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Review

Current Knowledge and Future Directions for Improving Subsoiling Quality and Reducing Energy Consumption in Conservation Fields

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Abstract: Subsoiling has been acknowledged worldwide to break compacted hardpan, improve soil permeability and water storage capacity, and promote topsoil deepening and root growth. However, there exist certain factors which limit the wide in-field application of subsoiling machines. Of these factors, the main two are poor subsoiling quality and high energy consumption, especially the undesired tillage depth obtained in the field with cover crops. Based on the analysis of global adoption and benefits of subsoiling technology, and application status of subsoiling machines, this article reviewed the research methods, technical characteristics, and developing trends in five key aspects, including subsoiling shovel design, anti-drag technologies, technologies of tillage depth detection and control, and research on soil mechanical interaction. Combined with the research progress and application requirements of subsoiling machines across the globe, current problems and technical difficulties were analyzed and summarized. Aiming to solve these problems, improve subsoiling quality, and reduce energy consumption, this article proposed future directions for the development of subsoiling machines, including optimizing the soil model in computer simulation, strengthening research on the subsoiling mechanism and comprehensive effect, developing new tillage depth monitoring and control systems, and improving wear-resisting properties of subsoiling shovels.

Keywords: subsoiling machine; subsoiling shovel design; anti-drag; tillage depth detection; tillage depth control; tillage depth stability; soil mechanical interaction

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1. Introduction

As the important factor in crop growth, soil is a valuable agricultural resource, a significant production factor, and an indispensable foundation supporting the sustainable development of agriculture [1]. The ideal farmland soil is composed of 50% soil particles with organic matter and 50% pores; additionally, with respect to pores, the moisture and air respectively account for 25% [2]. However, due to long-term conventional ploughing practices, hardpan has been shaped, which is a typical form of soil compaction [3,4]. Consequently, the failure layer is formed, resulting in the rearrangement of soil particles under external forces [5,6], and giving rise to a reduction in soil porosity and an increase in bulk density [7–9]. The root-system penetrability is affected by soil compaction, and especially the high-level compaction inhibits the root growth [10]. The hardpan binds root proliferation, reduces root penetration, and decreases root length and dry matter [11]. In addition, the key enzymes required for plant respiration show a downward trend with increasing compaction stress, which leads to impaired root function and the loss of nutrient absorption [12–15].

Subsoiling can break the hardpan and alleviate the soil compaction without turning ploughing soil and disrupting the original topsoil structure [16]. Compared with conventional ploughing, the subsoiling tillage at 30 cm, 35 cm, and 40 cm decreased the mean bulk density by 4.59%, 7.13%, and 8.27% and reduced soil compactness by 17.62%, 23.63%, and 36.42%, respectively [17]. Meanwhile, subsoiling increased soil porosity, enhanced soil infiltration and water storage capacity, and decreased water inputs per growing day [18]. Additionally, in comparison with the rotary tillage, the subsoiling practice significantly increased the average root length density by 13% due to the better root penetration in both horizontal and vertical directions. Moreover, the average grain yield and dry matter weight of maize were respectively increased by 6.3% and 3.7% [19]. Furthermore, subsoiling improved the activity of plant-protective enzymes in maize root, reduced the degree of peroxide in cell membrane substances, and delayed the senescence of maize root. It is conducive to maintaining root system vitality in the later growth stage of maize [20]. Therefore, subsoiling is classified as a resource-saving and environmental-friendly technology, and is significant in promoting the sustainable development of agriculture [21–24].

In the early 1930s, some countries in North America and Europe began to use subsoiling technology to solve soil problems. Thanks to the significant effects of subsoiling on the repair and protection of arable land, the combination of tillage methods and comprehensive utilization of subsoiling technology has become increasingly close in these regions. The proportion of arable land that adopted subsoiling in Europe was 15.4% in 2005. Meanwhile, the proportion in North America exceeded 40% in 2006. Until 2015, the proportion in European and American areas had reached 60% [25]. In some Asian countries, subsoiling technology was adopted relatively late. To address the issue of the crop yield decline caused by soil compaction, China has promulgated a series of associated regulations to promote subsoiling and land preparation technologies since 2009 (Table 1). By the end of 2018, the subsoiling was practiced on 10.6 Mha, accounting for 7.41% of the total arable land [26]. At present, subsoiling technology is being widely used in scientific experiments and actual productions of various crops such as wheat, corn, cotton, sugar cane, tobacco, and soya beans.

Table 1. Relevant development regulations of subsoiling and land preparation technology in China.

Regulation	Related Content
Ministry of Agriculture and Rural Affairs: National agricultural machinery subsoiling and land preparation operation implementation plan (2016–2020) [27]	In 2016–2020, the nationwide annual operation area of subsoiling and land preparation via agricultural machinery exceeds 10 million ha
State Council: Government Work Report [a] (2015) [28]	Promote land renovation, add 13.33 million ha land under subsoiling and land preparation
State Council: Government Work Report (2014) [29]	Launch a pilot project to adopt subsoiling and land preparation technology covering 6.67 million ha
State Council: Central Document No.1 [b] (2014) [30]	Give great impetus to advance mechanization of subsoiling and land preparation
Ministry of Agriculture: National agricultural machinery subsoiling and land preparation operation implementation plan(2011–2015) [31]	A total of 71.3 million ha area in the nation will be subsoiled in 2011–2015
State Council: Opinions of the State Council on promoting sound and rapid development of agricultural mechanization and agricultural machinery industry (2010) [32]	Implement pilot projects to subsidize subsoiling and land preparation at suitable regions
State Council: Central Document No.1 (2010) [33]	Give great impetus to extend subsoiling and land preparation machinery
Ministry of Finance: Interim measures for the administration of the centralized use of the newly increased central funds for comprehensive agricultural subsidies for the building of basic grain capacity (2009) [34]	Bring conservation tillage methods such as subsoiling and land preparation into the key support scope of the newly increased agricultural funds for comprehensive subsidies
State Council: Central Document No.1 (2009) [35]	Implement pilot projects to subsidize the mechanized operation in the key link

