The effect of soil water content and crop canopy on passive UHF-RFID wireless links

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Baumbauer, C. L., Baumbauer, D. A., & Arias, A. C. (2025). The effect of soil water content and crop canopy on passive UHF-RFID wireless links. Computers and Electronics in Agriculture, 237, 110506.

Computers and Electronics in Agriculture 237 (2025) 110506

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

The effect of soil water content and crop canopy on passive UHF-RFID wireless links

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ARTICLE INFO

Keywords:
RFID
Wireless communication
Antennas
Agriculture IoT

ABSTRACT

High spatial density agricultural sensors that monitor soil fertility and moisture levels are quickly developing and could revolutionize precision agriculture once they are integrated with wireless communication systems. Passive Ultra High Frequency Radio Frequency Identification (UHF-RFID) is a wireless communication protocol for battery-free sensor nodes which could enable continuous soil monitoring. Soil texture, soil water content, and crop canopy impact the vertical read range between a passive RFID tag near the soil and a reader raised above the crop. Here, we evaluated these impacts and found that increases in soil water content decreased read range by 30–40 cm compared to dry soil. Adding 3.4 cm of distance between the wet soil and the tag increased the read range by 1–1.4 m. Crop canopy did not have a significant impact on read range once the soil water content had been accounted for.

1. Introduction

The development of low cost, in-situ plant wearable and soil sensors has accelerated in recent years (Ikram et al 2024, Faqir et al 2024, Xu et al 2024). Sensors for soil moisture (Kim et al., 2013; Su & Chang, 2018), soil nitrate (Baumbauer, et al., 2022; Ali et al., 2016, Abdollahzadeh et al., 2024), and other soil characteristics could provide agriculturalists and scientists with valuable information to improve crop production efficiency and further understanding of element cycling in soil. Unlike remote sensing, in-situ sensors offer direct measurement, measurements of subsurface layers, and continuous temporal data. Ground truth data from in-situ sensors could also be used to calibrate remote sensing data. However, these novel sensors are typically demonstrated using benchtop or hand-held equipment to read them, which is not scalable to field deployment. Many soil properties display high spatial variation, such that one sensor per acre, or several hundred sensors per field, are needed to accurately map a field (Goodrich, et al, 2023, Longchamps & Khosla, 2017). Strategies for wireless sensor data collection and system power management are required to achieve the potential benefits of in-situ sensors in precision agriculture. This need can be addressed by Ultra High Frequency Radio Frequency Identification (UHF-RFID.).

UHF-RFID is a wireless communication protocol defined by EPC Gen2 standards which operates in the 902–926 MHz band in the United States. On one end of the wireless link is a reader antenna, which is controlled by reader electronics and powered by a battery or other power supply (Fig. 1a). The other end is a passive RFID tag which consists of an antenna, an electronic chip, and a sensor or sensors, as shown in Fig. 1b. The reading process begins when the reader sends a pulse of radio frequency (RF) energy to a nearby passive sensor tag or tags (Fig. 1c). The tag harvests the RF energy sent by the reader to power up and take a measurement, then it modulates its impedance to change how RF energy is reflected from the tag. By doing so, the tag encodes its unique ID number and sensor information in the signal it reflects back to the reader (Fig. 1d). RFID tags can incorporate a variety of sensors such as temperature, humidity, light, soil moisture, or soil electrical conductivity. The communication protocol, which is the focus of this study, does not significantly depend on the type of sensor that is connected to the RFID chip.

UHF-RFID tags can be active, including a battery to supplement their power requirements, or passive, relying entirely on the RF energy sent by the reader. Passive RFID tags are battery-free, avoiding leaching of toxic chemicals used in batteries to the environment and eliminating the need to replace hundreds of batteries in the field during the busy crop season (Virtanen et al., 2011, Motroni et al., 2022).

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https://doi.org/10.1016/j.compag.2025.110506
Received 15 August 2024; Received in revised form 23 January 2025; Accepted 3 May 2025

In a field, the stationary tags would be on or near the ground so that soil-based sensors could contact the soil, while the reader would be mounted on a mobile piece of equipment such as an airborne drone, a tractor, or an irrigation system. As the equipment with the reader moves along the field, it collects data from sensors in different locations and it must be near the tag to do so. The maximum distance between reader and tag over which the tag receives enough power to transmit data is called the read range (Fig. 1e). Long read ranges are desirable to enable the reader to move around above the crop canopy.

