



Review

How to Analyze, Detect and Adjust Variable Seedbed Depth in Site-Specific Sowing Systems: A Case Study

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Abstract: Sowing or seedbed depth is an important agro-technological parameter that varies with specific on-field soil and microclimatic conditions and depends on crop biology. There is a lack of detailed information regarding how seedbed depth relates to other seedbed parameters and affects the development of agricultural crops. Several seeder constructions and methods for seeding condition detection and depth adjustment have been investigated in high-precision, digitally backgrounded, in-site sowing systems; however, there is still a gap in knowledge due to the limited use of these technologies in conditions of high soil and micro-climatic variability. Therefore, the aim of this study was to highlight the impact of sowing depth on crop seedbed parameters, mainly established by the Kritz method, to ascertain the correlation between sowing depth, germination, crop development and productivity, and to overview the methods and equipment used for detection, adjustment and control of sowing depth in precision site-specific sowing systems. Our results showed that, in most cases, when sowing depth extended beyond the optimum, the moisture content in the seedbed decreased significantly. Sowing depth also correlated with the roughness of the seedbed (surface and bottom) and seedbed aggregate size distribution, but the direction of the relation depended on crop type and maximum sowing depths. Sowing depth correlated with crop germination, development and productivity parameters; however, the direction of exposure and intensity also varied with respect to crops, weather conditions, tillage and sowing equipment. Sowing depth uniformity is greatly influenced by the regulation of clamping force, the spatial variability of soil in fields and sowing operation speed.

Keywords: sowing depth and seedbed interaction; Kritz method; depth regulation; machinery and equipment



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1. Introduction

The main objectives of the sowing operation are to distribute the seeds evenly both vertically and horizontally depending on the characteristics of the crops. Seed placement in the seedbed must be uniform and close to the optimum to ensure adequate seedbed moisture, structural and nutrition conditions [1]. Sowing depth influences crop germination and establishment, crop seedlings, yield strength and—the most important factor—final yield [2]. Sowing too shallow inhibits seed swelling and germination; if sowing is too deep, the seed consumes too much energy and the surface of the seedbed becomes highly uneven, leading to increased soil respiration, moisture loss, erosion risk and pesticide leaching [3–5]. Fuel consumption will also be increased [6].

The most important factors influencing recommendations of sowing depth are soil characteristics, such as soil type, texture, volume of stubble and other plant residues; moisture content; crusting or firming; and applied herbicides, fungicides and fertilizers (especially organic ones). As well as the type and design of machines, the possibility of testing variations in sowing depth also depends on site-specific conditions [7].

Nowadays, agricultural machines require precise monitoring, control equipment and embedded systems and digital transmission of data [8]. Sensors are effective tools for precision sowing [9]. There are sensor-based and map-based systems in precision site-specific sowing. Soil texture has been a relatively static property of soil for decades and is related to soil moisture content and temperature. Other properties can vary greatly during a single vegetative season [10], but soil resistance or compaction and moisture content are also useful mapping and sensing properties [11–19]. For example, heavier (clayic) soils have higher water contents and holding capacities [20]. Therefore, sowing depth could be decreased with the increase in clay content. This relation is important in map-based site-specific sowing systems [10]. Automated soil electric conductivity sensing and mapping are well-equipped and -documented nowadays. According to the soil conductivity map, a field can be divided into zones with unique sowing depths [21,22]. The sowing depth also could be determined and evaluated during sowing. For example, proximal soil sensing comprises several methods: electrical and electromagnetic, optical and radiometric, mechanical, acoustic, pneumatic and electrochemical [10,23].

Kritz's [24] method for crop seedbed testing and evaluation is well-known in some Scandinavian and Baltic counties but less often used elsewhere. The relation between sowing depth on other seedbed parameters (based on Kritz's method, such as the roughness of seedbed surface and bottom, aggregate distribution, moisture content), including crop germination, development and productivity, have been documented even less often. Such detailed information characterizes Heinonen–Kritz–Håkansson's modelling of seedbeds of many agricultural crops and could provide a background for precision seedbed preparation in site-specific sowing systems.

The development of site-specific sowing systems has been ongoing for a couple of decades, but automatic detection and regulation of sowing depth is still actual, especially in no-till systems with a high volume of residues and fields with large variability in soil properties (e.g., texture, penetration resistance or moisture content). Thus, the aims of our study are as follows: (i) to demonstrate the relation of sowing (seedbed) depth to other seedbed parameters of major agricultural crops; (ii) to ascertain the correlation–regression between sowing depth and crop germination, development and productivity; and (iii) to overview the methods and equipment for detection and adjustment of sowing depth in precision site-specific sowing systems.

