2019

Using gprMax to Model Ground-Penetrating Radar (GPR) to Locate Corn Seed as an Attempt to Measure Planting Depth

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Abstract
Planting depth (PD) plays an essential role in crop production by substantially impacting germination rates and yield potential. However, techniques to measure PD nondestructively have not been developed. A two-dimensional gprMax simulation study was conducted to investigate the effects of soil electromagnetic properties on ground-penetrating radar (GPR) waves. The primary objective was to examine the possibility of using GPR as a nondestructive sensor to detect subsurface corn seeds with the goal of measuring PD. A conventional fixed-offset gprMax antenna in contact with the soil surface was used in the simulations. Corn seed models of different materials and sizes were simulated, with properties of natural and synthetic (metal) corn seeds. The seed models were spherical, with radial dimensions of 0.006 and 0.024 m to simulate small and large corn seeds, respectively. Corn seed models were embedded in three homogeneous soil models (sandy loam, loam, and clay), and 1.6 and 2.6 GHz antenna models were used as excitation frequencies. A-scans and B-scans were obtained from the simulations. The A-scans showed that all targets (small natural corn and metal corn models, and large natural corn and metal corn models) successfully provided response amplitudes proportional to their dielectric properties in sandy loam and loam, but not in clay. In high bulk density soils, GPR waves failed to penetrate the soil models, and the targets were not detected. The 2.6 GHz antenna provided better response amplitudes from the targets. In the driest soil models (2.5%, and 5%), no response amplitude signatures were observed. In dry and relatively dry soil models (15%), the simulation times were much shorter to obtain a response amplitude from the targets (with feeble response amplitudes) compared to relatively wetter soils. To validate these models, laboratory experiments were conducted with three treatment factors (soil type, planting depth, and moisture content). In dry soils, corn seeds could be detected using a 2.6 GHz GPR antenna; however, the detection varied substantially within replicates of the same moisture group. Further research is necessary to understand the effects of soil moisture on the detection variability of buried corn seeds.

Keywords
Corn seed, Dielectric permittivity, Electromagnetic waves, Finite difference time domain, GPR, gprMax

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
This article is published as Mapoka, Kenneth OM, Stuart J. Birrell, Mehari Tekeste, Brian Steward, and David J. Eisenmann. "Using gprMax to Model Ground Penetrating Radar (GPR) to Locate Agricultural Corn Seed As an Attempt to Measure Planting Depth." 62, no. 3 Transactions of the ASABE (2019): 673-686. DOI: 10.13031/trans.12809. Posted with permission.

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ABSTRACT. Planting depth (PD) plays an essential role in crop production by substantially impacting germination rate and yield potential. However, techniques to measure PD nondestructively have not been developed. A two-dimensional gprMax simulation study was conducted to investigate the effects of soil electromagnetic properties on ground-penetrating radar (GPR) waves. The primary objective was to examine the possibility of using GPR as a nondestructive sensor to detect subsurface corn seeds with the goal of measuring PD. A conventional fixed-offset gprMax antenna in contact with the soil surface was used in the simulations. Corn seed models of different materials and sizes were simulated, with properties of natural and synthetic (metal) corn seeds. The seed models were spherical, with radial dimensions of 0.006 and 0.024 m to simulate small and large corn seeds, respectively. Corn seed models were embedded in three homogeneous soil models (sandy loam, loam, and clay), and 1.6 and 2.6 GHz antenna models were used as excitation frequencies. A-scans and B-scans were obtained from the simulations. The A-scans showed that all targets (small natural corn and metal corn models, and large natural corn and metal corn models) successfully provided response amplitudes proportional to their dielectric properties in sandy loam and loam, but not in clay. In high bulk density soils, GPR waves failed to penetrate the soil models, and the targets were not detected. The 2.6 GHz antenna provided better response amplitudes from the targets. In the driest soil models (2.5% and 5%), no response amplitude signatures were observed. In dry and relatively dry soil models (1.5%), the simulation times were much shorter to obtain a response amplitude from the targets (with feeble response amplitudes) compared to relatively wetter soils. To validate these models, laboratory experiments were conducted with three treatment factors (soil type, planting depth, and moisture content). In dry soils, corn seeds could be detected using a 2.6 GHz GPR antenna; however, the detection varied substantially within replicates of the same moisture group. Further research is necessary to understand the effects of soil moisture on the detection variability of buried corn seeds.

