Use of Affordable Sensors to Investigate Aeration and Resistance to Plant Root Penetration for Soil Assessment

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***Abstract*— To understand how plant roots navigate the soil environment it is required several key factors. Instrumentation plays a crucial role in measuring these factors. Mostly of them are related to oxygen diffusion rate, which affects root respiration and growth, soil redox potential that indicates the level of available oxygen in the soil, and the resistance to root penetration. By analyzing such combined measurements, scientists can gain valuable insights into root health and plant performance in different soils conditions. This paper presents a combination of three affordable sensors to perform the measurements of those key factors, in order to provide an effective solution to enhance agricultural productivity, food security, and supporting sustainable agriculture. This innovative approach with accessible sensors offers an effective way to understand and monitor soil conditions, thus promoting more productive and sustainable issue.**

Keywords- affordable sensors; agriculture; soil resistance; soil-water-plant measuring; Oxygen Diffusion Rate (ODR), redox potential, soil aeration.

I. INTRODUCTION

The applications of sensors, and more specifically the affordable sensors, are the basis for instrumentation developing, which is also related to automation, precision agriculture, and digital agriculture.

The global agricultural sensors market size was valued at USD 4.74 billion in 2021. It is expected to reach USD 16.83 billion by 2030, growing at a Compound Annual Growth Rate (CAGR) of 15.12% during the forecast period (2022–2030) [1].

In such universe of sensors, the low-cost sensors are technologies that can attend consumer and research applications. Competitive, the low-cost sensors can be useful to attend an economy-of-scale. In fact, these technologies for sensing may allow either new applications or more economical use not only for agricultural production but also environmental use [2].

Plant roots play a crucial role for the ecosystem's health, but their growth can be hindered by various soil conditions. Understanding these limitations requires investigating factors like oxygen availability, soil chemistry, and physical properties. This is where sensor-based instrumentation can provide valuable insights related to the belowground world. One of the critical factors influencing root growth is the oxygen diffusion rate within the soil. Roots require oxygen for respiration, and their limited availability can restrict root elongation and penetration in soil [3]. Instruments like microelectrode probes can measure oxygen concentration at specific depths within the soil profile. These probes consist of fine wires that react to oxygen levels, generating an electrical signal that is related to oxygen concentration. By measuring oxygen diffusion rates across different soil types and moisture conditions, researchers can identify potentially areas limiting root growth due to hypoxia (low oxygen availability) [4][5].

Another critical parameter is soil redox potential, often abbreviated as Eh. Its measurement reflects the overall tendency of the soil environment to gain or lose electrons. A positive Eh indicates a more oxidizing environment favorable for root growth, while negative values suggest a reducing environment with limited oxygen and CO_2 availability in paddy fields [6]. Instruments like redox electrodes are used to measure Eh. These electrodes generate a voltage based on the soil's electron activity, allowing researchers to assess the overall oxidative state and predict potential limitations for root development.

Finally, resistance to root penetration is other a crucial factor affecting root growth. This resistance can be caused by soil compaction, rocks or debris, and even root hairs of other plants [7]. Penetrometers are instruments used for measuring such a soil-resistances to root penetration. These devices typically consist of a metal rod with a force sensor. The rod is pushed into the soil at a controlled rate, and the force required for penetration can be measured. Such collected data may help researchers to understand roots' physical limitations as they navigate the soil matrix.

By combining data on oxygen diffusion rate, soil redox potential, and resistance to root penetration, researchers comprehensively understand the factors influencing root growth in a dynamics way [8]. Based on such information one can develop strategies for improving soil health, such as practices that enhance aeration, drainage, and organic matter content. Understanding these factors also has significant implications for agriculture, i.e., in terms of value aggregation. Optimizing soil conditions for root growth can lead to healthier plants with improved nutrient uptake, better water utilization, and increase in crop yields.

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The main objective of this work is to present a sensors-based instrument for investigating aeration (Oxygen Diffusion Rate (ODR) and Redox potential (Eh)), and the resistance to root penetration in soil (SSRPM) assessment.

In Section II, a discussion is carried out regarding the systems in relation to their operation, theoretical and practical data, as well as the modeling of them.

In addition, in Section III are presented conclusions and a proposal for future works.

