The Ground CO_2 Mapper - An innovative tool for the rapid and precise mapping of CO_2 leakage distribution

Beaubien S.E., Graziani S., Tartarello M.C., Ruggiero L., Bigi S.

Università degli Studi di Roma La Sapienza, Dipartimento di Scienze della Terra, Italy

Corresponding Author: *stanley.beaubien@uniroma1.it*

The recently developed Ground CO_2 Mapper ("Mapper" for short) is an inexpensive, light, robust, and low power consuming tool for determining the distribution of CO_2 at the soil-atmosphere contact as an indicator of CO_2 leakage. The basic premise behind the Mapper is that the contact between the ground surface and the atmosphere represents an interval where CO_2 leaking from the subsurface can accumulate in anomalous concentrations due to two mechanisms, the higher density of CO_2 with respect to air and the tendency of wind speed (and thus mixing) to approach zero near the ground surface due to frictional drag. Because of its measurement target and the tool's very rapid response time, Mapper surveys can be conducted very quickly at a high sampling density, yielding accurate maps of CO_2 spot anomalies. The unit can be used by anyone and deployed within only 5-10 minutes after sensor and GPS signal warm-up. Here we describe the Mapper and present results from a site of natural diffuse CO_2 degassing in central Italy.

Introduction

The flux of biogenic CO_2 from the ground surface to the atmosphere is ubiquitous due to microbial and root respiration in the soil. This flux is controlled by numerous geological (soil type, permeability, organic matter content, etc.) and environmental (temperature, water content, etc.) conditions, resulting in relatively smooth spatial distributions that are influenced by higher-order variables (topography, land-use, etc.) and temporal variations that are closely linked with diurnal and seasonal variations. In some settings the leakage of a second source can be superimposed on this background distribution due to the upward migration of deep-origin geologically produced CO_2 along faults and discontinuities in geothermal or volcanic settings. This flux, commonly referred to as diffuse degassing, can range from levels similar to those of biogenic up to 3-4 orders of magnitude higher, tends to be more stable in time, and is distributed both as low-level leaks controlled by diffusion and as high-level, smaller "vents" controlled by advection. A second potential deep source could be the leakage of man-made CO_2 stored in deep geological reservoirs (i.e., Carbon Capture and Storage, CCS), although to date this has not been observed [e.g., Beaubien et al., 2013].

The goals of measuring CO_2 flux for either geogenic- or CCS-related studies are typically one of the following: i) to map its distribution to understand the underlying migration pathway (e.g., fault distribution); ii) to quantify the total amount being released to determine, for example, heat flow in geothermal areas, carbon loading to the atmosphere, or CCS storage integrity / carbon credit auditing; or iii) to assess any potential leakage-related risks to human health or the local ecosystem. These goals are usually accomplished by making many point flux measurements over the study area, using the accumulation chamber technique, followed by statistical/geostatistical analysis and spatial interpolation [e.g., Cardellini et al., 2003]. However, point sampling of a spatially variable parameter, especially one that can exhibit small sized anomalies with values significantly higher that background (i.e., "hot spots") risks to completely miss anomalies if sample spacing is too large, which could in turn

lead to errors in data interpolation. Because the number of flux measurements (and thus sample density) is limited by logistics and costs, a rapid, reconnaissance tool to focus flux surveying on areas of interest, or even act as a proxy, could potentially be very helpful.
The Ground CO_2 Mapper ("Mapper" hereafter) was recently developed with this goal in mind, extending and greatly improving upon a proof-of-concept prototype that was previously created by the present authors [Annunziatellis et al., 2008; Jones et al., 2009]. Here we describe the characteristics and capabilities of this new low-cost, robust, low power consuming, precise and sensitive tool and illustrate its potential using field test results from a natural diffuse degassing site in central Italy.

Methods

The Mapper is premised on the fact that CO_2 released from the soil tends to accumulate at the contact between the ground surface and atmosphere due to the higher density of this gas relative to air as well as near-zero wind speeds in this interval (known as the roughness height) due to frictional drag [Garratt, 1994]. The Mapper is mounted on a small hand cart and pushed around the area of interest at a normal walking speed. While moving, air is constantly pumped from a 6 mm diameter tube (whose inlet is dragged along the ground surface) into a fast-response, low-cost miniature NDIR CO_2 sensor (Alphasense IRC-A1) and the resultant CO_2 concentration is paired with coordinates from an integrated differential Global Navigation Satellite System (D-GNSS) (UBlox C94-M8) for precise spatial mapping. Operation is via a touch screen, data are saved to an internal flash memory, and data is downloaded via WiFi using a cellular phone or computer. Measurements are made at 4Hz, resulting in a sample spacing of 20-40 cm along line while lateral line-to-line spacing is chosen by the operator based on the area to cover and expected anomaly size; typical line spacing would be on the order of 2-5 m.
Point flux measurements were performed using an accumulation chamber system built by the authors, and whose response has been verified by comparison with commercial instruments.