Many RFID tags are designed to operate in open air, and their read range can be reduced by close proximity to soil or by obstructions, such as crops, in the line-of-sight between the reader and the tag. Several studies that investigated passive RFID communications in soil have found that increased soil moisture reduces power transmission for tags buried under the soil (Bauer-Reich et al., 2014; Bogena, 2009; Froliket al., 2018). When a tag is buried, the dielectric constant of the soil, which is a function of soil texture and soil moisture (Hallikainen et al., 1985), significantly impacts its resonant frequency. When a tag's resonant frequency changes but the reader's does not, the resulting frequency mismatch inhibits communication. Additionally, when electromagnetic waves propagate through moist soil containing mobile ions, the signal strength decreases exponentially with propagation distance. A tag placed on the soil surface avoids the problem of wave propagation through the soil, but is still impacted by the soil's high and variable dielectric constant.

Crops in the sight line between a tag and reader reduce the power transfer by scattering the electromagnetic waves. The impact of crop canopy on horizontal wireless links operating at 2.4 GHz and 920 MHz between two powered nodes at the same height above the ground has been studied in wheat, corn, rice paddies, gardens and vineyards (Li et al., 2013; Correia et al., 2014; Li and Gao, 2011; Balachander et al., 2013, Kuramoto et al 2018). However, the impact of crop canopy on communication between a ground level and an elevated antenna has not been well documented in the literature. Here we report the characterization of the vertical read range for near- soil passive UHF RFID tags at 915 MHz as a function of soil type, soil water content, and presence of crop canopy of different crops.

2. Materials and Methods

2.1. Reader, Antenna, and tags

The RFID tags were read using a commercially available RFID reader system (Thingmagic Sargas, Trimble, Sunnyvale, CA, USA) connected to a circularly polarized RFID antenna (MT- 262024/TRH/A/K from MTI Wireless Edge) with 30 dBm output power. The passive tags used in the study were Asygn AS3213.3 demonstration tags (Asygn, Grenoble, France). The tags included an on-chip temperature sensor and were not connected to any additional external sensors.

2.2. Soil Preparation and Details

Five types of soil were used: sand, a clay loam top soil (composite from McWilliams and Sons, Belgrade, MT), a 1:1 mix by volume of the loam and sand, a 1:1:1 mix by volume of peat moss, the loam, and sand, and a Farnuf series soil with high-clay content from north central Montana. The soils were used in azalea round pots (11.7 cm depth, 16.5 cm diameter). The dry bulk density, ρ, of each soil type was calculated by weighing soil samples after drying in an oven at 48 °C and 8 % relative humidity for a week. Subsequently, soils were watered to their holding capacity and weighed again. Table 1 shows the dry bulk density and holding capacity of each soil type. The saturated and dry masses

