ICPA
17th INTERNATIONAL CONFERENCE ON PRECISION AGRICULTURE
ConBAP 2026
CONGRESSO BRASILEIRO DE AGRICULTURA DE PRECISÃO E DIGITAL
13-16 July 2026 | Porto Alegre, Brazil
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# Impact of Soil Heterogeneity and Precision Air Seed Drill Settings on Maize Emergence Uniformity: Toward Sensor-based Predictive Models

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**A paper from the Proceedings of the**

**17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture**

**13-15 July 2026**

**Porto Alegre, Brazil**

## Abstract.

*Soil spatial heterogeneity influences crop establishment, but sowing is typically performed using uniform machine settings that do not account for within-field heterogeneity. This study aimed to assess how factors affecting maize (Zea mays L.) emergence vary between growing seasons by integrating sowing parameters, soil conditions, and soil–machine interactions. Field experiments were conducted over two growing seasons (2025 and 2026) in silt loam soils in northern France using a modified precision air seed drill equipped with proximal soil sensors. A Box–Behnken design was used to test the effects of three sowing parameter, sowing depth, downforce, and closing-wheel weight. Soil variables, including moisture, electrical conductivity, and optical reflectance, as well as gauge wheel load (GWL), were continuously recorded. Emergence was quantified through early emergence (E1), cumulative emergence (CE), and the Emergence Rate Index (ERI). Soil moisture was higher in 2025 than in 2026, indicating more limiting conditions in 2026. In 2025, emergence was primarily influenced by sowing parameters, particularly sowing depth and its interaction with downforce, while soil variables played a secondary role. In contrast, in 2026, sowing depth remained a significant factor influencing emergence, but the overall contribution of machine settings decreased, while soil-related variables and soil–machine interactions became important factors of emergence variability. These results demonstrate that the factors influencing emergence highly depend on environmental conditions, especially water availability. Under non-limiting water availability conditions, machine settings dominate, whereas under limiting conditions, soil conditions and soil–machine interactions become critical. This highlights the need for adaptive, sensor-based sowing strategies to dynamically adjust machine settings to spatial and temporal variability.*

***Keywords:*** *sowing optimization; crop emergence; sowing parameters; soil heterogeneity*

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# Introduction

Soils are naturally heterogeneous due to their formation processes and the influence of land use and management (McBratney and Mulla, 2001). At the intra-field scale, this heterogeneity becomes particularly relevant in agricultural systems, as different areas of a field respond differently to tillage, traffic, and moisture dynamics. This spatial variability is a fundamental component of soil-specific farming and underpins precision agriculture approaches such as site-specific management and variable-rate applications (Lal and Stewart, 2015). Within-field soil heterogeneity directly affects plant responses and crop performance (Earl et al., 2003; Groß et al., 2023). It strongly influences crop establishment by modifying the local conditions surrounding each seed. Uniform seedling emergence is a key determinant of yield potential, as early growth stages are highly sensitive to environmental constraints (Lamichhane et al., 2018; Rajjou et al., 2012). Delays in emergence can lead to uneven plant development and increased intra-row competition, ultimately reducing yield (Andrade and Abbate, 2005; Pommel et al., 2002).

These spatial variations in emergence are driven by soil physical properties such as moisture, temperature, bulk density, and mechanical resistance, which affect water uptake, germination, and seedling growth (Egli and Rucker, 2012; Lipiec et al., 1991; Paul W. Unger et al., 1994). However, current sowing practices generally rely on uniform machine settings, which do not account for this spatial variability.

Precision air seed drills offer the possibility to partially control the seedbed environment through adjustments such as sowing depth, downforce, and closing-wheel pressure. Previous studies have shown that these parameters significantly influence emergence (Nemergut et al., 2021; Virk et al., 2021). However, they are often studied independently, whereas in field conditions they interact with each other and with soil properties to determine crop establishment.

Recent advances in proximal soil sensing provide new opportunities to characterize soil conditions at fine spatial scales and to integrate this information into sowing operations (Oliveira et al., 2025; Viscarra Rossel et al., 2011). However, the combined influence of sowing parameters and soil conditions on crop emergence remains poorly understood. The objective of this study was to investigate the influence of soil heterogeneity and sowing parameters on crop emergence under field conditions, and to assess how these relationships vary across two contrasting growing seasons, with the aim of improving emergence uniformity.