2. Methods

The Kritz (Sweden) method is described in this study for the testing and evaluation of the most important crop seedbed parameters [24,25]. Roughness of seedbed surface and bottom, sowing depth, moisture content, structural composition and sowing uniformity were tested using a validated methodology (Figures 1 and 2) [26]. The test was performed as follows:

- (1) A steel frame (40 × 40 cm, 10 cm height) (Figure 1a) with an opening frame (25 × 40 cm, 10 cm height) was pressed into the ground with a hammer and levelled with a level.
- (2) A profilometer was used to measure the roughness of the seedbed surface (the distance from the frame top to the soil surface) by estimating the difference between the points of the highest and lowest profile (Figure 1b).
- (3) The row of sown seeds was excavated and the distance from the frame top to the seeds' placement was measured with the same profilometer. From the average of these distances the average of the distances from the frame top to the soil surface was subtracted to calculate the seedbed depth.

(4) In the small steel frame, which was pressed above the sowing line, three (or four) layers of soil were scraped in turn (Figure 2a). L1—seedbed surface layer; L2—layer up to the depth of seed placement; L3—seedbed bottom layer up to 20 mm below the seeds.

(5) The excavated soil was sieved and the fractions of soil aggregates <2 mm, 2–5 mm and >5 mm in diameter were separated (Figure 2b). Their percentage composition was determined by pouring the individual fractions into a measuring cylinder (approximately 2 L capacity). Knowing the total volume of the fractions of the excavated seedbed layer aggregates, the aggregate percentages for the seedbed were calculated [26]. The most important is the percentage of agronomically valuable aggregates of 2–5 mm in diameter [27] and stratification of soil aggregates by size [28].



Figure 1. Steel frames, pressed to the soil (a); the measurement of seedbed surface roughness using a K. Trečiokas profilometer (b). The profilometer has seven rulers that measure the distance from the frame and seedbed surface. The measurements were performed at seven frame spots, resulting in a total of 49 seedbed surface measurements. These data were used for evaluation of seedbed surface and bottom roughness and sowing depth.

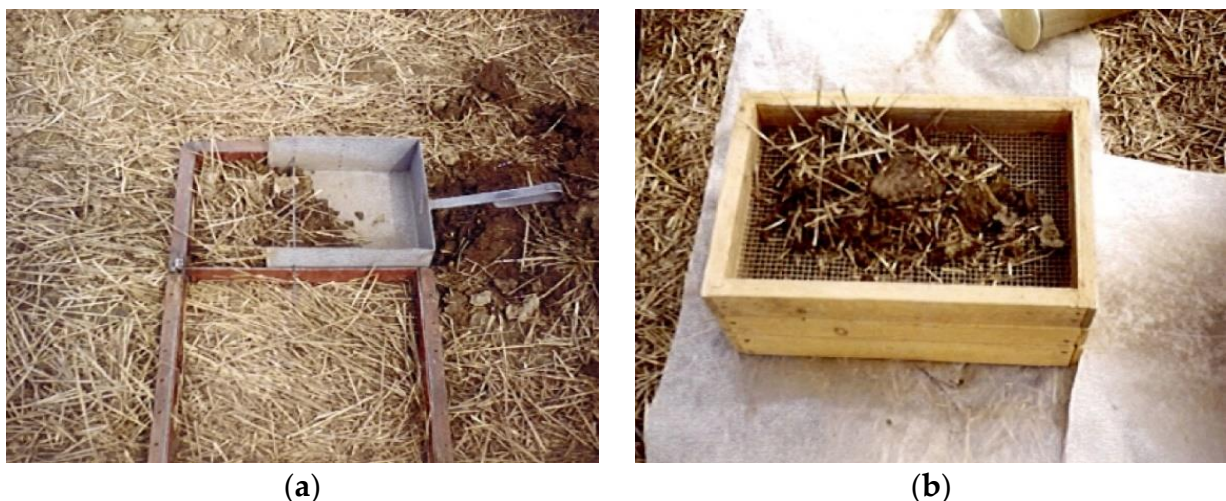


Figure 2. Dozing of soil layers (a); the estimation of soil aggregate fraction percentages (b).

