Sensor-Based Platform for Evaluation of Atmospheric Carbon Sequestration's Potential by Maize Crops

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***Abstract*—The development of sensor-based techniques has been allowing advanced studies for agriculture's decision support systems. This paper discusses an innovative sensor-based method for the evaluation of CO_2 sequestration potential from the atmosphere by agricultural crop environments. This study has led to new insights into the management of crop fields for food and biomass production for energy. It also brings together information related to the carbon sequestration potential, which can allow opportunities not only for the use of sensors and related techniques in soil science but also for value aggregation for the agricultural process and environmental care. For validation, an experimental maize crop area has been used. Besides, studies about atmospheric carbon sequestration potential were evaluated. Such analyses have become possible by using vegetation indexes related to the normalized difference vegetation and the modified chlorophyll absorption in reflective, both calculated with data acquired using a multispectral sensor. In addition, three other sensors have been used for solar light intensity, soil water content, and air temperature measurements. Results have shown the spatial variability of the carbon sequestration potential, as well as its temporal variability when considering different phenomenological phases of the maize culture. Furthermore, a positive correlation with plant management and the carbon sequestration potential has been found, i.e., leading to an adequate new sensor-based descriptor for atmospheric carbon sequestration by plants evaluation.**

Keywords-light-band sensors, carbon sequestration, agricultural sensor, intelligent instrumentation.

I. Introduction

Atmospheric carbon sequestration is the process of capturing and storing carbon dioxide (CO2) from the air. It is a way to reduce the amount of CO_2 in the atmosphere and slow climate change occurrences. CO_2 sequestration by living organisms can be stored in plants, animals, soil, oceans, and other bodies of water, like lakes, rivers, and watersheds. In fact, this can be done based on reforestation, agricultural crops, and wetland restoration, i.e., considering sustainable management and good environmental practices [1]. In addition, it is important to observe that still there are other methods related to the use of technologies that extract CO_2 directly from the atmosphere.

Beyond considering the use of agricultural crops for food, fiber, and biomass energy production, atmospheric carbon sequestration can also be considered. To get a better understanding of this process, one may think of the concepts related to photosynthesis [2]. Photosynthesis is a photochemical reaction. It uses light energy to convert carbon dioxide and water into oxygen and glucose. Photosynthesis is also observed in other organisms besides green plants. These include several prokaryotes, such as cyanobacteria, purple bacteria, and green sulfur bacteria. These organisms exhibit a photosynthesis system just like green plants. The glucose produced during photosynthesis is then used as a carbon source and fuel for various cellular activities and growth. The by-product of this physiochemical process is oxygen [3].

The leaves of plants contain microscopic cellular organelles known as chloroplasts. Each chloroplast contains a green-colored pigment called chlorophyll. In fact, chlorophyll molecules absorb light energy, whereas carbon dioxide enters the leaves through the tiny pores of stomata located in the epidermis [4].

The glucose produced in photosynthesis is then sent to the roots, stems, leaves, fruits, flowers, and seeds. In other words, the plants use this sugar as an energy and carbon source, which helps them to grow. Glucose molecules, water, and other nutrients are used in several biochemical processes, producing a larger number of small organic compounds as well as more complex carbohydrates like cellulose and starch.

The following factors can affect the photosynthesis process, which means light intensity, concentration of CO_2, temperature, water availability, and air pollution, since pollutants and other particulates may settle on the leaf surface, blocking the pores of stomata [5].

Increasing either the light intensity or the CO_2 concentration in the air results in raising the photosynthesis rate. On the other hand, low light intensity or low CO_2 concentration results in a lower photosynthesis rate, respectively. For efficient photosynthesis processes, it is important to have a temperature range between 25°C and 35°C.

Likewise, since water is an important factor in photosynthesis, its deficiency can lead to problems in the intake of CO2. This occurs due to the fact that low water availability from soil leads to the refusal of stomatal opening to retain the amount of water they have stored inside.

However, despite these factors being critical, the chlorophyll content in the leaves must be evaluated to estimate the potential of crops for carbon sequestration from the atmosphere.

Chlorophyll is a green pigment found in the chloroplasts of the plant cell and in the mesosomes of cyanobacteria. In fact, they are used by plants and bacteria to absorb energy from sunlight. Most land plants have two forms of chlorophyll, designated as A and B. In such a context, differences permit the absorption of different wavelengths of light. Figure 1 shows a typical chlorophyll chemical structure found in plants [6].