[a] "Government Work Report" is a form of the official document of the Government of the People's Republic of China, which clearly points out the government's tasks for the current year; [b] "Central Document No.1" is the name originally given to the first document issued by the central authority every year, and focuses on the development of agriculture, rural areas, and farmers in 1982.

Subsoiling machines are indispensable to mechanized subsoiling, and their performance directly affects the hardpan's broken quality, topsoil structure, soil permeability, soil microbial quantity, root growth, and crop yield [36]. According to their working function, subsoiling machines can be divided into single-function subsoiling machines and multi-function subsoiling machines. The single subsoiling machines can be further divided into two categories: subsoiling ploughs and omni-directional subsoilers [37]. Some typically available subsoiling machines around the world are discussed in Table 2. Subsoiling machines in certain countries with large per-capita arable land areas (e.g., America, Canada, Australia, Russia) are mainly matched with high-power tractors which have several advantages, such as large tillage width, fast operation speed, high operation efficiency, and advanced machining technology. On the contrary, for those countries with small per-capita arable land areas, such as China and Japan, the per-capita arable land areas are respectively only about 0.08 ha and 0.03 ha, which are merely approximately one-sixth and one-twentieth of that in America, and about 0.038 and 0.014 times as large as Australia, respectively [38]. The subsoiling machines are mainly matched with small or medium-power tractors. The features of subsoiling machines in these countries include small size, light weight, flexible operation, and low cost. Nevertheless, current subsoiling machines have some problems with their performance, such as poor soil loosening quality, undesired soil disturbance, unstable tillage depth, high power consumption, and rapid wear of shovels.

Table 2. Comparison of different kinds of subsoiling machines.

Working Function	Type	Company	Country	Mechanism	Working Width (mm)	Matched Power (kW)	Features
Combined machine	DIABLO [39]	Maschio	Italy	Two-row winged shovels; Stubble breaking discs; Rear rollers with two rows of discs	5000–7000	300–400	Having ample clearance between shovels and rear discs
Combined machine	2730 [40]	John Deere	USA	Two rows of stubble breaking discs arranged symmetrically; Spring-tooth harrows; A suppress roller	4300–6800	250–460	Lower operation costs
Subsoiling plough	AP31 [41]	Agrowplow	Australia	Nine deep tillage ploughs; Two supporting wheels	2310–2970	73.5–132.3	Bolt-less for the quick changing of ploughs and points
Subsoiling plough	9200 [42]	Salford	Britain	Seven shovels with 0.99m spacing	5320	206	Equipped with automatic spring reset obstacle protection system
Omni-directional subsoiler	1S-300C [43]	Dahua	China	The chisel shovel with left and right winged shovels; Three rows beams; A suppress roller; Two gauge wheels	3000	147–191.1	With overload protection
Omni-directional subsoiler	1SQ-330 [44]	Aolong	China	Six side bended shovels; Two gauge wheels; A suppress roller	3300	99.2–154.4	Tips of two shovels arranged symmetrically forms an inverted trapezoid

In order to improve subsoiling quality and reduce energy consumption in the field with cover crops, several studies have been conducted on subsoiling shovel structure, anti-drag technologies, tillage depth detection and control, and soil-mechanical interaction [45–51]. Various subsoiling shovels are capable of meeting the needs of different regions in different countries. Reducing tillage resistance during subsoiling makes subsoiling machines more prominent with the advantages of resource saving and being environmentally friendly. Modern sensor detection technology and electronic-hydraulic control technology are used to accurately control the tillage depth of subsoiling machines, which benefits in terms of conserving moisture and preparing a good seedbed [19,52–55]. Additionally, soil-mechanical interaction mechanisms presented in micro and macro ways, mainly clarified via theoretical analysis and simulation, are an important means to realize the efficient development of the abovementioned studies. The integration of abovementioned technologies contributes greatly to the improvement of subsoiling quality and the reduction of energy consumption in the field with cover crops.

The goal of this study was to comprehensively review the existing literature related to technologies for improving subsoiling quality and reducing energy consumption currently being used in subsoiling machines. This article was based on the following aspects and organized as follows. Section 2 states the methods of design and optimization of subsoiling shovels, commenting on the different types of available shovels. Then, Section 3 explores five ways to reduce tillage resistance. Sections 4 and 5 provide a review of tillage depth detection and control, applying sensor detection technology and electro hydraulic control technology. Section 6 delves into the application of theoretical analysis and discrete element analysis in research on soil-mechanical interaction. Finally, in Section 7, recommendations are given for the future development of subsoiling machines.

