A Novel *In-situ* Method for Measuring Soil Organic Carbon Using Photoacoustic Sensor

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***Abstract*—Organic and inorganic elements of soil exhibit a wide range of physical and chemical characteristics. Exact soil composition estimates are required for many ecological and soil science studies and global climate change research. The most typical method for estimating soil variables involves collecting and analyzing data in a laboratory, which is time-consuming and expensive. This paper proposes a rapid, *in-situ* approach for assessing soil organic carbon utilizing the soil combustion method. In the suggested approach, a metal tube with a heating probe heats the soil to approximately 400°C. The heat oxidizes a known-volume soil sample, creating CO_2 . To estimate soil organic carbon, a CO_2 sensor measures the accumulated CO_2 concentration at the tube's top. A laboratory experiment was undertaken to demonstrate the proposed method's potential.**

***Index Terms*—soil organic carbon, CO_2 , *in-situ* sensing, loss-on-ignition**

I. Introduction

The amount of soil organic carbon (SOC) significantly impacts the quality of the soil and the rate of plant growth. It also plays a regulatory role in a variety of physical, chemical, and biological processes that occur in the soil environment. As a crucial indication of soil quality, it is linked to vital ecosystem services like nutrient cycling and storage, pollutant absorption and retention, and carbon dioxide sequestration. Carbon can be found in two different forms: inorganic and organic (IC and OC, respectively). In soil, IC is represented by carbon dioxide, carbonic acid, and its dissociation products. There is also calcite in the form of particles. The total amount of organic carbon in the world's soils is roughly 2344 gigaton, making them the giant terrestrial organic carbon pool [1]. Even minute shifts in the amount of organic carbon in the soil can significantly affect the amount of carbon in the atmosphere. The fluxes of SOC change in response to a wide variety of potential natural and anthropogenic driving factors. As a result, it is necessary to develop a system that can estimate the amount of SOCs quickly and affordably to improve environmental monitoring, modeling, and precision agriculture.

Most of the time, the SOC content is measured in the laboratories. Combustion methods [2]–[5], chemical analysis [1], [6], and spectroscopic [7]–[9] methods are all common methodologies that can be used to estimate the amount of carbon in soil. However, standard laboratory studies to determine the content of SOC require a significant amount of time, are very expensive, and are unable to effectively depict the geographical and temporal fluctuations of SOC contents across large areas. Although, in [10], *in-situ* measurement of total soil carbon has been tested, this method suffers from tedious experimental setup and accuracy is susceptible to soil moisture and availability of the local spectrum data. As a result of this, we have been motivated to design an *in-situ* system that will be capable of making a prediction in real time regarding the amount of OC that is contained within the soil.

II. Portable soil heating-probe sensor

In our proposed method we make use of the soil combustion method. SOC decomposes at 400 degrees Celsius, while the decomposition of inorganic carbon takes place between 500 and 600 degrees Celsius [3]. The loss-on-ignition(LOI) method is one common approach to measure SOC by combustion. In this technique, soil samples are burned at high temperatures, and the SOC content is calculated based on the weight loss [5], [6]. Soil is first air-dried in the laboratory to remove moisture and then heated at high temperatures in a metal container. The loss in mass after the heat is the indicator of soil organic matter. Then an elemental analyzer is used to measure OC. Elemental analyzers are expensive large pieces of equipment, and unsuitable for *in-situ* analysis. In addition, precise measurement is necessary for determining weight reduction. Therefore, we propose a direct measurement for CO_2 produced using a photoacoustic sensor to estimate SOC.

A. Hardware Design: The hardware configuration is shown in full detail in Fig. 1(a). Inner and outer steel rods provide the primary structural elements of this device. Inside the tube, the inner rod can move vertically. It aids in the setup's ability to dig down to a specific depth and collect a predetermined volume of soil for burrowing. A heating probe is fitted to the outer tube's bottom to heat up the soil. Portable power supply is used to power the thermal probe. Changing power supply voltage and current regulates the probe's temperature. A small gap between the inner rod and outer tube provides oxygen for soil burning. When the heated probe burns soil, produced CO_2 moves up the tube through the gap.

