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Review

Conservation Tillage Improves Soil Quality and Crop Yield in Hungary

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Abstract: This paper provides an overview of the progress of tillage in Hungary. The local and international impacts on the national practice are summarized, and some adoption of the conservation tillage results is presented concerning Hungary. The interest in conservation agriculture in Hungary dates back almost 120 years; however, any significant changes only occurred in the last 50 years. Interestingly, the factors of progress and restraint in tillage have appeared simultaneously over the years. Among the factors restraining tillage progress, the most retarding were the beliefs that have existed for many decades, as soil conservation was not considered nor was the need to mitigate climate-related hazards. Progress was driven by the commitment to soil protection, the opportunity to raise farming standards, and the need to mitigate climate-related threats. Since the average yield in Hungary was usually sufficient for the domestic need, the main objective of crop production was to avoid yield loss. Long-term experimental data and monitoring results were considered for this study. The impacts of new tillage solutions, elaborated in foreign countries, on tillage modernization were reviewed. The experiences and first results in no-till (direct drilling) and strip-tillage showed that difficulties can gradually be reduced through site-specific technology solutions. The need for subsoiling is not a matter of debate nowadays but rather the timing of operation and the investigation of the duration of the effects. Due to its complex advantages, tine tillage occupies an increasing rank among soil conservation systems. The area of ploughed soils has decreased; however, improved implementation is required.

Keywords: no-till; strip-till; tillage systems; tillage history; soil health; soil moisture; conservation agriculture

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1. Introduction

Tillage, in classic theory, provides optimized soil conditions for crop establishment [1]. Long time ago, Blake [2] referred to the reconsideration of the fundamental notions of tillage. Birkás [3] outlined that tillage may preserve and/or improve the physical and biological conditions of the soil in a way and to a depth that is suitable for the required soil protection and cropping tasks. The history of the development of tillage in Hungary is divided into seven eras with positive and negative impacts on the quality of soils [4]. Among them, the era of multiploughing systems and the overestimation of crop requirements resulted in the high deterioration of soil quality [5].

Many scientific articles that help look back on the history of tillage were published in Hungarian. Multiploughing systems dominated tillage from the mid-1700s for one hundred and fifty years [6]. The soil degradation associated with frequent soil disturbance was first observed by specialists monitoring the practice. Cserháti [7] identified that the main cause of the problem is the high number of tilling operations and the poor timing of tillage. His idea, namely, “Hungarian reasonable tillage”, was aimed at reducing tillage interventions without increasing the risk of crop production in arable fields. A remarkable fact is that the geographical location of the country in Europe and its language also entailed a certain degree of isolation. This may have been the reason why Hungarian reasonable tillage could not become the forerunner of minimum tillage [8].

In dry years, cultivation and growing difficulties increased; therefore, soil degradation received more attention [9]. In addition to describing the phenomenon, writers also attempted to find mitigating solutions in the scientific journal, titled “Köztelek” [10–13]. However, the book of Gyárfás [14] had a greater impact on tillage practices, as the author did not distance himself from the practice of ploughing, which was strongly supported by the practice, and his proposals only included reducing the number of ploughing operations.

The new tillage methods that had been developed abroad emerged in the first decades of the 1900s. The method of the North American Campbell system [15] raised more interest, while the principles of German Bippart’s antiploughing campaign attracted less attention [16,17]. The results of the test methods varied, but they showed that it was possible to cultivate soils differently from the usual ploughing. The new methods were often accompanied by new equipment that attracted the interest of the stakeholders. Campbell’s disc offered the possibility of skipping the plough for stubble tillage in the primary tillage of autumn-sown crops [16,18,19]. The cultivator, as a newly developed device, also offered the chance to sow winter cereals in a more favourable soil condition than ploughed soil [19,20]. Manninger [19,20] and Kemenesy [21] were the first scientists who drew attention to the possibilities lying in biological tillage, that is, in keeping the soil in a mitigated state. Furthermore, Manninger also developed the practice of reasonable shallow tillage, which he proposed to use after deeper loosening.

The alleviation of plough pan compaction, which inevitably accompanies ploughing, was first emphasized in Cserháti’s book [22]. Interestingly, at that time, tillage to slightly deeper than 20 cm was also noted as a factor that increases yields. From the late 1950s, however, targeted research attempts were made to evaluate the applicability of deepening the loosened layer and using shallower, cost-effective systems in two deeper tillage operations [23].

Until the change in the political regime, the tillage trends were lagging behind the Western European and North American practices, with 25% of arable land under soil-friendly tillage. Three decades later, there was a relatively quick catch-up due to the strengthening of expertise and the use of modern machinery [4,5,24]. It should be noted that the new tillage methods developed abroad initially had an impact on our education and experimentation and, more recently, with a broader outlook, also had an impact on practice [4,5]. Nowadays, the task of soil quality preservation and enhancement has been complemented by reducing the severity of climate damage [25–27]. Besides testing the mitigation measures against the adverse effects of climate change, which was developed and successfully proven abroad, the dissemination of solutions developed for domestic conditions is also required [5,28].