According to the Heinonen [28], “the seeds are placed directly on a firm and moist seedbed base to guarantee capillary transport of water to the seed (mainly from below as indicated by arrows directed towards the seed). The seed is covered by a layer of fine aggregates, at least 30 mm deep that protects from evaporation by acting as a barrier (indicated by the black bands) against upward movement of water evaporation (vertical

arrows). To improve water infiltration (indicated by a curved arrow) and stability against the impact of rain drops (indicated by inclined arrows) coarse aggregates are sorted to the soil surface. Fertilizer is placed a few centimeters to the side of the seed rows, somewhat deeper than the seed”.

(6) After pouring all the soil from the ploughed layer into a bucket and mixing it, three samples were taken to determine the soil moisture.

(7) When sieving the soil through sieves, the seeds found in each excavated layer were counted. These data represent the evenness of seed placement (seed distribution) in the seedbed.

Seedbed tests can be performed by one person using the Kritz method [24] but a group of 3–4 people is optimal, especially on a windy day. The duration of one study is 10–15 min. The seedbed must be tested in 4–5 spots at least to evaluate one tillage or sowing treatment [26].

Håkansson et al. [25] described the model conditions of a seedbed for cereals; these could be useful for many crops with small- or average-sized seeds, except with respect to seedbed depth, which varies depending on crop species. The model describes sowing depth, seedbed roughness, aggregation and moisture conditions.

Most favorable is a seedbed with surface roughness up to 40 mm, bottom roughness of 10–15 mm, soil volumetric moisture content in the seed placement zone of 18–25% and predominant soil aggregates 2–5 mm in diameter (or with >50% aggregates <5 mm) [29–35]. Such seedbed conditions were used as a model for comparison with other findings in this study.

3. Relation between Seedbed Depth and Other Seedbed Properties

Seeding depth (or seedbed depth) is the main technological factor in optimal crop establishment [36]. The relation of seedbed depth to other seedbed parameters in the cultivation of different crops is presented in Table 1 and Table S1. The most important parameters are roughness of seedbed surface and bottom, soil aggregate distribution and size, seed distribution and moisture content per each measured seedbed layer.

According to the investigations of many authors, the optimal depth of the seedbed for most of grain crops is 30–50 mm [24,37–40]. Smaller sugar beet seeds should be sowed at a depth of 30–40 mm in dry soil and 20–30 mm in moist soil. This guarantees the preservation of soil moisture and the potential to retain a higher moisture content (19–22%) until the seeds germinate [25,41,42]. Crops with smaller seeds should be sown shallower and those with larger seeds sown deeper. Large seeds require low-precision seedbed preparation and sowing [25].

Usually, seedbeds prepared in tilled soils are deeper and closer to the optimal model values. However, in conditions of zero tillage, seedbed depth can be several times shallower than in ploughed soil [43]; for example, at an average depth of 15.6 mm depth compared with a depth of 57.4 mm (Table 1 and Table S1), or 18.7 mm when seed is sowed with a conventional drill and 21.8 mm when sowing is performed with a direct drill [26,44].

3.1. Roughness of Seedbed Surfaces and Bottoms

In Romaneckas’ and Šarauskis’ experiments [26,44] (Table 1 and Table S1), sugar beet seedbed surface roughness varied from 37.2 to 46.4 mm and seedbed bottom roughness varied from 7.0 to 12.3 mm, meeting the Heinonen–Kritz–Håkansson model requirements. In sugar beet sowing depth and rolling experiments, as the seedbed depth increased, the roughness of the seedbed surface also increased ($r = 0.524$). A more even seedbed surface was formed by rolling with a ring roller to obtain a more ridged surface in unrolled plots or by rolling with a spur roller. The deeper seedbeds were levelled by rollers more than shallowly prepared seedbeds. The roughness of seedbed bottoms consistently decreased ($r = -0.778$) (Table 1 and Table S1) [46,47].

Table 1. The relation of seedbed depth to other seedbed parameters.