II. APPLICATION, EVALUATION AND EXAMPLES OF CUSTOMIZED AND AFFORDABLE ODR, EH AND SSRPM SENSORS FOR AGRICULTURE.

The system consists of three sensors: soil oxygen diffusion rate sensor, soil redox potential sensor, and soil resistance to root penetration sensor; a computational system with analog-to-digital converter and digital signal processor, responsible for reading and acquiring signals from the sensors and processing them; and a Human-Machine Interface (HMI) for graphical or text visualization of the processed signals, like a Dashboard.

Figure 1 shows in block diagram the organized structure for the accessible sensors used to investigate soil aeration and soil resistance to root penetration.

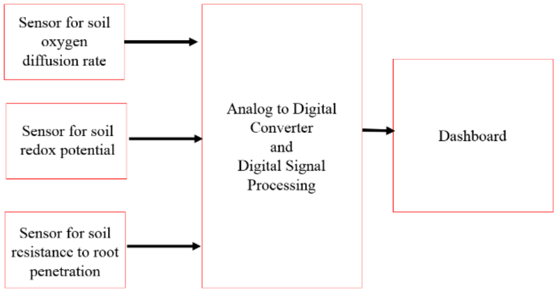

Figure 1. Block diagram for root soil information processing and related instrumentation based on the use of affordable sensors.

Related to the development and use of oxygen diffusion rate and redox potential sensors, both can be used in laboratory experiments and also in agricultural plots. In relation of these two key-factors sensors, the instrumental arrangement was prepared take into account an advanced version in relation that presented by Silveira and collaborates [9]. The main advances in this new arrangement were: the replacement of the analog reading system with a digital one, with the two readings (ODR and redox potential) being presented on a 3 1/2-digit LCD (Liquid Crystal Displays). The selection of these sensors is made by using a high-performance micro relay, activated by a thumbwheel switch instead of a wave switch.

The electrodes were constructed using electrostatic welding, a process similar to that used in the preparation of thermocouples, which fuses the platinum wire (sensor) to the copper wire (connection between the sensor and the device). The electrodes were then wrapped with acrylic resin, which provides mechanical resistance and precisely controls the length of the platinum wire exposed for measurement. The electrode length is an important parameter, since the ODR is dependent on the sensor area, given by (1) and (2). This manufacturing process simplified the construction of the sensors, compared to that proposed in [8][10], which consists of fusing a glass tube together with platinum wire and copper wire. Such a process can cause contact problems, and it is difficult to accurately control the length of the exposed platinum wire, i.e., improvement was required.

A. Oxygen Diffusion Rate (ODR)

To measure ODR, a potential of 0.65 VDC is applied between the platinum electrodes and the calomel electrode [11]. After a minimum of four minutes, the current stabilizes, and a microampmeter is ready to be read.

According to [9], the current that circulates between the two electrodes is proportional to the ODR in the soil and can be expressed by (1), which is an adaptation of Fick's diffusion law:

$$i = 10^{-6} = \eta * F * A * f \tag{1}$$

Where i is the electric current in microamperes, n is the number of electrons required to reduce an oxygen molecule, which is equal to 4, F is the Faraday's constant (approximately equal to 9.65 x 10^{4} C/mol), A is the surface area of the platinum electrode (cm^{2}) and f is the flux or ODR to the electrode surface, in number of moles of oxygen per second per cm^{2}.

The ODR can be calculated in ($\mu g.cm^{-2}.min^{-1}$), using (2):

$$ODR = \frac{(i * 10^{-6}) * 60 * (32 * 10^{8})}{4 * 96.500 * A} \tag{2}$$

Where the factors 60 and 32 x 10^{8} are used to convert seconds and moles to minutes and micrograms [10].

B. Redox Potential (Eh)

When measuring the redox potential, the electrode voltage is deactivated and they are connected to the input of the operational amplifier, in a non-inverting configuration (Figure 2). The output of the operational amplifier is connected to a digital voltmeter to read the electrode potential, which by definition of the “International Union of Pure and Applied Chemistry” (IUPAC), it is the availability of the electron or the electrochemical potential of the electron in equilibrium.

