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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

Citation: Romaneckas, K.; Steponavičius, D.; Jasinskas, A.; Kazlauskas, M.; Naujokienė, V.; Bručienė, I.; Švereikaitė, A.; Šarauskis, E. How to Analyze, Detect and Adjust Variable Seedbed Depth in Site-Specific Sowing Systems: A Case Study. *Agronomy* **2022**, *12*, 1092. https://doi.org/10.3390/agronomy12051092

Academic Editor: Małgorzata Szczepanek

Received: 4 February 2022
Accepted: 25 April 2022
Published: 29 April 2022

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.

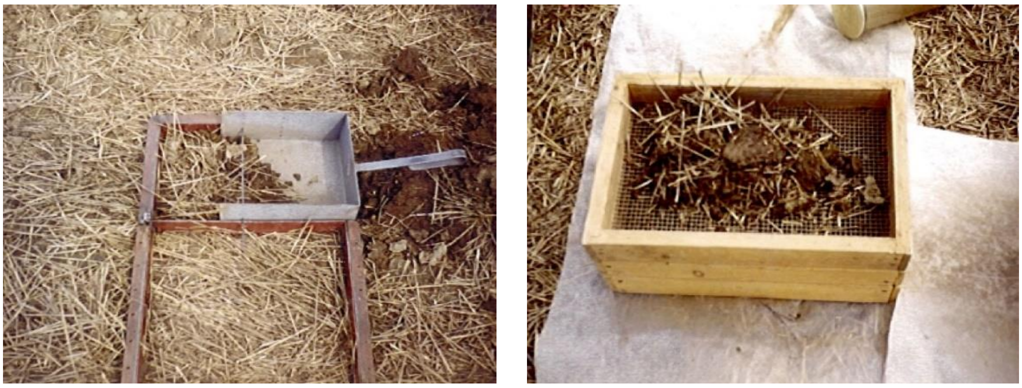
(2) A profilometer was used to measure the roughness of the seedbed surface (the distance from the frame top to the soil surface) by estimating the difference between the points of the highest and lowest profile (Figure 1b).

(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.

(**a**) (**b**)

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.

(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.



(**a**) (**b**)

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

(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].

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 Tables 1 and 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 (Tables 1 and 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].

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]
Maize	47–77 mm	Roughness of seedbed surface and bottom (mm); L2 and L3 moisture content (%); L1 soil particles < 2 m, 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.

3.1. Roughness of Seedbed Surfaces and Bottoms

In Romaneckas’ and Šarauskis’ experiments [26,44] (Tables 1 and 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 ($r = -0.778$) (Tables 1 and S1) [46,47].

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 (Tables 1 and 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 Eevenness–Uniformity

Sowing depth is also significantly influenced by sowing evenness (Tables 1 and 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 ±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 (Tables 2 and 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.

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 Romaneckas and Šarauskis [46] and Romaneckas 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 (Tables 2 and 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].

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]

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 (Tables 2 and 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.

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]

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

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) SureForceTM 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.

Author Contributions: Conceptualization, K.R., A.J. and D.S.; methodology, K.R. and E.Š.; software, K.R.; validation, K.R.; formal analysis, K.R., D.S. and M.K.; investigation, K.R. and E.Š.; resources, K.R., D.S., A.J., M.K. and A.Š.; data curation, K.R., D.S. and A.J.; writing—original draft preparation, K.R., D.S., A.J., M.K. and A.Š.; writing—review and editing, K.R., D.S., A.J., M.K., V.N., E.Š. and I.B.; visualization, K.R., D.S. and M.K.; supervision, K.R. and E.Š.; project administration, E.Š.; funding acquisition, E.Š., V.N. and I.B. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Regional Development Fund (project no. 01.2.2-LMT-K-718-03-0041) under a grant agreement with the Research Council of Lithuania (LMTLT).