2. Subsoiling Shovel Design

Subsoiling shovels are the main working parts of a subsoiling machine [37]. Their design has a significant influence on subsoiling quality and tillage resistance [56,57]. The common types of commercial shovels are chisel, winged, "V" shaped, and side bended shovels. Through optimizing the penetrating angle, the opening angle of winged shovels, and the shovel-handle structure, some subsoiling shovels with better working performance have been developed. The comparisons among these shovels are shown in Table 3.

Table 3. Subsoiling shovel type, model, country, working width, working depth, matched power, number, and feature.

Type	Model	Country	Working Width (cm)	Working Depth (cm)	Matched Power (KW)	Number	Feature
chisel	1S-225C [58]	Germany	200	50–65	55–129	3	Adjustable of chisels for any tractor track width
chisel	1S-150A (Figure 1a) [59]	China	150	25–30	36.8–51.5	3	Low tillage resistance
winged	PINOCCHIO200 [60]	Italy	130–300	45	50–160	3–7	Available in different widths and shovel numbers
winged	1S-200 (Figure 1b) [61]	China	200	300–400	70	5	Good flow of soil under the shovel
V shaped	1SQ-340 (Figure 1c) [62]	China	155	40–50	73.6–88.3	3	Forming mole drains at the bottom with smaller resistance
side bended	DALBO Ratoon [63]	Denmark	120–300	55	30–120	2–8	Low power requirement
side bended	1S-250 (Figure 1d) [64]	China	250	25–50	89–106.6	6	Special cambered surface

In order to improve quality, reduce resistance, and increase efficiency, a cambered subsoiler shank was designed by Chen [65]. The test showed that the subsoiling resistance was the smallest when the sweep angle was 50°. Based on the orthogonal experiment's results, i.e., the penetrating angle had a significant effect on subsoiling resistance, Liu et al. [47] optimized the chisel shank's structure and found that the resistance was minimal when the rack angle was 21°. Zhao et al. [66] designed a fitting curve-shaped shank and clarified the effect of the shovel tip on the soil particle's movement. The results of the comparison test between the fold-line-typed shank and the circular shank showed that the fitting curve-shaped shank effectively reduced soil disturbance and tillage resistance. By simulation analysis and digitized soil-bin experiments, Wang et al. [67] demonstrated that, on the circular shank, the optimum installing height of the winged shovel was 75 mm.

The shank type, penetrating angle, opening angle of the winged shovel, and shovel-handle structure are the main factors influencing the tillage resistance of subsoiling shovels. In order to improve subsoiling quality and reduce tillage resistance, these factors are used as the target parameters. Through subsoiling simulation and soil-bin and field trials, the effect of shovel structure on the tillage resistance as well as soil disturbance were analyzed and their impacts were clear. Then, these target parameters were optimized on the basis of the above results, and the shovel structure was accordingly improved to obtain better subsoiling quality and lower tillage resistance. Design and optimization of subsoiling shovels has always been one of the key technologies of subsoiling machines.

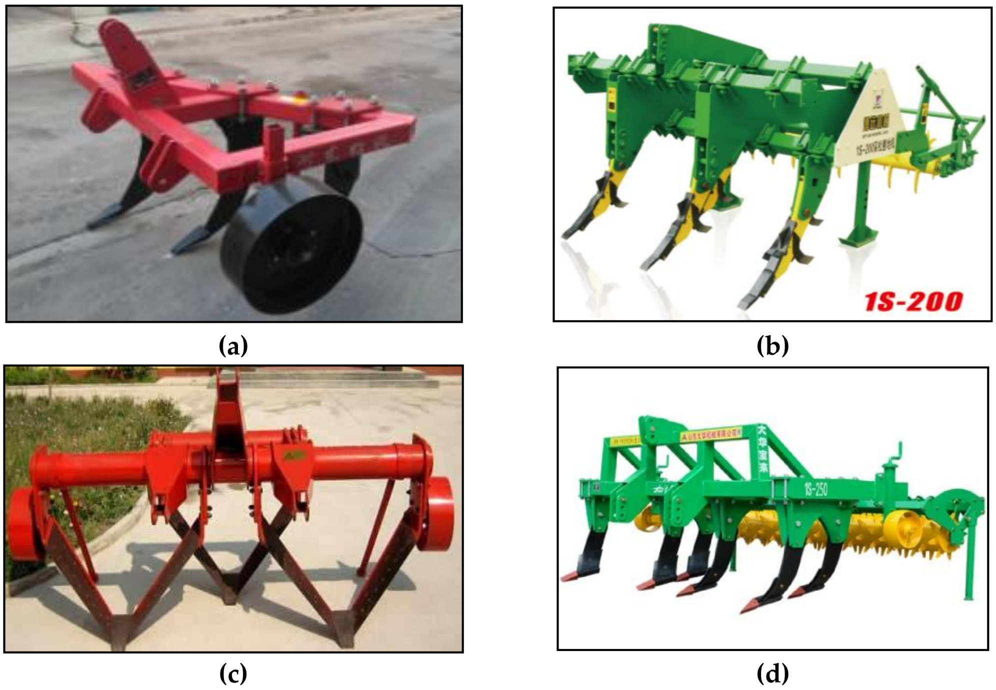


Figure 1. (**a**) Chisel shovels of the Hedongxiongfeng 1S-150A subsoiler (http://www.hedongxiongfeng.cn/pd.jsp?id=52#_pp=103_366 (accessed on 15 September 2020)); (**b**) Winged shovels of the Zhongnong-boyuan 1S-200 subsoiler (http://www.boyomac.com/product/17.html (accessed on 14 May 2021)); (**c**) V shaped shovels of the Woye 1SQ-340 subsoiler (https://www.nongjitong.com/product/3072.html (accessed on 15 September 2020)) (**d**) Side-bended shovels of the DaHua BaoLai 1S-250 subsoiler (https://www.dhbl.net/product/53.html (accessed on 15 September 2020)).