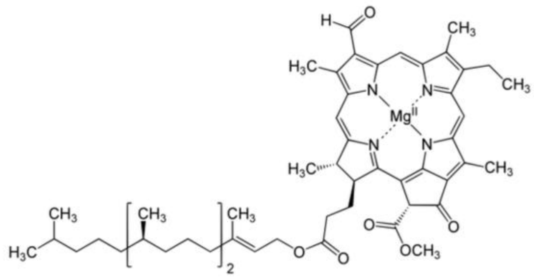

Figure 1. The typical structure of Chlorophyll A in plants [6].

The adequate estimation of leaf chlorophyll content is also important in monitoring the growth status of plants in agriculture, such as, for instance, in maize production based on precision farming management. Therefore, for the evaluation of chlorophyll content in plants, one may use different vegetation indexes, which can be obtained based on the use of multispectral data collected with adequate sensors.

This paper presents a sensor-based method for atmospheric CO_2 sequestration potential evaluation in agricultural crop management.

After this introduction in Section I, this paper is structured as follows. Section II presents the materials and methods, including not only the used materials and the agricultural experiments' descriptions for the method's validation but also the adopted sensor-based architecture and the computational model for the CO_2 sequestration potential index evaluation by crops. Section III presents the results and discussions based on the evaluation of atmospheric carbon potential sequestration into a productive rainfed maize crop and its relationship with the agricultural management practices. The final conclusions are presented in Section IV.

II. MATERIAL AND METHODS

Figure 2 shows the block diagram for the sensor-based architecture used for atmospheric carbon sequestration potential evaluation from crops. In the block diagram, one may observe the use of the Normalized Difference Vegetation Index (NDVI) and the Modified Chlorophyll Absorption in Reflective Index (MCARI), both calculated based on data acquired with a multispectral camera, as well as taking into account three other sensors for solar light intensity, soil water content, and air temperature measurements.

The NDVI was proposed in 1974 [7] and was validated five years later [8]. In fact, in 1979, the linear combinations of the bands of the Red wavelength (called RED) (668 nm ± 10 nm) and the Near Infra-Red wavelength (called NIR) (840 nm ± 40 nm) light bands became a monitor of biomass density. NDVI values from -1.0 to 1.0 can be found in literature. However, since soil has an NDVI value close to zero and for plant evaluation the values can be in the range from 0.1 to 1.0, the interval of [0.0-1.0] has come to be used in agricultural applications. The higher the value, the greater the plant density. Despite some limitations, it has a good linear correlation with crop growth [9]. Equation (1) shows the NDVI calculation formula, i.e., to allow in this work information regarding the biomass amount evaluation in the regions related to plant growth only.

On the other hand, the MCARI was published in the year 2000 [10], and it is recognized as an evolution of the Chlorophyll Absorption Ratio Index (CARI), whose development occurred in 1994 [11]. The CARI has been primarily used to estimate not only chlorophyll content in leaves but also frost content damage and the monitoring of the yield and physiological response of crops. Such a vegetation index improvement brought not only a better index focus but also a much stronger relationship with plant leaves' chlorophyll content. For the MCARI calculation, (2) is used considering the RED, Green wavelength (called GREEN) (560 nm ± 20 nm), and NIR light bands, i.e., in this work to estimate the amount of chlorophyll crop's leaves.

For solar light intensity measurements, a luxmeter based on a silicon photodiode with a spectral filter has been used, which can allow measurements up to 4 × 105 Lux and an accuracy of ±5%.

For soil moisture measurements, a capacitive sensor has been used, which can allow measures from 0.0 to 75.0 cm^3/cm^3 and accuracy of ±4%. Characteristics in relation to less invasive measurements have been considered in relation to such a selection. Soil moisture analyses have been carried out from horizon A (root zone) at specific sites on the sampling grid.