Crop	Variation in Seedbed Depth	Parameter Related to Seedbed	Reference
Winter wheat	38.5–40.5 mm	Roughness of seedbed surface (mm); L1 and L2 moisture content (%); L1 soil particles 2–5 mm and > 5 mm (%); L1 sowing evenness (%)	[39]
Spring wheat	39–43 mm	L3 soil particles > 5 mm (%); roughness of seedbed bottom (mm); L3 moisture content (%); L2 soil particles < 2 mm (%); L3 sowing evenness (%)	[38]
Spring barley	40.4–45.6 mm	Moisture content L2 and L3 (%); L1 soil particles < 2 mm (%); L2 soil particles < 2 mm and > 5 mm (%); L3 soil particles 2–5 mm and > 5 mm (%)	[40]
	15.6–57.4 mm	Roughness of seedbed surface (mm); L1 and L3 sowing evenness (%)	[43]
Sugar beet	14–53 mm	L1, L2 and L3 soil particles < 2 mm (%); L1, L2 and L3 moisture content (%)	[3]
	12.8–45.7 mm	Roughness of seedbed surface and bottom (mm); L1 and L2 moisture content (%); L1 soil particles < 2 mm (%); L1 soil particles > 5 mm (%); L2 soil particles < 2 mm, 2–5 mm and > 5 mm (%); L3 soil particles < 2 mm and > 5 mm (%); L1 and L3 sowing evenness (%)	[26,44,45]
	22–55 mm	Roughness of seedbed surface (mm)	[46,47]
	47–77 mm	Roughness of seedbed surface and bottom (mm); L2 and L3 moisture content (%); L1 soil particles < 2 mm, 2–5 mm and > 5 mm (%); L2 soil particles < 2 mm and > 5 mm (%); L3 soil particles > 5 mm (%); L1, L2 and L3 sowing evenness (%)	[48]
Winter oilseed rape	24–37 mm	Moisture content L2 and L3 (%); L1 soil particles > 5 mm (%); L2 soil particles 2–5 mm (%); L3 soil particles < 2 mm and 2–5 mm (%); L3 soil particles > 5 mm (%); L1 and L2 sowing evenness (%)	[38,39,49]
Spring oilseed rape	28–38 mm	Roughness of seedbed surface (mm); L2 and L3 moisture content (%); L1 soil particles 2–5 mm and > 5 mm (%); L2 soil particles < 2 mm, 2–5 mm and > 5 mm (%); L3 soil particles < 2 mm, 2–5 mm and > 5 mm (%); L1, L2 and L3 sowing evenness (%)	[40]

Note: L1–L3 seedbed layers are explained in the Methods section.

3.2. Seedbed Moisture Content

Soil moisture content mainly relates to tillage intensity and depth [50]. For example, in an on-farm experiment, in reduced (disked) tillage conditions, a winter oilseed rape seedbed was formed about 4 mm shallower than conventionally tilled plots and had significantly higher (around 20%) moisture content in the seed placement zone. These conditions increased winter oilseed rape crop density at the beginning of the vegetative season (Table 1 and Table S1) [38,39,49]. In another experiment with sugar beet, most of the moisture in the seedbed surface layer and in the seed placement zone was retained when sugar beet was sowed into untilled stubble because the soil surface was covered with straw [26,44]. Sugar beet seedbed rolling increased moisture content in the seed placement zone from 8% to 19%. If the working depth increased, the moisture content in the seed placement zone decreased significantly. Moisture evaporated faster from rolled plots than from unrolled ones [46,47].

3.3. Seedbed Aggregate Size Distribution

Environment, vegetative period, soil texture and layer depth and tillage and sowing methods strongly influence soil aggregation in crop seedbeds [51–54] and affect the germination, development and productivity of crops [25,55–58]. Soil aggregation also relates to other soil properties, such as moisture content, temperature, aeration, among others [27,56,59–62].

In crop seedbeds, soil structural composition is one of the most important parameters. Seedbed soil aggregates of 2–5 mm in size are the most valuable; otherwise, in seedbeds at least 50% of soil aggregates should be smaller than 5 mm [25,57]. According to Morris et al. [51], the volume of such aggregated soil could be up to 33%. After analysis of the results of Romaneckas' and Šarauskis' [26,44] previous experiments, it was observed that the requirements for sugar beet seedbed aggregate size distribution (according to the Heinonen–Kritz–Håkansson model) were better satisfied when a seedbed was prepared using a cultivator with rollers.

3.4. Sowing Evenness–Uniformity

Sowing depth is also significantly influenced by sowing evenness (Table 1 and Table S1) or sowing depth uniformity. If at least 60% or more sowed seeds are placed in a concrete seedbed layer, such evenness is superior with respect to uniform seed germination. In Özmerzi et al.'s [1] experiment, maize sowing depths of 40, 60 and 80 mm were investigated. The most uniform sowing depth was 60 mm. The sowing depth variation (coefficient) was less than 5%. In another experiment with image acquisition and seed geolocation in a site-specific sowing system, the results were also good—98% of the recorded seeding depths were within the error range of $\pm 10\%$ [63]. Nielsen et al. [64] found that using state-of-the-art sowing machines with an electro-hydraulic control system, the depth of sowing varies with changes in soil resistance. The results showed a strong positive correlation between the angle of the sowing coulter and sowing depth. Further, the uniformity of sowing strongly depended on the speed of operation [65,66].