# Materials and Methods

### 2.1 Experimental site

Field experiments were conducted during two growing seasons (2025 and 2026) in neighboring maize (Zea mays L.) fields located in Troissereux (Oise, Hauts-de-France, France; 49°28′24″N, 2°04′23″E). Both fields, cultivated within the same farm under similar pedological conditions (silt loam soil), were considered field-scale repetitions of the experimental setup. The use of two distinct fields across consecutive years was dictated by crop rotation constraints, precluding maize cultivation on the same plot while ensuring comparable soil conditions. The sites exhibited spatial heterogeneity due to historical management practices. Sowing dates were April 29, 2025, and April 21, 2026. Assuming that plant-available water was at field capacity at the beginning of winter, the initial plant available water (PAW) at sowing was estimated between 10 and 40 mm for both years (Schell et al., 2025). However, in 2025, sowing occurred shortly after rainfall events (15 mm), resulting in moderate but transient water availability, whereas in 2026, the absence of recent precipitation led to very low water availability.

## 2.2 Experimental design

A Box–Behnken experimental design (Gauchi, 2016) was implemented in both years to evaluate the effects of three key precision air seed drill settings (i.e. sowing parameters): sowing depth, hydraulic downforce, and closing-wheel additional weight. Each factor was tested at three levels, enabling the evaluation of linear, quadratic, and interaction effects, soil conditions were characterized using continuous data collected by embedded sensors during sowing, allowing the joint analysis of machine settings and soil properties.

In 2025, a broad range of factor levels was explored to characterize response patterns. Based on these results, the experimental domain was refined in 2026, particularly for sowing depth, to focus on agronomically relevant ranges while maintaining the ability to assess interactions. The specific factor levels and treatment combinations for both years are presented in Table 1.

**Table 1. Experimental design showing the combinations of sowing parameters (downforce, sowing depth, and closing force) for the 2025 and 2026 trials.**

| Treatments | Downforce (bar) | Sowing Depth (cm) | | Additional Closing Force (kg) |
|---|---|---|---|---|
| | | 2025 | 2026 | |
| **1** | -20 | 3.2 | 4.5 | 25 |
| **2** | -20 | 7.5 | 7 | 25 |
| **3** | 60 | 3.2 | 4.5 | 25 |
| **4** | 60 | 7.5 | 7 | 25 |
| **5** | -20 | 5.5 | 5.5 | 0 |
| **6** | -20 | 5.5 | 5.5 | 50 |
| **7** | 60 | 5.5 | 5.5 | 0 |
| **8** | 60 | 5.5 | 5.5 | 50 |
| **9** | 20 | 3.2 | 4.5 | 0 |
| **10** | 20 | 3.2 | 4.5 | 50 |
| **11** | 20 | 7.5 | 7 | 0 |
| **12** | 20 | 7.5 | 7 | 50 |
| **13** | 20 | 5.5 | 4.5 | 25 |
| **14** | 20 | 5.5 | 4.5 | 25 |
| **15** | 20 | 5.5 | 4.5 | 25 |

To ensure adequate coverage of soil heterogeneity, treatments were spatially distributed across the field based on previously delineated soil zones derived from proximal sensing data. Within each zone, three replicates were established, and treatments were randomly assigned. Experimental areas were defined by excluding a 24 m buffer zone along field borders and removing sprayer tracks. Each experimental unit of one treatment consisted of a 50 m × 3 m sowing strip.

## 2.3 Sowing system and instrumentation

Experiments were conducted using a modified KUHN MAXIMA 3 TI (6-row) precision air seed drill (KUHN S.A., Saverne, France). The system was adapted to allow independent adjustment of sowing parameters and to monitor soil–machine interactions during operation. Gauge wheel load (GWL) sensors were installed on the first-row unit to monitor the residual load applied by the gauge wheels during sowing, providing a continuous signal of soil–machine interaction. In addition, a Veris® FurrowScan system (Veris Technologies Inc., Salina, KS, USA) was used to characterize soil conditions in the furrow, providing measurements of moisture, apparent electrical conductivity (ECa), and optical indicators (red and infrared reflectance). Soil moisture was estimated by the sensor system based on dielectric permittivity measurements.

