UV-BASED, IN-SITU, LOW POWER, WIRELESS SOIL CARBON MEASUREMENT SYSTEM

Steven Tran, Rabiul Hasan, Ashrafuzzaman Bulbul, Seungbeom Noh, Carlos Mastrangelo, and Hanseup Kim*
Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA

ABSTRACT

This paper reports the development and initial testing of a UV based soil organic carbon prediction system that takes advantage of the interaction of micro-LED UV emissions with the soil to estimate the total amount of soil organic carbons (SOC) for the first time. This unique system comprises of an optical CO_2 sensor, 415-nm UV LEDs, a micro-controller programed with a sleep mode algorithm and a LoRa based wireless communication electronics, all of which were integrated into a 25-cm-long soil-penetrating shank structure. The prototype utilized a photo-oxidation effect that near-instantly yielded CO_2 when a long-wavelength UV interacts with the soil. Energy from the UV emissions act as a catalyst in the formulation of singlet oxygen molecules, which then goes through a dismutation and Fenton reaction to produce hydroxyl radicals. These radicals will eventually interact with the dissolved organic carbon (DOC) component of the soil to actively form CO_2 molecules. Thus, this method was able to eliminate the conventional tedious soil sample extraction process and high-powered machinery commonly used in today's soil carbon analysis. This constructed prototype successfully produced photo-oxidated CO_2 of up to 128 ppm from soil at a depth of 15 cm within 30 minutes of UV exposure, while consuming an average power of 167.71 mW per 150 min sampling period. Preliminary deployment of the device at four locations around the United States successfully showed the feasibility of accurate, in-situ predictions of SOC, relatively closely matching the national soil database from the United States Department of Agriculture (USDA) relatively well with an average error of 2.64%.

KEYWORDS

Soil Organic Carbon (SOC) measurement, Ultra-Violet, In-Situ, Carbon Prediction, Photo-Oxidation

INTRODUCTION

With rapidly growing concerns over climate changes in recent years, carbon monitoring and sequestration in large agricultural land become vital means in diagnosing and resolving the problem [1]. Today there are 4.62 billion hectares of farmland in the world, which produces roughly 10% of the world's greenhouse gases according to the Food and Agriculture Organization (FAO) [2]. Of these 4.62 billion hectares, only a small percentage of the land utilize agricultural practices for carbon sequestration, limiting the potential in reducing global climate change [3]. Studies have also shown that for every 5–10° C increase in the average temperature, the CO_2 production from soil respiration within agricultural soil doubles, resulting in a cycle of ever-increasing concern [4]. Thus, the efforts in soil carbon monitoring and sequestration in large agricultural lands carries significant impacts toward global efforts in suppressing climate changes.

Current state-of-the-art soil carbon measurement methods can be primarily categorized into two categories, active and passive carbon measurements, depending on whether data is acquired from underground soils or not, all of which are unsuitable in one way or another in producing precise SOC estimation over a large area. Passive measurement techniques include infrared spectroscopy, satellite imaging, and eddy covariance. These techniques quantify parameters, such as light reflection or color variances, which can be correlated to the total soil carbon resulting in rapid soil analysis only at the surface of soils, thus suffering from high uncertainty and being limited in the estimation accuracy in comparison to the gold standard, the dry soil combustion technique. On the other hand, the active carbon measurement techniques, including the wet-oxidation and soil burning techniques, rely on (1) sampling and relocation procedures of soil from a field to a laboratory setting involving extensive excavation and a serial process unsuited for near real time, in-situ measurements and (2) power-hungry analysis methods, such as combustion, heating, or laboratory ultra-violate lasers, limiting the feasibility of in-situ measurement due to significant power consumption.