Tillage and crop production field experiments, lasting for 5–15 years or more, have been carried out from the 1960s in the frame of universities and research institutes to compare different methods of tillage. They have been used on different soil types, involving different tillage treatments and different crop sequences. The published results are cited in this article.

The advances and benefits of conservation tillage are accepted as a worldwide fact [1,29–31], and the results justify the improvements in soil quality [32]. Beneficial observations include loose layer depths suitable for water infiltration, well-timed moderate soil disturbance associated with organic matter conservation and surface protection, the flourishing of soil biota, and moderate climate exposure [33–35]. Establishing the necessary loose layer depth for crop safety [36] often requires tillage interventions [37]; however, maintaining it requires improvements in tillage management [38]. Organic matter recycling is an essential factor for organic matter conservation, and it can be stabilized through low-impact tillage that leaves a high amount of organic residue (mulch) on the soil surface [35,39]. Soil surface conservation has become an essential soil quality enhancement factor since the recognition of the adverse effects of climate change [25,40]. In addition to the improvement in soil moisture conservation, soil quality factors have been extended through earthworm activity, soil structure protection, and climate tolerance [8,25,26,41].

In the articles cited above, the references include the factors that promote and/or hinder the development of soil conservation tillage in Hungary. The *objectives* of this paper are (1) to analyse the first probes in tillage modernization in Hungary, (2) to evaluate the impacts of the soil conservation trends on the national tillage practice, (3) and to investigate the results of the tillage practices at a particular site and climatic condition in Hungary.

2. Basic Data for Soil Tillage Review in Relation to Hungary

2.1. Country Data

The total area of Hungary is 9,303,000 ha of which 57.1% or 5,310,000 ha is agricultural land and of which 46.4% or 4,318,000 ha is cultivated land [42]. The topsoil textures of Hungarian soils can be characterized with the following composition: 15% sand, 12% sandy loam, 47% loam, and 26% loamy clay and clay [43]. For 59% of the soils, the demands of the crops can easily be met through tillage, while, for 41%, this is more difficult. Approximately 34.8% of the soils are sensitive to degradation and compaction (e.g., Solonetz, Gleysols, and Vertisols), 13.9% are nonsensitive (Calcisols), 23.0% are slightly sensitive (Arenosols, Cambisols, and Histosols), and 28.3% have moderate sensitivity (Luvisols and Chernozems) [8]. The climate is continental, although extreme phenomena have occurred more frequently in the last three decades. The average annual precipitation decreases from 800 mm in the west to 500 mm in the east. During the past decade, two years were dry, one year was rainy, and seven years were extreme due to the alternation of the dry and rainy periods [44].

2.2. Long-Term Tillage Experiment

The experiment aimed to improve the soil quality and humus content in degraded soil and to suppress weeds in a highly infected field [45]. The experiment was initiated at the Józsefmajor Training and Experimental Farm (JTEF) of GAK (Gödöllői Agrár Központ—Agricultural Centre Gödöllő) Ltd. (Gödöllő, Hungary) near the town Hatvan (47°41′31.7′′ N, 19°36′36.1′′ E, 110 m a.s.l.) in 2002 on Endocalcic Chernozem (Loamic) soils [46] (Figure 1). The one-factorial experiment was arranged in a randomized block design with four replicates. Plot size was 13 × 180 m [44]. Five ploughless tillage treatments were applied in addition to a mouldboard ploughing treatment; these were subsoiling, tine tillage (deep and shallow), disk tillage, and no-till farming [27–29,45]. Primary and secondary tillage were carried out in a single pass for cereals and soybeans, and seedbed preparation was applied for maize and sunflowers. A crop sequence was planned for soil quality improvement and the suppression of weeds [45]. For organic matter enrichment, over 18 years, cereals (winter wheat, spring barley, spring and winter oats) were grown in 11 years, wide-row crops (maize and sunflowers) were sown in 5 years, and legumes (peas and soybeans) were grown in 2 years. Green manure crops (green rye, wheat mustard, and phacelia) were grown in five summers. Crop residues were chopped and spread in a single pass during the harvest. Soils after harvest remained undisturbed until primary tillage to conserve water. Nitrogen was applied to the crops at a rate of 100 kg N ha^{-1} in two doses, while phosphorus (P_2O_5) and potassium (K_2O) were applied at 100 kg ha^{-1} and 50 kg ha^{-1}, respectively. Postemergence herbicide was used during April, while a direct chemical treatment was applied to cereal stubbles at the end of August [44].