A sensor node is attached to the top of the outer tube. The sensor node has two CO_2 sensors in the inner and outer

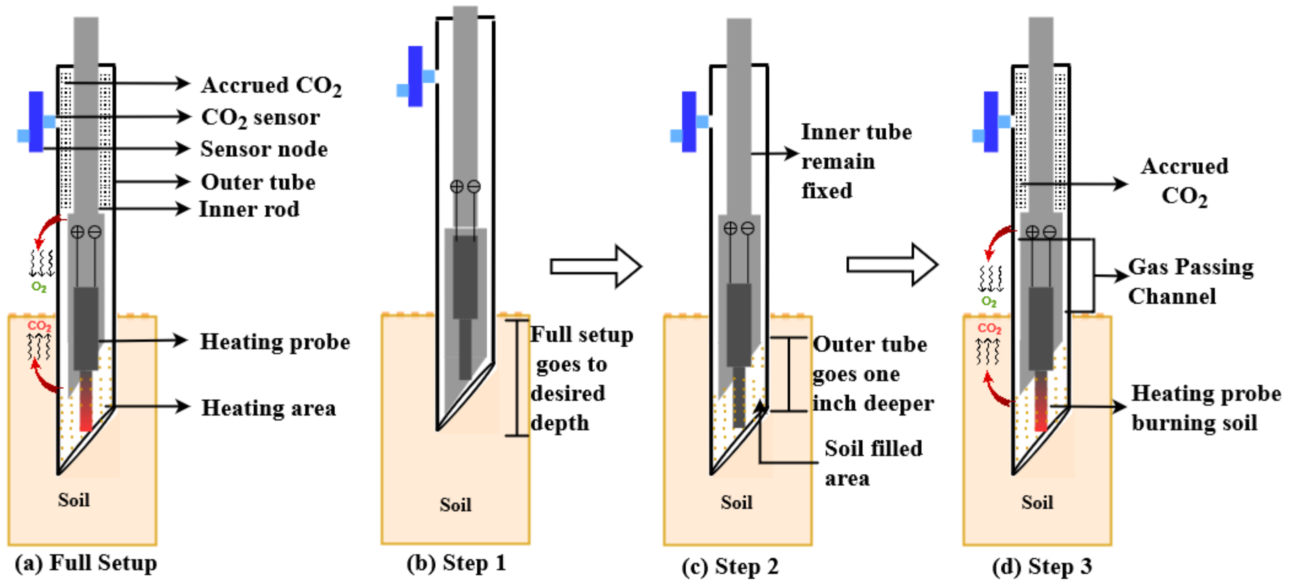

Fig. 1: (a) Full setup, (b) Setup pushed to target depth, (c) The outer tube is pushed to make room for soil, (d) Probe heating the soil releases CO_2 as measured by the sensor.

directions of the tube. The outer sensor measures the air CO_2 content, and the inner sensor should provide a similar measurement prior to combustion. The concentration change inside the tube is determined based on the differential measurement of the inner and outer sensor after combustion. Additionally, the two-sensor configuration aids in identifying any sensor output anomalies. The tube will be pushed into the soil using a portable hydraulic press. The entire apparatus may be mounted to a all-terrain vehicle (ATV) to gather samples from multiple places and conduct *in-situ* analysis.

B. Soil Sampling Process: The soil sampling method is depicted in the Fig.1(b)-(d). An ATV transports the setup to several sampling locations. Hydraulic presses are used to lower the entire assembly to the required depth. The tube has no soil in it at this point. A second pressing of the tube causes the outer tube to go an additional one or two inches deeper while the inner rod remains where it is. The soil then fills the gap between the inner rod and the outer tube. The volume and weight of the soil is calculated from the diameter of the tube and the height of the gap between inner rod and outer tube.

When applying heat the soil will gradually burn and generate CO_2 which will go up through the tube and be accumulated at the top. The CO_2 sensor mounted on the top then measures the concentration. The sensor reading keep increasing as more and more CO_2 is comes out of the soil. After some time the sensor reading will saturate as when all the soil is completely burned. At this point we can easily estimate the total CO_2 from the initial and final concentrations reading.

III. Laboratory Analysis

A. Laboratory Experimental Setup: For the lab experiment, we took a steel tube of 10 inches in length and one inch in diameter. We collected four buckets of sandy soil samples from New Hampshire, US. The tube fills up from the bottom when it goes into the soil. Consequently, the amount of soil is measured from the tube's depth. To burn the soil, we used a heating probe that could go up to 1000°C. We used a glow plug heating probe for this (Fig. 2(b)). The heating probe was wired up to a programmable DC power supply. The voltage was set to 9 volts, and the current was set to 5 amps. The probe's tip reached a temperature of approximately 400°C at this setting, which was sufficient to decompose the OC in the soil.

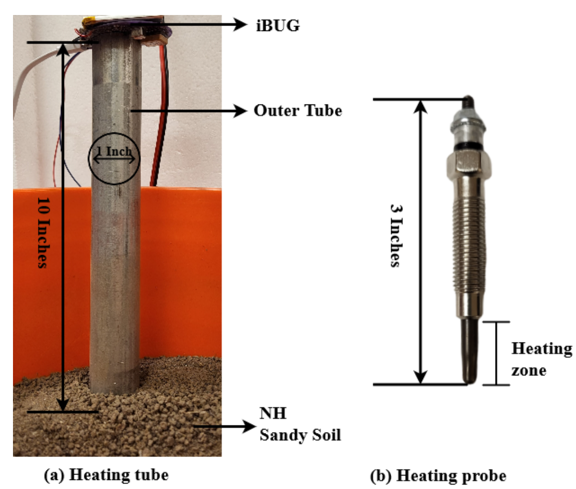

Fig. 2: (a) Heating tube used in lab experiment, (b) Heating probe inside the heating tube.