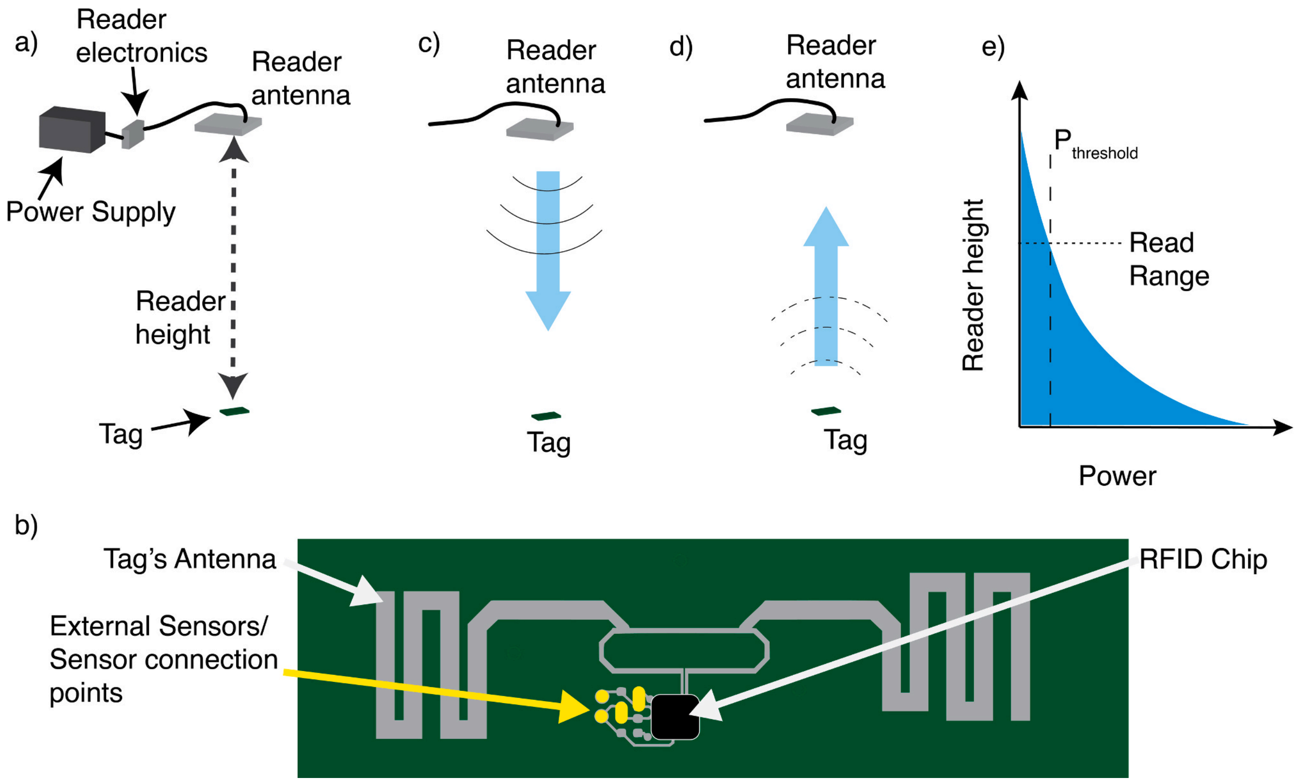

Fig. 1. (A) The RFID reader system includes a power supply, the reader electronics which initiate reading and process the received signals, and a reader antenna. (b) The passive tag includes an antenna, an RFID chip, and one or more sensors. (c) To initiate a reading, the reader sends an RF signal out. If a tag is in the vicinity of the reader, its own antenna will harvest some of the energy in the RF pulse to power on. (d) The tag modulates the reflected wave, encoding its ID number and sensor information in an RF signal sent back to the reader. (e) The power received by the tag decreases as the reader height increases. The read range is the maximum height at which the tag receives a minimum required (threshold) power.

Table 1
Soil density and water content bins.

Soil type	Dry Bulk Density (g/ cm^3)	Holding capacity VWC (%)	Range for low VWC	Range for medium VWC	Range for high VWC
Loam	0.75	48	0–16 %	16–32 %	32–48 %
Clay	0.85	38	0–13 %	13–25 %	25–38 %
Sand	1.12	22	0–7 %	7–15 %	15–22 %
1:1 Loam: Sand	0.98	28	0–9 %	9–19 %	19–28 %
1:1:1 Loam: Sand: Peat	0.77	47	0–16 %	16–31 %	31–47 %

were used to calculated volumetric water content, or VWC, which is defined as

$$\mathrm{VWC} = \frac{\text{volume water}}{\text{total soil volume}} = \frac{\text{dry bulk density} \times \text{mass water}}{\text{mass dry soil} \times \text{density of water}}$$

The mass of the pot was recorded every time RFID measurements were performed. The soil mass value was used to calculate the VWC for each soil type each day.

2.3. *Tag read range measurements*

An adjustable wooden stand was constructed to measure the read range, as shown in Fig. 2a. The reader was attached to a horizontal arm which extended 70 cm away from the vertical support piece. The vertical attachment position of the arm could be fixed by sliding pegs on the arm into a series of holes spaced in 5 cm increments in the vertical support. The height of the vertical support could be increased to achieve reader heights up to 2.75 m.

For each measurement, the reader started at 2.75 m and was lowered in 5 cm intervals until a signal from the tag was received. The height of the reader above the surface of the soil in the pot when the signal was received was recorded as the read range. The tags were placed parallel to the surface of the ground. The height of the tag above the ground was controlled by placing zero, one, or two 1.7-cm thick closed-cell foam blocks between the soil and the tag. Measurements were taken for two unique but identical tags at three different tag heights, for five soil types, on six days.

The VWC for each soil type was recorded on each day. Numerical VWC values were then binned as high, medium, or low. The cutoff points used to define the bins were set for each soil at 33 % of holding capacity and 67 % of holding capacity for that soil. The specific bins for each soil were defined so that each type included high, medium, and low. Defining the bins per soil type makes sense from an electromagnetics perspective as well because sandier soils, which have lower holding capacity, have higher dielectric constant at a given volumetric water content compared to finer textured soils (Hallikainen et al., 1985). The bin definitions for each soil type are shown in Table 1.