3. Anti-Drag

The energy consumption caused by subsoiling is three to five times as much as that of other planting procedures such as seeding, managing, and harvesting [68]. Decreasing tillage resistance during subsoiling is the main measure to reduce energy consumption. Several methods of decreasing resistance are available, such as vibration anti-drag technology, bionic anti-drag technology, layered subsoiling structure, shovel design with anti-drag structure, and surface coating technology of shovels.

3.1. Vibration Anti-Drag

Vibration anti-drag refers to adding an excitation source on the subsoiling machine to make subsoiling shovels constantly subject to the repeated positive and negative forces. The greatest advantage of the vibration subsoiling machine is its low traction resistance. According to the driving mode of excitation source, vibration machines can be divided into self-excited and forced-excited categories. Shovels of the forced-excited vibration subsoiler are capable of vibrating via connecting an eccentric mechanism. Sun et al. [69] adopted two eccentric discs to drive connecting rods and shovels reciprocating vibration in the vertical direction. The minimum resistance and energy consumption were obtained under the optimum combination of forward speed, vibration frequency, amplitude, angle, and speed ratio [70–73]. A typical forced-excited vibration subsoiler is shown in Figure 2. Self-excited vibrating can be obtained by applying elastic elements, such as pressure springs (Figure 3a), leaf springs (Figure 3b), and hydraulics [74–76] (Figure 3c). This anti-drag method not only has little impact on soil, but also protects shovels and other components [77].

Figure 2. DaHua BaoLai 1SZ-180 forced-excited vibration subsoiler (http://www.nongjitong.com/product/dahua_1sz-270_deep_loosening_machine.html (accessed on 12 November 2020)).

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

Figure 3. (**a**) Great Plains SS1300 subsoiler (http://www.greatplainsmfg.com.ua/en-gb/products/710/sub-soiler-narrow-tillage (accessed on 8 December 2020)); (**b**) Kverneland GLG-II subsoiler (https://www.kverneland.cn/node_80887/node_80897/node_80958# (accessed on 8 December 2020)); (**c**) AGRI-WELD subsoiler (https://www.plowmanbrothers.com/plowman-agricultural/ (accessed on 8 December 2020)).

3.2. Bionic Anti-Drag

The primary task of bionic anti-drag is to extract biological information, which includes the function, structure, process, or behavioral characteristics and mechanisms of the biological system. On this basis, a technology similar to the function of biological-systems was developed and applied to shovels to reduce resistance [78]. The contour line of the claw toe from house mice (Mus musculus) was extracted and found to feature an exponential function curve, and Zhang et al. [79] converted the upper contour line of the longitudinal profile of their (Mus musculus) claws into the technical parameters of the shovel's cutting edge curve. Then, the contour curve was enlarged properly and applied to the structural design of the cutting edge of the shovel handle. The comparative field experiment between the shovel with the feature of an exponential curve and the conventional shovel showed that the tillage resistance of the bionic shovel was reduced by 8.5–39.5% compared with the traditional shovel. Li et al. [80] obtained the accurate shape and dimension of a bear claw by a three-dimensional laser scanner and established a claw model. By the discrete element simulation, they found that the overall performance of the claw was the best when the rack angle was 30°. A bionic vibratory subsoiler was designed by Zhang et al. [81], which combined vibration anti-drag with bionic anti-drag. It was reported that the draft force of the bionic vibratory subsoiler was respectively reduced by 13–18% and 8.5–39.5% compared with the 1SZ-460 lever-type subsoiler and bionic anti-drag subsoiler.

In addition to the above two methods, the layered subsoiling structure is capable of reducing tillage resistance and mainly depends on two shovels. Along the forward direction, the shovel with a small depth is in front, while the shovel with a large depth is in the back [82,83]. The shovel design with an anti-drag structure optimized the handle or tip via experiment or simulation, thereby obtaining better subsoiling quality and less tillage resistance [84,85]. The surface-coating technology aims at obtaining better soil-removal performance of shovels by changing the properties of surface material, hence decreasing tillage resistance [86].

The above mentioned anti-drag technologies can effectively reduce resistance, whereas in studies of reducing shovel resistance, less consideration is given to the thickness of the three soil layers (tillage layer, hardpan, subsoil layer) and the soil's physical properties, as well as the soil smashing process. Apart from reducing tillage resistance, the power consumption of subsoilers and straw blocking of shovels should also be reduced. Although the forced-excited vibration subsoiler is capable of decreasing the traction, the required fuel consumption is much higher. In order to balance the traction and energy requirements and to improve the overall efficiency, better methods should be explored through further studies so as to drive the vibrator.