4. Influence of Seedbed Depth on Agricultural Crops

Seedbed depth uniformity affects seed germination and crop density, development of seedlings and crop productivity (Table 2 and Table S2). In Håkansson et al.'s [25] experiments, seeds of barley were sown at depths of 20, 40 or 60 mm and covered with different sizes of soil aggregates (<2, 2–5, 5–10 or 10–25 mm). The best emergence was observed when seeds were incorporated at a 40 mm depth and covered with <2 mm-sized soil aggregates, which ensured better contact between the soil and the seed.

Table 2. Relation of seedbed depth to crop germination, development, quantity and quality parameters.

Crop	Variation in Seedbed Depth	Parameter Related to Crop	Reference
Winter wheat	38.5–40.5 mm	Productive stems (m^{-2}); mass of 1000 grains (g); yield of grain (t ha^{-1})	[39]
Spring wheat	39–43 mm	Seed germination (plants m^{-2}); productive stems (m^{-2}); mass of 1000 grains (g); yield of grain (t ha^{-1})	[38]
Spring barley	40.4–45.6 mm	Seed germination (plants m^{-2}); height of plant (cm); mass of 1000 grains (g)	[40]
	20, 40, 60 mm	Seed emergence (%)	[25]
Sugar beet	14–53 mm	Seed germination (%)	[3]
	22–55 mm	Seed germination (%)	[46,47]
	0–60 mm	Seed germination (%); mass of seedling (g); height of seedling (cm)	[69]
	27–93 mm	Technical length of root crop (cm); Diameter of root crop (cm)	[70,71]
	20, 30, 40 mm	Seed emergence (%)	[57,67]
Maize	47–77 mm	Seed germination (plants m^{-2}); final crop density (plants m^{-2}); mass of 1000 kernels (g); yield of grain (t ha^{-1})	[48]
Oilseed rape	24–37 mm	Number of siliques (m^2); Yield of seeds (t ha^{-1})	[38,39,49]
	20, 40, 60 mm	Seed emergence (%)	[67,68]
Canola	25, 50 mm	Seed emergence (%); white mold	[72]
Fiber flax	0–60 mm	Height of plant (cm); fresh yield (t ha^{-1}); dry matter content (%)	[73]

The best emergence of smaller crops' seeds (white mustard, oilseed rape, sugar beet and red clover) was found when the seeds were placed at a depth of about 30 mm. Cruciferous crops germinated most rapidly, which facilitated their emergence from a shallow depth. In well-textured soils, the seedbed depth could be slightly shallower [67,68].

Rolling after sowing could also improve this contact and increase the emergence of cereals by 4% and grain yield by 2%. Delaying rolling decreased the positive effect [25]. Similar conclusions were obtained by Romanekas and Šarauskis [46] and Romanekas et al. [47] regarding sugar beet cultivations. The influence of soil rolling on sugar beet seed germination was inconsistent and depended on soil moisture conditions during rolling and seed germination. Timely rolling of the soil, especially after sowing, improved seed germination in the arid spring and worsened it in the humid seasons. Delayed firming of overdried soil was also detrimental (Table 2 and Table S2). In Håkansson's experiments, in the experimental plots with high initial water content, the emergence of seeds was delayed by firming. The response of sugar beet to firming of the seedbed after sowing was very similar to that of small-grain cereals [68].

According to Håkansson et al., crops with large seeds (e.g., 52 mg) are not as sensitive to sowing depth [57] because seeds have higher sprouting power than small-seeded crops. However, in some experiments, the increased sowing depth of up to 77 mm negatively influenced maize seed germination and crop density, though the mass of kernels and the yield of grain increased (Table 2 and Table S2) [48]. Similarly, Liu et al. [74] found a higher correlation between maize seed germination and sowing depth than with horizontal seed distribution [75,76].

Oilseed rape seeds are small and decrease in seedbed depths from 24 to 37 mm, influenced by the depletion of silique number and the yield of seeds [38,39,49]. In other experiments, the final emergence of seeds was increased with an increase in sowing depth from 20 to 40 mm, but at 60 mm depth the emergence of seeds decreased [67]. In experiments with canola, the environmental conditions decreased the pure live seed emergence (PLSE) by 24–41% in the deeper-seeded (50 mm depth) plots compared with shallowly sowed (25 mm) ones. Additionally, white mold incidence was 4.5 times higher in deeply sowed plots [72].