Keywords. Corn seed, Dielectric permittivity, Electromagnetic waves, Finite difference time domain, GPR, gprMax.
SOIL MIXING MODEL

Soils are inherently complex, and the effects of soil physical properties on GPR performance must be considered. GPR sensors respond to changes in dielectric properties. Soil physical properties that have potential to influence soil dielectric properties are the bulk density, composition (sand, silt, and clay content), moisture content, and particle density. Thus, soil mixing models have been developed to predict the influence of soil physical properties on soil dielectric properties (Peplinski et al., 1995). A soil mixing model is a semi-empirical dielectric model that estimates the real and imaginary components of the dielectric permittivity (dispersive material properties) of a soil. Soil mixing models have been used to relate soil physical properties and soil composition with the dielectric permittivity and electrical conductivity of bulk soil (Miller et al., 2004; Chen et al., 2014). A realistic soil model can be modeled based on stochastic distributions of the soil properties. Some researchers have referred to these models as pedo-transfer functions in which soil dielectric properties are functions of the natural soil composition (Hendrickx et al., 2003).

GPR OPERATION PRINCIPLES

A typical GPR system consists of a transmitter antenna and a receiver antenna. The two antennas may be separated by some distance or packaged as a combined transmitter/receiver antenna. The antennas are located above the soil surface at a height determined by the operator. GPR transmits electromagnetic waves into the soil at center frequencies that can range from ~100 Hz to 2.6 GHz. In most cases, the center frequency is associated with the application and desired resolution. Electromagnetic waves are transmitted into the test material, and depending on the material’s dielectric properties, some fraction of the energy is reflected, while the remaining energy is transmitted through the material or absorbed by the material. Additionally, the center frequency and the dielectric properties of the test material can lead to polarization of the material, which can affect wave propagation (Neal, 2004; Sadiku, 2010). A typical GPR system includes a common-offset bistatic antenna placed near the soil surface, transmitting waves into the soil and receiving reflected waves from both the air-soil and soil-seed interfaces, as governed by the dielectric properties of each material (fig. 1). In GPR terminology, a plot of the reflected wave amplitude as a function of time is called a trace or A-scan. The A-scan represents a single static response from a target material, cell size (Δx, Δy, Δz) and time step (Δt), are used to discretize the domain with specific spatial and temporal resolutions, which affect the FDTD accuracy. The cell size needs to be smaller than the smallest wavelength. In modeling GPR wave propagation, the cell size has to be at least one-tenth less than the propagating electromagnetic wavelength (i.e., Δx = λ/10) to minimize numerical errors within an orthogonal grid. In this study, this criterion was used for selecting the most effective cell size and time step. The time step must

ELECTROMAGNETIC THEORY

Electromagnetic (EM) theory involves the study of moving EM fields in a given space and time. EM theory is governed by Maxwell’s equations and constitutive laws (Jol, 2009; Sadiku, 2010). The constitutive laws define the dielectric properties that govern the behavior of EM signals moving through a test material. The constitutive laws employ three dielectric properties: electrical conductivity (σ), dielectric permittivity (ε), and magnetic permeability (μ). These dielectric properties describe a material’s relationship with the EM field (Norimoto, 1976; Odhiambo et al., 2002; Orfanidis, 2002; Neal, 2004; Annan, 2009; Jol, 2009; Sadiku, 2010). In this study, the dielectric properties of soils were estimated using soil mixing models, and the subsequent effects on EM wave propagation were modeled. EM wave technology has been used in numerous agricultural sensing applications (Topp et al., 1980; Brisco et al., 1992; Yoder et al., 2001; Odhiambo et al., 2002; Allred et al., 2004, 2005, 2008). This study examined the possibility of determining corn seed depth using EM waves, which has not been previously investigated.
be less than the ratio of the cell size and the speed of light \( (c, \text{ m s}^{-1}) \) to satisfy the Courant limit condition that relates the stability of the spatial discretization to the required time step. The discretized components follow the Yee cell lattice, in which the constitutive properties for a particular medium are defined per cell joint of the Yee cell (Kunz and Luebbers, 1993; Ketata et al., 2010; Schneider, 2010; Warnick, 2011).

The FDTD framework uses the Yee scheme, in which the two complementary meshes of the electric and magnetic fields components are solved alternately. Yee (1966) termed the principle “leapfrog,” as the electrical component at time \( t \) is used to calculate the magnetic component at time \( t + 0.5\Delta t \), and, in turn, the electrical component at time \( (t + \Delta t) \). The sequential updating of the two components continues until the defined simulation time (time window) has elapsed. The absorbing boundary conditions are defined to truncate an infinite simulation domain to a finite size. Fields reaching the edge of the medium are truncated and absorbed, preventing reflections into the computational domain; hence, all components are zero at the boundaries. In this study, a Gaussian waveform signal source was defined and injected into the gprMax model to initiate wave propagation (Warren et al., 2016).