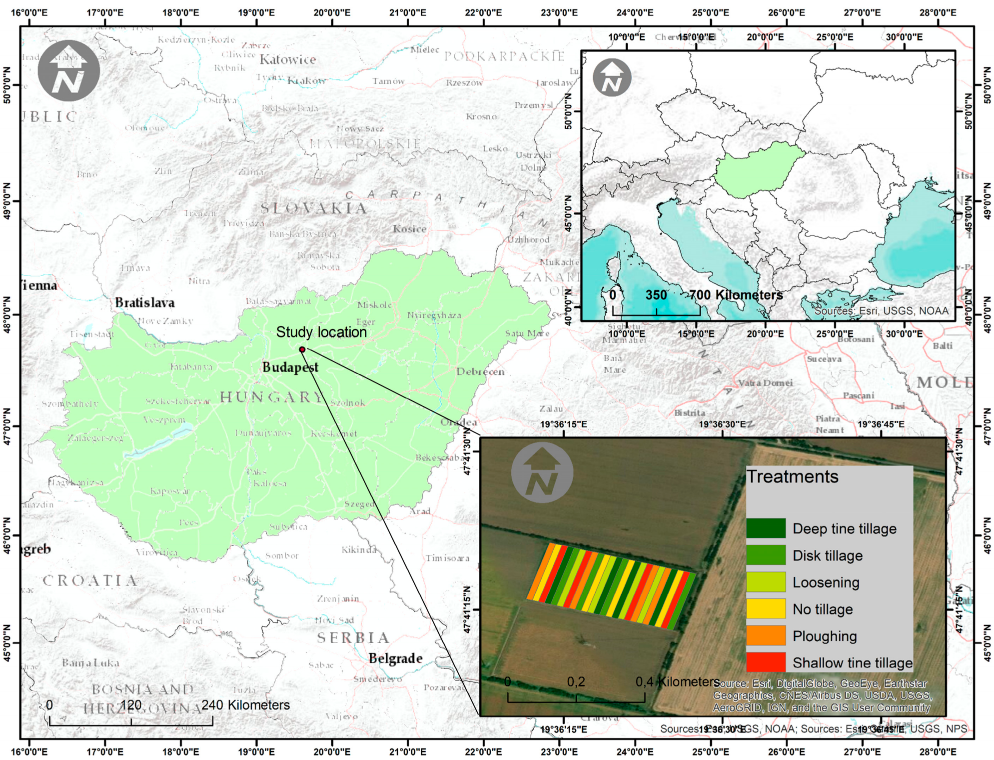

Figure 1. Location of the Józsefmajor Training and Experimental Farm (Source: Dekemati et al., 2020) [44].

The data originating from the long-term experiment provided the opportunity to evaluate the different tillage systems (no-till farming, subsoiling, tine tillage, disking, and ploughing) that are discussed in detail in this paper. For evaluation, where it was found necessary, the results of the monitoring carried out at the different arable sites of the country were considered. The publications referenced in this paper reflect the changes in the soil quality observed in the long-term experiment.

3. Tillage Modernization in Hungary

The development of tillage techniques, regarding tillage in general, its position in the system of cropping, and the efforts made to conserve the soil along with the acceptance of new methods, has always been substantially affected by traditions. This influence has hindered more frequently than encouraged the adoption of new techniques according to the papers in periodicals on farming in various phases of the history of tillage. The attitude of farmers, concerning rationalizing tillage, could, in retrospect, be explained by a shortage of capital, but this would be only part of the reasons [17]. In other words, most of the tillage practices that were entrenched for centuries and were largely detrimental to the soil were seen as obstacles to development from the late 1800s. The impact of tillage on yields was not a critical issue during the centuries solely ruled by the plough [4]. Therefore, the efforts of the authors who developed better tillage methods than the standard solutions can only be given proper recognition in the present era.

The interest in the Campbell system [15] was sparked by so-called "dry farming", as dry periods caused cropping difficulties in our country in the early 20th century. Nearly a hundred articles were published in farmers' journals during those years, and experiments were set up to test this special new method. The results, however, did not confirm the high expectations. When reading Campbell's book [15] precisely, one finds that winter wheat was sown after up to 12–14 tillage passes, while it took up to 20 passes to work the soil before seeding in the spring. That many tillage passes were bound to lead to soil degradation; posterity refers to this period as the "Campbell boom" [16]. The positive aspects were the surface preparation of ploughed soil with a subsurface packer and the use of flat discs [16]. Experiments based on the Campbell method did not produce any significant results that would have brought a change in the domestic tillage practice. Bippart's principles only generated moderate interest, although the value of ploughing began to be questioned at this time [10]. Two authors are credited with the first results of rational tillage (Baross, 1909; Manninger, 1938) [18,20], who proved that ploughing could be omitted from the winter wheat cropping system without any risk by using a flat disc and a cultivator instead of a plough. Further progress included the announcement of the possibility of biological tillage in the work of Kemenesy [21]. Although these authors did not refer to Pethe's [47] efforts, in retrospect, we can see that Pethe's Hungarian Plough Planter did offer new possibilities for the use of tools and methods other than those of the rigorous conventions. Unfortunately, the above-mentioned efforts have not brought about any significant change in the practice of soil tillage in Hungary, mainly due to the sceptical attitude of farmers.