ANOVA was carried out using R packages car, emmeans, and ggplot2 (RStudio 2024.09.1 + 394) on the data set which included measured read range for two separate and nominally identical tags as a function of soil type, moisture level, and tag height above the soil.

2.4. *Crop canopy read range*

During crop canopy measurements, the reader was erected above a garden located at the Montana State University Horticulture Farm in

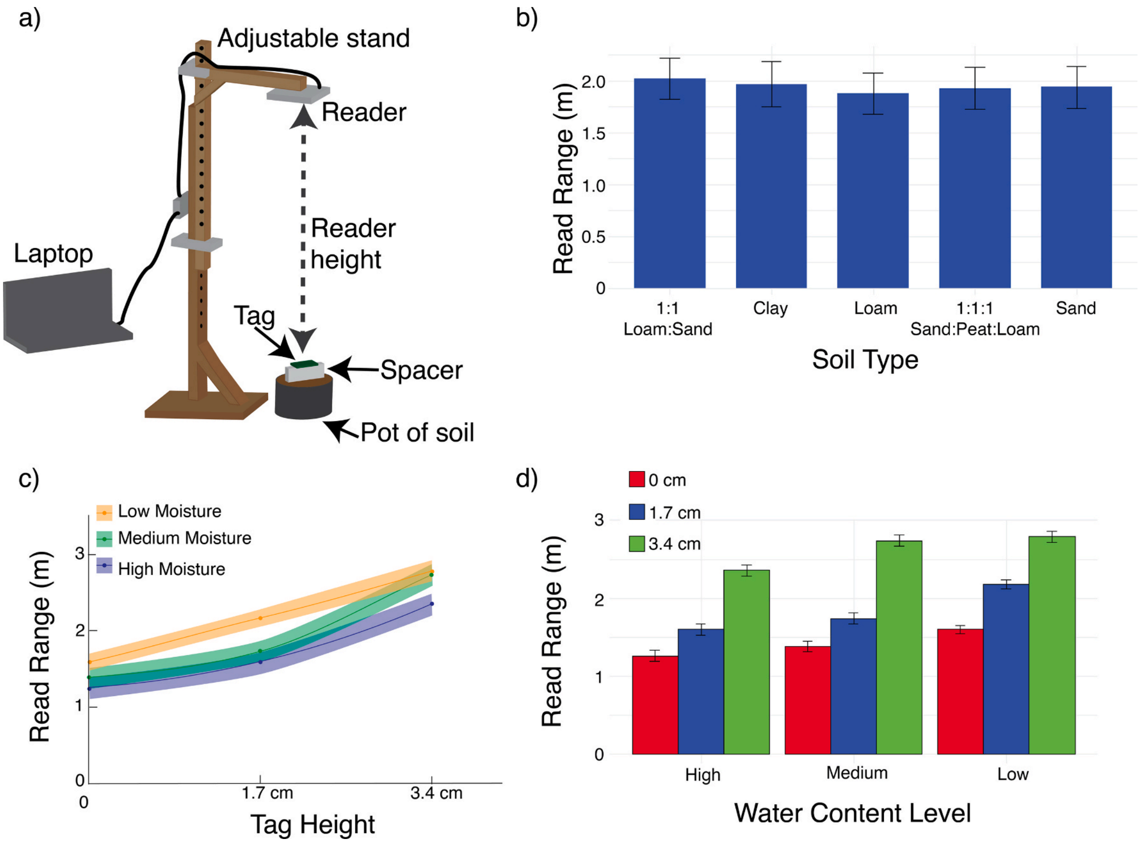

Fig. 2. (A) The measurement set up for studying the impact of soil type and VWC on read range. The sensor tag was placed on or slightly above the pot of soil, then the reader was moved towards the tag until the signal was established. (b) Read range as function of soil type. Error bars represent standard error. (c) Read range as a function of tag height and water content level. The area between the upper and lower 95% confidence levels are shaded. (d) The read range as a function of VWC and soil-tag spacing. Error bars represent the standard error.