### 2.4 Measurements

During sowing, soil- and machine-related variables were continuously recorded using the embedded sensors described in *Section 2.3*. These variables included moisture, apparent electrical conductivity, optical indicators (red and infrared reflectance), and residual load measured at the gauge wheels. Sensor data were used as explanatory variables to characterize soil conditions and soil–machine interactions along each sowing strip.

Following sowing, seedling emergence was monitored within each sowing strip. A 10 m-long section was delimited at the center of the experimental area, including rows 3 and 4. Seedling emergence was monitored over three consecutive days, to quantify early emergence and the assessment of emergence uniformity. One week later, an additional observation was conducted to record late-emerging plants, defined as those emerging between the fourth day after sowing and one week after the beginning of the initial observations. Seedling emergence was monitored during early crop development using three complementary indicators: (i) early emergence (E1), defined as the number of plants emerging on the first day; (ii) cumulative emergence (CE), corresponding to the total number of emerged plants recorded during the observation period; and (iii) the Emergence Rate Index (ERI), calculated according to the emergence speed index (Maguire, 1962), which integrates both emergence rate and uniformity.

$$\mathrm{ERI} = \sum \frac{\mathrm{Ei}}{\mathrm{Ni}} \quad (1)$$

where *Ei* the number of seedlings emerged on day i, and *Ni* is the number of days since first seedlings emerged.

### 2.5 Statistical analysis

Linear mixed-effects models were used to assess the influence of sowing parameters and soil-related variables on emergence indicators. Fixed effects included sowing depth, downforce, closing-wheel weight, their interactions and soil variables derived from proximal sensing, while spatial structure was treated as a random effect. Analyses were performed separately for each year, and results were compared evaluating the stability of the factors controlling crop emergence under contrasting environmental conditions.

## Results

Model performance differed across emergence indicators, with higher marginal and conditional $R^2$ values consistently observed for E1 and ERI compared to CE in both years. In contrast, lower $R^2$ values were observed for CE, particularly in 2026, indicating a reduced explanatory power of the model for cumulative emergence. Marginal $R^2$ represents the variance explained by fixed effects, whereas conditional $R^2$ includes both fixed and random effects.

**Table 2. Model performance (marginal and conditional $R^2$) for emergence indicators in 2025 and 2026.**

| Year | Indicator | $R^2$ Marginal | $R^2$ Conditional |
|---|---|---|---|
| **2025** | CE | 0.770 | 0.781 |
| **2025** | E1 | 0.832 | 0.833 |
| **2025** | ERI | 0.875 | 0.880 |
| **2026** | CE | 0.426 | 0.591 |
| **2026** | E1 | 0.765 | 0.771 |
| **2026** | ERI | 0.802 | 0.802 |

Based on the models, the influence of sowing parameters on crop emergence was further examined. In 2025, crop emergence was influenced by sowing settings across all analyzed indicators. Sowing depth had a dominant effect on all response variables ($p < 0.001$), with a significant quadratic component consistently observed, indicating a pronounced non-linear response. Applied load also significantly affected E1, CE, and ERI ($p < 0.001$), and its interaction with sowing depth was highly significant across all models, highlighting a strong combined effect of these parameters on crop establishment. Closing-wheel weight showed a significant influence on early-stage emergence (E1) and emergence dynamics (ERI) but had no significant effect on cumulative emergence (CE). Similarly, the interaction between sowing depth and closing-wheel weight was significant for E1 and ERI, but not for CE.

Regarding soil-related variables, some factors showed significant associations with emergence, particularly in early stages. ECa significantly influenced E1 and ERI, while infrared measurements and soil moisture were negatively associated with CE and ERI. However, these effects were less consistent and generally weaker compared to those of machine settings. Overall, sowing parameters, particularly sowing depth and its interaction with downforce, were the primary drivers of emergence variability, while soil-related variables contributed as secondary factors.