This study investigated the possible use of GPR for detecting corn seeds in a closed furrow with different soil conditions. The objectives of this study were to:
1. Model GPR transmission through a lossy medium.
2. Evaluate the probability of using GPR to detect corn seeds in a closed furrow with different soil conditions.
3. Investigate the effects of corn seed material and size on corn seed response.

**METHODOLOGY**

**SEED MODEL PROPERTIES**

In the simulation model, two materials were modeled to represent corn seeds with two different sizes. First, the physical and dielectric properties of corn (Zea mays) seeds were used. Second, a synthetic seed was modeled using the conductance of metal. These two seed models helped us to develop an understanding of the effects of seed material and size on the energy reflected from the seeds. Corn seeds have distinct shapes that can be modeled using conical, rectangular, triangular, or even spherical forms (fig. 2a). In the model, a spherical shape was used because it represented corn seeds well and was easy to implement. Measurements to estimate seed size were taken from a sample of 50 corn kernels. A digital caliper with 0.01 mm resolution was used to acquire these measurements (fig. 2b). The rectangular length, width, and thickness of each kernel were measured and averaged to estimate the mean kernel size and rectangular volume of the sample corn harvested in 2016 (20% MC, Iowa State University farm, Boone County, Iowa). The equivalent spherical volume was determined, and the corresponding spherical radius was 0.006 m. Thus, a spherical corn seed model was implemented with a 0.006 m radius and classified as a small size kernel. To evaluate the effect of kernel size, a large spherical corn kernel model was implemented with a radius four times that of the small kernel model (i.e., 0.024 m).

Research by Nelson (1987, 2005) and Trabelsi and Nelson (2003) predicting the dielectric permittivity of bulk corn samples enabled estimation of the dielectric permittivity of a single corn kernel. The bulk dielectric permittivity of corn is a function of the bulk density, single-kernel density, moisture content, temperature, and frequency. The bulk density of corn is 0.7208 g cm\(^{-3}\) (56 lb bu\(^{-1}\)); for a single kernel, the density ranges from 1.27 to 1.38 g cm\(^{-3}\) (Mészáros, 2007). The optimum moisture content is 11% for corn kernels stored at room temperature of 12.78°C to ensure the highest possible percentage germination rate (Sayre, 1940). Therefore, the dielectric permittivity of a single kernel was calculated according to the models developed by Nelson and Datta (2001) and Nelson (2015) for corn kernels with 11% moisture content, 1.275 g cm\(^{-3}\) kernel density, and 0.7208 g cm\(^{-3}\) corn bulk density.

The relative dielectric permittivity (\( \varepsilon_r \)) of a single corn...
seed was estimated to be 3.90 (unitless), and the magnetic permeability ($\mu$) of a dielectric or food material is usually equal to the permeability of free space: $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$ (Datta, 2001). Therefore, the relative magnetic permeability ($\mu_r$) of the corn seed models was set to 1 (unitless). Corn seeds in storage have low moisture levels; therefore, they have extremely low ionic movement, which leads to low ionic conductivity. However, based on Datta (2001), the electrical conductivity ($\sigma$, S m$^{-1}$) of a dielectric or food material is directly related to the dielectric permittivity and frequency ($f$, Hz), given as $\sigma = \epsilon \omega$, where $\omega$ is the angular frequency ($\omega = 2\pi f$ rad s$^{-1}$), and $\epsilon$ is the dielectric permittivity (F m$^{-1}$). Metals (e.g., stainless steel) are highly conductive or perfect electrical conductors (PEC). PEC is a built-in material function in gprMax (Warren et al., 2016). Based on the electrical conductivity table for metals, a stainless steel corn seed was defined to have an electrical conductivity of $\sigma = 1.45 \times 10^5$ S m$^{-1}$ (ECT, 2013). The electrical conductivity of a metal overshadows its dielectric permittivity polarization effect; therefore, the relative dielectric permittivity and permeability of stainless steel were defined as $\epsilon = -1$ (unitless) and $\mu = 1$ (unitless) (Howlader and Sattar, 2015).

Soil Model Properties

Soil heterogeneity is known to adversely affect GPR performance by decreasing the signal-to-noise ratio due to dielectric discontinuities in the soil, which leads to additional reflections or random scattering back to the soil surface, consequently masking the intended target responses. For instance, Chaudhari (2015) found that the organic matter content in a soil had a substantial impact on the soil’s dielectric properties. An increase in the soil organic matter content increased both the soil dielectric permittivity and loss factor. The soil surface roughness due to soil irregularities (e.g., rocks, soil texture, aggregates) can also have an impact on incidental waves and polarization, which may affect wave penetration (Flores et al., 2009). For instance, on rough surfaces, it is possible to have step changes in the dielectric properties of heterogeneous soils, which can influence GPR wave propagation.