These limitations seen in existing soil carbon measurements can potentially be resolved by combining the functionality of both a MEMS micro-bolometer and a micro-UV LED, for a direct, sampling-free, and low-power system capable of actively producing CO_2 directly from the soil. Previous research has shown that UV exposure can be utilized to extract carbon from a soil component called dissolved organic carbon (DOC) through a photo-chemical reaction [5]. Using the process of photo-oxidation, previous research demonstrated the feasibility of quantifying a subset of soil carbons in correlation to the total SOC amounts [6]. However, these previous oxidation methods involved sampling and transferring of soils to a laboratory, producing a time-delayed analysis and is impractical-for-large-area analysis, as well as the usage of a high-powered and bulky UV lasers [5]. Unlike the bulky UV lasers, a micro-UV LED can provide a compact form factor and thus enable multiple depth analysis.

This paper reports the development and the initial testing of the first, within our knowledge, near-real-time, on-spot, and in-soil carbon measurement system. Specifically, this paper reports the operation principle, device prototyping, test methods, and the field testing results of the in-soil SOC predictions based on the developed UV based soil carbon prediction system.

OPERATION PRINCIPLE

The key operation principles are centered around (1) the production of CO_2 through the UV extraction of photo-oxidative carbons from the soil and (2) the in-situ measurement of the produced CO_2 by commercial or MEMS sensors. First, the shank of the sensor system is implanted into the ground. Once implanted, the UV LED is turned on, inducing a photo-oxidative reaction and CO_2 sampling. By exposing UV light to the soil, singlet oxygens are created, acting as catalysts for the full photo-oxidation reaction. Through the process of dismutation and a Fenton reaction, the energy from the singlet oxygen helps release hydroxyl radicals. These radicals then react with the aromatic carbons that are part of the dissolvable organic matter (DOM) component of soil resulting in the complete photo-oxidation reaction that converts the aromatic carbons into CO_2 [7]. The CO_2 extracted from the soil then diffuses across the through holes on the shank, which is then quantified by an integrated non-dispersive infrared (NDIR) sensor, which will be later replaced with a MEMS micro-bolometer. Once the UV LED is turned off, the CO_2 level in the shank then reduces back to the leveled state that represents the microbial-respirated CO_2 output. The measured sensor values are subsequently transmitted to a cellular gateway where the data is transferred to a database and utilized in estimating the total soil organic carbon quantity. As

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compared to the "gold standard" dry combustion technique, described in Fig. 1, the manufactured UV-based photo-oxidation system allows for in-situ SOC measurement, resulting in accurate, rapid, and low-power measurements. These measurements are free of biases caused by time-delayed, soil transportation which may cause a reduction in nutrients or beneficial microbes in soil samples [8]. This method also reduces the average test time from 1-5 days down to 2.5 hours by removing the tedious and power consuming process of sampling and burning soil.

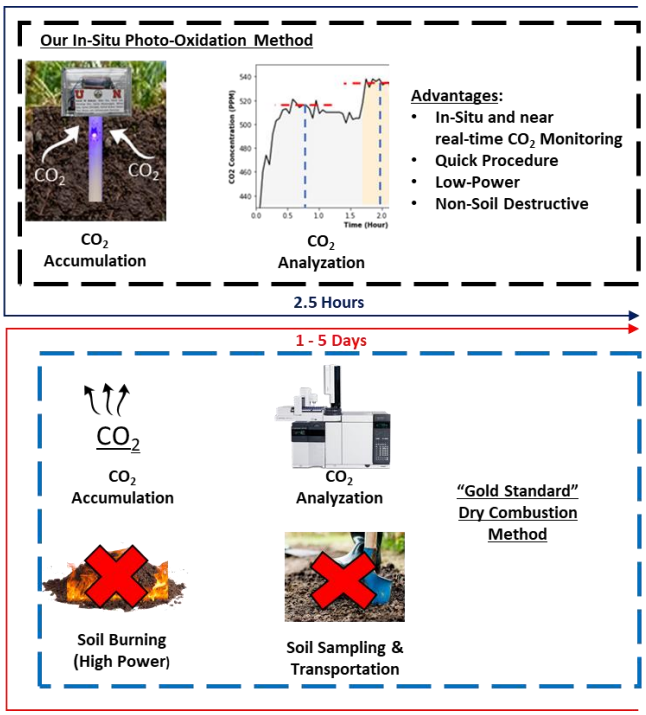


Fig 1. In-situ photo-oxidation based methods allows for near real time-monitoring, lower power, and is non-soil destructive in comparison to the current "Gold Standard" dry combustion methods.