The electrode potential, whose adopted symbol is Eh, is related to the oxidation distribution state of the ion by the Nernst equation:

$$Eh = Eh^{0} - \frac{R * T}{n * F} * ln \frac{(Red)}{(O_{x}) * (H^{+})} \tag{3}$$

Where Eh is the cell potential in Volts, n is the number of electrons transferred in a half reaction (this is when the chemical equation related to the cell reaction can be separated into two portions) generalized from a redox couple, R is the universal gas constant 8.3145 (J.K^{-1} .mol^{-1}), Red = Ox + ne-+ aH^{+} (called half reduction), and T is the temperature in Kelvin. In (3), "Red" and "Ox" refer, respectively, to the reduction and oxidation forms of substances, and Eh° is called the standard potential for the half-reaction [12].

The choice of the 0.35 mm platinum electrode is due to two experimental aspects: 1) characterization of the ODR conditions for root thickness with the same dimension as the electrode, and 2) stiffness of the wire, to avoid its breakage when of its insertion into the soil.

The dimensions of the platinum wire alter the geometry of the solid-liquid-gaseous state of the medium around the electrode, which may not appropriately characterize the oxygen diffusion that a root requires. The correct quantification of ODR, together with other parameters, makes it possible to correlate the degree of root growth to its environment [13][14].

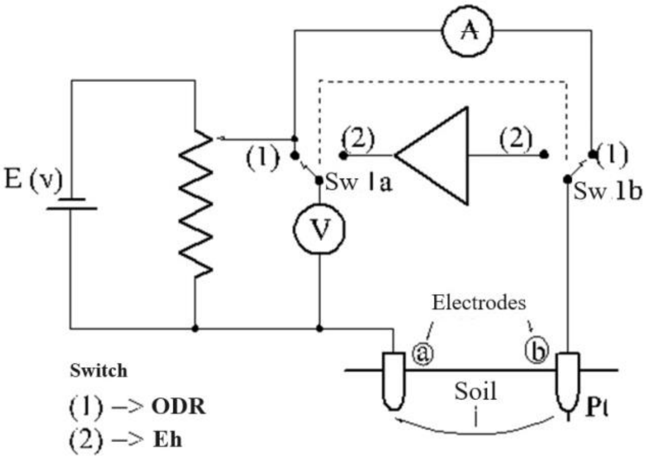

Figure 2. Schematic diagram for measurements of ODR, and Eh.

Figure 3 presents the results that show the influence of water in the water-soil system, in the attenuation of microwaves, through the relation of the attenuation of the signal in dB by the volumetric soil moisture in sandy soil (1.20 < soil density (g/cm^3) < 1.26), clayey (0.83 < soil density (g/cm^3) < 0.92)) and glass microsphere (1.13 < soil density (g/cm^3) < 1.19)). The error in sample preparation was 4.7%. All measurements were conducted under laboratory conditions (room temperature ~23.0 ± 0.5 ^{0}C and relative humidity 36%).

Figure 4 shows the correlation (R2 =0.937) between the results obtained in five measurements with the redox potential meter developed and a Digimed DM-PV. The differences between these results can be explained by the spatial variation of the redox potential that occurs in the field (point measurements), and therefore the analysis of redox potential in the field is more qualitative than quantitative. Readings with values greater than +200 mV (pH 7) denote oxidized conditions, and values lower than this demonstrate reduced conditions in the soil [15].

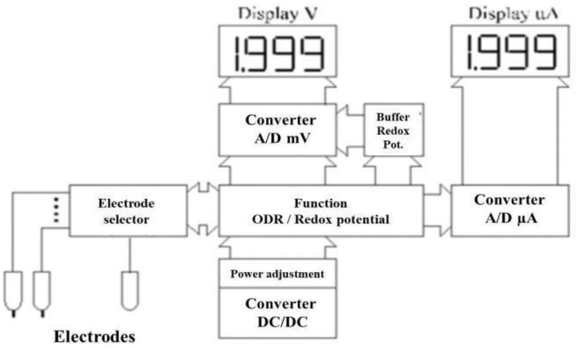

Figure 3. Block diagram of the sensor-based arrangement to obtain the oxygen diffusion rate and redox potential.