In general, waves are more diffuse on rough surfaces and more directional on flat surfaces, and rough soil surfaces may lead to total absorption of the transmitted wave by the dielectric medium, a phenomenon referred to as Brewster angle (Hajnsek and Papathanassiou, 2005). Therefore, in the proposed lossy soil models, the soil surface was considered flat, and other interferences that could cause unwarranted backscatter, such as grass and woody materials (organic matter) were not included to reduce model complexity. In the developed models, the soil was assumed to be homogeneous, time-invariant, and isotropic. The homogeneity assumptions made the soil models linear, providing an explicit and easy understanding of the numerical results as influenced by critical soil and target factors that could limit in situ GPR wave surveys (Tzwere, 2011). However, these model assumptions also suppressed in situ soil conditions that are likely to degrade GPR waves during actual GPR measurements to locate corn seeds.

Soil mixing models were used to predict the soil dielectric permittivity and electrical conductivity. Three soil physical properties were investigated: volumetric moisture content (VMC), soil composition (sand, silt, and clay content), and soil bulk density. Typically, the soil VMC at planting is 15.00% to 40.00% (Weiler et al., 1998), where 15.00% is the minimum soil moisture required at planting. Therefore, in our simulation, two VMC values (2.5% and 5%) below the minimum required soil moisture and three VMC values (15%, 25%, and 40%) within the acceptable soil moisture range were investigated.

Three soil textures were investigated: sandy loam, loam, and clay. The soil compositions for the three soil textures, shown in table 1, were based on the Soil Survey Laboratory Information Manual (NSSC, 2011). In addition, three soil bulk densities were assessed: two standard (acceptable) soil bulk densities at planting were used to compute soil dielectric properties: 1.42 g cm$^{-3}$ for the sandy loam soil, and 1.2 g cm$^{-3}$ for the loam and clay soils (Hillel, 2003). A third soil bulk density (3.00 g cm$^{-3}$) was selected for all soil textures to investigate the impact of high soil bulk density on GPR wave propagation. The selection of the bulk density values was based on the soil bulk density of <1.60 g cm$^{-3}$ required at planting.

A soil particle density of 2.66 g cm$^{-3}$ was used for all simulations (Hendrickx et al., 2003; Miller et al., 2004). Because soils are inherently heterogeneous, it is challenging to understand the individual effects of different soil parameters (e.g., VMC, bulk density, and soil composition) on sensor response. In the simulation, three soil textures (sandy loam, loam, and clay) were used with different soil conditions. For each soil texture, one soil property was varied at a time, while the other properties were kept constant. With this approach, a range of soil dielectric properties was determined as a function of the different soil properties (tables 2 and 3) to investigate the effects of individual soil properties.

Water has high relative dielectric permittivity (~81), which influences the effective soil dielectric permittivity. The soil texture (e.g., clay) and soil bulk density mainly influenced the soil electrical conductivity (tables 2 and 3). When the soil bulk density was increased to 3 g cm$^{-3}$, each soil had increased soil electrical conductivity. These soil electrical properties were used in gprMax to evaluate the possibility of using GPR to detect different target materials and sizes.

Model of a Seed in the Soil

A 2-D simulation model consisting of a homogeneous distribution of relevant soil properties and seed dielectric properties was developed and used as the input to the gprMax software. The 2-D model was used to investigate the likelihood of obtaining a response from embedded corn seeds within the soil model. The corn seed targets were modeled to be at a 0.07 m depth in the soil medium. The 2-D model specified a rectangular domain with dimensions of

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>60%</td>
<td>22%</td>
<td>18%</td>
</tr>
<tr>
<td>Loam</td>
<td>48%</td>
<td>30%</td>
<td>22%</td>
</tr>
<tr>
<td>Clay</td>
<td>20%</td>
<td>10%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table 1. Soil compositions used to determine soil dielectric properties.
0.24, 0.21, and 0.002 m (x, y, z; 2-D models in gprMax are a single-cell slice of a 3-D model), whereby the soil model coordinates within the rectangular domain were at 0, 0, 0 m (bottom corner) and 0.24, 0.17, 0.002 m (top corner), creating a space for the antenna above the soil (fig. 3). The geometric model shown in figure 3b was stored as a vti object file, and a paraview package was used to display the geometry (a paraview package is a visualization tool used to display gprMax simulation images in vti format). The wave was discretized in space and time with a cell size of Δx = Δy = Δz = 0.002 m and a time step of Δt = 4.717 ps. This cell size was maintained throughout the simulation.