For air temperature measurements, the use of a platinum resistance sensor (PT100) calibrated for operation in the range of 0.0 to 80.0°C has been considered, which achieves an accuracy of up to ±0.4 °C, with a resolution of 0.1 °C. The electronics have been configured to have all the calculated indexes and the sensors' measurements provided to a computer model.

$$NDVI = \left(\frac{NIR-RED}{NIR+RED}\right) \quad (1)$$

$$MCARI = \left((NIR - RED) - 0.2(NIR - GREEN)\right)\left(\frac{NIR}{RED}\right) \quad (2)$$

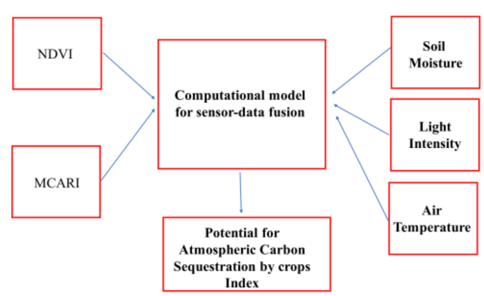

Figure 2. The sensor-based arrangement for the potential of atmospheric carbon sequestration by crops.

In fact, to have the vegetation indexes estimation, eight flight missions were conducted, i.e., based on the use of a

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multirotor Unmanned Aircraft System (UAS), DJI Matrice 100 (Figure 3).

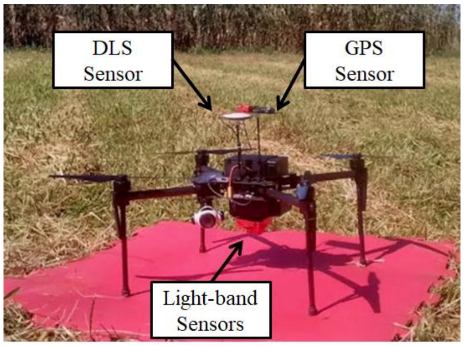

Figure 3. The UAS and hardware setup for the RGB, RED, GREEN, and NIR images acquisition.

For imaging, each flight has been considered to attend to each phenomenological state of the maize culture [12]. Then, in such a context, a MicaSense RedEdge-M multispectral camera has been considered and embedded onboard. The specifications of the multispectral sensors from the Micasense camera are detailed in Table I [13].

TABLE I. SPECIFICATIONS FOR THE MICASENSE CAMERA

Parameters	Specifications
Weigth	170 g (Including DLS)
Dimensions	9.4 cm × 6.3 cm × 4.6 cm (3.7" × 2.5" × 1.8")
External Power	4.2V−15.8V, 4W nominal, 8W peak
Spectral Bands	Narrowband: Blue, Green, Red, Near-IR
Capture Rate	1 capture per second (per band), 12−bit RAW
Ground Sample Distance (GSD)	5.95 cm/pixel (per band)
Wavelength	Blue (475 nm center ± 20 nm) Green (560 nm ± 20 nm) Red (668 nm center ± 10 nm) Near-IR (840 nm ± 40 nm)

In addition, for the light bands data acquisition protocol, the use of the Ground Control Points (GCP), a high-precision GPS in conjunction with a Real-Time Kinematic (RTK) receiver (i.e., allowing accuracy of ± 1 cm, and a Downwelling Light Sensor (DLS) to allow images' contrast correction due to possible superimposition of clouds in the sky has been considered. Furthermore, in accordance with the UAS settings and the onboard light-band sensors, for all the flights, the morning periods have been considered to be a time from 11 A.M. to 12 A.M.

For validation of the method, an experimental agricultural area has been used, i.e., following the study standards of Embrapa Instrumentation. The crop area is located 860 m from the geographic coordinates 21°57'3.9" S and 47°51'10.9" W at the National Reference Laboratory for Precision Agriculture (LANAPRE) in São Carlos, SP, Brazil.

Such an experimental crop area has been cultivated with maize (Zea mays L.), having 4,000 m² and a sampling grid equal to 10 m × 10 m. Figure 4 shows such an arrangement for specific management with the UAS navigation's flight route, i.e., divided into 40 blocks (from B1 to B40). The crop area has been divided into four plots of 1,000 m² (20 m × 50 m) aiming to manage Nitrogen (N) with surface and broadcast fertilization, associated with soil fertilization for the process of corn seeding.

Soil fertilization by N has been considered with scaled applications equal to 0, 18, 36, and 72 kg/ha, representing 0%, 50%, 100%, and 200%, respectively, in relation to the agronomic recommended dose [14]. All the other nutrients have been applied in recommended doses.