Periodical deep tillage, developed by Sipos [23] between 1958 and 1968, had a greater impact on the domestic practice and offered the possibility of using shallow tillage without any risk following deep soil loosening. Determining the optimal and economical depth and method of tillage, the expected duration effect and the knowledge of the response of the crops made it possible to reduce the inputs of two deep interventions. Sipos pointed out that improvements in the physical condition of the soil also have a beneficial effect on the soil's biological processes [48]. Based on his results, he stated that, on heavily cultivated meadows and salt-effected soils, soil loosening is safer than ploughing [48]. This finding, nowadays, is widely proven in soils with heavy textures. The duration of deeper loosening could be detected for 2–4 years under the weather conditions of the time [49]; however, today, probably due to the settling effect of heavy rains, such a beneficial effect is not generally observed. It is also credited to Sipos that he drew attention in good time to the need to establish or maintain soil conditions that are conducive to the deeper rooting of crops. These factors are of paramount importance today for meaningful climate mitigation [50].

4. Conservation Tillage and Benefits

4.1. No-Till Farming vs. Strip Tillage

Domestic tillage, as indicated above, was not strongly influenced by the foreign trends that were famous before the 1960s, including Campbell's dry farming and Bippart's antiploughing campaign [16]. On the contrary, the influence of the North American minimum tillage and soil conservation movements [51], which were implemented with a radically different approach from the previous solutions, can still be seen today. There were no precedents for no-till and strip-till farming, which were developed in North America, in the Hungarian tillage practice.

4.1.1. No-Till (Direct Drilling) System

No-till farming refers to the sowing of crop seeds directly into the undisturbed soil of the preceding crop stubble, where all the crop residue is left on the soil surface [30] (Figure 2). No-till implements consist of a series of tines or discs that form a narrow band of soil and create an environment suitable for the seed, which is then placed behind the coulter and is firmed with a rear roller or harrow [30]. The interest in direct seeding was aroused, first of all, by its soil protection effect and, later, especially in arid regions, by its efficient soil moisture retention capacity due to low soil disturbance [52]. The use of no-till farming became popular worldwide, mainly in dry arable sites where minimized soil disturbance became the primary factor in crop production [41,53–55].

Figure 2. Direct drilling (no-till farming) at JTEF (Source: Igor Dekemati).

Research on no-till farming in Hungary started in the 1960s and coincided with the research on the rooting depth requirements of field crops and the interrelations between tillage and fertilization systems [56]. The new method, no-till farming, not known before, was compared to the conventional and reduced tillage methods. The first experiments were carried out under a variety of climatic and soil conditions with cereals, maize, and sunflowers [57–59].

In 1970s, field experiments were supplemented with technology developments at the earlier research sites [60,61]. No-till experiments were also conducted in the 1990s with the following main research topics apart from crop yield: its impact on the soil condition, weed infestation, changes in weed flora, its economic aspects, and its applicability to dry farming [5,6,45].

Nowadays, sowing in narrow seed furrows is scaled up to strip tillage or entire-surface crumbling methods in arable fields [24]. The more recent domestic research includes studies on soil condition changes over longer periods, the impacts on the organic carbon content and soil respiration, and earthworm abundance [28,29,44,62].

The fact that assessing no-till experiments is still a popular research topic worldwide [36,38,41,63–65] certainly played a role in the continuation of domestic no-till experiments. Many of the positive results published abroad (e.g., Cannell, 1985) [1] have also been reported in domestic experiments [59]; however, the yield levels have mostly lagged behind those of other soil conservation practices (e.g., mulch tillage and loosening tillage) [5,24]. The data from Kende et al. [45] showed that, in the dry season, the yield achieved by no-till farming can be higher than that obtained with other tillage methods but that the level is still below the typical level for the site. However, yields produced by no-till farming are in line with the expenditures [41,60,61]. In our long-term experiment, the crop yields of no-till farming in two dry years (2009, 2012) were 10 and 60% higher compared to the yields achieved in the other treatments, and nine times it surpassed 4–5% of the yield achieved by the disk treatment.

The positive features, such as more moisture in the soil, slow but gradual improvements in the soil conditions, an increasing humus content [66], and greater earthworm activity [29,44], all confirmed the international trends.

Moreover, the presence of plant material (food source) was found to be an indispensable factor in the earthworm habitat and activity of no-till soils [29,44]. An important observation is the soil retention in the areas subjected to an erosion risk, which is attributed to low disturbance and covering with stubble residues [54].

Since the scientific literature on no-till farming is very abundant, we only explain the specific findings detected by our experiments in this chapter.