A lossy soil medium was defined by the dielectric permittivity, the magnetic permeability, and the soil electrical conductivity, as described in the Soil Model Properties section. The simulation time window was specified to be 5 ns. The algorithm was designed to have perfectly matched layer (PML) absorbing boundaries conditions (ABC), which enclosed the entire simulation domain at the edges. The purpose of the absorbing boundaries conditions was stated earlier in the gprMax Modeling section; further information on ABC is presented by Mur (1981, 1998) and Schneider (2010).

A Gaussian pulse waveform was provided as the excitation source in the gprMax model. The Gaussian waveform source had a current source of 1 A with a pulse time of 5.3125 × 10⁻⁸ s. The polarization was specified to be in the z-direction. The specified current was converted internally by the gprMax software to a related electric field strength amplitude in V m⁻¹ (herein referred to as the response amplitude). Based on the dielectric properties specified in the simulation model, the response amplitudes were simulated (tables 4 through 6). Simulations were conducted at two frequencies: 1.6 and 2.6 GHz. A conventional fixed-offset antenna was used in the simulations, whereby the antenna was positioned directly on top of the soil surface and stepped at increments of 0.002 m across the x-direction (horizontal) of the domain to locate the buried seed target. Every time the antenna was moved, a new A-scan was recorded; therefore, 60 A-scans were specified to create the B-scan. The total horizontal distance covered by the transmitter and receiver as they moved over the corn seed model was 0.12 m. The A-scan results were exported to Matlab for visualization.

### RESULTS AND DISCUSSION

In the GPR A-scans, the responses due to reflections at the air-soil and soil-seed interfaces can be observed (fig. 4). The response amplitudes for both target materials were reasonable and as expected. However, the responses at 2.5% and 5% VMC are not included in the plots because they had very low response amplitudes. Second reflections from the bottom of the large natural corn seed (0.024 m radius) were observed (fig. 4b). The small natural corn seed did not have observable second reflections (fig. 4a). The electric field interactions with the large seed provided higher peak response amplitudes compared to the small seed. The GPR wave response to the small seed approximated Raleigh scattering, as the natural corn seed model was small in comparison to the dominant pulse wavelength.

All A-scans showed a clear soil reflection (fig. 4). The magnitude of the signal transmitted into the soil decreased proportionally according to the magnitude of the soil dielectric permittivity and electrical conductivity. The dielectric contrast governed wave reflections at the air-soil and soil-seed interfaces; hence, the response amplitudes shown in figure 4 indicate the magnitude of the dielectric contrast between media in the model. For relatively dry soils, the reflections at the air-soil interface were lower, and the energy transmitted into the soil was higher, compared to wet soils.

In contrast, at higher soil VMC (25% and 40%), the soil absorbed a significant proportion of the GPR energy that was transmitted into the soil, and more energy was reflected at the air-soil interface. Higher VMC contributed to a higher dielectric contrast between the natural corn seed and the soil model, and hence the relatively higher response amplitudes in lossy wet soils (fig. 4). However, this phenomenon was the opposite for the metal seed models, for which the response amplitudes decreased with an increase in VMC (tables 4 and 5). In drier soils (≤15% VMC), the simulation time was much shorter for the response amplitude from corn seeds (i.e., less computation time was required to compute a model solution) compared to simulations with wetter soils.

As expected, the response amplitudes from wetter soils exhibited a longer time of flight (fig. 4), which means that the GPR wave velocity was reduced with high soil VMC. This phenomenon was observed for both the natural and
Throughout the simulations, the soil bulk density was kept constant for the sandy loam, loam, and clay soils, respectively.

The response amplitudes were extracted from the A-scans and recorded to indicate the presence of corn seed models. The magnitude of the response amplitude was proportional...
to the dielectric properties causing the change at the soil-seed interface, the GPR wave frequency, and the size and material of the corn seed model. The time of flight was influenced by the soil conditions, which governed the transmission of GPR waves through the soil model (tables 4 through 6).

Figure 4. A-scans for evaluating transmission of GPR waves through sandy loam soil at different volumetric moisture contents (VMC) with (a) small natural corn seed model (0.006 m radius) and (b) large natural corn seed model (0.024 m radius).
The metal seed models were subjected to the same soil simulation parameters used for the natural seed models, as listed in tables 2 and 3. The metal seeds were distinguishable by their response amplitudes, which were associated with size. The large metal seeds had higher response amplitudes compared to the small metal seeds (tables 4 and 5). The time of flight trends were similar to natural corn seeds when soil VMC was high. Large seeds provided a large surface area with which the GPR wave could interact. Regardless of size, metal corn seeds were highly responsive to GPR waves in dry and wet sand and loam soil conditions. At the driest soil conditions (2.5% VMC), the response amplitudes for both metal seed sizes were large. Unlike the natural corn seeds, the metal seeds did not have strong second reflections because metals are highly conductive. The electric field reaching the conductive seed induces a magnetic field that creates a current flow in the conductor, leading to a zero net electric field within the conductor. Thus, the entire GPR wave was reflected. Moreover, as the GPR wave traveled through wet soil, it was subjected to higher impedance due to the VMC and soil composition.