B. Data Collection: For data collection, we use a sensor node named iBUG developed by the remote sensing lab of the University of New Hampshire [11]. iBUG is a low-cost, TinyML and IoT-enabled sensing platform. It has a preinstalled SCD4x photoacoustic sensor that measures true CO_2 [12]. iBUG can process sensor data in real-time or transfer it to cloud using LoRa. The iBUG was placed at the top of the tube. It was then connected to a computer via a micro USB cable to log the sensor readings. First, the sensor reading was taken at room temperature for a few minutes to measure the initial CO_2 Concentration. After some time, the heating probe was turned on, and the data collection process continued. The amount of soil that we considered for the experiment did not require more than five minutes to burn out. So, the heating probe was turned off after five minutes. Python was used to analyze the CO_2 concentration change trend once the data was collected. We discarded some data points at the beginning and the end as those was insignificant.

C. SOC Estimation: Concentrations of chemicals in soil are typically measured in units of the mass of chemical (grams(g), milligrams(mg), or micrograms(ug)) per mass of soil (kilogram, kg). Concentrations can be expressed as parts per million (ppm) using a conversion factor. Each chemical's conversion factor is based on its molecular weight. The CO_2 sensor used provides measurements in(ppm). It is converted to milligrams using equation 1.

$$C(mg/m^3) = 0.0409 \times C(ppm) \times M \tag{1}$$

Where, C is concentration in ppm; M is the molecular weight of CO_2 (44.01 g/mol)

The amount of SOC per unit area in a given depth of soil can be calculated using following equation:

$$SOC = \%C \times \rho \times d \tag{2}$$

Where, SOC is soil organic carbon (g/m^2); $\%C$ is carbon concentration; ρ is soil bulk density; d is depth of soil sample [13]. Here, bulk density is the dry weight of a known amount of soil.

IV. Results and Discussion

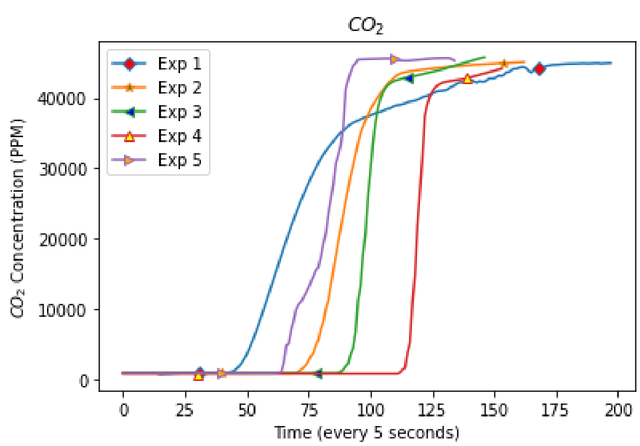

Fig. 3: CO_2 Concentration change from burning soil samples in five difference experiments. Markers show pre-heating and post-heating saturation points.

Five lab experiments were run on the same amount of soil (around 5g) to verify for consistency. Fig. 3 shows CO_2 concentration change in the five experiments. Before heating, the CO_2 concentration line is flat and indicate the normal CO_2 concentration. After the heating is turned on, the CO_2 concentration line starts to ascend rapidly, and this trend continued. After a certain amount of time has passed, the line begins to flatten once more. At this point, the concentration of CO_2 reaches its maximum level. When all CO_2 from soil sample comes out the sensor reading saturates. CO_2 concentration change is recorded from the final and initial saturation points converted to a common unit (g/Kg) to compare with soil weight loss (table I). The fourth column in table I shows the accrued CO_2 concentration converted using equation 1. Then, the OC percentage was calculated from the fourth column to calculate the SOC using equation 2. The soil weight loss was calculated by weighing the soil before and after heating. The weight loss occurred due to the evaporation of the OC from the soil. OC percentage was calculated from this weight loss, and then equation 1 was used to estimate SOC from LOI. SOC estimates from weight loss corresponds to the results of heating-probe sensor. In addition to SOC, water particles and some other soil constituent come through soil combustion. These components also contribute to soil weight loss. As a result, there is a corresponding difference between LOI and CO_2 sensor estimates. However, this is offset by adding a value of 10 in the final result.