4. Tillage Depth Detection

Initially, the tillage depth could only be measured manually, which had great labor intensity and low detection accuracy. Additionally, these measured depth data were limited and discrete, and could therefore not reflect continuous changes including the variation of tillage depth with surface and time; consequently, it is unable to study the dynamic characteristics of depth. To this purpose, sensors, which have higher detection accuracy and provide a basis for depth adjustment of subsoiling machines, are used for measuring tillage depth. At present, there are two main kinds of sensors used in tillage depth detection: ultrasonic sensors and inclination sensors.

4.1. Tillage Depth Detection Based on Ultrasonic Sensor

The detection method of ultrasonic sensors utilizes a constant speed transmission of acoustic waves. The signal generator generates acoustic waves with a certain oscillation frequency and which travels through the air at a constant speed. The ultrasonic echo is generated when the acoustic wave encounters impurities and interfaces, and then it is received by the signal-receiving end. Therefore, the distance is obtained by calculating the formula of time interval and sound speed [87].

Tests were carried out to evaluate detection accuracy of the ultrasonic sensor on different fields by Mouazen et al. [88], and the ultrasonic sensor was installed on the bottom of the frame. Compared with the manual measurement values, it was found that the detection accuracy of the ultrasonic sensor was better in the soft sandy loam, while it was lower in the soil with cover crops. A tillage depth measurement device based on the ultrasonic sensor was designed by Li [89], and proved to behave better than the resistance-stain type measurement device in terms of measuring accuracy. Adamchuk et al. [90] developed a closed-loop automatic control system for tillage depth, and the ultrasonic sensor was applied to measure tillage depth. An online measuring device of subsoiling depth was proposed in the Chinese Academy of Agriculture Mechanization Sciences [91]. It used an ultrasonic sensor to detect the distance between the frame of the subsoiling machine and the surface, and thus the tillage depth was obtained. A tillage depth detection system was designed by Suomi et al. [50], which used an ultrasonic sensor installed in front of the frame with an inclination sensor mounted on the connection arm of the gauge wheel and the frame to measure the height and the angle; the depth was obtained by calculating the formula related to these two physical properties. The field experiment showed that the detection error of this system was within 10 mm.

4.2. Tillage Depth Detection Based on Inclination Sensor

Inclination sensors determine the position of the object according to the three-dimensional angle change, which should be attached to the objects' surface to measure the inclination of the object from the horizontal plane [92]. When the inclination sensor is used to detect tillage depth, it is often on the hitch device or profiling mechanism to measure the angle change. Then, the tillage depth is obtained by formula calculation.

A detector, consisting of a frame, an inclination sensor, and a sliding plate which undulated with the surface, was designed by Zhao et al. [93] and used to measure tillage depth. By detecting the relative angle between the frame and the tractor, the depth was acquired through geometric modelling of the depth and angle. Li et al. [94] developed a measurement device, and the inclination sensor was on the linkage of the frame and gauge wheel. By angle measurement and calculation, the tillage depth was obtained. Results showed that the error of this measurement method was within 6%. Xie et al. [95] installed inclination sensors on the lift arm of a tractor to detect angle change from the horizontal plane. The actual tillage depth was calculated according to the inclination of the lift arm and the geometrical dimension relation of the linkage mechanism. In addition to the abovementioned detection methods based on ultrasonic sensors and inclination sensors, potentiometers and encoders, of which the detection principle is similar to that of the inclination sensor, are also used to detect tillage depth [96,97].

In existing research on the technology of tillage depth detection, ultrasonic sensors and inclination sensors are widely used because of their low cost, simple working principles, and convenient installation methods. However, there still exist some problems. The detection accuracy of ultrasonic sensors would be affected by weeds, straws, and clods, which could lead to unstable detection results. In addition, inclination sensors can be used to measure the horizontal dip angle of the rear-suspension lifting arm. Although this method avoids the negative influence of surface unevenness and other abovementioned factors on detection accuracy, other problems may appear. As there are many connecting rods between the tractor boom and the suspension unit, drivers may adjust the length of the lift rod and the upper pull rod in practice, which leads to a change in the geometric parameter. Thus, it is inconvenient to use this method due to the need to recalibrate the sensor. Besides, the method, applying inclination sensors to measure the angle change of the profiling mechanism and calculate the mathematical model to get the tillage depth, results in the mismatch between the adjustment completion point and detection point of tillage depth. This is because the profiling mechanism is generally placed behind the tillage component, which leads to the delay of profiling.

5. Tillage Depth Control

Because of the complexity and variability of the field-work environment, the tillage depth often needs to be adjusted many times to achieve stable and consistent outcomes. It is essential to develop the control technology of tillage depth to obtain precise and efficient adjustments. Currently, there are two major control modes of tillage depth: the method of unified adjustment of each row and the method of independent adjustment of a single row. The adjusting mechanism belonging to the first adjustment mode is based mainly on the attachment position of the tillage machine and its tractor. This method commonly combines the hydraulic device of three-point suspension with mechanical and electrical technology to achieve automatic control of tillage depth [98]. With regard to the method of independent adjustment of a single row, separate adjustment mechanisms, hydraulic mechanisms, or electrical mechanisms need to be designed and installed on the machinery, and the number of mechanisms is equal to the number of subsoiling shovels. This method is capable of avoiding undesired tillage depth of each subsoiling shovel.