The clay soil had high electrical conductivity, which created high impedance and attenuation during GPR wave propagation. In the simulations, a small proportion of the transmitted wave penetrated the soil surface and instantly decayed to zero, failing to reach the corn seed targets. No response amplitude was registered from the embedded seed models in the clay soil. A higher proportion of the GPR wave was reflected at the soil interface. The model indicated that clay-rich soils might present challenges that would complicate GPR mapping of seeds. Neither target (natural or metal) provided a response amplitude in the clay soil.

SOIL BULK DENSITY AND ANTENNA FREQUENCY

The effects of high soil bulk density (3 g cm⁻³) and antenna frequency were evaluated. High soil bulk density adversely impacted GPR wave propagation by increasing the soil dielectric permittivity and electrical conductivity. These two parameters contributed to high soil impedance, creating an impenetrable and highly attenuating soil surface. As with the clay soil, high soil bulk density confounds GPR sensing applications. The high bulk density completely impeded GPR waves from entering the soil, making them unable to detect the target. Thus, no target response was observable in high bulk density soil. In addition, with the same high bulk density at the higher frequency of 2.6 GHz, shallowly embedded seed models could not be mapped due to high attenuation or absorption of the signal.

Consequently, there were no obvious target responses with high clay content and high soil bulk density at 2.6 GHz. However, when the high frequency was used with sandy loam soil with a low soil bulk density of 1.42 g cm⁻³, all targets (small natural corn and metal corn, and large natural corn and metal corn) were observed with larger response amplitudes. Table 6 presents the responses from the small and large natural corn seed models in sandy loam.

The high center frequency (2.6 GHz) led to shorter wavelengths and increased resolution, which improved the response amplitudes of small and shallow corn seed models. For instance, at the low center frequency (1.6 GHz), the response amplitudes for small natural corn seeds (0.006 m radius) were low (fig. 4a and table 4). However, for similar sandy loam soil conditions at 2.6 GHz, the response amplitudes increased by approximately 25.00% compared to the response amplitudes shown in table 4. For the large natural corn seed, the increase was approximately 30.00%. For all targets, the higher frequency provided larger response amplitudes for both target sizes.

This simulation study evaluated soil conditions and targets that would lead to successful GPR detection and identified soil conditions in which seeds could be detected by GPR after planting. For instance, clay-rich and denser soils should be avoided because of rapid attenuation in those conditions. Conversely, a higher center frequency would be beneficial, as the high center frequency (2.6 GHz) provided higher response amplitudes than the low center frequency (1.6 GHz).

The B-scans shown in figures 5 through 8 illustrate the dielectric contrast between the modeled soil and seed. A
stronger blue color in the B-scans indicates a higher negative response amplitude, and a brighter reddish color indicates a higher positive response amplitude. The implication is that a dielectric material (soil or seed) has a negative response (blue color) first, followed by a positive (red) response, and then blue again, as shown in figures 5 through 8, and vice versa for the metal corn models. For example, for the large natural corn seed (fig. 6), the first blue color response can be seen at the top and the second blue response at the bottom, with red in between. These color contrasts were more apparent for the large natural corn seed model with an increase in soil VMC. In practice, the response amplitude needed to detect the presence of a target depends on the contrast between the electrical properties of the target and of the surrounding medium. The results of the simulation models in this study indicate that natural corn seeds could be detected by GPR waves, under certain conditions.

SIMULATION MODEL VERIFICATION

The gprMax simulation models developed in this study correspond with other work on the detection of dielectric and conductive targets. Twizere (2011) showed that an increase in soil clay content led to an increase in dielectric properties, particularly the effective dielectric constant, of the soil model. According to his model evaluation, the wave velocity decreased rapidly due to the high dielectric constant and absorption, and the reflection of the waves increased at high soil density. Thus, a limited amount of GPR energy can penetrate the surface, with higher time delays and rapid attenuation. This phenomenon corresponds to the findings of our study, in which no corn seed response amplitudes were observed in the soil with high clay content with both low and high VMC.

Miller et al. (2002) showed that moist soils and clay soils markedly attenuated GPR waves. In our study, GPR waves
entering the soil surface decreased proportionally with an increase in VMC. Our simulation results indicated that corn seed models provided better response amplitudes as the VMC increased from 2.5% to 40%, which coincides with the results of Miller et al. (2002). Their results showed that nonmetallic landmines with dielectric constants of 3.2 were more detectable at higher soil moisture rather than at lower moisture. At lower VMC, there was not enough contrast between the soil and the nonmetallic landmine to provide a substantial response, similar to our study. The metal corn seed models were highly responsive to GPR waves in all soil conditions. However, at higher VMC, the response amplitudes tended to decrease.