In 2026, the influence of sowing parameters on crop emergence was less pronounced compared to 2025, with fewer significant effects observed across the evaluated indicators (E1, CE, and ERI). For cumulative emergence (CE), sowing parameters did not show significant effects. In contrast, the residual gauge wheel load (GWL), representing soil–machine interaction, significantly influenced CE ($p < 0.01$), together with several soil-related variables such as infrared and red reflectance, indicating a role of soil conditions and mechanical feedback in determining emergence outcomes 2026.

Early emergence (E1) remained sensitive to sowing depth, which showed a significant linear and quadratic effect ($p < 0.001$), confirming a non-linear response. Closing-wheel weight also had a significant effect ($p < 0.05$), whereas downforce showed no significant influence. Both GWL and soil-related variables, including ECa, infrared reflectance, and soil moisture, were significantly associated with E1, highlighting the combined influence of soil conditions and soil–machine interaction on early emergence.

For emergence dynamics (ERI), sowing depth was the only machine adjustment with a significant effect ($p < 0.01$), including a quadratic component. In contrast, GWL and soil-related variables played a major role, with ECa, infrared reflectance, red reflectance, moisture, and GWL all showing significant contributions. Figure 1 presents the coefficients for ERI in 2025 and 2026, allowing comparison of the relative magnitude and direction of the effects of the explanatory variables.

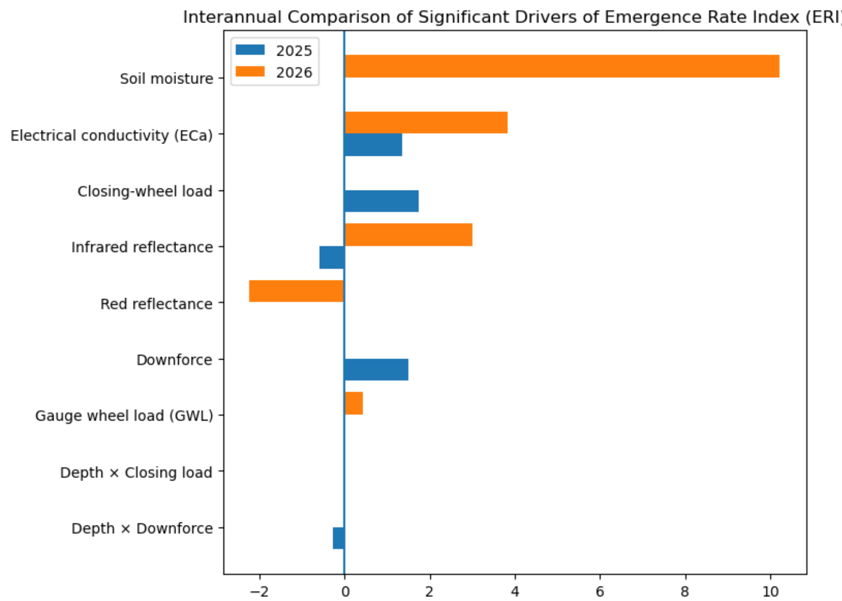


**Figure 1. Coefficients for the Emergence Rate Index (ERI) in 2025 and 2026. Bars represent the direction and relative magnitude of variable effects. Sowing depth was excluded from the figure to improve readability due to its dominant effect.**

# Discussion

The results revealed contrasting drivers of crop emergence over the years. While machine settings were the primary determinants of emergence in 2025, soil conditions and soil–machine interactions became more important in 2026.

Sowing depth remained the key factor influencing early emergence and emergence dynamics, with a significant quadratic response, indicating the existence of an optimal depth beyond which emergence performance declines. This result was consistent with the findings of(Nemergut et al., 2021), who reported that emergence uniformity in maize is maximized within an intermediate placement interval (51–76 mm). As shallow placement increases sensitivity to microscale fluctuations in soil moisture and temperature (Knappenberger and Köller, 2012; Schneider and Gupta, 1985). While moving the seed deeper improves access to more stable moisture conditions, However, in the studied context, sowing depths beyond approximately 6–7 cm tended to be associated with reduced emergence performance, which may be related to increasingly limiting soil conditions, such as higher mechanical resistance, reduced porosity, or lower thermal accumulation. These conditions slow mesocotyl elongation and increase the energy required for the seedling to reach the surface, thereby offsetting part of the moisture related benefits gained from deeper placemen (Bulgakov et al., 2022; Lipiec et al., 1991; Paul W. Unger et al., 1994).