5.1. Method of Unified Adjustment of Each Row

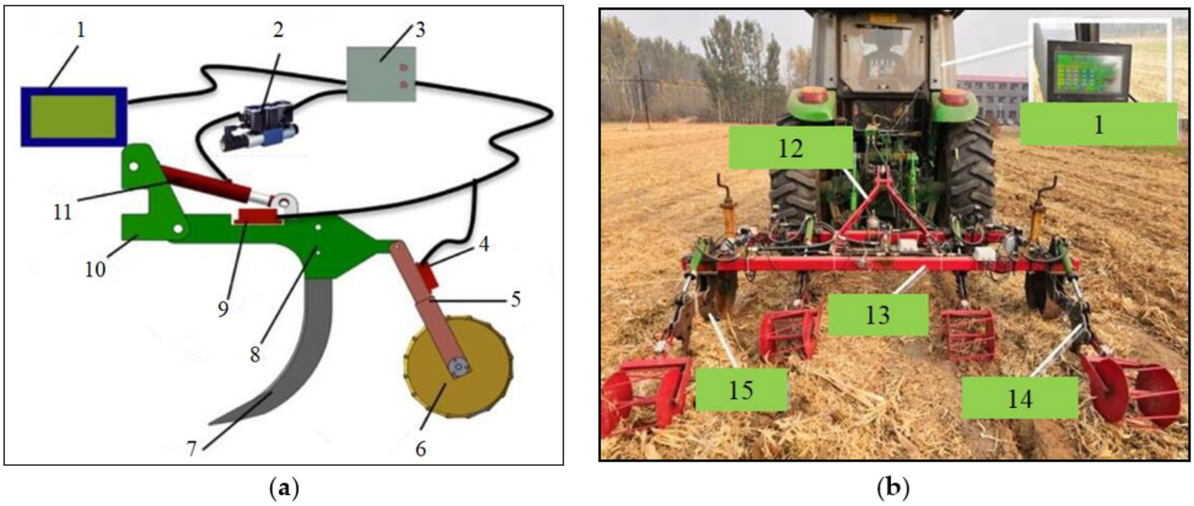
The method of unified adjustment of each row aims at adjusting the tillage depth of the whole machine (adjusted on the three-point suspension) or a group of tillage components of the combined land-preparation equipment. Therefore, the hydraulic suspension system with electronic control technology (EHC) is an important support for this mode. The method of controlling depth using EHC mainly involved three control methods, including force control, position control, and integrated control of the two abovementioned modes. Long-term research on the automatic control of tillage depth based on these three methods has been conducted. In order to improve control accuracy, Lee et al. [48] developed a tillage depth control system. Some sensors were used to detect inclination of the three-point suspension, pitch angle of the tractor, and distance from the transducer to the surface. The drive circuit of the electromagnetic valve was controlled by a controller to change the state of the hydraulic circuit, and thus the position of the three-point suspension was adjusted. For the electro-hydraulic suspension system composed of a cartridge valve, a suspension control scheme based on the Controller Area Network (CAN) bus was proposed by Xie et al. [99] to improve the control accuracy, which mainly included the suspension subsystem ECU and two intelligent nodes. The experiment demonstrated that the developed nodes were capable of meeting the working requirements of the suspension system. Nie et al. [100] developed a tillage depth automatic control system, which was based on the original hydraulic suspension system and applied sensors, microcomputers, and stepping motors to realize automatic control. Moreover, the reliability and stability of the system were verified by experiments.

In addition, combined tillage equipment with the function of monitoring and controlling depth was researched and developed by some agricultural machinery enterprises such as OPICO, John Deere, and CASE. The HE-VA combined land preparation machine consists of groups of subsoiling components and disc harrows, of which the tillage depth is controlled by adjusting the height of the suppress roller through the hydraulic system [101]. John Deere developed a TruSet monitoring system for the land preparation equipment. Depth detection sensors, which are mounted on the supporting wheels and frame, are capable of accurately measuring the depth of the whole machine. Additionally, the depth of each group of tillage components is adjusted via the matched AccuDpthTM hydraulic system [102]. The AFS (Advanced Farming System) tillage depth intelligent monitoring system was developed by CASE, and is capable of precisely adjusting the tillage depth of the whole machine according to different soil conditions [103]. Before operation, the prescription map containing the predetermined tillage depth information of the field is input into the system. Owing to the tractor being equipped with a GPS positioning system, when the equipment moves to the corresponding position, the tillage depth is automatically adjusted by the hydraulic system to the required tillage depth. A stroke-detection sensor is installed in the hydraulic cylinder to provide real-time access to length changes of the hydraulic cylinder, and this is the key to the precise control of tillage depth.

5.2. Method of Independent Adjustment of Single Row

The abovementioned technologies in Section 5.1 are capable of adjusting the tillage depth of the whole machine or a group of tillage components of the combined land preparation equipment. However, due to surface relief or soil resistance variation, there exists the problem of lateral instability of tillage depth of the machine with several subsoiling shovels, which leads to the inconsistency of soil conditions in the lateral distribution. Therefore, it is necessary to develop subsoilers with special subsoiling assemblies that are capable of independently adjusting tillage depth of each subsoiling shovel. The method of independent adjustment of a single row is capable of avoiding undesired tillage depth of each subsoiling shovel to improve the tillage depth stability between rows.