Data Availability Statement: All data generated or analyzed in this study are included in the present article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Özmerzi, A.; Karayel, D.; Topakci, M. PM—Power Machinery: Effect of Sowing Depth on Precision Seeder Uniformity. *Biosyst. Eng.* **2002**, *82*, 227–230.
2. Pinheiro, M.G.; Souza, C.A.; Carneiro, J.F.C., Jr.; Elijanara Raissa Silva, E.R.; Vieira Stefen, D.L. Initial Development of Wheat and Triticale under Different Sowing Depth. *Am.-Eurasian J. Agric. Environ. Sci.* **2018**, *18*, 206–215.
3. Romaneckas, K.; Šarauskis, E.; Romaneckienė, R. The influence of soil agrophysical properties on seedbed formation and sugar beet seeds germination. *Zemdirbyste* **2002**, *77*, 21–31. (In Lithuanian with English summary)
4. Heege, H.J. Site-Specific Sowing. In *Precision in Crop Farming*; Heege, H., Ed.; Springer: Dordrecht, The Netherlands, 2013; pp. 171–192. https://doi.org/10.1007/978-94-007-6760-7_8.
5. Nielsen, S.K.; Munkholm, L.J.; Lamandé, M.; Nørremark, M.; Skou-Nielsen, N.; Edwards, G.T.; Green, O. Seed drill instrumentation for spatial coulter depth measurements. *Comput. Electron. Agric.* **2017**, *141*, 207–214.
6. Shanmuganathan, V.; Benjamin, L.R. The influence of sowing depth and seed size on seedling emergence time and relative growth rate in spring cabbage (*Brassica oleracea var. capitata* L.). *Ann. Bot.* **1992**, *69*, 273–276.
7. Agriculture and Food. Monitoring Sowing Depth. 2015. Available online: https://www.agric.wa.gov.au/mycrop/monitoring-sowing-depth (accessed on 17 May 2021).
8. Birner, R.; Daum, T.; Pray, C. Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Appl. Econ. Perspect. Policy* **2021**, *43*, 1260–1285. https://doi.org/10.1002/aepp.13145.
9. Gautam, P.V.; Kushwaha, H.L.; Kumar, A.; Kushwaha, D.K. Mechatronics Application in Precision Sowing: A Review. *Int. J. Curr. Microbiol. Appl. Sci.* **2019**, *8*, 1793–1807.
10. Munnaf, M.A.; Haesaert, G.; Van Meirvenne, M.; Mouazen, A.M. Site-specific seeding using multi-sensor and data fusion techniques: A review. *Adv. Agron.* **2020**, *161*, 241–323.
11. Mouazen, A.M.; Anthonis, J.; Ramon, H. An automatic depth control system for online measurement of spatial variation in soil compaction, part 4: Improvement of compaction maps by using a proportional integrative derivative depth controller. *Biosyst. Eng.* **2005**, *90*, 409–418.
12. Mouazen, A.M.; Ramon, H. Development of on-line measurement system of bulk density based on on-line measured draught, depth and soil moisture content. *Soil Tillage Res.* **2006**, *86*, 218–229. https://doi.org/10.1016/j.still.2005.02.026.
13. Hemmat, A.; Adamchuk, V.I. Sensor systems for measuring soil compaction: Review and analysis. *Comput. Electron. Agric.* **2008**, *63*, 89–103.
14. Topakci, M.; Unal, I.; Canakci, M.; Celik, H.K.; Karayel, D. Design of a Horizontal Penetrometer for Measuring On-the-Go Soil Resistance. *Sensors* **2010**, *10*, 9337–9348. https://doi.org/10.3390/s101009337.
15. Kokoshin, S.N.; Kizurov, A.S.; Kirgintsev, B.O. Disc Seeder with the System for Automative Tracking of Sowing Depth. In Proceedings of the International Scientific and Practical Conference Agro-SMART-Smart Solutions for Agriculture (Agro-SMART 2018), Tyumen, Russia, 16–20 July 2018; pp. 355–358.
16. Nielsen, S.K.; Munkholm, L.J.; Lamandé, M.; Nørremark, M.; Edwards, G.T.; Green, O. Seed drill depth control system for precision seeding. *Comput. Electron. Agric.* **2018**, *144*, 174–180.
17. Badua, S. Control System Response for Seed Placement Accuracy on Row Crop Planters. Ph.D. Thesis, Kansas State University, Manhattan, KS, USA, 2020.
18. Kokoshin, S.N.; Kirgintsev, B.O.; Tashlanov, V.I. Disc seeder with auto tracking system depth of sowing seeds. *J. Phys. Conf. Ser.* **2020**, *1614*, 012051.