Although soil moisture contributed to explaining early emergence and emergence dynamics, no significant effect was observed on cumulative emergence (CE), which may be attributed to rainfall events occurring between observation dates that likely reduced spatial differences in soil water availability and enabled the emergence of previously delayed seedlings over time. Under the relatively homogeneous and non-limiting moisture conditions of 2025, crop emergence was primarily governed by sowing parameters, whereas in 2026, reduced and more heterogeneous moisture conditions likely constrained emergence processes and enhanced the influence of soil-related variables and soil–machine interactions. This interpretation is consistent with the wet-thermal framework of germination, which assumes that thermal time contributes to germination only when sufficient moisture is available (Hardegree et al., 2018).

Electrical conductivity (ECa) showed an increased contribution to emergence dynamics in 2026 compared to 2025, suggesting a stronger influence of soil conditions under more limiting moisture conditions. As ECa reflects a combination of soil properties, including moisture, texture, and structure (Corwin and Lesch, 2003; Peralta et al., 2013), this result indicated that variations in the soil physical environment became more relevant for crop establishment in 2026. In parallel, infrared values followed a similar trend, with consistently higher levels observed in 2025 and a clear decrease in 2026. While lower soil moisture is generally associated with increased reflectance (El Alem et al., 2022; Knadel et al., 2014), the observed pattern suggested that the infrared signal is influenced not only by moisture but also by underlying soil properties such as surface soil structure. This interpretation is further supported by the concurrent increase in the contribution of infrared reflectance and soil-related variables, highlighting a strengthening of both soil variability effects and soil–machine interactions under 2026 conditions.

Under the relatively homogeneous and non-limiting moisture conditions of 2025, crop emergence was primarily governed by sowing parameters. In contrast, in 2026, reduced and more heterogeneous moisture conditions, as captured by both direct measurements and infrared reflectance, likely constrained emergence processes and enhanced the influence of soil-related variables and soil–machine interactions.

Moreover, the higher explanatory power of the models for early emergence and emergence dynamics relative to cumulative emergence highlighted differences in the processes governing crop establishment. Early emergence (E1) and emergence dynamics (ERI) were better captured by the model, as they were directly influenced by both machine sowing settings and local soil conditions included among the explanatory variables. In contrast, cumulative emergence (CE) integrated processes over time and was therefore more sensitive to additional sources of variability, such as rainfall events and fluctuations in temperature, which were not accounted for in the model. This contrast was particularly pronounced in 2026, where lower explanatory power for CE indicated that emergence outcomes were increasingly influenced by environmental variability. This suggested that while the model effectively captured the influence of both sowing parameters and soil conditions on the onset and rate of emergence, the final emergence outcome remained influenced by additional dynamic processes occurring over time.

## Conclusion

This study demonstrated that the drivers of maize emergence, soil conditions, and sowing parameters were strongly influenced by environmental conditions, particularly soil water availability. Under relatively non-limiting conditions, as observed in 2025, crop emergence was primarily governed by machine settings, with sowing depth playing a dominant role. In contrast, under more limiting and heterogeneous conditions, as observed in 2026, soil-related variables and soil–machine interactions became increasingly important in explaining emergence variability. These findings highlighted that early emergence, and emergence dynamics were more predictable than cumulative emergence, which was influenced by subsequent climatic events. Furthermore, the increased contribution of variables such as electrical conductivity, infrared reflectance, and residual gauge wheel load indicated that proximal sensing technologies could be used to capture integrated soil properties that were critical under stress conditions. Overall, this study emphasized the need to move beyond static sowing strategies toward adaptive, sensor-driven approaches that account for spatial heterogeneity in soil conditions. Integrating real-time soil information and machine feedback showed strong potential to improve crop establishment in heterogeneous fields, particularly under increasingly variable climatic conditions.

## Acknowledgements

This work was carried out under a CIFRE agreement supported by Kuhn and the French National Association for Research and Technology (ANRT). The authors gratefully acknowledge T.

Beeuwsaert, field technician and T. Baudet, agronomic engineer for their valuable assistance in conducting sowing experimentations.

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