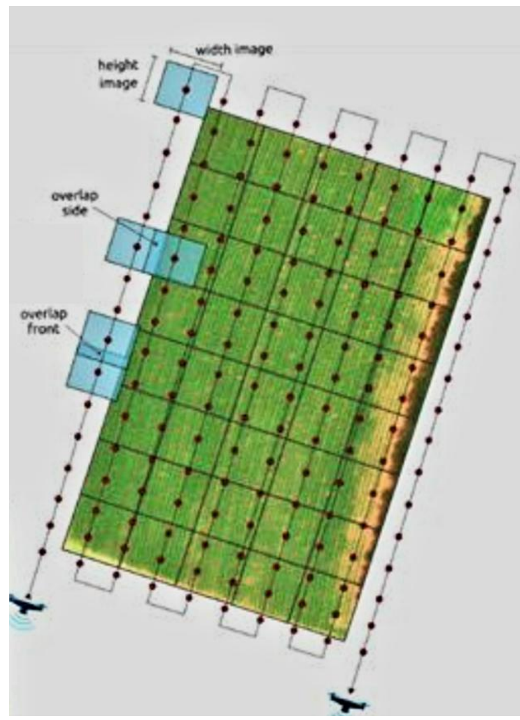

Figure 4. Experimental arrangement for sensors-based potential evaluation of atmospheric carbon sequestration with `specific site management, including the UAS navigation`s flight route.

Besides, to perform the analysis regarding atmospheric carbon sequestration's potential in the crop having maize plants, an extraction of information from each site-specific block has also been considered. Therefore, sensor data have been collected from each block, referred to as Region Of Interest (ROI), not only from the multispectral light bands but also from the sensors related to solar light intensity, soil moisture in the A-horizon, and air temperature.

Furthermore, to improve Signal to Noise Ratio (SNR), all the collected images have been filtered with a Gaussian filter using (3), and each ROI has been rotated, i.e., taking into consideration the angle calculation by (4) as follows.

$$G_\sigma(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (3)$$

$$Rotation = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -t_x \\ 0 & 1 & -t_y \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where the Gaussian function G_σ (x,y) is controlled by the variance σ^2, since the mean value is equal to zero, and the parameters $-t_x$, and $-t_y$ correspond to the translation of the ROI to the origin, whereas t_x, and t_y can allow shifting it back to its original position.

For data analysis, a Potential Atmospheric Carbon Sequestration Index (PACSI) has been defined, which allows assessing such potential by agricultural crops, i.e., considering (5) for each specific site from the experimental agricultural field, as well as the integration of the measurements and calculated variables.

$$PACSI \triangleq g\begin{pmatrix} Light\ Intensity, Air\ Temperature, \\ Soil\ Moisture, NDVI, MCARI \end{pmatrix} \quad (5)$$

To perform this operation, the fusion of variables is considered based on the use of the figure of merit's concept [15]. This fusion technique considers the set of normalized variables in the interval [0.0–1.0] and the respective plots of their values on a circle with unit radius, equally equidistant from each other (Fig. 5). From the marking of the resulting points on the equidistant radii, they are treated as vertices, and their connections represent edges (Eai) and (Ebi) of triangles, which, when united, generate a figure of merit whose area represents the result of the fusion or index resulting from the set of measurements or metrics used.

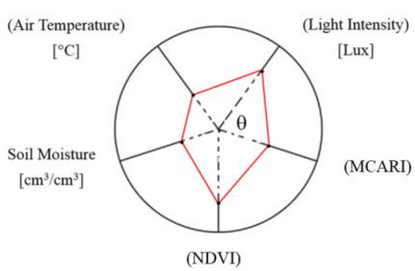

Figure 5. Sensor data fusion based on plotting normalized variables and equally equidistant from each other (θ=72°) on a circle with unit radius.

In this work, the referred index results from the sum of five areas of triangles formed within the circle with unit radius. Once the angles and edge measurements of each triangle are known, the total area can be calculated, as expressed in (6) as follows.

$$PACSI = \sum_{I=1}^{5} \frac{Ea_i Eb_i \sin\theta_i}{2} \quad (6)$$

Additionally, to complete the method's validation, after the determination of the PACSIs values, one for each specific site, the relationship with the nitrogen management was evaluated.