Device Prototyping

System Components and integration

Figure 2 summarizes the components makeup of the prototype, which consists of an optical CO_2 sensor, 415 nm UV LED, a micro-controller programed with a sleep mode algorithm, a LoRa based wireless communication electronics, and a 25 cm support shank structure. The entire sensing system was powered by a 3.7 V, 18650 battery which sits atop a 3D printed base encased in a 4.0 x 8.0 x 7.8 cm^3 acrylic rectangular prism to shield the circuitry from environmental hazards (e.g., wind, rain) during in-situ testing in soil. The prototyped system averaged a power consumption of 167.71 mW, in addition to a UV with a 30-min on period during a single sampling period (Power consumed by UV LED: 420.47 mW). With each component of the device supported by a 3.7 V battery, the estimated energy consumption per sampling period (150 min) for the sensor system was 617.9 mJ/sec, resulting in a prototype lifetime of ~44 days.

The optical CO_2 sensor (Sensair S8) utilized in the current prototype was an off-the-shelf nondispersive infrared (NDIR) sensor that identified the CO_2 levels through ratioing the input and output intensities of the infrared at 4.26 µm. Note that the selected 4.26 µm was the wavelength that CO_2 molecules strongly absorbed. This optical sensor held a volume of 8.5×32.7×19.7 mm^3 and was integrated within a circuitry that allowed for a time-controlled sleep mode. This sleep mode operation was controlled by a clock-based algorithm that cyclically powered an Arduino pro-mini microcontroller on and off, which would subsequently power on and off all other electrical components within the sensing system to reduce the overall power consumption. Future prototypes will utilize a fabricated micro-bolometer array that is capable of precisely quantifying the captured CO_2 within the device at low concentration through the absorption of reflected infrared off of gas molecules.

The prototypical system utilized a high-density UV LED from LuminLED that irradiated a UV intensity of 35 W/cm^2 from a tiny footprint of 1.3×1.3 mm^2 at a wavelength of 415 nm. Each LED was embedded along the side of the shank at the soil depth of interest for UV emissions to act as a catalyst for the photo-oxidation process in yielding CO_2. Current prototype measured the CO_2 at a depth of 15 cm within the soil. The UV LED, powered by an additional 3.7-V 18650 battery, was surrounded by 11 through-holes with a 0.25-mm radius. These through holes permitted the diffusion of the extracted carbon molecules from the soil into the shank as a result of the relative pressure difference between the inner and outer shank interface.

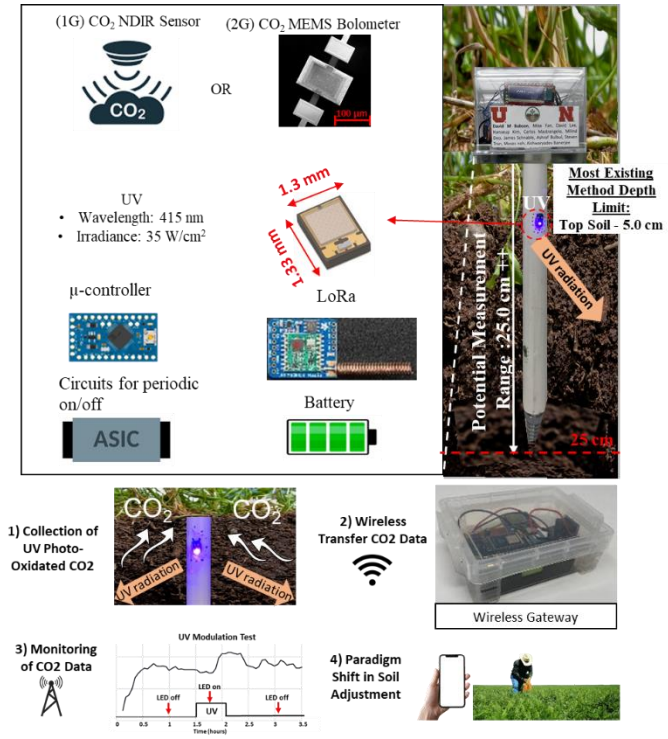


Fig 2. UV based soil carbon measuring system prototype full body image, circuit components, and overarching working principle.