19. Li, B.; Tan, Y.; Chen, J.; Liu, X.; Yang, S. Precise Active Seeding Downforce Control System Based on Fuzzy PID. *Math. Probl. Eng.* **2020**, *2020*, 5123830. https://doi.org/10.1155/2020/5123830.
20. Li, X.; Chang, S.X.; Salifu, K.F. Soil texture and layering effects on water and salt dynamics in the presence of a water table: A review. *Environ. Rev.* **2014**, *22*, 41–50. https://doi.org/10.1139/er-2013-0035.
21. Nawar, S.; Corstanje, R.; Halcro, G.; Mulla, D.; Mouazen, A.M. Delineation of soil management zones for variable-rate fertilization: A review. *Adv. Agron.* **2017**, *143*, 175–245. https://doi.org/10.1016/bs.agron.2017.01.003.
22. Virk, S.S.; Porter, W.M.; Li, C.; Rains, G.C.; Snider, J.L.; Whitaker, J.R. On-farm evaluation of planter downforce in varying soil textures within grower fields. *Precis. Agric.* **2021**, *22*, 777–799. https://doi.org/10.1007/s11119-020-09755-x.
23. Adamchuk, V.I.; Hummel, J.W.; Morgan, M.T.; Upadhyaya, S.K. On-the-go soil sensors for precision agriculture. *Comput. Electron. Agric.* **2004**, *44*, 71–91. https://doi.org/10.1016/j.compag.2004.03.002.
24. Kritz, G. Physical conditions in cereal seedbeds. In *Reports from the Division of Soil Management*; Swedish University of Agricultural Sciences: Uppsala, Sweden, 1983; pp. 25–36.
25. Håkansson, I.; Myrbeck, E.; Etana, A. A review of research on seedbed preparation for small grains in Sweden. *Soil. Tillage Res.* **2002**, *64*, 23–40.
26. Romaneckas, K.; Šarauskis, E. The investigations of sugar beet seedbed by Kritz method (Sweden) under different soil tillage and sowing pattern. *Zemdirbyste* **2003**, *81*, 168–183. (In Lithuanian with English summary)
27. Nugis, E. Seedbed quality preparation in Estonia. *Agron. Res.* **2010**, *8*, 421–426.
28. Heinonen, R. *Tillage Properties of Various Types of Soils*; Konsulentavdelningen Publikationer, Agricultural College of Sweden: Uppsala, Sweden, 1979; 42p. (In Swedish)
29. Thomson, D. *Depth of Drilling*; British Sugar Beet Research Organisation: Norwich, UK, 1975; Voluem 1, pp. 55–78.
30. Techler, P. Forschungsergebnisse zum Faktoren—Komplex Feldaufgang von Zuckerrüben. *Mech. Der Zuckerrübenproduktion* **1984**, *1*, 142–144. (In German)
31. Stenberg, M.; Håkansson, I.; von Polgár, J.; Heinonen, R. Sealing, crusting and hardsetting soils in Sweden—Occurrence, problems and research. In Proceedings of the 2nd International Symposium on Sealing, Crusting and Hardsetting Soils: Productivity and Conservation, Brisbane, Australia, 7–11 February 1994; pp. 287–292.
32. Aubertot, J.N.; Dürr, C.; Kiên, K.; Richard, G. Characterization of sugar beet seedbed structure. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1377–1384.
33. Dürr, C.; Aubertot, J.N. Emergence of seedlings of sugar beet (*Beta vulgaris* L.) as affected by the size, roughness and position of aggregates in the seedbed. *Plant Soil* **2000**, *219*, 211–220.
34. Dürr, C.; Aubertot, J.N.; Richard, G.; Dubrulle, P.; Duval, Y.; Boiffin, J. A model for simulation of plant emergence predicting the effect of soil tillage and sowing operations. *Soil Sci. Soc. Am. J.* **2001**, *65*, 414–423.