Results and Discussion

Laboratory tests

Sensitivity of a mobile system is based not only on sensor stability but also on response time, as the faster the response the closer the instrument will come to measuring the true value before moving into an area with a different value. These two instrument characteristics can be in conflict, however, because the increased flow rate necessary to decrease response time tends to increase sensor noise. Extensive development work on the Mapper focused on finding a compromise between these two parameters, with the resultant values presented below.
The background noise level was assessed by running the Mapper in acquisition mode and drawing outdoor atmospheric air from a third-floor window, where concentrations were expected to remain essentially constant for the 10-minute monitoring period (Figure 1a). The measurements yielded 2σ = 20 ppm, meaning that values greater than the average background value plus 20 ppm can be considered anomalous at the 95% confidence level (given the Gaussian distribution of the data). In addition, it should also be noted that sensor background noise is high frequency, whereas a true anomaly encountered during motion across a leakage area will result in a lower frequency anomaly, opening the possibility for time domain filtering. This is simply illustrated by calculating a two-point running average of the same data, which yields 2σ = 16 ppm.

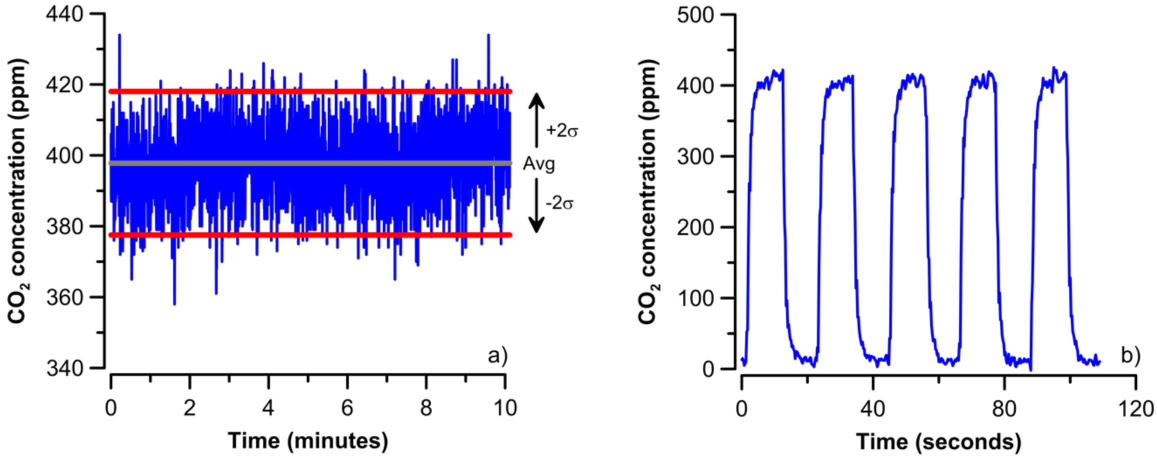

Figure 1 Results showing the level of background noise (a) and the response time (b) of the Mapper. Data are collected at 4 Hz; raw data are presented in (a) while a 2-point running average is given in (b) to remove the strong signal oscillations that occur during very rapid, large concentration changes.

The response time of the Mapper was assessed by attaching the system's inlet tube to a two-way valve that gave alternating access to 1L Tedlar bags filled with i) pure nitrogen and ii) a CO_2 standard of 395 ppm. The valve was actuated manually every 10 seconds and at the same time a text character was inserted into the data stream to mark the time zero of each switch. Results of the 11 valve switches performed over a two-minute period show highly reproducible behavior (Figure 1b), defining a T_{70} (i.e., time required to reach 70% of the new value) of about 1.75 seconds. It should be remembered, however, that in actual field conditions changes will tend to be along a gradient and not via instantaneous, drastic changes like those tested here. The response time could affect field data in two ways. If the leakage area is sufficiently large relative to the surveying speed, the resultant anomaly will simply be shifted slightly but measured concentrations will not be strongly affected. Instead with a small anomaly there is also the potential that the measured concentration anomaly will be smaller because there is insufficient exposure to the sampled gas. These relations must be taken into consideration when deciding the survey walking speed.

Field tests

Field testing of the Mapper was conducted in October 2018, near the town of Ailano, Italy, in an area known for extensive diffuse CO_2 degassing [Ascione et al., 2018]. A total of four fields were measured, each being unique in terms of the strength and size of the leaks and the height of the vegetation (which impacts on the roughness height). Surveys were performed over a 5-day period, during which the light wind conditions varied only slightly. Duplicate surveys were conducted in different directions in all measured fields. Results from the "Ailano-2" field are presented here, which are representative of the collected data.