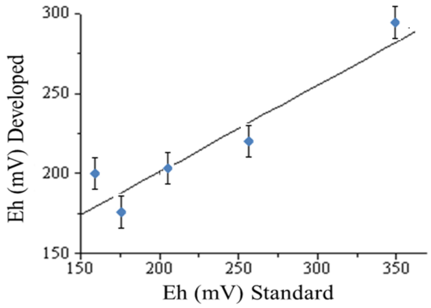

Figure 4. Correlation of data obtained in the field (R^2= 0.937) with the redox potential meter, developed and produced by Digimed equipment, being used as a comparison standard (error bar based on the standard deviation of the measurement).

Figure 5 shows the relationship between the soil matric potential and the ODR variation. This type of result, with an increase and subsequent reduction in ODR with variation in humidity, has been observed by other authors and is an artifact of the ODR technique [9][11].

As the ODR method is based on the movement of oxygen in the liquid phase of the soil, this has been explained by the rupture of the water film around the electrode, at low humidity values [8]. Therefore, only ODR measurements at high humidity levels are more appropriate.

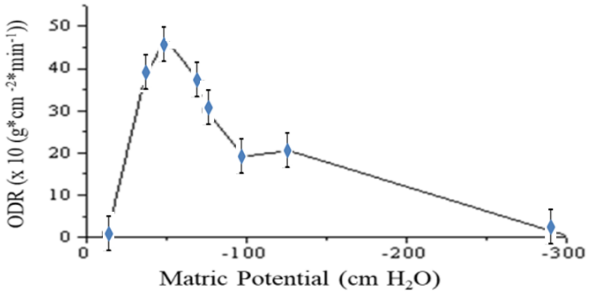

Figure 5. Variation of Oxygen Diffusion Rate (ODR) (x 10 (g*cm $^{-2}$*min^{-1})) as a function of soil water matric potential (cm $H_2$0) (error bar based on the standard deviation of the measurement).

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C. Sensor for Soil Resistance to Root Penetration Measurements (SSRPM)

A sensor-based instrumentation was prepared to evaluate the spatial variability of soil resistance to root penetration, for area and profile and due to natural or artificial soil compaction processes. Many researchers have studied the formation of surface layers of soil compaction and its effects on seed emergence, water infiltration, and soil erosion. Penetrometers do not have reasonable precision for measuring the degree of compaction of compacted soil crust and for quantifying the force exerted by seed during germination to overcome this crust and root development in this region. Small probes have been used to simulate root penetration force but on a laboratory scale to characterize soil structure.

The SSRPM was developed (cone angle of 30º, base diameter of 1.6 mm, and total length of 130 mm), based on the ASAE R 313.3 standard for penetrometers [16], sensed by a load cell and electronic circuit for signal conditioning and treatment.

Results have shown that measurements of soil resistance to root penetration could be accomplished up to (49.03±0.07) kgf, with a resolution equal to 1.57 kgf.

Calculations for values of Soil Resistance to Penetration (RSP) as a function of the normal stress under the probe's metal cone (σ_n), friction (μ), tangential adhesion stress (c_a), soil Resistance to Cone Penetration (RP), soil density (ρ) and soil moisture (θ), can be given as follows [17][18].

$$RSP = g(\sigma_n, \mu, c_3, RP, \rho, \theta) \quad (4)$$

Likewise, the RSP also can be represented by the equation (5).

$$RSP = 6.98 * \rho^2 + A + B + C - D - 10.44 * 10^{-2} \quad (5)$$

where:

$$A = [-1.62 * 10^{-1} + 1.36 * 10^{-3}(A_1)] * \rho$$

$$A_1 = h_a + R_c\left(\frac{RP - \sigma_n}{(\mu * \sigma_n) + c_a}\right)$$

$$B = [1.98 * 10^{-1} - 9.20 * 10^{-3}(B_1)] * (\theta * \rho)$$

$$B_1 = h_a + R_c\left(\frac{RP - \sigma_n}{(\mu * \sigma_n) + c_a}\right)$$

$$C = 9.80 * 10^{-2}\left[h_a + R_c\left(\frac{RP - \sigma_n}{(\mu * \sigma_n) + c_a}\right)\right]$$

$$D = 2.0 * 10^{-3}\left[h_a + R_c\left(\frac{RP - \sigma_n}{(\mu * \sigma_n) + c_a}\right)\right]$$

h_a is the height of the microprobe within the soil, and R_c is the cone radius of the microprobe tip, equal to 0.08 cm.