35. Naudžiūnas, K. Presowing soil tillage for sugar beet in light loam soil. *Zemdirbyste* **1996**, *51*, 83–87. (In Lithuanian with English summary)
36. O'Connor, B.J.; Gusta, L.V. Effect of low temperature and seeding depth on the germination and emergence of seven flax (*Linum usitatissimum* L.) cultivars. *Can. J. Plant Sci.* **1994**, *74*, 247–253.
37. Velykis, A.; Satkus, A. Factors of seedbed quality on heavy soils. *Zemdirbyste* **2005**, *1*, 53–66.
38. Martinkus, M.; Šarauskis, E.; Romaneckas, K. *The Report of Research Project "Research of Minimal Tillage Technologies and Integrated Farm Management Systems Combining Precision Farming, Business and Machinery Management, Agronomic Information"*; Lithuanian State Science and Studies Foundation: Vilnius, Lithuania, 2003.
39. Martinkus, M.; Šarauskis, E.; Romaneckas, K. *The Report of Research Project "Research of Minimal Tillage Technologies and Integrated Farm Management Systems Combining Precision Farming, Business and Machinery Management, Agronomic Information"*; Lithuanian State Science and Studies Foundation: Vilnius, Lithuania, 2004.
40. Bogužas, V.; Romaneckas, K.; Jodaugienė, D.; Putys, E. *The Report of Research Project "The Ploughless Tillage for Main Field Crops"*; Vytautas Magnus University: Kaunas, Lithuania, 2003.
41. Gummerson, R.J. Seed-bed cultivations and sugar beet seedling emergence. *J. Agric. Sci.* **1989**, *2*, 159–169.
42. Giles, J. Effect of seedbed preparation on sugar beet emergence. *Sugar Beet Res. Ext. Rep.* **1992**, *22*, 233–241.
43. Kriauciuniene, Z.; Velicka, R.; Cekanauskas, S.; Butkeviciene, L.M.; Masilionyte, L.; Šarauskis, E.; Karayel, D.; Lazauskas, P. Evaluation of soil tillage process to improve seedbed preparation and crop density. *Acta Tech. Corviniensis Bull. Eng.* **2016**, *9*, 53–56.
44. Romaneckas, K.; Šarauskis, E. The investigation by the Kritz method of sugar beet seedbed under different soil tillage and sowing patterns in Lithuania. In Proceedings of the Soil Management for Sustainability: International Soil Tillage Research Organisation 16th Triennial Conference, Brisbane, Australia, 14–18 July 2003; pp. 1029–1035.
45. Romaneckas, K.; Šarauskis, E.; Masilionytė, L.; Sakalauskas, A.; Pilipavičius, V. Impact of different tillage methods on silty loam Luvisol water content in sugar beet (*Beta vulgaris* L.) crop. *J. Environ. Prot.* **2013**, *4*, 219–225.
46. Romaneckas, K.; Šarauskis, E. The influence of soil rolling time and methods on sugar beet seedbed formation. *Lucr. Stiintifice Ser. Agron.* **2006**, *49*, 125–139.
47. Romaneckas, K.; Šarauskis, E.; Pakulytė, N.; Tamulionis, A. The investigations of sugar beet seedbeds under different depth and density formation methods. *Vagos* **2008**, *78*, 29–36. (In Lithuanian with English summary)
48. Romaneckas, K.; Šarauskis, E.; Pilipavičius, V.; Adamavičienė, A.; Avižienytė, D. Impact of primary soil tillage intensity on maize (*Zea mays* L.) seedbed formation and productivity parameters. *J. Food Agric. Environ.* **2010**, *8*, 679–682.