A universal-type device which automatically monitors and controls the tillage depth of each subsoiling shovel was developed [104]. Laser-ranging sensors were used to measure the distance between the stand and surface. Then, the corresponding signal was sent to the Programmable Logic Controller (PLC) to be analyzed and calculated, and the real-time tillage depth was recorded. Comparing the real depth with the set value, the PLC sent an execution signal to the driver circuit of the electromagnetic valve to change the solenoid valve switch, and the hydraulic cylinder was adjusted to extend or shorten. Therefore, the tillage depth, in real time, was controlled to be consistent. Wang et al. [105] designed an electric-hydraulic control system which was capable of adjusting the tillage depth of subsoiling assemblies in a timely manner (Figure 4a). Two inclination sensors were used to detect the dip angle in the horizontal direction, and were mounted horizontally on the subsoiler frame and inclined frame of the suppress roller, respectively. Through internal algorithm, the tillage depth was calculated. The hydraulic cylinder performed the action, elongating or shortening to obtain desired tillage depth. Moreover, the performance of the system was evaluated in the aspect of the tillage depth stability between rows and within rows. Wu [106] developed a subsoiling machine to automatically monitor and control tillage depth based on ultrasonic sensors and hydraulic drivers. It was capable of independently monitoring and controlling the depth of each subsoiling shovel.



1. Touch screen 2. Proportional value and value amplifier 3. Controller box 4. Inclination sensor 5. Press roller frame 6. Press roller 7. Curved shovel 8. Shovel frame 9. Inclination sensor 10. Fixed frame 11. Hydraulic cylinder 12.Three-point suspension 13.Frame 14.Subsoiling assembly with the electric-hydraulic control system 15. Supporting wheel.

Figure 4. (**a**) Subsoiling assembly with the electric-hydraulic control system (Wang et al., 2018); (**b**) Subsoiler equipped with four subsoiling assemblies with the electric-hydraulic control system (Wang, 2019).

In conclusion, the control method of unified adjustment of each row adopts integrated adjustment and position adjustment combined with force adjustment. This mode not only ensures the tillage depth stability to a certain extent, but also takes the influence of tillage resistance into account. The control precision of tillage depth by this mode meets the operation requirements. However, relevant parameters in the proportional fuzzy control are difficult to determine, and the control process is more complicated. This control mode is suitable for the operations in flat fields. Furthermore, the single-row tillage depth cannot be independently adjusted according to undulation of local surfaces. By comparison, for the method of independent adjustment of a single row, the designed mechanism used to adjust depth has strong applicability. By adjusting the connecting parts of the control device, the adjustment mechanism can be installed on the different tillage machines. In addition, the main program of the automatic control system belonging to the separate adjustment mechanism is relatively simple. Moreover, tillage depth of subsoiling assemblies can be independently adjusted. Therefore, this control mode is excels at obtaining consistent depths of each subsoiling shovel.

6. Soil Mechanical Interaction

The interaction mechanism analysis of subsoiling shovels and soil is the key to the study of the shovel force and the effect of shovels on the dynamic changes of soil disturbance [107]. Wheeler [108] developed a mechanical model and studied the influence of speed on tillage resistance. Manuwa [109] set up models for the resistance prediction of different shovels and analyzed the effect of loosening depth on draft force. Based on the mechanical principle of two-side wedge and three-side wedge in soil, Ma and Zhou [110,111] studied the straight-legged shank and the circular shank and built mathematical models. In recent years, the Discrete Element Method (DEM) has been widely used to study the tillage mechanism [112,113]. Shmulevich [114] used PFC2D discrete-element software to research the interaction between the wide shovel and soil, and four types of shanks were chosen for simulation. Results showed that soil accumulation in front of shovels increased horizontal resistance during movement, and the soil flow below the tip influenced the vertical force applied to the shovel. A soil-tool-residue interaction model was developed by Zeng et al. [115] using the DEM and was used to investigate and compare the effects of forward speed on soil displacement, residue displacement, and residue cover reduction resulting from four types of shovels (Figure 5). Considering the normal tension generated among elements, Momozu et al. [116] used coefficients to modify the traditional discrete element model, and then to represent the adhesion generated by moisture among soil particles. Tamas et al. [117] developed a discrete element model to analyze the effects of the sweep rack angle and speed on soil loosening and porosity. Results showed that the comparison between the measured and simulated draught of subsoiling shovels with a 30° sweep rack angle behaved as a good match. In the selected speed interval of 0.5–2.4 m s^{-1}, the error range was 4–15%. A working model of subsoiling was established by Hang et al. [118], applying the DEM. Through simulation based on this model and an indoor soil-bin test, they compared and analyzed the micro-movement and macro-disturbance behavior of subsoil at different locations under the combined effect of two shovels (Figure 6).

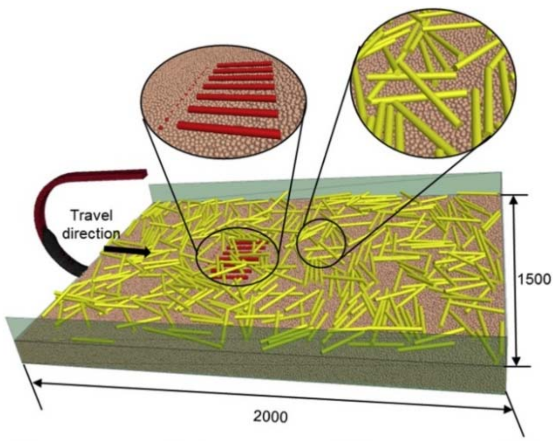


Figure 5. The soil-tool-residue interaction model (Zeng et al., 2020).