The specific stratification of the soil and the formation of an angular structure due to settling is a normal process in the case of no-till farming. However, looseness of the stratified soil is considered appropriate after a critical 6 to 8 years [44,60,61]. It is known that soil fertility is stratified, i.e., that topsoil is richer in humus and nutrients, while deeper layers are poorer [54]. Kader et al. [40] observed an improvement in the soil structure, and we found a striking reduction in the dust ratio in our experiment [24]. Several authors emphasized the beneficial impacts of no-till farming on soil preservation [36,54,63,66,67]. In our long-term experiment, the increase in the crumb ratio and the depth of the loosened layer was detected as a result of soil conservation [28]. The soil under no-till farming was only disturbed in the seed furrow and was continuously covered by the stubble remnants, which proved the benefits of this system [29]. Earlier, Cannell and Hawes [66] referred to an increase in the soil organic matter content in the topsoil, which was also demonstrated in our experiments by Kende [50]. Cold soil in the spring, previously considered to be a disadvantage [1], is, nowadays, considered to be more of an advantage due to the early warming of the soil in Hungary. The microbial activity in the topsoil is constantly high due to the presence of stubble residues [40]. Crop rotation is justified by the limitation of pests, pathogens, and weeds [45,54]. The survival of pests and pathogens may occur, but a biological equilibrium is reached after 6–8 years [68]. Weed infestation is critical in the first years of no-till farming but decreases to a manageable level after effective weed control year by year [45]. In addition, the spread of noxious weeds can be effectively limited by rotating crops with different growing seasons [45,60,61]. In case weed control is not carried out sufficiently or is completely neglected, the weed cleaning process must be started over again. The soil cover did not limit weed emergence due to the favourable soil moisture status; thus, weed control was possible. As it was mentioned earlier, the soil cover had a significant effect on the improvement in the soil condition. Cereals, cereal stubble, and maize stubble were considered to be important factors in improving the soil condition, which was enabled by at least a 50% or, in the optimal case, 70–80% soil cover. On the contrary, sunflowers and their stubble, which only covers 20–25%, caused a decline in the soil condition. One of the main conclusions we gained in our experiment on no-till farming was that the beneficial impacts of continuous no-till farming on soils may be observed after 6–8 years. A similar finding was reported by Klik and Rozner [68] in Austria and by Cannell [1] and Soane et al. [38] while evaluating their experiments. Typical settling is expected in the first years of the transition to no-till farming, similar to the conventional system [69]. However, if the soil condition improves, the rooting depth may increase [44,52]. The area of direct seeding in Hungary is smaller than in other countries. Its continuous application is currently only typical in long-term experiments. However, several farmers are attempting to develop the no-till system based on international examples. The seeding of secondary cover crops and green manure crops is currently carried out through the no-till farming of the stubble to decrease soil moisture loss. The future of no-till farming will be influenced by the weather extremes in the fields with variable soil conditions in the country. The increasing frequency of dry periods in the summer may suggest the use of no-till farming regardless of the arable sites.

4.1.2. Strip Tillage

Strip tillage is a relatively new method for reducing tillage interventions, where a soil disturbance of less than one-third of the total field is tilled [53,70]. This system requires a completely different approach compared to the usual tillage methods [1]. Cannell [1] in Europe was among the first to draw attention to the usefulness of strip tillage. Crop residue is removed from the cultivated strips and placed between the rows of the tilled strips with the seed being drilled into the strips either in the spring or autumn [30]. A strip tillage system was developed for wide-row crop production; however, trials have started with cereals. Most successful strip tillers use satellite navigation and RTK (real-time kinematic) autosteer to perfectly align the planter with the strip. The basic mechanics of the strip tillage system (tine, disc, and roll combination) are quite different from those of the usual design, which could be an obstacle to the rapid spread of the practice. In recent studies, Luna and Staben [71], due to a higher coverage with crop residue, found benefits in the soil which were recognized as an increased plant available water content, enhanced infiltration, and reduced soil compaction.