TABLE I: Validation of the proposed sensor for measuring SOC

	Soil Weight Loss(g)	Soil Weight Loss(g/kg)	Accrued CO_2 (g/kg)	SOC from LOI (g/m^2)	SOC from Sensor (g/m^2)
Exp 1	0.31	54.87	43.06	49.38	48.75
Exp 2	0.25	55.31	44.15	49.78	49.74
Exp 3	0.27	53.78	41.93	48.41	47.74
Exp 4	0.34	58.72	44.84	52.85	50.36
Exp 5	0.32	59.93	44.5	53.93	50.05

Lab experiments show promising results that can be applied in the field. Next step would be to 3D print the proposed setup and undertake on-field trials. Comparing field results to existing methodology is also important. Additionally, it will be fascinating to see if iBUG's machine learning capacity can be used for real-time SOC prediction. During data collection, we plan to record temperature, humidity, and gas resistance to see if a tiny machine learning model can be developed to predict CO_2 concentration.

V. Conclusion

A novel *in-situ* soil heating-probe sensing method for determining the amount of organic carbon in the soil has been suggested. Experiments conducted in the lab also demonstrated that there is potential for the proposed approach to be applied successfully in the real world. The next stage would be to test the concept in the field and compare the results to the established methods. The most significant obstacles to overcome are the soil's inherent characteristics, such as its high moisture content, gravel content, and wide range of variability.

Acknowledgment

This work was supported by NSF SitS Award # 1920965 and the University of New Hampshire.

References

[1] J. H. Sato, C. C. de Figueiredo, R. L. Marchão, B. E. Madari, L. E. C. Benedito, J. G. Busato, and D. M. de Souza, "Methods of soil organic carbon determination in Brazilian savannah soils," *Scientia Agricola*, vol. 71, no. 4, pp. 302–308, Aug. 2014.

[2] X. Yu, W. Zhou, Y. Wang, P. Cheng, Y. Hou, H. Du, X. Xiong, L. Yang, Y. Wang, and Y. Fu, "Sequential combustion separation of soil organic carbon fractions for AMS measurement of 14C and their application in fixation of carbon," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 323, no. 1, pp. 169–177, Jan. 2020.

[3] M. Hoogsteen, E. Lantinga, E. Bakker, and P. Tittonell, "An Evaluation of the Loss-on-Ignition Method for Determining the Soil Organic Matter Content of Calcareous Soils," *Communications in Soil Science and Plant Analysis*, vol. 49, no. 13, pp. 1541–1552, Jul. 2018.

[4] T. K. Boguski, "Understanding Units of Measurement," *Environmental Science and Technology Briefs for Citizens*, p. 2, 2006.

[5] S. R. Abella and B. W. Zimmer, "Estimating Organic Carbon from Loss-On-Ignition in Northern Arizona Forest Soils," *Soil Science Society of America Journal*, vol. 71, no. 2, pp. 545–550, Mar. 2007.

[6] W. R. Roper, W. P. Robarge, D. L. Osmond, and J. L. Heitman, "Comparing Four Methods of Measuring Soil Organic Matter in North Carolina Soils," *Soil Science Society of America Journal*, vol. 83, no. 2, pp. 466–474, 2019.

[7] T. Angelopoulou, A. Balafoutis, G. Zalidis, and D. Bochtis, "From Laboratory to Proximal Sensing Spectroscopy for Soil Organic Carbon Estimation—A Review," *Sustainability*, vol. 12, no. 2, p. 443, Jan. 2020.

[8] M. Ladoni, H. A. Bahrami, S. K. Alavipanah, and A. A. Norouzi, "Estimating soil organic carbon from soil reflectance: A review," *Precision Agriculture*, vol. 11, no. 1, pp. 82–99, Feb. 2010.

[9] X. Peng, T. Shi, A. Song, Y. Chen, and W. Gao, "Estimating Soil Organic Carbon Using VIS/NIR Spectroscopy with SVMR and SPA Methods," *Remote Sensing*, vol. 6, no. 4, pp. 2699–2717, Apr. 2014.

[10] N. K. Wijewardane, S. Hetrick, J. Ackerson, C. L. Morgan, and Y. Ge, "Visnir integrated multi-sensing penetrometer for in situ high-resolution vertical soil sensing," *Soil and Tillage Research*, vol. 199, p. 104604, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167198719305136

[11] M. F. Yousuf, T. Siddique, and M. S. Mahmud, "iBUG: AI Enabled IoT Sensing Platform for Real-time Environmental Monitoring," in *2022 IEEE 31st Microelectronics Design & Test Symposium (MDTS)*, May 2022, pp. 1–7.

[12] (2021) Sensirion co2 sensors scd4x datasheet. [Online]. Available: https://www.mouser.com/datasheet/2/682/

[13] R. Zeng, Y. Wei, J. Huang, X. Chen, and C. Cai, "Soil organic carbon stock and fractional distribution across central-south China," *International Soil and Water Conservation Research*, vol. 9, no. 4, pp. 620–630, Dec. 2021.