In Couture et al.'s experiment [73], fiber flax was sown at depths of 0, 10, 20, 40 or 60 mm with and without rolling (firming). Seedbed rolling had little effect but seedbed depths of 10–40 mm (compared with 60 mm) initiated higher stand height, fresh yield and dry matter content (Table 2).

5. Methods and Equipment for the Detection and Adjustment of Sowing Depth

5.1. Dynamic Seed Depth Control Actuators and Downforce Systems

In conventional cereal seed drills, sowing depth is determined manually before sowing by changing the position of the gauge wheels relative to the seed coulters [77]. The support wheels control the furrows as they roll over the soil surface, i.e., the depth of the seedbed, and prevent the furrow openers (e.g., double disc, hoe-type or runner-type) from deepening. Optimization of planter performance requires developing technologies that permit the adjustment of sowing-unit depth and downforce settings to changing field conditions [78].

One of the most important indicators of sowing quality is sowing depth uniformity and stability [79]. A constant sowing depth is maintained in drills by a so-called “downforce” system, which may include a mechanical (spring) and, more recently, pneumatic or hydraulic controls [77,80]. For seed drills such as the 6-meter-wide Horsch Avatar 6.16 SD (HORSCH Maschinen GmbH, Schwandorf, Germany), one cylinder controls the 2-meter-wide section. Depending on the changing spatial variability in the same field, such as soil particle size distribution, texture, organic matter content, moisture or hardness, a downforce system can help to maintain the same depth or reduce it if necessary. This is especially important when the seed coulters are raised to the surface of the field and the sowing depth decreases, entering the field area of harder soil in the same field [81]. Thus, with the downforce system, it is not possible to increase the sowing depth on-the-go, as the depth of the coulters is limited by the gauge wheel.

Nowadays, traditional sowing unit clamping force systems (i.e., mechanical systems) can be replaced by pneumatic or hydraulic drives (i.e., dynamic systems) that allow the sowing unit clamping force to be adjusted in the field during planting [82]. However, these technologies are only a first step in the development of more sophisticated technologies that are expected to provide active control of row depth and clamping force drill settings. Developing sowing/planting technologies with such capabilities is challenging and success requires the development of a unified control algorithm to properly adjust row depth and clamping force settings to changing soil conditions [80].

Various constructions can be used for dynamic sowing depth adjustment mechanisms (Table 3).

Existing systems can usually control the coulter downforce over the entire working width of the drill, individual drill sections or individual drill rows. Some mechanisms can also estimate the change (decrease) in seed hopper weight during sowing. The efficiency of a variable seed drill system depends on the sensitivity of the sensors and the efficiency of the actuator. Hydraulic clamping systems have a faster response time than pneumatic clamping systems.

Drills for variable depth sowing technology must have two elements—a measuring system (sensors) and dynamic sowing depth control mechanisms [93–95]. In Bourgault Paralink™, the AccuSet™ system (Bourgault Industries Ltd., Saint Brieux, SK, Canada) adjusts sowing depth by changing the position of the frame and each coulter hydraulic cylinder [96].

Table 3. Sowing depth adjustment mechanisms.

Mechanism	Reference
1. Tractor suspension (hitch) for mounted seed drills only	[77]
2. Hydraulic cylinders	[77,83,84]
3. Hydraulic cylinders (via a four-chain mechanism, e.g., Bourgault)	[85]
4. Electro-hydraulic downforce control system	[64,79,86–90]
5. Electric motors with a mechanical drive (e.g., Precision Planting)	[91]
6. Pneumatic system	[77,80]
7. Magnetorheological cylinders	[92]

According to Baker and Saxton [77], the main disadvantages of direct air use are the limited amounts of pressure that can be obtained in practice and the facts that oxygen in high-pressure air can explode and that high-pressure cylinders must be lubricated separately, which is the problem with semistatic systems.

The pneumatic clamping system uses airbags or replaceable airbags inflated by a hydraulically driven compressor to automatically control the clamping force in real time. John Deere Seedstar XP (Moline, IL, USA), AirForce by Precision Planting (Precision Ag Solutions, Aberdeen, SD, USA) and Great Plains (Great Plains AG, Salina, KS, USA) currently have this type of downforce technology available. On the other hand, hydraulic downforce systems can replace mechanical springs or airbags with hydraulic cylinder(s) to automatically control the downforce. Case IH, Kinze, Horsch, John Deere and most other seed drill models can use a hydraulic system to control the clamping force of individual rows of blocks.