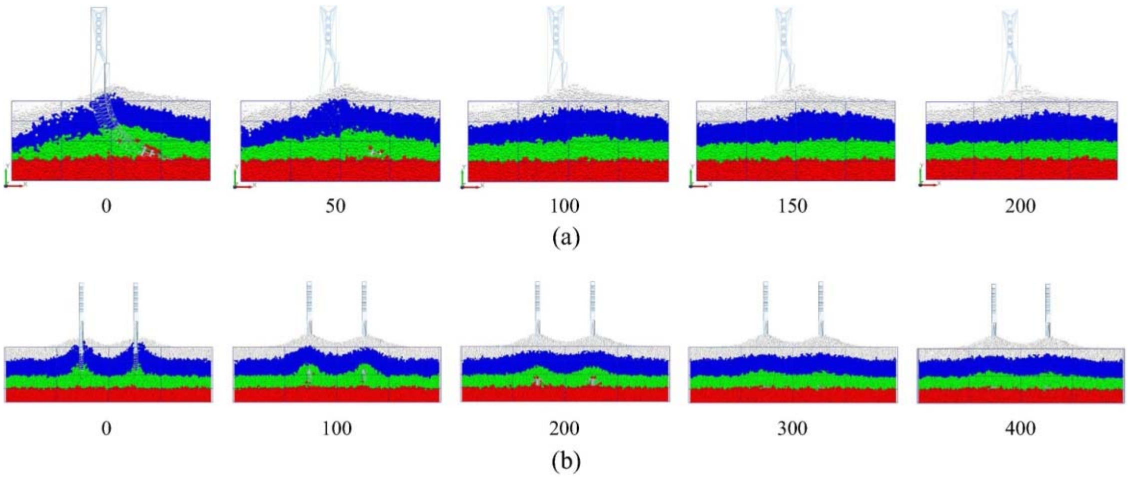


Figure 6. Analysis of the soil disturbance process (Hang et al., 2017): (**a**) Schematic diagram of the disturbance process in the longitudinal-sectional; (**b**) Schematic diagram of the disturbance process in the transverse-sectional.

In the subsoiling process, the soil is sheared, extruded, and uplifted by the subsoiling shovel, which provides the reacting force from the soil. Although the soil-mechanical interaction is a complex process, the disruption and deformation of soil under the force of subsoiling components still have some regularity. According to the soil structure, soil mechanics, as well as the failure and deformation regularity, the virtual soil model can be built in the simulation software, which is capable of replacing actual soil within a certain range of error. Furthermore, the simulation test of subsoiling machines and soil models can be carried out to study machines' performance and optimize structural parameters, which is conducive to the shortening of the development cycle of subsoiling machines, improving research efficiency, and saving time and resources. Additionally, the soil smashing mechanism during subsoiling and interaction between the shovel and soil in the process of adjusting tillage depth can be revealed.

7. Summaries and Recommendations

A large amount of research on subsoiling shovel design, anti-drag, tillage depth detection and control, and soil mechanical interaction have been done to improve subsoiling quality and reduce energy consumption. However, most soil models established in simulation software lacking plant root or straw are inconsistent with the field soil condition. There is insufficient information regarding the broken soil characteristics, stubble-breaking process analysis, and comprehensive effects of subsoiling. Further research should focus on the interaction mechanisms between soil, subsoiling shovels, and plant root or straw. The combination of tillage depth detection and control can effectively improve tillage depth stability, whereas the influence of different soil conditions on the control system is unclear. It is necessary to develop monitoring and control systems of tillage depth with good applicability. Apart from using the abovementioned methods to save energy, the performance of subsoiling components should be considered with more attention. As shovels directly make contact with soil, they wear severely. For this reason, studies on the wear resistance of subsoiling components should be conducted. Therefore, to develop high-performance subsoiling machines with good subsoiling quality and low energy consumption, this article proposes the following four recommendations.

(1) It is very important to improve simulation accuracy by optimizing the soil model in computer simulation. The discrete element model of a root-soil composite model with straw should be established, and the key parameters of soil models need to be calibrated by simulation and laboratory tests. Furthermore, the accuracy and reliability of soil models should be verified by subsoiling simulation and field experiments.

(2) Comprehensive methods combining computer simulation, field experiments, and theoretical analysis need be adopted to strengthen research on subsoiling mechanism and comprehensive effect. Thus, the interaction mechanism between root-soil composite models, subsoiling shovels, and straw, as well as the interactive relationship between energy consumption and yield, increase the benefits from subsoiling and can be clarified from macroscopic and microscopic perspectives.

(3) New tillage depth monitoring and control systems should be developed via mechanism innovation, algorithm optimization, and software development, which has the advantages of accurate detection, fast adjustment, convenient use, and suitability for different soil conditions. Moreover, by the combination with GPS positioning technology and data sharing technology, the tillage depth will be correlated to some information, such as nutrient, moisture, and yield, to provide guidance for the future management of farmland.

(4) Improving the wear-resisting properties of subsoiling shovels is a necessary method to save energy. According to Zhao [119], more than 80% of subsoiling shovels' failure is caused by wear, which is the main cause of low efficiency, poor quality, and high operating costs. Therefore, some wear-resistance improvements of subsoiling shovels should also be taken into account, such as applying advanced processing technologies, adopting wear resistant materials, and designing shovels with wear-resistant geometry of the biological surface.

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