III. RESULTS AND DISCUSSIONS

For multispectral image acquisition, it was necessary to perform radiometric calibration to convert the metadata of the digital image to a physical scale. On the other hand, the geometry of the aerial image was established by the size of the sensor, the focal length, and the height of the UAS flights, which together determine its Ground Sample Distance (GSD) (Table II). The GSD provides the corresponding measure for the pixels of the surface of the experimental area or the area covered by the image. The percentages established for both the lateral and frontal overlapping of the aerial images were equal to 80% respectively.

The total number of registered images was equal to 300 for each spectral band, i.e., leading to a total amount of 9600 images, i.e., leading to a required storage capacity equal to 29.52 GB (gigabytes), because the surface width and height were equal to 27 m × 20 m, respectively, and the distances between each front and side capture were 4 m and 5 m, respectively.

TABLE II. PARAMETERS USED FOR DATA ACQUISITION

Description	Values	Units
Flying altitude	138	m
Mission flying time	12	min
Max. speed of flying	11	m/s
Front and side overlap	80	%
Ground sample distance	5.95	cm/pixel

Figure 6 shows examples of results obtained from the eighth flight, i.e., considering the rotation of the images and Regions Of Interest (ROI) for analysis of block 25, in terms of the RGB, NIR, RED, and GREEN light-bands.

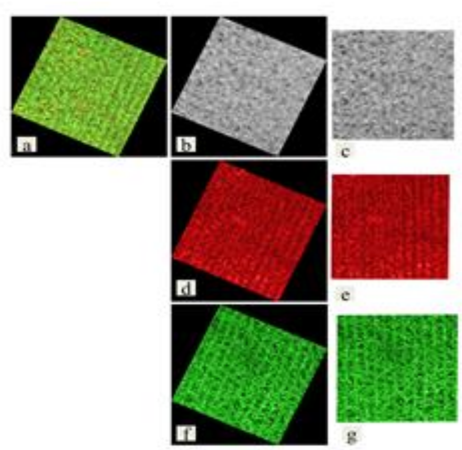

Figure 6. Sample of analysis for the block 25: from the eight flight - (a) RGB, (b) NIR, and (c) ROI NIR; (d) RED and (e)ROI RED; (f) GREEN, and (g) ROI GREEN.

Data analyses for collected data were carried out for the eight flights, that is, considering not only the reflectance measurements and the calculations based on the use of (1) and (2), but also the additional sensors and their measurements for each site-specific area in the culture area. An example of the obtained results can be observed in Table III for all the blocks from the experimental field.

Besides, based on such a calculation of the vegetation indexes and the sensor-based data measurements, as well as using the (6), it was possible to figure out the PACSI values (in units of area) for each ROI presented in the experimental maize agricultural field (Table IV). In fact, before calculating the area of the figure of merit, all the values were normalized to be included in the circle having the unit radius, i.e., to make it possible to infer the potential of each block to sequester the atmospheric carbon by maize crop.