49. Romaneckas, K.; Šarauskis, E.; Pilipavičius, V.; Sakalauskas, A. Impact of short-term ploughless tillage on soil physical properties, winter oilseed rape seedbed formation and productivity parameters. *J. Food Agric. Environ.* **2011**, *9*, 295–299.
50. Aura, E. Yield improvement of cereals by minimum tillage during dry summers. In *Soil Tillage and Environment: Proceedings of NJF-Seminar No. 228, Jokioinen, Finland, 8–10 June 1993*; NJF: Helsinki, Finland, 1993; Volume 88, pp. 289–294.
51. Morris, N.L.; Miller, P.C.H.; Orson, J.H.; Froud-Williams, R.J. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. *Soil Tillage Res.* **2010**, *108*, 1–15.
52. Mallory, J.J.; Mohtar, R.H.; Heathman, G.C.; Schulze, D.G.; Braudeau, E. Evaluating the effect of tillage on soil structural properties using the pedostructure concept. *Geoderma* **2011**, *163*, 141–149.
53. Ciric, V.; Manojlovic, M.; Nesic, L.; Belic, M. Soil dry aggregate size distribution: Effects of soil type and land use. *J. Plant Nutr. Soil Sci.* **2012**, *12*, 689–703.
54. Myrbeck, E.; Stenberg, M.; Arvidsson, J.; Rydberg, T. Effects of autumn tillage of clay soils on mineral N content, spring cereal yield and soil structure over time. *Eur. J. Agron.* **2012**, *37*, 96–104.
55. Keller, T.; Arvidsson, J.; Dexter, A.R. Soil structures produced by tillage as affected by soil water content and the physical quality of soil. *Soil Tillage Res.* **2007**, *92*, 45–52.
56. Atkinson, B.S.; Sparkes, D.L.; Mooney, S.J. Using selected soil physical properties of seedbeds to predict crop establishment. *Soil Tillage Res*. **2007**, *97*, 218–228.
57. Håkansson, I.; Arvidsson, J.; Rydberg, T. Effects of seedbed properties on crop emergence: 2. Effects of aggregate size, sowing depth and initial water content under dry weather conditions. *Acta Agric. Scand. B Soil Plant Sci.* **2011**, *61*, 469–479.
58. Munkholm, L.J.; Heck, R.; Deen, B. Long-term rotation and tillage effects on soil structure and crop yield. *Soil Tillage Res*. **2013**, *127*, 85–91.
59. Gallardo-Carrera, A.; Leonard, J.; Duval, Y.; Dürr, C. Effects of seedbed structure and water content at sowing on the development of soil surface crusting under rainfall. *Soil Tillage Res*. **2007**, *95*, 207–217.
60. Satkus, A.; Velykis, A. Modelling of seedbed creation for spring cereals in clayey soils. *Agron. Res.* **2008**, *6*, 329–339.
61. Muukkonen, P.; Hartikainen, H.; Alakukku, L. Effect of soil structure disturbance on erosion and phosphorus losses. *Soil Tillage Res*. **2009**, *103*, 84–91.
62. Al-Kaisi, M.M.; Douelle, A.; Kwaw-Mensah, D. Soil microaggregate and macroaggregate decay over time and soil carbon change as influenced by different tillage systems. *J. Soil Water Conserv.* **2014**, *69*, 574–580.
63. Badua, S.; Sharda, A.; Flippo, D. Sensing System for Real-Time Measurement of Seed Spacing, Depth, and Geo-Location of Corn: A Proof-of-Concept Study. *Trans. ASABE* **2019**, *62*, 1779–1788.
64. Nielsen, S.K.; Nørremark, M.; Green, O. Sensor and control for consistent seed drill coulter depth. *Comput. Electron. Agric.* **2016**, *127*, 690–698.