GPR has been considered by agricultural researchers as a method to improve data collection for precision agriculture applications, such as measuring soil moisture, locating drainage pipes and hardpans, and studying root morphology and biomass. Butnor et al. (2001) investigated tree root biomass in soil with high clay and VMC. Attenuation was rapid, and the assessed depth was severely restricted (Butnor et al., 2001). Butnor et al. (2001) used two antenna center frequencies (400 MHz and 1.5 GHz) and reported that 1.5 GHz provided higher resolution and distinguished more roots in the upper soil profile compared to 400 MHz. In our simulations, the dielectric corn seed provided higher response amplitudes at 2.6 GHz compared to 1.6 GHz. Butnor et al. (2001) also demonstrated that root size had a profound effect on response amplitude: the larger the target, the higher the response amplitude. They also indicated that the root moisture content had a significant impact on the detectability of roots.

Our gprMax simulation results align with the results reported by Butnor et al. (2001). A positive implication for GPR detection of in situ corn seeds is that seeds are live grains and have a certain moisture content. In our simulations, the corn seed dielectric constant was estimated using a moisture content of 11.00%. The estimated dielectric constant created a substantial dielectric contrast between the seed model and the surrounding soil model, which led to the proportional GPR wave response amplitudes presented in this article. For the natural corn seed model, the dielectric contrast resulted in increasing response amplitudes that were proportional to the increase in soil VMC for the different soil types.

**EXPERIMENTAL VERIFICATION**

The simulation results indicated that corn seeds could be detected in certain soil conditions, with strong response amplitudes (tables 4 through 6) or hyperbolic responses (figs. 5 through 8). Based on the simulation results, we opted to use soils with low electrical conductivity (non-saline), low clay content, and low bulk density for possible mapping of corn seeds. In sandy loam soil using a 2.6 GHz antenna, the response amplitudes (table 6) were much improved compared to the 1.6 GHz antenna results (table 4). Because the soil models were homogeneous, real soils were processed (crushed and sieved to remove clods and other sediments) and prepared accordingly.

Laboratory experiments were performed under controlled conditions in soil bins using a 2.6 GHz GPR antenna. A non-saline sandy loam soil with 67% sand, 25% silt, 8% clay, and a measured density of 1.41 g cm\(^{-3}\) was used for the validation. Three soil moisture contents, classified as dry (2.95% average), low (11.34% average), and medium (16.67% average), were assessed. The measured VMCs of 2.95%, 11.34%, and 16.67% corresponded to the simulation VMCs of 2.50% to approximately 15.00%. The corn seeds were variety P0339AMXT with Precision Design Round size (Pioneer Hybrids, Johnson, Iowa) with a measured moisture content of 10.05% (corresponding to the 11% corn moisture content used in the simulations). A low soil VMC of 2.95% and corn seed moisture content of 10.05% created an environment in which GPR might not detect the corn seeds because the corn and soil moisture contents were similar. The corn seeds were buried at three depths (0.0381, 0.0635, and 0.0889 m) and two seed spacings (0.1524 and 0.254 m). Five replicates were collected per soil moisture level. Data were processed using the matGPR package to enhance readability and interpretation (Tzanis, 2013, 2015). The acquired data
were first filtered to suppress horizontal bands, ringing noise, reverberations, and clutter in the B-scans. In some cases, filtering suppressed pixels with important target information, making detection of the target more difficult. Fast discrete curvelet transform (FDCT) was then used to clarify edges within the images, followed by an edge-detection algorithm to enhance the images (Tzanis, 2013, 2015). The algorithm parameters used in the filtering were dependent on each B-scan.

**EXPERIMENTAL RESULTS**

The GPR data collected in the verification experiment showed mixed success. Figures 9 and 10 show raw B-scans with partial detection of corn seeds and processed B-scans with enhanced edges and reduced clutter or noise.

The B-scan in figure 9a was collected in dry sandy loam in which not all buried corn seeds were detected. Shallower seeds had the highest probability of being detected. The deeper the corn seeds were buried, the harder they were to detect. Moreover, in some of the replicated B-scans, no traceable responses were visible in the raw or processed image. In general, drier soils presented greater probability that corn seeds could be detected. Even though the soils were dry, it is evident from figure 9a that seed responses were evanescent, quickly fading as the GPR wave traversed deeper depths, and the targets exhibited faint hyperbolic responses. However, in our simulation results, no response amplitude was registered in dry soils. GPR waves are sensitive to moisture, and the sandy loam soil and field corn had average moisture contents of 2.95% and 10%, respectively. The moisture difference (7.1%) between the two materials may have contributed to the detectability of corn seeds in the laboratory tests, which was not like the simulation results. In the simulation, the dielectric contrast between the soil model ($\varepsilon = 3.41$ or 4.25 at 2.5% or 5% VMC) and corn model ($\varepsilon = 3.9$ at 11% moisture) was approximately 0.35 or 0.49, which did not create a strong dielectric contrast.