TABLE III. BLOCKS RESULTS FOR FLIGHT EIGHT

Specific Site (Block #)	X - UTM [m]	Y - UTM [m]	MCARI	NDVI	Light Intensity [Lux]	Air Temperature [°C]	Soil Moisture [cm³/cm³]
1	205,320.60	7,569,399.92	0.0295	0.6627	84,500	31.3	0.61
2	205,324.77	7,569,409.01	0.0283	0.6884	84,432	31.2	0.60
3	205,311.51	7,569,404.09	0.0309	0.5991	84,495	31.5	0.60
4	205,315.68	7,569,413.18	0.0289	0.6583	84,502	31.4	0.62
5	205,302.42	7,569,408.26	0.0295	0.6338	84,505	31.6	0.61
6	205,306.59	7,569,417.35	0.0291	0.6360	84,504	31.4	0.62
7	205,293.33	7,569,412.43	0.0295	0.6760	84,506	31.3	0.40
8	205,297.50	7,569,421.52	0.0292	0.6307	84,504	31.7	0.42
9	205,284.24	7,569,416.60	0.0326	0.7398	84,508	31.8	0.35
10	205,288.41	7,569,425.69	0.0292	0.6889	84,506	32.0	0.33
11	205,292.58	7,569,434.78	0.0261	0.7166	84,508	32.1	0.40
12	205,296.75	7,569,443.87	0.0256	0.7459	84,507	31.9	0.34
13	205,301.67	7,569,430.61	0.0270	0.7135	84,508	32.0	0.44
14	205,305.84	7,569,439.70	0.0260	0.7508	84,505	31.7	0.43
15	205,310.76	7,569,426.44	0.0262	0.7340	84,504	31.8	0.64
16	205,314.93	7,569,435.53	0.0268	0.7349	84,506	31.5	0.63
17	205,319.85	7,569,422.27	0.0267	0.7450	84,500	31.9	0.62
18	205,324.02	7,569,431.36	0.0253	0.7756	84,501	31.7	0.63
19	205,328.94	7,569,418.10	0.0254	0.7704	84,504	32.0	0.63
20	205,333.11	7,569,427.19	0.0253	0.7803	84,506	31.8	0.62
21	205,337.28	7,569,436.28	0.0223	0.8155	84,508	32.0	0.61
22	205,341.45	7,569,445.37	0.0220	0.8205	84,504	32.1	0.62
23	205,328.19	7,569,440.45	0.0228	0.8067	84,507	31.9	0.62
24	205,332.36	7,569,449.54	0.0223	0.8161	84,502	32.0	0.61
25	205,319.10	7,569,444.62	0.0242	0.7875	84,506	31.4	0.63
26	205,323.27	7,569,453.71	0.0224	0.8093	84,504	31.3	0.62
27	205,310.01	7,569,448.79	0.0238	0.7894	84,501	31.7	0.44
28	205,314.18	7,569,457.88	0.0224	0.8068	84,508	31.8	0.45
29	205,300.92	7,569,452.96	0.0248	0.7489	84,504	32.1	0.34
30	205,305.09	7,569,462.05	0.0257	0.7443	84,509	32.2	0.33
31	205,309.26	7,569,471.14	0.0235	0.7491	84,497	31.9	0.30
32	205,313.43	7,569,480.22	0.0244	0.7628	84,500	31.8	0.35
33	205,318.35	7,569,466.97	0.0219	0.8101	84,506	31.8	0.45
34	205,322.52	7,569,476.05	0.0231	0.7959	84,504	31.9	0.46
35	205,327.44	7,569,462.79	0.0213	0.8189	84,506	31.6	0.60
36	205,331.61	7,569,471.88	0.0229	0.7937	84,508	31.8	0.61
37	205,336.53	7,569,458.62	0.0209	0.8293	84,500	31.7	0.60
38	205,340.70	7,569,467.71	0.0214	0.8224	84,510	31.4	0.62
39	205,345.62	7,569,454.45	0.0211	0.8290	84,513	31.6	0.62
40	205,349.79	7,569,463.54	0.0220	0.8310	84,614	31.9	0.61

Figure 7 shows the relationship observed between the applied N dose and the PACSI calculated values for all the blocks from the experimental agricultural maize crop field.

For the example of results presented here with data from the eighth flight, the values found for PACSI were between 0.151 and 0.655, both values in units of area, with higher values indicating greater potential for sequestering carbon from the atmosphere by the corn crop.