Bozeman, MT. Soil in these plots consisted of 27 % sand, 42 % silt, 31 % clay. Plots of corn, sunflowers, and cabbage were selected to represent three distinct leaf shapes and plant architectures. To measure read range in crops, a ladder was set up near the edge of each plot. The reader, attached to its wooden extended arm, was taken up the ladder until the signal from the tag on the ground was lost, then lowered again until the signal was received. The height of the antenna was measured and recorded as the read range. Measurements were taken for tags directly on the soil and with 1.7 cm of space between the soil and the tag, and were repeated for two nominally identical tags. This experimental set up is shown in Fig. 3a.

2.5. Electromagnetic simulation

The electromagnetic finite element solver Ansys HFSS (AnsysEM20.1, Ansys, Canonsburg, PA, USA) was used to simulate the impact of the ground on antenna resonance. The simulated antennas used the silver folded dipole design described in (Baumbauer et al 2020). The reflecting plane was modeled as a perfect electrical conductor. Simulations were in Driven Modal mode and used a lumped port with 50 Ω impedance.

3. Results and Discussion

3.1. Soil type and water content impacts on read range

The read range was measured using pots of soil, with the tags placed on the surface, 1.7 cm, and 3.4 cm above the soil on three different days corresponding to different moisture contents. The maximum height of the stand was 2.75 m; in some conditions the read range exceeded the height of the stand, in these cases, the read range was recoded as 2.8 m.

We started with data of read ranges for two tags at three different tag heights, for five soil types, at three different VWC bins. We ran three-way ANOVA on this data and found significant effects at the 95 % confidence level for water content, tag height, and their interaction (Table 2). Soil type was not found to be significant, as shown in Fig. 2b and Table 2. Soil type did not interact significantly with tag height or water content.

We then ran two-way ANOVA to see the interaction of tag height and water content; the results are shown in Table 3. Fig. 2d shows the read ranges as a function of water content and tag height, where the bars represent the standard error. Fig. 2c shows the read range as a function of tag height for each water content; the shaded areas represent the 95 % confidence interval.

Tag height is the most significant factor impacting read range. Within each of the three water content bins, all three tag heights were significantly different, with no overlap of their confidence intervals.

Table 2
ANOVA table using a linear model with a three way interaction between tag height, water content, and soil type.

	Degrees of Freedom	Sum of squares	Mean Square	F Value	P
Soil Type	4	0.33	0.08	0.98	0.42
Tag Height	2	37.56	18.78	222.3	$< 2.2 \times 10^{-16}$
Water Content	2	6.25	3.12	36.99	3.1×10^{-13}
Soil Type: Tag Height	8	0.15	0.02	0.22	0.99
Soil Type: Water Content	8	0.66	0.08	0.97	0.46
Tag Height: Water Content	4	0.89	0.22	2.64	0.04
Soil Type: Water Content: Tag Height	16	1.02	0.06	0.75	0.74
Residuals	120	10.14	0.08		

Table 3
ANOVA table using a linear model with a two way interaction between tag height and moisture level.

	Degrees of Freedom	Sum of squares	Mean Square	F Value	P
Tag Height	2	37.51	18.76	232.97	$< 2.2 \times 10^{-16}$
Water Content	2	6.02	3.01	37.38	5.5×10^{-14}
Tag Height: Water Content	4	0.90	0.22	2.79	0.03
Residuals	156	12.56	0.08		