For validation, a 13 cm probe was used, designed without the recess in the probe body and maintaining the cone tip angle equal to 30º. The test aimed to evaluate the behavior of the soil resistance to root penetration sensor is illustrated in Figure 5. In deeper measurements of soil resistance to root penetration for maize (Zea Mays), results reach approximately 20 cm deep.

For validation, an agricultural plot was used, i.e., located at coordinates 21º 57' 5.33728 S" and 47º 50' 45.9429 W", area from Embrapa Southeastern Livestock, located in the municipality of São Carlos, São Paulo state, Brazil.

The region's soil type comprises a *Dark Red Dystrophic Latosol*, which presents a clayey texture in the tropical sub deciduous savanna phase. These deep soils range from reddish-brown to dark reddish-brown. They are formed from very diverse material, which give them a specific variability in morphological characteristics and influences their chemical properties. In general, these soils have low base saturation and low aluminum saturation.

Data was collected within an area of 16 cm X 16 cm, with a variation of 1 cm distance between them. A computer program was responsible for controlling a table of coordinates XY, as well as to carry out the data acquisition [19]. The coordinates provided to the sensor-based system are indicated in Table 1.

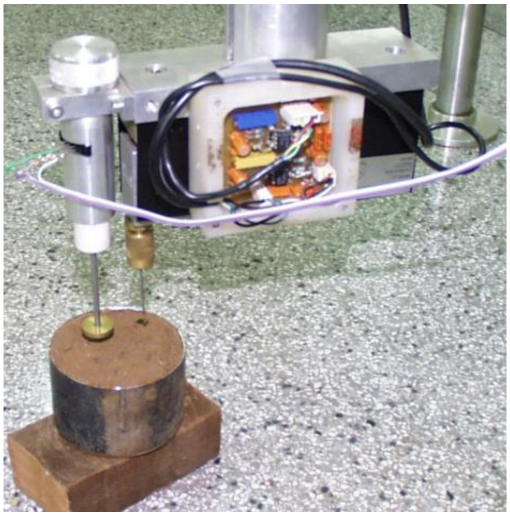


Figure 5: illustration of *SSRP arrangement* for laboratory calibration.

TABLE I. FIELD TEST FOR 13 CM PROBE - COORDINATES TO MEASURE SOIL RESISTANCE TO ROOT PENETRATION.

starting position		end position		Increment	
X(cm)	Y(cm)	X(cm)	Y(cm)	X(cm)	Y(cm)
0	0	15	15	1	1

Table II summarizes the parameters of the carried-out analysis with the 13 cm probe.

TABLE II. SOIL MOISTURE FOR TESTING WITH A 13 CM PROBE.

Container number	1.0
Sample thickness	7.2 cm
Sample length	5.5 cm
Average soil moisture in experiment area <**θ**>	11.3%
Soil type	Dark Red Dystrophic Latosol - clayey texture

With the aim of characterizing the field test, as well as due to the large amount of data, two coordinates were selected, (440,120) and (110,60), to verify the variation in soil resistance to root penetration, represented in figure 6(a) (b), as a function of depth Z, in the range of 0 to 30 mm and 0 to 130 mm respectively.

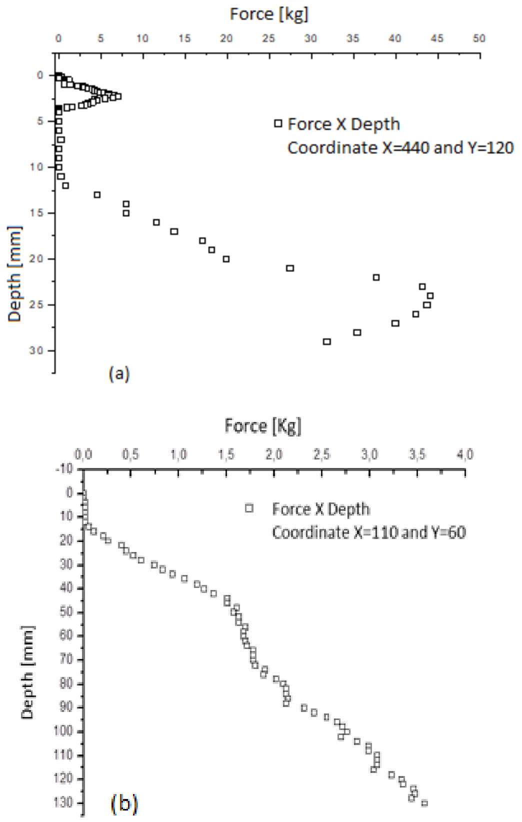


Figure 6: Variation in soil resistance to root penetration for the 3cm (a) and 13cm (b) probe as a function of depth Z, for coordinates (X=440, Y=120) and (X=110, Y=60) respectively.

