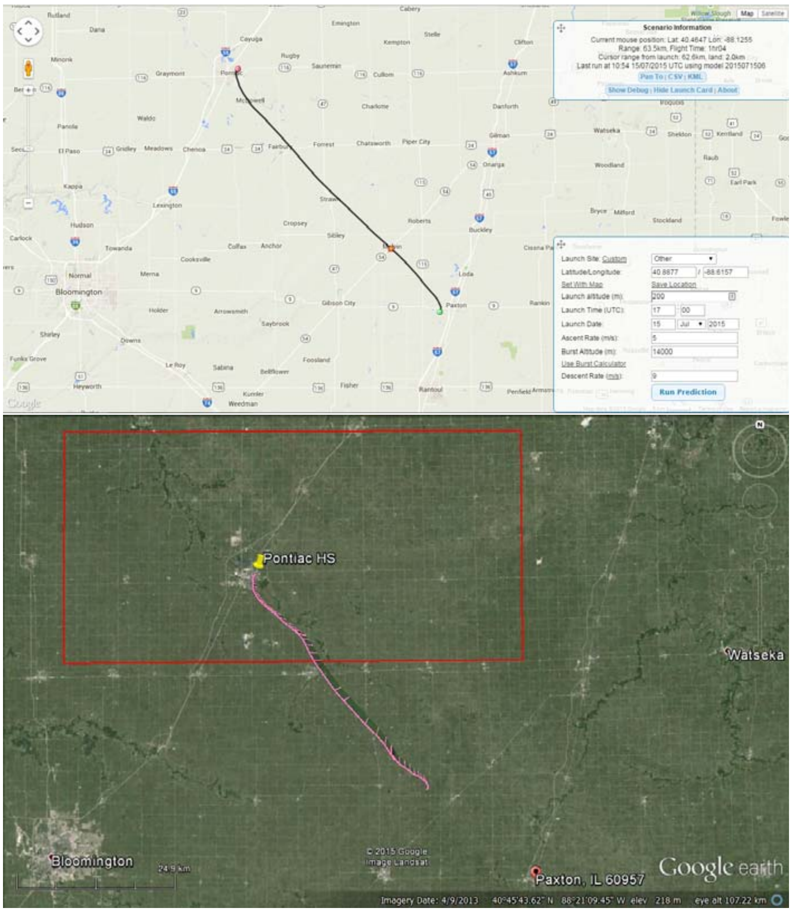

Figure 3. Comparison of actual (bottom) and predicted (top) flight paths on 15 July 2015. Flights were predicted prior to launch using NOAA GFS (National Oceanic and Atmospheric Administration Global Forecast System) Models. The actual flight path was tracked using a Stratostar Command Module. The red box in the bottom panel indicates the bounding box for the NDVI dataset.

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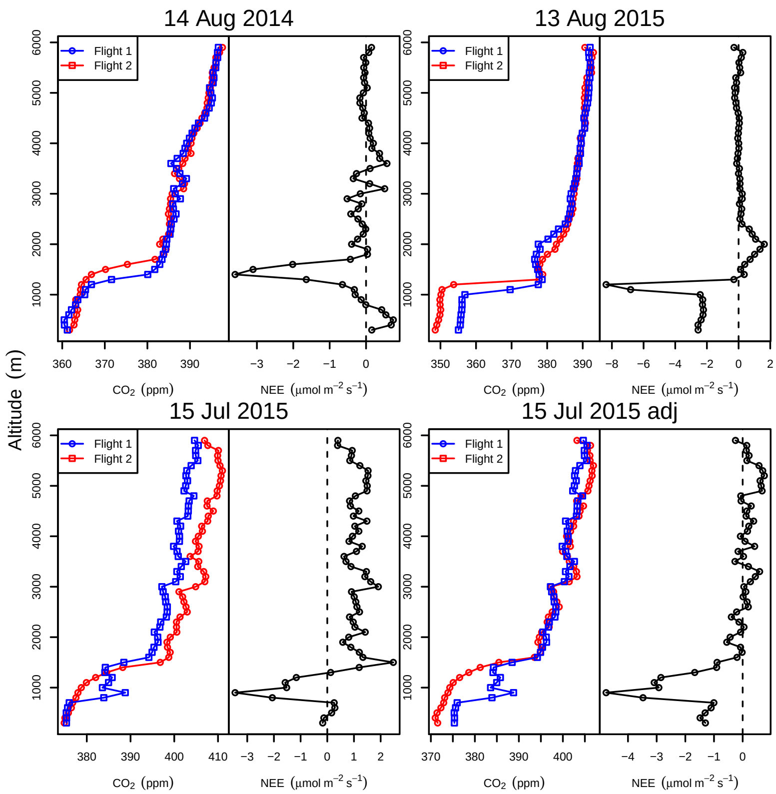