65. Quanwei, L.; Xiantao, H.; Li, Y.; Dongxing, Z.; Tao, C.; Zhe, Q.; Bingxin, Y.; Mantao, W.; Tianliang, Z. Effect of travel speed on seed spacing uniformity of corn seed meter. *Int. J. Agric. Biol. Eng.* **2017**, *10*, 98–106.
66. Badua, S.A.; Sharda, A.; Strasser, R.; Ciampitti, I. Ground speed and planter downforce influence on corn seed spacing and depth. *Precis. Agric*. **2021**, *22*, 1154–1170. https://doi.org/10.1007/s11119-020-09775-7.
67. Håkansson, I.; Arvidsson, J.; Etana, A.; Rydberg, T.; Keller, T. Effects of seedbed properties on crop emergence. 6. Requirements of crops with small seeds. *Acta Agric. Scand. B Soil Plant Sci.* **2013**, *63*, 554–563.
68. Håkansson, I.; Rydberg, T.; Keller, T.; Arvidsson. J. Effects of seedbed properties on crop emergence. 3. Effects of firming of seedbeds with various sowing depths and water contents. *Acta Agric. Scand. B Soil Plant Sci.* **2011**, *61*, 701–710.
69. Romaneckas, K.; Pilipavičius, V.; Šarauskis, E.; Sakalauskas, A. Effect of sowing depth on emergence and crop establishment of sugar beet (*Beta vulgaris* L.). *J. Food Agric. Environ.* **2009**, *7*, 571–575.
70. Romaneckas, K. The Influence of presowing soil tillage on morphometric properties of sugar beet. *Vagos* **2004**, *65*, 43–47. (In Lithuanian with English summary).
71. Romaneckas, K. The optimization of soil tillage for sugar beet. *Žemės Ūkio Moksl.* **2011**, *18*, 83–93.
72. Lamb, K.E.; Johnson, B.L. Seed size and seeding depth influence on canola emergence and performance in the Northern Great Plains. *Agron. J.* **2004**, *96*, 454–461.
73. Couture, S.J.; Di Tommaso, A.; Asbil, W.L.; Watson, A.K. Influence of seeding depth and seedbed preparation on establishment, growth and yield of fibre flax (*Linum usitatissimum* L.) in Eastern Canada. *J. Agron. Crop Sci.* **2004**, *190*, 184–190.
74. Liu, W.; Tollenar, M.; Stewart, G.; Deen, W. Response of corn grain yield to spatial and temporal variability in emergence. *Crop Sci.* **2004**, *44*, 847–854.
75. Karayel, D.; Özmerzi, A. Comparison of vertical and lateral seed distribution of furrow openers using a new criterion. *Soil Tillage Res.* **2007**, *95*, 69–75.
76. Karayel, D.; Özmerzi, A. Evaluation of three depth-control components on seed placement accuracy and emergence for a precision planter. *Appl. Eng. Agric.* **2008**, *24*, 271–276.
77. Baker, C.J.; Saxton, K.E.; Ritchie, W.R.; Chamen, W.C.T.; Reicosky, D.C.; Ribeiro, F.; Justice, S.E.; Hobbs, P.R. *No-Tillage Seeding in Conservation Agriculture*, 2nd ed.; FAO: Rome, Italy; CAB International: New York, NY, USA, 2007; 341p.
78. Knappenberger, T.; Köller, K. Opportunities and Challenges of a Real-Time Control of Seeding Depth. *Agrartech. Forsch.* **2004**, *11*, 49–52.
79. Jing, H.; Zhang, D.; Wang, Y.; Yang, L.; Fan, C.; Zhao, H.; Wu, H.; Zhang, Y.; Pei, J.; Cui, T. Development and performance evaluation of an electro-hydraulic downforce control system for planter row unit. *Comput. Electron. Agric.* **2020**, *172*, 105073.