Some clamping systems, such as the DAWN Equipment hydraulic RFX system, perform instantaneous adjustment based on soil conditions by monitoring the row block using an X-Sense fluid connection pressure sensor. The sensor filters out mechanical vibration and noise generated by the planter's meter to precisely adjust the clamping force. Generally, a hydraulic clamping system responds faster than a pneumatic system.

Existing clamping force management systems are mainly developed by some well-known corporations, such as the John Deere (Moline, IL, USA) Active Pneumatic Clamping System with Seed Star™ Tracking Technology, the Precision Planting (Precision Ag Solutions, Aberdeen, SD, USA) Airforce® and DeltaForce® Clamping Force Management System with a 20/20 SeedSense monitoring system and the AG Leader (Ames, IA, USA) SureForce™ hydraulic control system with an InCommand® monitor. These systems ensure high stability and adaptability, and include load cells that are easy for users to install, maintain and replace.

The nonlinear characteristics of the adjustment parts of the coulter depth adjustment system, which consist of springs and damping elements, cause some difficulties in developing a suitable control strategy [92]. A magnetorheological (MR) damper can be installed in one of the seeding units to optimize its dynamics for better seed placement [97]. Active MR inhibitors, which are suspensions of magnetically reactive particles in magnetorheological fluids, have been used [92]. Modelling has shown a significant decrease in the amplitude of the generated forces, which may reduce the variation in sowing depth [98]. Using a MR damper, coulter dynamics were improved, with reductions in vertical and impact force amplitudes of 21.34 and 67.69%, respectively. The change in sowing depth with a MR damper demonstrated an 11.9 mm absolute error, while that without it demonstrated an error of 21.3 mm [97].

Precision Planting System has developed the SmartDepth system, in which the drilling depth is changed by electric motors installed in each section. The electric motor rotates the drilling depth change mechanism via the gears. When SmartDepth is used in conjunction with SmartFirmer, the sowing depth can be controlled according to the soil moisture. The drill operator can enter the minimum and maximum depth data on the 20/20 display

in the cab, which are assigned to the respective soil moisture values, and the drill will automatically adjust the drilling depth between the minimum and maximum depending on the fixed soil moisture. SmartFirmer can measure cation exchange capacity (CEC) and changes in soil organic matter, humidity and temperature [99].

The active downforce clamping system maintains the same sowing depth under different field conditions, such as topography, soil texture and moisture levels, and automatically regulates the optimal gauge wheel load, which ensures accurate seed placement without compacting the side walls. Further, it increases control resolution to accommodate variable clamping force as field sowing conditions change, reduces bounce and vibration of the row unit due to terrain and field conditions during sowing (e.g., stones, clumps, etc.) and regulates the clamping force or depth from the cab to suit the field conditions. It also collects sowing data to verify and determine field variability.

5.2. Sensors for Monitoring Sowing Depth

Automatic sowing depth adjustment technologies can operate prescription maps or real-time (online) sensor readings, which can be adapted to change the sowing depth according to certain algorithms. The primary temperature and humidity conditions, as well as germination and germination time, can be modelled for different environments and stored in a data file. During the seeding operation, sowing depths are taken from the database, depending on the terrain, soil temperature and soil moisture, and adjusted in the drill.

Site-specific properties in the field (soil properties, landscape differences, etc.) can be detected during sowing or before sowing using various sensors, which are presented in Table 4.

Table 4. Types of sensors and their operation peculiarities.

Type of Sensors	Peculiarities of Sensor Operation	Reference
1. Ultrasonic sensors	Determining the distance from the frame to the soil surface. The use of ultrasonic sensors is limited by plant residues on the soil surface and the fact that measurement is possible over a short distance above the soil surface	[4,5,84,100–104]
2. Optical sensors	Detecting the proportion of organic matter in the soil and/or moisture (e.g., SmartFirmer)	[99]
3. Strain sensors	Detecting tension or impact forces acting on the coulters	[97]
4. Resistance sensors	Determining the level of deformation of the support wheel tire	[105]
5. Electromagnetic induction sensors	Detecting the electrical conductivity or moisture of the soil (e.g., EM38, TopSoil Mapper)	[106–108]
6. Electrical resistance sensors	Determining the electrical conductivity of the soil from which the soil moisture is determined (e.g., Veris Soil EC 3100 equipment)	[22,109]
7. Gamma-ray sensors	Determining the proportion of organic matter in the soil and texture (e.g., SoilOptix)	[110]
8. Linear variable displacement transducers (LVDT)	Measuring the position of the support wheel relative to the frame	[100,111–113]

There are both contact and noncontact methods for measuring soil conductivity or electromagnetic induction [106]. The first sort of method uses electrodes that are in physical contact with the soil to supply electricity and measure the resulting voltage. Electromagnetic induction sensors do not make contact but use a transmitter coil to generate a magnetic field in the ground and a receiver coil to measure the response. Studies have shown that

both methods achieve similar results [114]. Knappenberger and Köller suggested using a multistep procedure [78].