Figure 4. The left portion of each panel shows the concentration of carbon dioxide to an altitude of 6000 m for the two launches (blue for the first launch, red for the second). Using Equation 1, the differences in carbon dioxide concentration are used to compute the equivalent surface exchange for each 100 m interval for the right portion of each panel. The top-left panel from 14 August 2014 shows a flight that has little change in the mixed-layer carbon dioxide concentration, but the increase in boundary layer height leads to a negative value for NEE. The top-right panel from 23 July 2015 shows a flight that has both a decrease in mixed-layer carbon dioxide concentration and an increase in the boundary layer height contributing to a negative NEE. But there is also a positive NEE contribution above the mixed layer that is not straightforward to interpret. The bottom panels from 15 July 2015 demonstrate a flight that was corrected due to instrumentation error. The original data (bottom-left) had carbon dioxide concentrations that differed consistently in the free atmosphere. This was corrected to match free-atmosphere carbon dioxide concentrations between flights and produced reasonable profiles of carbon dioxide concentration and NEE in the boundary layer (bottom-right).

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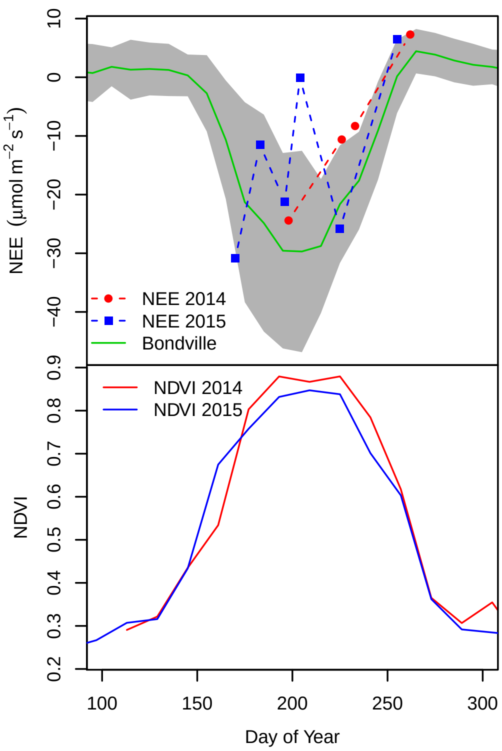

Figure 5. Seasonal patterns in NDVI (bottom panel) and NEE (top panel) for 2014 and 2015 and data from the Bondville eddy flux site for 1996 to 2008. NEE data in the top panel includes the NEE HAB estimates (dashed lines and filled circles (2014) and squares (2015)) and 10-d averages of midday (11:00–15:00 local standard time) NEE for Bondville (green solid line). The gray shaded region indicates one standard deviation above and below the mean for Bondville. HAB-based NEE falls within or very close to the shaded region, except for one measurement on 23 July 2015 that may have been influenced by local anthropogenic sources. NDVI generally tracks NEE well, but NEE from both Bondville and the HAB technique approach zero sooner than NDVI in the fall.