TABLE IV. NORMALIZED RESULTS AND THE PACSI VALUE

Specific Site (Block #)	Normalized value for MCARI	Normalized value for NDVI	Normalized value for Light Intensity	Normalized value for Air Temperature	Normalized value for Soil Moisture	PACSI
1	0.735	0.274	0.895	0.273	0.600	0.294
2	0.633	0.385	0.000	0.182	0.733	0.191
3	0.857	0.000	0.000	0.182	0.733	0.173
4	0.679	0.255	0.000	0.182	0.733	0.183
5	0.732	0.158	0.000	0.182	0.733	0.178
6	0.701	0.159	0.000	0.182	0.733	0.172
7	0.730	0.331	0.000	0.182	0.733	0.207
8	0.710	0.136	0.947	0.182	0.300	0.151
9	1.000	0.606	0.882	0.091	0.067	0.294
10	0.706	0.387	0.974	0.091	0.000	0.168
11	0.443	0.507	0.947	0.000	0.300	0.190
12	0.403	0.633	0.987	0.182	0.033	0.245
13	0.518	0.493	0.934	0.091	0.367	0.233
14	0.435	0.654	0.961	0.182	0.333	0.293
15	0.452	0.581	0.895	0.000	0.567	0.236
16	0.500	0.586	0.000	0.182	0.600	0.159
17	0.490	0.629	0.829	0.091	0.600	0.285
18	0.373	0.761	0.829	0.091	0.533	0,281
19	0.386	0.739	0.961	0.000	0.567	0.275
20	0.369	0.781	0.947	0.364	0.933	0.467
21	0.120	0.933	0.974	0.273	0.233	0.313
22	0.090	0.955	0.947	0.636	0.300	0.411
23	0.160	0.895	1.000	0.727	0.067	0.414
24	0.120	0.935	0.974	0.909	0.000	0.433
25	0.280	0.812	0.974	0.364	1.000	0.458
26	0.125	0.906	0.947	0.273	0.967	0.367
27	0.246	0.820	0.908	0.636	0.367	0.420
28	0.122	0.895	1.000	0.727	0.400	0.470
29	0.332	0.646	0.947	1.000	0.233	0.473
30	0.407	0.626	0.934	0.909	0.300	0.473
31	0.220	0.647	0.961	0.636	0.267	0.364
32	0.298	0.706	0.947	0.727	0.300	0.426
33	0.081	0.910	0.974	0.455	0.400	0.367
34	0.187	0.849	0.895	0.818	0.433	0.473
35	0.030	0.948	0.908	0.636	0.900	0.469
36	0.166	0.839	0.947	0.909	0.933	0.635
37	0.000	0.992	0.974	0.727	0.900	0.529
38	0.042	0.963	0.934	0.909	0.967	0.615
39	0.016	0.991	0.947	1.000	0.967	0.655
40	0.094	1.000	0.987	0.818	0.933	0.622

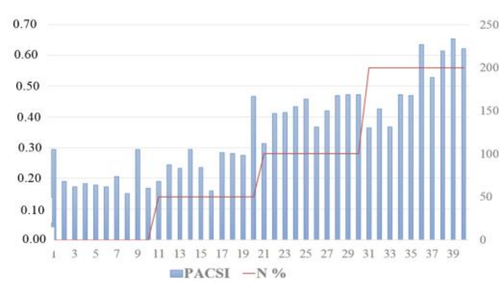

Figure 7. Histogram of the calculated PACSI values for the specific sites of the experimental maize crop field, considering the flight eighth and the N doses applied (in percentages).

However, since chlorophyll content is related to photosynthesis and nitrogen fertilization, the application of N at different doses was also considered for validation in the field experiment. The existing relationship can be explained by considering that chlorophyll is dependent on nitrogen and is involved in photosynthesis, which in turn is also related to the potential for carbon sequestration from the atmosphere. Nitrogen is a nutrient that is present in the chloroplasts of leaves, where it participates in the synthesis of chlorophyll. Without nitrogen, there is no chlorophyll, which makes photosynthesis unfeasible and prevents plant development. It is important to note that in the example results, although there is a region of blocks where no additional nitrogen fertilization occurred (0%), there are indications of PACSI values, blocks from 1 to 10. This occurrence was observed due to the preliminary fertilization that was carried out in the soil for planting corn seeds, that is, the fertilization of the entire crop area that occurred at the beginning of the agricultural process. For the other blocks, that is, from 11 to 40, the impact of the additional percentage of N applied and its relationship with the increasing PACSI values was imperative. Evidently, the efficiency of the results depends on the values of light intensity, air temperature, and soil moisture.

Furthermore, one may observe that such a new PACSI index has the potential to also be used to indicate the need for nitrogen fertilization in the observed crop, thus helping the rural producer to save inputs and maximize contributions to the sequestration of atmospheric CO_2, which helps air quality and minimizes the effects of climate change.

The total cost to figure out this development of the sensor-based platform's prototype for the potential evaluation of atmospheric carbon sequestration by agricultural crops was about USD 75,000. Nevertheless, the developed solution based on such a sensor platform can be useful not only for large crop areas but also for small farms. In fact, alternatives to decrease costs in relation to its application can be reached by different pathways, i.e., using it as a service to be offered by others or even taking into consideration its cooperative use by a group of smallholder farmers.