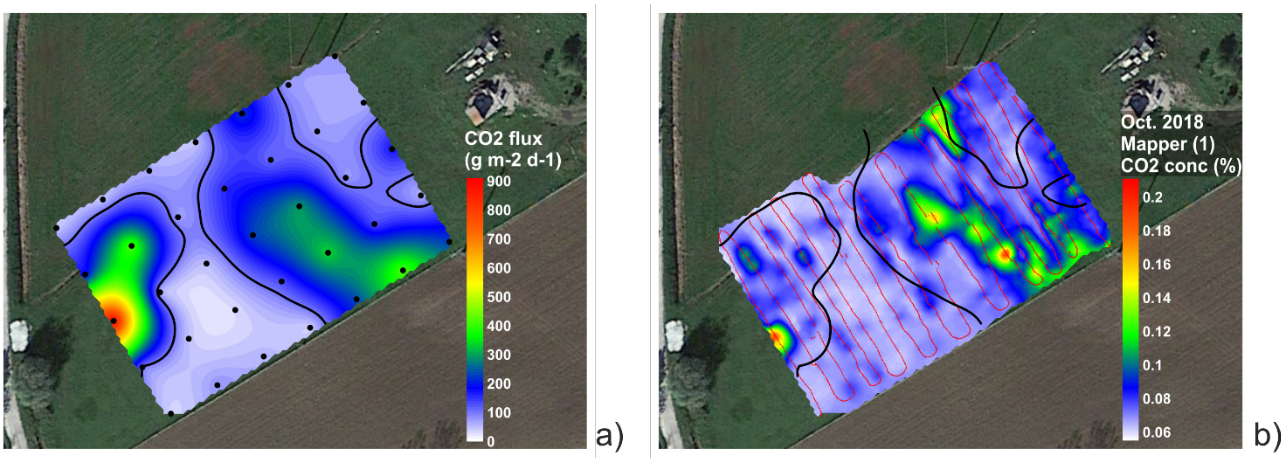

Figure 2 Mapper field test: a) contoured CO_2 flux based on point flux measurements performed on a 10 m spaced grid; and b) contoured Mapper CO_2 concentration results, with the 100 g m^{-2} d^{-1} flux contour (black line) plotted for reference and red dots showing the Mapper sample points.

The Ailano-2 field is flat, generally not cultivated, and covers a total area of about 4500 m^2; measurements were performed on a central area covering 2400 m^2. In an aerial photograph there are no obvious signs of CO_2 leakage, although visual inspection during the survey period did show some areas of thin vegetation. At the time of the campaign the field was filled with grasses and weeds ranging in height from 3 to 30 cm. Point flux measurements were made on a regular 40 x 60 m grid having 10 m sample spacings (Figure 2a). Results highlight two primary areas of enhanced leakage, one elongated feature trending generally NW-SE on the eastern side of the grid and a more oval feature located on the western edge. Values range from 30 to 900 g m^{-2} d^{-1}, although only one sample point (in the middle of the grid's western boundary) exceeds 400 g m^{-2} d^{-1}.
A Mapper survey was conducted over the same area, performed at a walking speed that resulted in c. 25 cm sample spacing along lines and a chosen 2 m spacing between lines. Measured CO_2 concentrations ranged from 550 to 2000 ppm, with Mapper anomaly distribution (Figure 2b) matching closely that defined by the point flux measurements (Figure 2a). The much closer sample spacing of the Mapper permitted a more detailed definition of the leakage points, highlighting a series of nearby, semi-amalgamated, concentrated leakage areas rather than the smoother, more homogeneous image resulting from interpolation of the more widely spaced CO_2 flux results. A second Mapper survey conducted in an orthogonal direction in the same field (data not shown) yielded very similar results. It is important to note that while measurement of the flux grid of 35 samples required approximately 2 hours the Mapper survey was completed in about 15 minutes. Similar results were obtained in the other three fields, despite the fact that some had been recently cut leaving vegetation that was only 2-3 cm high.

Summary and Conclusions

A new tool, the "Mapper", has been developed for the rapid reconnaissance mapping of CO_2 spot leakage areas, to quickly cover large areas and to focus more detailed and time-consuming point flux measurements. Laboratory tests show that anomalies can be defined as 20 ppm above CO_2 average baseline values and that the response time (T_{70}) of the present configuration is about 1.75 seconds. Field surveys at a site of natural defuse degassing in central Italy illustrate excellent correlation with CO_2 flux distribution defined using point measurements and show good instrument reproducibility and sensitivity under real-world conditions of different leakage rates, different vegetation lengths, and slightly variable wind conditions.

Highly detailed tests under controlled leakage conditions are now being conducted to better define the sensitivity of the tool, both in terms of absolute sensor response as well as its response as a mobile platform that is moved across spatially discrete anomalies. These experiments, being conducted on a constructed test site, will address such issues as anomaly size, flux rate, walking speed, vegetation height, and wind conditions, and how they may impact on the tool's capabilities. The goal of this work is to determine the minimum CO_2 flux level that can be recognized by the Mapper, under both ideal and less-than-ideal conditions. Experiments are also being conducted to improve sensor response time and signal to noise ratio, with progress having been made since the version used during the October 2018 campaign reported here.

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