A strip tillage treatment, due to a lack of equipment, was not applied in our experiment. However, monitoring, completed with soil condition measurements, was performed for four kinds of soil (sandy loam, loam, clay loam, and clay) in eight counties. The depth of the loosened layer was 25–30 cm in which soil penetration resistance was considered favourable and was between 1.5 and 1.8 MPa. A major advantage of the strip tillage system is that it provides significantly better conditions for growing crops compared to disk tillage, with a deteriorated hard compacted layer [1,30]. The loosening part of the Kultistrip equipment was lengthened and strengthened; thus, it formed at least 60 cm deep strips under sugar beets. The formation of these strips in the autumn was beneficial during spring sowing; however, some settling occurred, which did not have any negative effect on rooting. The ratio of the 0.25–10.0 mm (crumb) fraction was usually favourable (65–75%) in the freshly cultivated strips. However, the ratio of the smaller (0.25–2.5 mm) fractions (small crumbs) on the top of the strips in the springtime increased similarly to the other uncovered soils. The coverage of the uncultivated rows is extremely important to emphasize according to the above-mentioned facts. The uncovered rows detected during the experiment decreased the benefits of the system with respect to soil moisture retention and soil surface protection. On the contrary, the covered rows functioned as beneficial habitats for earthworms, which recently proved the benefit of a soil surface cover. The exposure of the uncovered rows was observed after heavy rains, especially at the end of the summer after the emergence of winter rapeseed. In this case, siltation and crust formation decreased due to the plant cover. However, Morris et al. [30] outlined that clean strips allow for early spring soil evaporation and warmer soil temperatures for sowing. More important facts were cleared during the monitoring works, e.g., tillage defects cannot cover a line of furrows. Mistakes must not be considered, as they were caused by the lack of ploughing. The recent weak points may be reduced through continuous technical developments. A deeper (≥45 cm) soil state improvement needed to be applied prior to the introduction of the strip tillage system or during the break time when narrow crops are sown [6]. During the nonstrip-till period (when narrow-row crops are usually sown), the application of subsoiling or deep tine tillage parallel with stubble residue mixing is highly recommended. Field monitoring showed that effectual weed management is needed before strip tillage adaptation. A combination of interrow tillage and chemical weed control may reduce the seed bank of the soil. However, any negligence causes more weed infestation and increases production costs. Covering the interrow area with preceding crop residues is advantageous for water and soil conservation. Crop residues that cover the interrow space may decompose in a year. However, long pieces of crop stalks will decompose over a longer time. The soil on the surface of tilled strips is clean, and, for this reason, there is no food source for earthworms. The state of a soil profile that is alternately disturbed and undisturbed over two to three years may improve over a longer period [6]. Field monitoring showed that applying a strip tillage system to heavy textured soils may require more accuracy considering the clod formation in the tilled strips. Attention must be paid to the sharpness of the mole knife. Soil compaction must be avoided under the loosened layer.

The adaptation of strip tillage seems to be limited nowadays considering the lack of equipment. At the same time, when stating the advantages of the strip tillage application, a slow but continuous spread is expected in the Hungarian tillage practice.

An evaluation of the effects of no-till and strip-till farming in the first years after conversion and in the long term is summarized in Table 1.

Table 1. Evaluation of no-till and strip-till farming in the first years and in the long term based on Birkás [17].

Assessed Characteristics	Time after Conversion	No-Till Farming	Strip-Till Farming
Soil state	1st year 2–3rd year After 6–8 yrs	Reflects the former condition Settling Improved looseness	Loosened in the tilled strips Good Very good
Soil structure	1st year After 6–8 yrs	Low ratio of crumbs More crumbs in angular forms	Reflects former management Crumb formation in the strips
Soil surface	In years	Covered by stubble residues	Clean strips, covered untilled rows
Weed infestation	1st year After 6–8 yrs	Mostly high Easily manageable	Reflects former management Well manageable
Earthworm abundance	1st year After 6–8 yrs	Quite low High	Medium High in the untilled rows
Yield	1st year After 6–8 yrs	Decreasing Stabilizing to moderated level	Good Very good
Adaptability to dry seasons	1st year After 6–8 yrs	Variable, mostly good Good	Good Good
Adaptability to wet seasons	1st year After 6–8 yrs	Variable, sometimes low Good	Mostly good Reflects the strip state

4.2. Subsoiling vs. Tine Tillage

In Hungary, mulch tillage has spread more rapidly than no-till farming, and its adoption has been accompanied by less opposition [5]. Compliance with the soil conservation conditions [30] is often lower than recommended; however, the adoption of a 10–20% surface cover is also an improvement compared to the previously preferred clean soil surface. Two systems were adopted, which are subsoiling and tine tillage.

4.2.1. Subsoiling System

The subsoiling system comprises loosening primary tillage and one or two secondary operations for surface consolidation. Subsoiling has been introduced as a soil improvement method that consists of loosening to a depth of 40–45 cm and surface protection by crop residues with a ratio of 25–35% or, occasionally, 40–50% (Figure 3). Its purpose, compared with Sipos's periodical deepening tillage [48], has been adapted to the present conditions.

Figure 3. Loosening at JTEF (Source: Igor Dekemati).