IV. CONCLUSION AND FUTURE WORK

This work presented a new sensor-based index for evaluation of agricultural crop potential for carbon sequestration (PACSI). It is based on information related to the biomass amount per area, chlorophyll absorption by the plants, solar light intensity, air temperature, and the agricultural soil moisture in the root zone. In fact, it has been proved to be useful not only to help in managing impacts due to climate change but also to be used as an indicator for needs in nitrogen fertilization by the farmers, i.e., allowing not only loss minimization but also gain in sustainability. Future research works will consider the development of an integrated and customized agricultural smart sensor platform coupled to a Convolutional Neural Network (CNN) for real-time evaluation of the potential for atmospheric carbon sequestration by crops.

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REFERENCES

[1] S. Dawid *et al.*, “Towards carbon neutrality: enhancing CO_2 sequestration by plants to reduce carbon footprint,” *Science of The Total Environment*, vol. 966, pp. 178763-178784, 2025.

[2] J. P. Dekker and R. Van Grondelle, “Primary charge separation in photosystem II,” *Photosynthesis Research*, vol. 63, pp. 195–208, 2000.

[3] N. Nelson and C. F. Yocum, “Structure and function of photosystems I and II,” *Annual Review of Plant Biology*, vol. 57, pp. 521–565, 2006.

[4] K. Ferreira *et al.*, “Architecture of the photosynthetic oxygen-evolving center,” *Science*, vol. 303, pp. 1831–1838, 2004.

[5] H. Ago *et al.*, “Novel features of eukaryotic photosystem II revealed by its crystal structure analysis from a red alga,” *Journal of Biological Chemistry*, vol. 291, pp. 5676–5687, 2016.

[6] R. Tanaka and A. Tanaka, “Chlorophyll cycle regulates the construction and destruction of the light-harvesting complexes,” *Biochimica et Biophysica Acta (BBA) – Bioenergetics*, vol. 1807, no. 8, pp. 968-976, 2011.

[7] J. W. Rouse *et al.*, “Monitoring vegetation systems in the great plains with ERTS,” in *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium*, National Aeronautics and Space Administration (NASA), SP-351, Washington DC, USA, pp. 309-317, 1974.

[8] C. J. Tucker, “Red and photographic infrared linear combinations for monitoring vegetation,” *Remote Sensing of Environment*, vol. 8, pp. 127-150, 1979.

[9] P. E. Cruvinel and W. N. C. Veramendi, “Using light-band sensors for stress evaluation in rainfed maize agricultural crop,” in *IARIA, Proceedings of the Ninth International Conference on Advances in Sensors, Actuators, Metering and Sensing (ALLSENSORS 2024)*, pp. 1-7, 2024.

[10] C. S. T. Daughtry *et al.*, “Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance,” *Remote sensing of Environment*, vol. 74, pp. 229–239, 2000.

[11] M. S. Kim *et al.*, “The use of high spectral resolution bands for estimating absorbed photosynthetically active radiation (A par),” in *CNES, Proceedings of 6th International Symposium on Physical Measurements and Signatures in Remote Sensing*, National Aeronautics and Space Administration (NASA), Report Number: GSFC-E-DAA-TN72921, February, pp. 299-306, 1994.

[12] M. W. L. Carvalho *et al.*, “Productive performance of maize crop irrigated with and without water deficit in different plant arrangements,” *Brazilian Journal of Maize and Sorghum*, vol. 19, pp. 1196-11208, 2020.

[13] MicaSense RedEdge-M™, Multispectral Camera, *User Manual*, vol. 1, pp. 1-47, 2017.

[14] A. P. Duarte, H. Cantarella, and J. A. Quaggio, "3.5. Maize (Zea mays)," in *Fertilization and liming recommendations for the state of São Paulo - Bulletin 100* (Organizers: H. Cantarella, J.A. Quaggio, Jr. D. Mattos R. M. Boaretto, B. van Raij), 3rd edition, Instituto Agronomic de Campinas, vol. 1, pp. 199-200, 2022.

[15] P. E. Cruvinel *et al.*, “Evaluation of models for establishing a risk figure for the occurrence of Black Sigatoka in banana plantations,” *Embrapa - Document Series*, ISSN: 1518-7179, n. 55, pp. 1-28, 2011.

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