The simulation results indicated that corn seeds could be detected in medium moisture conditions due to the high dielectric contrast. However, in the experimental results, low dielectric contrast was observed between the surrounding soil and the corn seeds in moist sandy loam (fig. 10a). If there was any dielectric contrast between the two materials, it was probably masked by other factors within the soil ma-

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**Figure 9.** (a) Raw and (b) processed GPR data collected from dry sandy loam soil. Red arrows indicate nominal corn seed positions, yellow arrows indicate responses that could be corn seeds or clutter, and white arrows indicate approximate corn responses ($t_1$, $t_2$, and $t_3$ represent the time of flight to the corn seeds, which corresponds to the nominal depth).

**Figure 10.** (a) Raw and (b) processed GPR data collected from moist sandy loam soil. Red arrows indicate corn seed positions.
trix, such as the attenuation of waves, slower wave velocity due to higher moisture, and irregular reflections due to clutter. The processed B-scan (fig. 10b) shows multiple hyperbolic responses, which suggests that corn seed responses could be among the several responses. Therefore, based on the raw and processed B-scans in figure 10, we indicated locations where corn seeds could reside. Multiple reflections, where corn seeds were thought to be, made it difficult to discern which responses were from corn seeds. This phenomenon was observed across the replicates collected at low and medium soil VMC.

The extracted time of flight (TOF) and response amplitude for the dry, low, and medium VMC soils are shown in table 7. The TOF and response amplitude data were extracted from the processed B-scans (figs. 9b and 10b) using a FORTRAN algorithm. In the algorithm, the apex of the hyperbolic response is identified in the B-scan by specifying a window in which the algorithm resolves the two parameters automatically. Features were defined in dry soils (less interference), which made it easier to specify the window in which to extract the information compared to wetter soils due to the high level of clutter. The extracted TOFs were adjusted to remove the coupling time at the soil-air interface (time zero-correction). The TOFs can be used to estimate nominal corn seed depths. Table 7 shows that the response amplitudes in dry VMC soils were high compared to the low and medium VMC soils.

An opposite trend in peak response amplitude was observed between the simulation results (table 6) and the experimental results (table 7). The time of flight followed the same trend in the verification experiment as in the simulation. At low VMC, the detection time was quicker; conversely, at high VMC, detection was slower.

**CONCLUSION**

Using ground-penetrating radar (GPR) for seed depth detection is highly dependent on the soil physical properties and on the contrast between the dielectric properties of the seed and the surrounding soil matrix. Two-dimensional grpMax simulation models were developed for preliminary evaluation of the potential of using GPR for seed depth detection. Laboratory experiments were conducted to validate the trends exhibited in the simulation results. The overall conclusions from this study include:

- The simulation results predicted that GPR could be used to locate natural corn seed models in certain soil conditions, including low clay content and low soil bulk density. There was substantial attenuation in soils with high clay content and high bulk density, which made successful seed detection unlikely.
- A higher frequency (2.6 GHz) was determined to have better probability of detecting small (standard size) corn seeds.
- The simulation results predicted that response amplitudes were better at 40%, 25%, and 15% soil VMC and low to negligible at 5%, and 2.5% soil VMC. Dielectric contrast between the seed and the soil was necessary for detection.
- Laboratory experiments showed that 2.6 GHz could detect shallow corn seeds in dry soil conditions; however, as seed depth increased, GPR wave strength rapidly decayed, leading to no detection.
- In the laboratory tests, corn seed detection became increasingly difficult at higher soil moisture contents. At higher moisture contents, clutter due to constructive and destructive interference between multiple overlapping hyperbolic responses resulted in greater clutter in the B-scans. This was not consistent with the simulation results.
- The results from the simulation model aligned with work performed by several researchers in locating buried metal and dielectric (roots) targets in different soil conditions.

The simulation and experimental results indicated that GPR has potential to locate corn seeds in sand, loam, and low clay content soils (unless the soil bulk density is high) at specific soil moisture contents. The overall conclusion is that detecting buried corn seeds in soils may be possible using GPR, but the method requires additional study to determine if robust and reliable detection of buried corn seeds is possible under all necessary field conditions.

**REFERENCES**