It was found that favourable physical conditions can be expected in a growing season that has, so far, proved to be sufficient for temporarily mitigating the effects of climate extremities [24]. The soil-condition-improving effect of subsoiling has been systematically confirmed by the results of soil tillage experiments [8,24] and it has also been confirmed by monitoring different arable sites [8,24]. Extending the depth of the loosened layer through improved water intake and storage [25] has gained an important role in climate damage mitigation [41]. The deeper loosened layer allows for deeper root penetration and results in longer drought tolerance [24]. Meanwhile the surface of the loosened soil remains mostly even, which may be attributed to moderate water loss [5]. In our experiment, there was no need for a surface treatment after subsoiling covered cereal stubbles. On the contrary, when the dry and compacted soil was subsoiled (e.g., after sunflowers), clods were formed which required surface treatments. This phenomenon was also observed in soils with a very high clay content. The covered surface and favourable loosened condition of the subsoiled surface provided a good habitat for earthworm activity [24,29]. In our experiment, subsoiling was the fourth tillage method after no-till farming and (shallow and deep) tine tillage with respect to earthworm abundance. The penetration resistance of soil at the time of subsoiling is lower than that under ploughing with the same soil and moisture conditions [4]. An important finding is that the favourable surface conditions created by subsoiling promote weed germination, thus giving a chance for efficient control [45]. By following the rules of subsoiling, the benefits of improved soil conditions can be exploited [24] regardless of the soil texture. Cannell [1] noted that subsoiling when the soil is sufficiently dry may be the only means of reducing the adverse effects of soil settlement. In Hungary, subsoiling has become one of the most practical tools for the alleviation of soil compaction, mainly in dry and moderately moist soils. In the Hungarian practice, subsoiling is used for the primary tillage of deep-rooting crops (rape, sugar beets, maize, soybeans, sunflowers); however the decision is based on the crop requirements rather than the soil conditions. Monitoring studies show that the soil condition could be the determining factor when assessing the need for subsoiling. In heavily settled soils, rooting looseness should be developed to the desired depth required by the crop, preferably without a rough intervention [1]. In the literature, subsoiling is assessed according to its necessity [1]. However, Arvidsson et al. [37] noted that the major objective of tillage is soil loosening, which reduces the soil mechanical strength and is intended to enhance root development. About 30–40 years ago, subsoiling was carried out on 25% of the arable land due to the belief that the soils would settle after four years. This approach has changed due to better knowledge of the soil conditions and the frequency of the weather conditions that enhance settling. Currently, the ratio of the yearly subsoiled areas can be estimated to be 30–35% within the arable lands (no official data, only observation). The future use of subsoiling in the domestic context is likely to be influenced by the need for water intake and storage, the importance of alleviating soil settlement, and the combined beneficial effects of the loosened layer depth and surface protection, particularly in dry seasons.

4.2.2. Tine Tillage System

This method was originally developed for the realization of mulch tillage. However, this system has been accepted with different amounts of soil surface cover depending on the specific site [31]. Tines are suitable for the gentle loosening and crumbling of the soil, and they even have an optimal mixing and surface consolidation impact. Approximately half of the crop residues remain on the soil surface, and the other half is mixed into the disturbed layer. The tillage depth depends on the design of the cultivators and the purpose of the works, e.g., shallow (<20 cm) for shallow stubble tillage and deep (25–35 cm) for primary tillage [24] (Figure 4).

Figure 4. Cultivator at JTEF (Source: Igor Dekemati).

Cultivator-based mulch tillage has been in use since the early 1980s; however, its current popularity has been made possible by the design of tools suitable for both shallow and deep tillage [5]. In the first years, the higher weed infestation of tine-tilled soils was a concern for its adopters. This phenomenon was also observed in our field experiment [45]. The direct weed control effect of tine tillage is usually questionable. According to our studies, the primary cause of weed infestation is the high weed seed content of the soil, and the secondary cause is the response of weeds to the favourable soil conditions created by the cultivator through mass emergence. The latter, however, provides an opportunity for effectual weed control. Hence, it is advisable to establish an optimal soil condition for weed emergence in the stubbles of cereals. In the domestic practice, shallow tillage suitable for moisture conservation is the basis for good weed seed emergence, which can be managed mechanically or chemically [45]. In the field experiment, a different approach has been used in the practice since 2011, i.e., undisturbed stubble soils covered well with straw residues provided effective weed control [45]. In the field experiment, tine tillage provided the expected benefits of favourable looseness; successful moisture uptake and storage; a good earthworm habitat; and safe soil conditions for plants after three to four years, which was earlier than no-till farming [17,24]. When tine mulch tillage was applied, unlike no-till farming, the layering that inhibited rooting in the first years was absent, and the loose layer depth was deeper. In addition, favourable crumbling was already observed in the second to third year, and the even distribution of stubble residues in the tilled layer was also beneficial for the earthworm habitat [28,50]. In the literature, leaving mulch residues was considered to be a factor that hinders next crop development before climate change [1], which has fortunately changed in recent years [28]. Favourable crop yield levels under variable rainfall conditions also demonstrated the benefits of tine tillage [25,50]. The most important findings call attention to the careful application of tine tillage. An effective soil loosening, crumbling, and mixing effect confirming soil structure preservation was found at different sites and soil conditions [27]. A further advantage was less damage occurrence in wet but trafficable soils [5]. A moderated surface raise resulted in a reduced loss of soil water and carbon content. Moreover, tine tillage realizes a high area capacity, saves energy, and has indirect economic benefits. Tine tillage is suitable for a variety of tillage purposes, e.g., stubble tillage, primary tillage, and surface preparation after subsoiling different types of soils [24]. However, tine tillage is carefully adapted in soils that are compacted close to the surface and desiccated. In this case, a tool adapted to difficult soil conditions is needed to overcome high soil resistance.