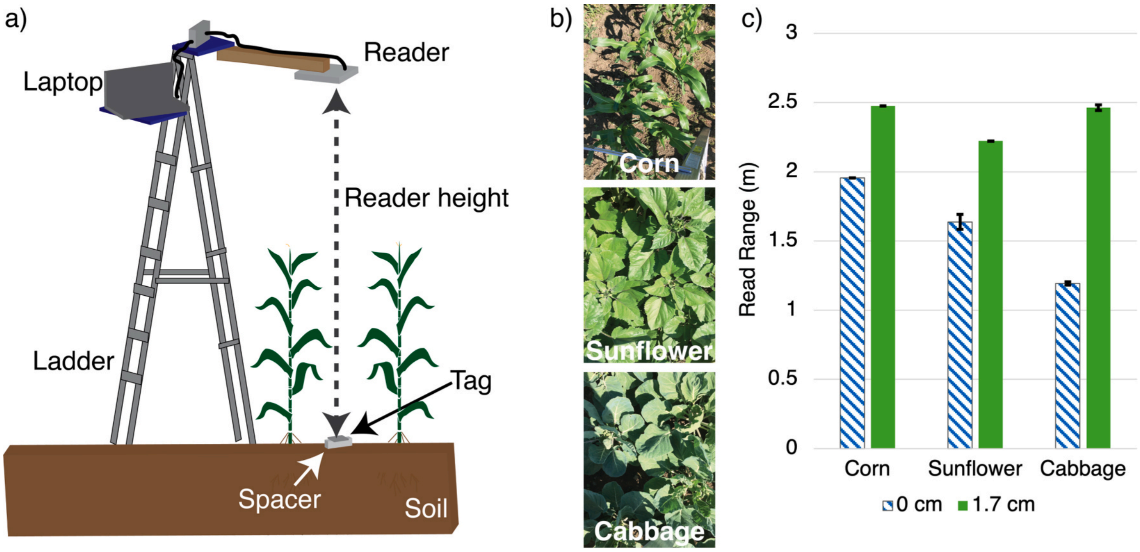

Fig. 3. (A) the measurement set up for studying the impact of crop canopy on read range. the sensor tag was placed on or slightly above the soil, under the crops, then the reader was moved away from the tag until the signal was lost. (b) areal views showing canopy closure of the corn (top), sunflower (center) and cabbage (bottom). (c) measured read range for tags under three types of crop canopies. error bars show the variance for each condition.

Water content was also statistically significant, as was its interaction with tag height. Lower water content is associated with higher read range and the impact of tag height was greatest for the dry soils. This suggests that for wetter soils, a tag height greater than 3.4 cm may be required to see the most significant increase in read range, and the heights tested in this study may not have captured the full impact of tag height for wet soil. It is also possible that even higher read ranges may be possible for dry soils, but we did not record them because the reader could only be raised to 2.75 m.

The dominance of tag height on read range is an important result. Because tag height is the most important factor to determine read range for all soil types and moisture levels tested, practitioners can use this finding regardless of the type of soil they work with.

3.2. *Influence of crop canopy on read range*

The impact of type of crop on read range was measured in the field. Tags were placed under growing crops and the maximum read range was measured, using the method described in section 2.4 and illustrated in Fig. 3a. The canopy height of the corn was 85 cm, sunflowers 92 cm, and cabbage 35 cm. The VWC in the top 10 cm of soil was measured with a handheld probe (HydroSense II, Campbell Scientific, Logan, Utah, USA) and found to be approximately 23 % under the corn, 32 % under sunflowers, and 35 % under cabbage. The saturation level for this soil was 35 % VWC. To quantify the canopy density, imaging processing software (MATLAB Image Processing Toolbox, MathWorks, Natick, MA, USA) was used to calculate canopy closure, or the percentage of the representative overhead image covered by green leaves. The corn had 43 % canopy closure, cabbage 90 %, and sunflower 100 %. Overhead images of the canopies are shown in Fig. 3b.

We performed 2-way ANOVA on the data using three crop types and two tag heights as independent variables with two replicates for each condition, and found that tag height was the most significant variable, while crop type and the interaction between crop type and tag height were also significant (Table 4). The read range for the different crop types and tag heights is shown in Fig. 3c and listed in table S1. The significant impact of tag height is clear in Fig. 3c, where the read range is considerably longer for the 1.7 cm case than the 0 cm case for all crop types. The interaction between tag height and crop type may be connected to the different soil moisture contents between the crop types. When the tag was on the surface of the soil, the read range varied primarily with soil VWC: cabbage had the wettest soil and the shortest read range. When the tag was raised on a block, the impact of VWC was reduced, and canopy density became a more significant factor: sunflowers had the densest canopy and the shortest read range. By studying three distinctly different crop architectures, we can see that multiple layers of overlapping leaves, as the sunflowers, led to the shortest read range with 1.7 cm of tag height. Although the cabbage's broad leaves blocked the line-of-sight between the tag and the reader, the single layer of leaves did not have a significant impact on read range.

This experiment was a small study with only two replicates, conducted at only one point in the growing season. Repeating it regularly as the crops grow would give greater insight into how increasing crop cover changes read range for each of the different plant architectures. The separate impacts of soil moisture and crops could be better distinguished by repeating measurements before and after an irrigation event.

Table 4
ANOVA table using a linear model with a two way interaction between tag height and crop type.