80. Poncet, A.M.; Fulton, J.P.; McDonald, T.P.; Knappenberger, T.; Shaw, J.N.; Bridges, R.W. Effect of heterogeneous field conditions on corn seeding depth accuracy and uniformity. *Appl. Eng. Agric.* **2018**, *34*, 819–830.
81. Kiani, S.; Kamgar, S.; Raoufat, M. Automatic on-line depth control of seeding units using a non-contacting ultrasonic sensor. In Proceedings of the XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR), Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB), Québec City, QC, Canada, 13–17 June 2010; pp. 1–8.
82. John Deere. Downforce System Options. 2021. Available online: https://salesmanual.deere.com/sales/salesmanual/en_NA/seeding/2022/feature/row_units_and_drill_opener/planters/downforce_system.html (accessed on 27 December 2021).
83. Burce, M.E.C.; Kataoka, T.; Okamoto, H.; Shibata, Y. Seeding Depth Regulation Controlled by Independent Furrow Openers for Zero Tillage Systems. *Eng. Agric. Environ. Food.* **2013**, *6*, 13–19.
84. Wen, L.; Fan, X.; Liu, Z.; Zhang, Y. The design and development of the precision planter sowing depth control system. *Sens. Transducers* **2014**, *162*, 53.
85. Rui, Z.; Tao, C.; Dandan, H.; Dongxing, Z.; Kehong, L.; Xiaowei, Y.; Yunxia, W.; Xiantao, H.; Li, Y. Design of depth-control planting unit with single-side gauge wheel for no-till maize precision planter. *Int. J. Agric. Biol.* **2016**, *9*, 56–64.
86. Badua, S.A.; Sharda, A.; Flippo, D.; Ciampitti, I.A. Real-time gauge wheel load variability of a row-crop planter during field operation. *Trans. ASABE* **2018**, *61*, 1517–1527.
87. Bai, H.; Li, S.; Fan, X.; Niu, K.; Zhou, L.; Fang, X.; Wang, D.; Xu, J. Research on pressure regulation performance of electro-hydraulic control system of planter in field. In Proceedings of the 2020 ASABE Annual International Virtual Meeting, Virtual, 13–15 July 2020; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2020; article 2000555. https://doi.org/10.13031/aim.202000555.
88. Oliveira, L.P.; Ortiz, B.V.; Silva, R.P.; Way, T.R.; Oliveira, M.F.; Pate, G. Variability of Gauge-Wheel Loads Resulting from a Hydraulic Downforce System and the Impacts on Corn Seeding Depth and Emergence. In Proceedings of the 2021 ASABE Annual International Virtual Meeting, Virtual, 12–16 July 2021; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2021; p. 2101200. https://doi.org/10.13031/aim.2101200.
89. Oliveira, L.P.; Ortiz, B.V.; Silva, R.P.; Way, T.R.; Oliveira, M.F.; Pate, G. Does the Applied Gauge-Wheel Loads Have Influence on Seeding Depth and Soil Structure? In Proceedings of the 2021 ASABE Annual International Virtual Meeting, Virtual, 12–16 July 2021; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2021; article 2101211. https://doi.org/10.13031/aim.202101211.
90. Strasser, R.; Badua, S.A.; Sharda, A.; Rothmund, M. Development of a test stand to quantify the response of a planter's automatic downforce control system. *Trans. ASABE* **2021**, *64*, 1533–1543. https://doi.org/10.13031/trans.14047.
91. Stewart, S.; Kitchen, N.; Yost, M.; Conway, L.S.; Carter, P. Planting depth and within-field soil variability impacts on corn stand establishment and yield. *Agrosystems Geosci. Environ.* **2021**, *4*, e20186.
92. Sharipov, G.M.; Paraforos, D.S.; Griepentrog, H.W. Validating the Model of a No-Till Coulter Assembly Equipped with a Magnetorheological Damping System. *Appl. Sci.* **2019**, *9*, 3969.
93. Dawn Equipment. Active Seed Depth Control. 2021. Available online: http://dawnequipment.com/depth-control.html/ (accessed on 27 December 2021).
94. Graham Electric Planter. Graham Force. 2021. Available online: https://grahamelectricplanter.com/products/graham-depth-control/ (accessed on 27 December 2021).
95. Precision Planting. Smart Depth. 2021. Available online: https://www.precisionplanting.com/products/product/smartdepth (accessed on 27 December 2021).
96. Bourgault. On-the-Go Depth Adjustment. 2021. Available online: https://www.bourgault.com/product/en-US/paralink-hoe-drills-features/845/On-The-Go%20Depth%20Adjustment.aspx (accessed on 27 December 2021).
97. Sharipov, G.M.; Paraforos, D.S.; Griepentrog, H.W. Implementation of a magnetorheological damper on a no-till seeding assembly for optimising seeding depth. *Comput. Electron. Agric.* **2018**, *150*, 465–475.
98. Sharipov, G.M.; Paraforos, D.S.; Griepentrog, H.W. Modelling and simulation of the dynamic performance of a no-till seeding assembly with a semi-active damper. *Comput. Electron. Agric.* **2017**, *139*, 187–197.
99. Meinel, T. Sätechnik (Seeding Technology). In *Jahrbuch Agrartechnik 2019*; Ludger, F., Ed.; Institut für mobile Maschinen und Nutzfahrzeuge: Braunschweig, Germany, 2019; pp. 1–13. https://doi.org/10.24355/dbbs.084-202001201529-0. (In German)
100. Mouazen, A.M.; Anthonis, J.; Saeys, W.; Ramon, H. An Automatic Depth Control System for Online Measurement of Spatial Variation in Soil Compaction, Part 1: Sensor Design for Measurement of Frame Height Variation from Soil Surface. *Biosyst. Eng.* **2004**, *89*, 139–150.
101. Adamchuk, V.I.; Skotnikov, A.V.; Speichinger, J.D.; Kocher, M.F. Development of an instrumented deep-tillage implement for sensing of soil mechanical resistance. *Trans. ASAE* **2004**, *47*, 1913.
102. Kiani, S. Automatic on-line depth control of seeding units using a non-contacting ultrasonic sensor. *Int. J. Nat. Eng. Sci.* **2012**, *6*, 39–42.
103. Suomi, P.; Oksanen, T. Automatic working depth control for seed drill using ISO 11783 remote control messages. *Comput. Electron. Agric.* **2015**, *116*, 30–35.
104. Caiyun, L.; Hongwen, L.; Jin, H.; Qingjie, W.; Chao, W.; Junxiao, L. A Preliminary Study of Seeding Absence Detection Method for Drills on the Soil Surface of Cropland Based on Ultrasonic Wave without Soil Disturbance. *J. Sens.* **2019**, *2019*, 7434197. https://doi.org/10.1155/2019/7434197.