Diffusion Hole Design

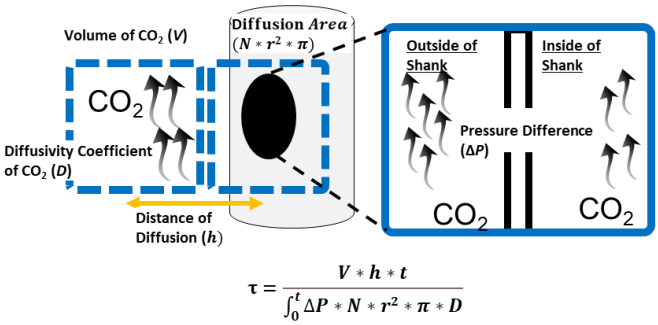
Through empirical testing, it was observed that the design of diffusion through holes could be adjusted or minimized the response time for the detection of microbial respirated and photo-oxidated CO_2. The response time, required to detect a saturated CO_2 concentration within the shank, was modeled by an analogy to that of a simple RC circuit electrical system. First, the speed at which CO_2 diffused into the shank was estimated by calculating a time constant (τ) that could be described by the quotient of the total volume (V) of present CO_2 by the CO_2 flow rate (Q) (Eq. 1). Here Q was obtained by Fick's law of diffusion of gas as a function of a pressure gradient at a discrete time, which was described in Eq. (2).

In Eq. (2), ΔP was the pressure difference at the through hole shank interface at a particular time, N was the number of holes, r was the radii of the holes, D was the diffusivity constant of CO_2, and h was the distance of diffusion, all of which is visually depicted in Fig. 3. The combination of Eq. 1 and Eq. 2 produced the time constant (Eq. 3) that indicated the charging and discharging rate of the prototype. The charging and discharging periods formula were then used to minimize the UV-exposure periods by optimizing the CO_2 production and power consumption. Based on empirically determined results, 11 through holes with a radius of 0.25 mm was selected to keep the time constant beneath 30 min as well as complying to any dimensional constraints. The 30 min period was selected such that the detection of the steady-state photo-oxidative and microbial-respirated CO_2 levels would be achieved within 60 min over various soils, while limiting power consumption below 200 mW.

$$\tau = \frac{V}{Q} \quad (1)$$

$$Q = \frac{\frac{\int_0^t \Delta P}{t} * N * r^2 * \pi * D}{h} \quad (2)$$

$$\tau = \frac{V * h * t}{\int_0^t \Delta P * N * r^2 * \pi * D} \quad (3)$$



$$\tau = \frac{V * h * t}{\int_0^t \Delta P * N * r^2 * \pi * D}$$

Fig 3. Visualization of the CO_2 permeation model due to a pressure interface of the diffusion through holes of the CO_2 prediction system.

TEST METHODOLOGY

Photo-Oxidation Based Real Time In-Soil CO_2 Measurements

To quantify the amounts of the produced photo-oxidative CO_2, the system utilized a time dependent modulation of the UV-LED located 15-cm below the soil. This UV-LED was activated and deactivated for 30- and 60-minutes intervals, respectively, while monitoring the formulation of photo-oxidated CO_2 captured within the shank structure utilizing a calibrated optical NDIR sensor over both on/off periods. Note that the measured CO_2 amounts, during the on period, was the combined summation of photo-oxidative, microbial respirated, and atmospheric CO_2. Thus, from the measured CO_2 quantity, the off-period baseline, which included microbial respirated and atmospheric CO_2, was subtracted to calculate only the quantity of photo-oxidative CO_2. Since the atmospheric CO_2 amounts could be measured above ground, all three CO_2 amounts could be computed. During the UV modulation periods, the sensor system was periodically turned on for 10 seconds to collect the baseline CO_2 data and off for 3 min before repeating the next sampling cycle to reduce the overall power consumption of the system. During the 30 min UV-on period, a UV LED consuming an average power of 420.47 mW, was used to produce photo-oxidative CO_2, while the CO_2 sensor system continuously measured in an identical manner as during the UV-off period. The described photo-oxidated, real-time CO_2 measurements were then performed at 4 locations in the US (Salt Lake City, Utah; Boise, Idaho; Savoy, Illinois; Lincoln, Nebraska) in order to verify the effectiveness of the in-situ, photo-oxidative method in obtaining accurate SOC values over various soil types. All field testing was performed between June and August in 2021. Tests were done during a timeframe when both the temperature and humidity were both relatively consistent throughout the duration of each test without on-going precipitation to limit any biases.