In Jia et al. [112], an adaptive tillage depth monitoring system was developed by measuring the angle between the implement and a surface-mounted swivel arm with a sensor. In Zhao et al.'s [105] experiments, a deformation sensor was made of polyvinylidene fluoride (PVDF) film, which was attached to the inner surface of the meter wheel, and the output voltage was determined by the wheel deformation. During the experiments, the relationship between the obtained stress and the deformation of the meter wheel was obtained. The control system was able to maintain the desired sowing depth within ± 8 mm at a speed of 2.78 m s^{-1} .

Mouazen et al. [100] used soil wheel linear variable displacement (LVDT) sensors to determine the height of the machine frame from ground level. Based on their research, soil wheel sensors could be used in fields covered with stubble and crop residues for which ultrasonic sensors incorrectly measure the height of the equipment frame from the soil surface.

According to the soil type, moisture content and dry bulk density, the correction factors must be determined and subtracted from the output of the wheel LVDT sensor to compensate for the additional distance occurring due to the wheel penetrating the light surface [100]. In Nielsen et al. [5], linear position sensors were mounted on every second coulter at a distance of 250 mm from the three-meter-wide seed drill, i.e., a total of 11. Two ultrasonic distance sensors were mounted perpendicular to the transverse frame of the drill, in front of the coulter, to measure the height of the vertical frame relative to the soil surface [5].

The application of ultrasonic sensors is limited due to uneven soil surfaces and short distance measurement [100]; however, such sensors could be used in sowing machinery.

Suomi and Oksanen [103] introduced an automatic sowing depth control system that includes sensors, electronics and software. The control system sends flow commands to the tractor's auxiliary hydraulic valve using ISO 11783, ISO 11,783 Class 3 TECU units or TIM, according to ISOBUS terminology. Several sensors were used to measure angles and distances in the drill. The working depth was estimated from the signals of the eight sensors. Ultrasonic ranges were inaccurate due to objects and plant residues in the field. The developed system was able to compensate for the error of the calculated working depth within ± 10 mm at a speed of 10 km h^{-1} . In Paraforos et al.'s [108] review, more precise information about the ISO 11,783 compatible industrial sensor is presented.

Weatherly and Bowers [109] developed an automatic drill depth control system to determine soil moisture and automatically adjust seed drilling depth based on humidity. The system consists of a humidity sensor, an electronically controlled proportional hydraulic valve and a seed drill. When the seedbeds dry out, deeper planting increases the likelihood of soil moisture increase and faster germination. Thus, site-specific information on the relative height of the landscape could help regulate sowing depth [115].

6. Conclusions

This study has focused on the effect of sowing depth on other crop seedbed parameters, seed germination, crop development and productivity, and overviewed the design of techniques and methods for sowing depth control and adjustment in site-specific conditions. In most cases, when the increase in sowing depth extended beyond the optimum, the moisture content in the seedbed decreased significantly. Additionally, sowing depth correlated with the roughness of seedbed surfaces and bottoms and seedbed aggregate size distribution, but the direction of the correlations depended on the crop species and maximum sowing depths. Positive relations between sowing depth and small (< 2 mm) seedbed aggregates and negative relations between sowing depth and larger (2–5 and > 5 mm) aggregates were more frequently observed. Sowing depth correlated with crop germination, development and productivity parameters; however, the direction of exposure varied between crop species, weather conditions, tillage and sowing practices.

In recent years, some automatic on-the-go sowing depth change systems have been developed and produced. They have two elements: a measuring system (sensors) and dynamic sowing depth control mechanisms (actuators). The most commonly used mechanisms of actuators are hydraulic, electrohydraulic, and electric. Most of them are universal and those with future potential are noncontact optical and electromagnetic induction sensors. They can measure soil organic matter and the humidity and temperature of soil. The efficiency of a variable seeding depth system depends on the sensitivity of the sensors and the efficiency of the actuator. Automatic sowing depth adjustment technologies can also operate on prescription maps.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy12051092/s1>, Table S1: Correlation between seedbed depth and other seedbed parameters, Table S2: Correlation between seedbed depth and crop germination, development, quantity and quality parameters.

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