105. Zhao, J.; Zhu, L.; Jia, H.; Huang, D.; Guo, M.; Cong, Y. Automatic depth control system for a no-till seeder. *Int. J. Agric. Biol.* **2018**, *11*, 115–121.
106. Heil, K.; Schmidhalter, U. The application of EM38: Determination of soil parameters, selection of soil sampling points and use in agriculture and archaeology. *Sensors* **2017**, *17*, 2540.
107. Lv, H.; Ren, J.; Liu, X.; Li, S.; Wu, G.; Zheng, Y. Review of the Monitoring Systems of the Machine for Precision Sowing and Fertilization of Wheat. In Proceedings of the 2018 ASABE Annual International Meeting, Detroit, MI, USA, 29 July–1 August 2018; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2018; article 1800736. https://doi.org/10.13031/aim.201800736.
108. Paraforos, D.S.; Sharipov, G.M.; Griepentrog, H.W. ISO 11783-compatible industrial sensor and control systems and related research: A review. *Comput. Electron. Agric.* **2019**, *163*, 104863.
109. Weatherly, E.T.; Bowers, C.G., Jr. Automatic depth control of a seed planter based on soil drying front sensing. *Trans. ASABE* **1997**, *40*, 295–305.
110. Adamchuk, V.I.; Biswas, A.; Huang, H.H.; Holland, J.E.; Taylor, J.A.; Stenberg, B.; Field, D.J. Soil Sensing. In *Sensing Approaches for Precision Agriculture*, *Progress in Precision Agriculture*; Kerry, R., Escolà, A., Eds.; Springer: Cham, Switzerland, 2021; pp. 93–132. https://doi.org/10.1007/978-3-030-78431-7_4.
111. Garrido, M.; Conceiçao, L.A.; Baguena, E.M.; Valero, C.; Barreiro, P. Evaluating the need for an active depth-control system for direct seeding in Portugal. In Proceedings of the 8th European Conference on Precision Agriculture, Prague, Czech Republic, 11–14 July 2011; pp. 371–381.
112. Jia, H.; Guo, M.; Yu, H.; Li, Y.; Feng, X.; Zhao, J.; Qi, J. An adaptable tillage depth monitoring system for tillage machine. *Biosyst. Eng.* **2016**, *151*, 187–199.
113. Conceição, L.A.; Barreiro, P.; Dias, S.; Garrido, M.; Valero, C.; da Silva, J.R. A partial study of vertical distribution of conventional no-till seeders and spatial variability of seed depth placement of maize in the Alentejo region, Portugal. *Precis. Agric.* **2016**, *17*, 36–52. https://doi.org/10.1007/s11119-015-9405-x.
114. Sudduth, K.A.; Kitchen, N.R.; Bollero, G.A.; Bullock, D.G.; Wiebold, W.J. Comparison of electromagnetic induction and direct sensing of soil electrical conductivity. *Agron. J.* **2003**, *95*, 472–482.
115. Coronel, E.G.; Alesso, C.A.; Bollero, G.A.; Armstrong, K.L.; Martin, N.F. Field-specific yield response to variable seeding depth of corn in the Midwest. *Agrosystems Geosci. Environ.* **2020**, *3*, e20034.