SOC Estimation

To enable prediction of the total SOC amounts in soil, an initial version of a CO_2-to-SOC conversion algorithm was developed. The initial version of the algorithm was produced by utilizing a least square linear regression model that minimizes the error between the collected data set at a depth of 15 cm and was compared to the SOC data from the USDA soil survey data set at the corresponding depth. Note that the USDA data set was collected and updated by the National Cooperative Soil Survey over the past century, providing a gold standard for comparison.

RESULTS

Real Time In-Soil CO_2 Measurements

Initial real-time, in-soil measurements in Salt Lake City (Fig.4) showed (1) that UV LED instantly produced photo-oxidative CO_2 levels up to 22 ppm, which were sufficiently detectable by an optical sensor within 30 min of testing at a soil depth of 15 cm; and (2) that it was feasible to distinguish photo-oxidative CO_2 levels from microbial-respirated levels in near real-time within the soils. Figure 4 shows the measured CO_2 levels over a 3.5-hour period starting with the implantation of the prototype into the soil at the 0-hour point. In the first 0.5-hour period, the measured CO_2 levels saturated at 516 ppm, settling to the baseline of CO_2 levels in the soil. The baseline CO_2 levels were composed of the microbial-respirated and atmospheric CO_2 levels. Once saturated at 0.5-hour point, the measured CO_2 levels of 516 ppm remained stable. This saturated concentration was higher by 83 ppm than the initial atmospheric CO_2 level of 433 ppm with the difference indicating the microbial-respirated CO_2 level. When the UV LED was activated, the CO_2 level subsequently increased by 22 ppm within a 14.4 minute time frame and was saturated at roughly 538 ppm with 30 minutes of UV exposure, confirming the feasibility of utilizing micro-LEDs to produce UV-oxidated CO_2 for near real-time and on-spot measurement. Upon saturation of the CO_2 concentration, the LEDs were deactivated. Within an 18.6 minutes time frame, the CO_2 level remained saturated before decreasing back to the baseline, in which another 47.7 minutes was needed before the baseline data was stabilized.

Four different field testing sites were used to verify the potential usage of the UV-based, soil carbon prediction system. These results showed (1) that the photo-oxidation based CO_2 generation and measurement were applicable to different soil types and (2) that there was a clear correlation of the CO_2 amount to the types of soils, as shown in Fig. 5. Soils tested at the Salt Lake City and Boise locations were grouped as non-agricultural soils with natural vegetation, while those in Lincoln and Savoy were grouped as agricultural farmland soils that were actively utilized to produce crops. When normalized to an atmospheric CO_2 level of 433 ppm, each collected data set from Salt Lake City, Boise, Savoy, and Lincoln showed different microbial-respirated CO_2 levels of 79 ppm, 47 ppm, 289 ppm and 199 ppm respectively. Once the

microbial-UV LED was activated, the CO_2 level increased producing a photo-oxidation of 26 ppm, 46 ppm, 128 ppm and 101 ppm for each test site.