	Degrees of Freedom	Sum of squares	Mean Square	F Value	P
Crop Type	2	0.32	0.16	11.1	2.8×10^{-5}
Tag Height	1	1.88	1.88	129.0	0.0096
Interaction	2	0.35	0.17	11.8	0.0082
Residuals	6	0.09	0.01		

3.3. *Simulation and theory*

In order to understand the theoretical basis for the significant impacts of both soil moisture and tag height on read range, and predict how larger tag heights could further increase read range, we turned to electromagnetic theory and simulations.

During a reading, electromagnetic waves propagate first from reader to tag, then from tag to reader. In both directions, the wireless channel includes losses from free space propagation governed by the Friis equation (Balanis 2005), scattering off crops, and soil impacts. Because most powered readers are highly sensitive and can receive even weak responses, the limiting direction for systems that use passive tags is typically reader-to-tag. The tag must receive at least a threshold power, which is a parameter set by the circuits in the IC, known as P_{th}. The maximum read range, r_{max}, of an RFID system is given by equation (2).

$$r_{max} = \frac{\lambda}{4\pi}\sqrt{\frac{G_T G_R P_T m_{pol}\tau}{P_{th}}} \tag{2}$$

Where λ is the wavelength in free space, G_T and G_R are the gains of the transmit and receive antenna respectively, P_T is the power transmitted by the reader, m_{pol} is the polarization mismatch factor, and τ power transfer coefficient between the antenna and the IC.

For a large read range, r_{max}, G_R should be large. G_R is determined by the physical shape of the tag's antenna as well as the materials in close proximity to the antenna. The antennas used in this study were designed to have large G_R in free space, but close proximity to materials such as soil change the way they behave. The effect of the soil can be thought of in two ways 1) as dielectric loading, and 2) as a reflective surface. In the first model, the soil loads the antenna and shifts its resonance frequency out of the band of interest, which causes short read ranges. The closer the tag is to the soil, and the wetter the soil, the greater the impact. In the second model, the soil is modeled as a reflector. Electromagnetic waves reflect off boundaries between dissimilar media according to

$$\boldsymbol{Reflectedpower} = \left(\frac{\boldsymbol{\varepsilon}_1 - \boldsymbol{\varepsilon}_2}{\boldsymbol{\varepsilon}_1 + \boldsymbol{\varepsilon}_2}\right)^2 \tag{3}$$

Where $\boldsymbol{\varepsilon}_1$ and $\boldsymbol{\varepsilon}_2$ are the dielectric constants of the two different mediums.

At the boundary between wet soil with $\boldsymbol{\varepsilon}_r = 25$ and air ($\boldsymbol{\varepsilon}_r = 1$), $\left(\frac{25-1}{25+1}\right)^2 = 92\%$ of the power is reflected. Therefore, the ground can reasonably be modeled as a reflecting surface in simulation. Antennas were modeled in an electromatic simulation software with reflecting plane between 1 and 10 cm away from the antenna. Their performance was characterized by their power reflection coefficient, S_{11}, a standard metric for antenna resonance. An antenna with strong resonance and high gain will have a deep peak in S_{11}. Fig. 4 shows simulated S_{11} for dipole antennas with various distances to a reflecting plane.

The optimal antenna-reflecting plane the spacing in simulation was found to be 8 cm. This agrees with electromagnetic theory, which says that when the distance between an antenna and a reflecting plane is $\lambda/4$, the waves reflecting off the ground plane constructively interfere with the wave generated by the antenna (Balanis, 2005). This constructive interference creates a stronger signal than if the reflecting plane were absent. At 915 MHz, this critical distance $\lambda/4 = 8.2$ cm.

The peak S_{11} values in Fig. 4 can be used to calculate upper limits on read range by assuming a lossless antenna and using equation (2). From the simulation, an antenna 2 cm away from a ground plane has S_{11} of -2.2 dB, while an antenna 8 cm away has S_{11} of -40 dB. This means the antenna 8 cm away from the ground plane could have a gain 2.5 times higher than the 2-cm antenna, which would result in a read range about

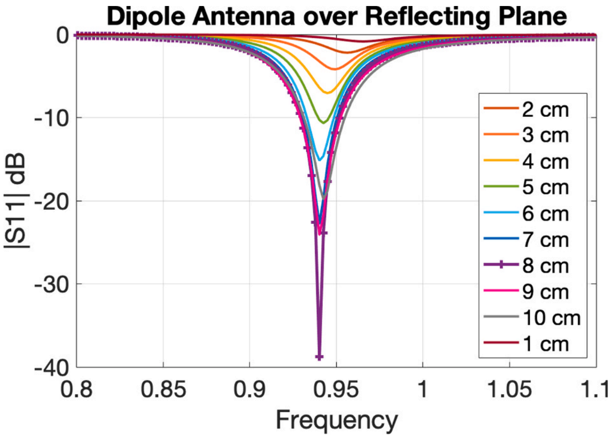

Fig. 4. Power reflection coefficient of antennas with different spacing between the antenna and a reflecting plane. The antenna spaced 8 cm from the plane has the deepest resonance peak, and the best performance.