The sequence of two-dimensional maps, generated from different depths is shown in Figure 7. In such evaluation, variation in resistance to the advancement of the probe was observed throughout the entire depth, which would also be the case for plant roots.

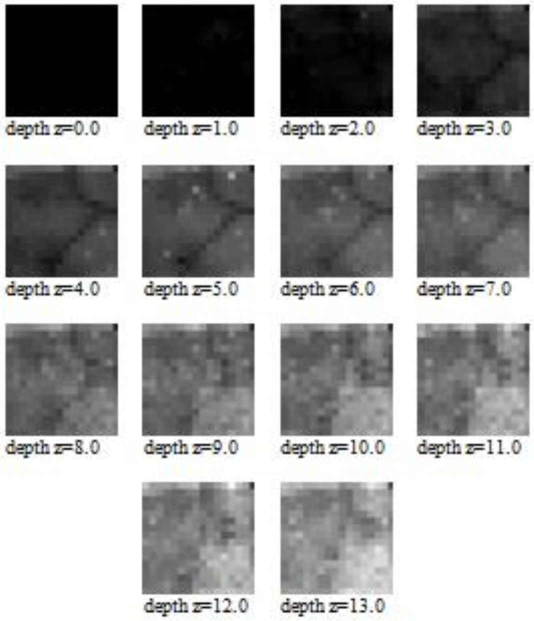
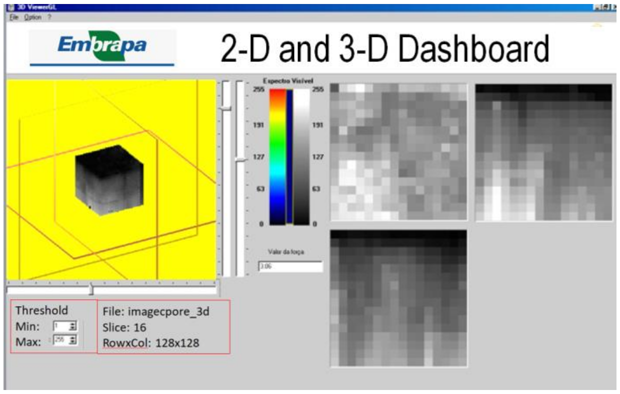


Figure 7. Sequence of two-dimensional maps of measures of soil resistance to root penetration for data collected in the field for the 13 cm, in the range from z=0.0 cm to z=13.0 cm, shades of gray: from black =0.0 kgf to white=50.0 kgf

The volumetric information on soil resistance to root penetration obtained in the field test from the two-dimensional maps for the 13 cm probe, with its transversal, coronal and sagittal sections, is seen in Figure 8.



Threshold
Min: 1
Max: 255

File: imagecpore_3d
Slice: 16
RowxCol: 128x128

Figure 8: Three-dimensional map of soil resistance to root penetration, collected in an agricultural field using the 13cm probe.

The presented results related to the soil resistance to root penetration analysis made it possible to measure soil resistance to a depth of 13 cm in almost real time. In addition, after the sensor's integration in a unique instrumental platform, an embedded software was also included for spatial variability analysis.

III. CONCLUSIONS AND FUTURE WORK

In this study, three affordable sensors were introduced that have proven to be quite useful in soil science studies. These sensors can be seamlessly combined. Results have demonstrated that the sensors are capable of accurately evaluating redox potential, oxygen diffusion rate, and aeration, even in soil that is nearly saturated, as well as the soil resistance to root penetration. The reached level of precisions makes the final arrangement with the three sensors ideal for agricultural applications.

As future work, there are plans to integrate sensors into an ARM architecture (Acorn RISC Machine) and incorporate computational intelligence to aid decision making in the agricultural setting.

ACKNOWLEDGMENT

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