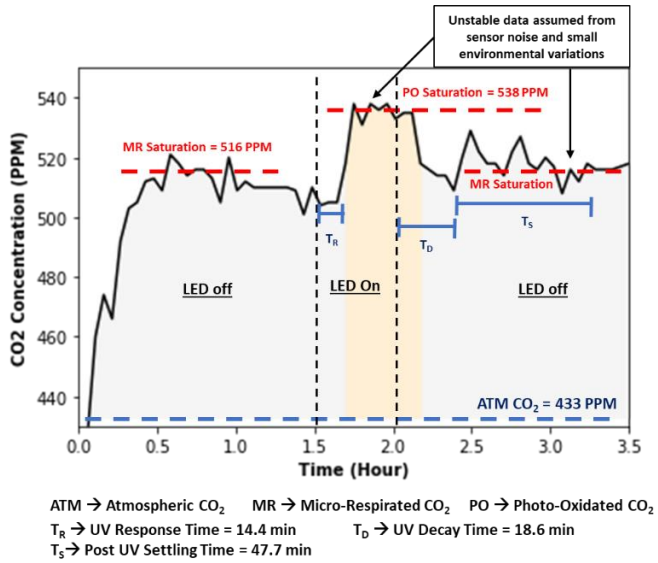


Fig 4. Measurement of CO_2 concentration by the developed prototype at a soil depth of 15 cm over time with the modulation of UV exposure. It was a 3.5 hr. test sampled in Salt Lake City, Utah for CO_2 collection. The measurement clearly showed three major CO_2 components (atmospheric, microbial-respirated, and photo-oxidated).

SOC Estimation

Based on the four site measurement data, a linear line of best fit algorithm was produced and utilized to produce an initial prediction of the total SOC values that showed high correlation to the USDA National Survey data. The established linear algorithm is shown in Eq. 4, where x was the measured photo-oxidation CO_2 level by the prototype.

$$(\text{Eq. 4})\ SOC\% = 0.008 * X + 0.8584$$

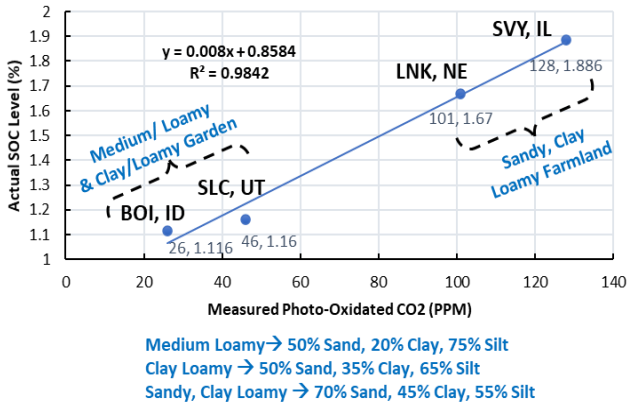


Fig 5. Captured Photo-Oxidated CO_2 in relation to the actual SOC values as reported by the soil survey database done by the USDA. A high correlation between the CO_2 and SOC is observed.

The linear SOC predictor equation (Eq. 4) predicted SOC% for the four different sites of Salt Lake City, Boise, Savoy, and Lincoln sites, which were plotted in Fig.5. Each site produced a prediction error 4.44%, 5.72%, 0.19%, and 0.22% respectively, resulting in an average percent error of 2.64% when matched with the USDA SOC soil survey data. The data also showed that there was a clear correlation between the soil types, the produced CO_2, and the actual SOC% amounts with a coefficient of determination of 0.984 (Fig. 5). This result indicated a potentially successful system that could accurately determine soil SOC% within various soils, implying a new paradigm in underground SOC measurement.

CONCLUSION

A UV-based, soil carbon prediction system was successfully developed to predict the soil organic carbon levels in-situ with the soil with an average error of 2.64%, improving upon the disadvantages seen in traditional techniques by being accurate, quick, and in-situ. Additionally, the prototype showed that a UV-based system was capable of consistent, near instantaneous CO_2 production with a time constant of 18.36 min, allowing the transient photo-oxidated and microbial-respirated CO_2 to be determined within 30 minutes. These results offer a preliminary demonstration for the possible usage of an in-situ, low power, wireless soil organic carbon prediction system that can predict the SOC% with relative accuracy within various types of soil.

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