1.6 times longer. For the Asygn RFID tags used in this study, we expect that at a tag height of 8 cm, the read range with saturated or very wet soils could be 2.4 m.

We modeled the soil as a reflecting plane in order to simplify the analysis, but did not investigate the impact of soil moisture, represented by the dielectric constant. The simulation results will be less accurate for drier soils, which have lower dielectric constants. We expect that for dry soils, the destructive interference at short tag heights and constructive interference at λ/4 will both be muted compared to the simulation. In brief, tag height will have a less significant impact on antenna performance in dry soil.

An antenna 8.2 cm above the ground might or might not be practical for field deployment, as it could be more intrusive and would require longer wires to connect to sub-surface sensors. Optimal antenna height/stake lengths become an application-specific optimization problem.

4. Discussion

The results of the soil type and water content study with those of the crop canopy study can be directly compared because the same RFID equipment was used in each study. The read ranges measured in corn are higher than the read ranges for dry soils. The read range for tag height 0 cm in cabbage was within the confidence interval for high moisture content soils at tag height 0 cm, which makes sense as the soil under cabbage was near saturation. However, the read range for cabbage with tag height 1.7 cm was 72 cm above the confidence interval for wet soil at that tag height. The read range in sunflowers was near the middle of the confidence interval for dry soil measurements for both tag heights. The discrepancy in read range between the two studies is interesting. The difference may be due to the different way that soils dry in pots compared to a garden plot. Antenna performance, and therefore read range, is primarily impacted by soil moisture at the surface. We measured soil moisture in the garden plot with a probe that reports average soil moisture in the top 20 cm, but if the surface layer is drier than that, the tag would primarily interact with drier soil.

The experiments presented here were done for RFID tags that included an embedded temperature sensor, but no external sensors. Some auxiliary sensors that can be attached to RFID tags require power. If such a sensor were attached, the threshold power for the tag, P_{th}, would increase and the read range would decrease (see Fig. 1e). This impact depends greatly on the type of sensor. For example, a 5 k Ω resistive sensor in a Wheatstone bridge configuration connected to the Asygn AS3213.3 chip we used does not change P_{th} for reading (Asygn, 2020). Tags by other manufacturers and other sensors will have different power requirements, and therefore different read ranges.

5. Conclusions

The novel, low cost, low power, plant-wearable and in-situ soil sensors which are rapidly being developed can only realize their full agricultural potential if their data can be collected.

UHF-RFID is a promising technique to power and collect data from these battery-free in-field sensors. Soil, especially wet soil, can reduce the read range of passive UHF-RFID tags by a meter or more. A highly effective way to avoid reductions in read range due to wet soil is to add space between the tag and the ground, which remains effective for all soil types, water content levels, and under crop canopies. Importantly, read ranges of over 2 m were recorded in all three crop types with only 1.7 cm of spacing between the antenna and the soil, even in the dense canopy of the sunflowers. This indicated that losses from crop canopies were less significant than losses from proximity to wet soil. With these long-read ranges, a system of many passive sensors and a few powered readers could be designed and deployed in agricultural fields with the powered unit mounted on existing infrastructure or drones that freely move above the crops.

CRediT authorship contribution statement

Carol L. Baumbauer: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David A. Baumbauer:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Ana C. Arias:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Jennifer Lachowiec for helpful discussions of statistical methods.

This work was supported by the National Science Foundation Graduate Research Fellowships under Grant No. DGE 1752814, and the Advanced Research Projects Agency— Energy award DE-AR0001013.

Author Statement*

Conceptualization: CB; Data curation: CB; Formal analysis: CB, DB; Funding acquisition: CB and ACA; investigation: CB and DB; methodology: CB and DB; project administration: ACA; resources: ACA, DB; software: CB; supervision: ACA; validation: CB; visualization: CB, DB; writing-original draft: CB; writing-review and editing: CB, ACA and DB

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2025.110506.

Data availability

Data will be made available on request.

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