Tine tillage is a noninversion tillage operation, which is a disadvantage in the conventional concept but an advantage in the conservational concept due to the improvement in the soil condition or the maintenance of good conditions. Nowadays, tine tillage is also applied to the primary tillage of crops that are demanding in terms of loose layer depth, i.e., rape, soybeans, sunflowers, maize, and sugar beets [5]. In addition, tine tillage is widely used for the primary tillage of winter and spring cereals. After having maize as a precrop, tine tillage is still not generally used for winter wheat. However, tine tillage can be used even if the soil is unsuitable for subsoiling, i.e., it is too dry or wet in the layer that should be loosened. In our view, two factors may be driving the further spread of tine tillage. One possibility is the realization that tines can form a favourable loosened layer without forming a tine pan layer. The other factor is the surface cover, which is increasingly important for soil protection against climate-induced damage, reducing the raindrop impact and, therefore, the soil erosion rates and runoff [72]; positively stimulating the restoration of the soil structure in compacted soils [73]; increasing the soil water content; improving the infiltration rate; and decreasing the value of soil penetration resistance [29,74].

An evaluation of the effects of subsoiling and tine tillage in the first years after the conversion and in the long term can be found in Table 2.

Table 2. Evaluation of subsoiling and tine tillage in the first years and in the long term based on Birkás [17].

Assessed Characteristics	Time after Conversion	Subsoiling	Tine Tillage
Soil state	1st yr 2–3rd yr After 6–8 yrs	Slightly improved Moderately improved Well loosened	Reflects the former soil condition Improved looseness Good condition
Soil structure	1st year After 6–8 yrs	Cloddy surface Well crumbled in the tilled layer	Reflects the former state Crumb formation in the tilled layer
Soil surface	In years	The cover ratio reflects stubble management	The cover ratio reflects stubble management
Weed infestation	1st year After 6–8 yrs	High Continuously reduced	High Continuously reduced
Earthworm abundance	1st year After 6–8 yrs	Moderate Moderate to high	Moderate High
Yield	1st year After 6–8 yrs	Acceptable Good, mostly high	Moderate Good, mostly high
Adaptability to dry seasons	1st year After 6–8 yrs	Good Very good	Moderate Good
Adaptability to wet seasons	1st year After 6–8 yrs	Moderate Mostly good	Moderate Very good

4.3. Shallow Tillage—Disking Systems

When the disk as a tillage tool was invented, it was made up of flat plates. A concave shape was developed later (in the 1930s), aiming to have disks work more like ploughs. These concave disk plates have a wider surface contacting the soil, and, thus, they cause an increased compacting impact on it, particularly when the soil is humid or wet. Flat plate disks were reintroduced at the end of the 1990s to preserve the soil structure. The flat plate disk cuts and slices the soil, and its pressure is limited to a narrow line below the edge of the disk plate (Figure 5).

Disc tillage is a shallow tillage operation, and its advantages and considerations should be evaluated in this context [75]. In our experiment, the depth of the loosened layer was between 12 and 15 cm. Even though the penetration resistance of the loosened layer was low (1.2–1.5 MPa), the penetration value of the underlying layer reached an unfavourable value ($\geq$3.0 MPa). A further unfavourable phenomenon was the relatively high ratio of small crumbs and dust (30–35 and 15–20%). In our field experiment, disk tillage was ranked unfavourably [24] due to higher exposure to weather extremes and lower yields (by 30–50%) in addition to the near-surface compaction.

Figure 5. Disking at JTEF (Source: Igor Dekemati).

Monitoring studies resulted in remarkable findings. The depth of the loosened state of the soil was always limited, crumb formation remained poor, and dust formation often increased; however, the mixing effect was rather optimal. Pan compaction often occurred at the depth of the disk plates, mainly in moistened and wet soils [8,76]. Moreover, structure deterioration, i.e., pulverization, appeared in dry soils. However, a minimized surface raise resulted in a reduced loss of moisture and soil carbon content. Further advantages were a high area capacity and saving energy [1]. Disk tillage is suitable for a variety of tillage purposes, e.g., stubble tillage, shallow primary tillage, and surface preparation after ploughing and subsoiling [30]. Field monitoring showed that disk tillage is carefully adapted if the soils are compacted and desiccated. The effect of direct weed control on disk tillage is questionable [45]. However, a shallow soil disturbance promotes good weed shooting and gives a chance for effectual control. It may be outlined that the farming benefits should be evaluated carefully considering all the impacts of disk tillage. Disk tillage is a noninversion process, and its disadvantages may often surpass its advantages. The lower costs of the disk tillage system are usually covered by the lower yield, but the cost of alleviating disk pan compaction increases the cost of the following tillage system. In the current climate, the depth of the loosened layer is expected to become more important than it was in the past. The shallow loosened layer is critical both in dry and wet periods, which may affect the further application of disk tillage.

In the case of "minimum tillage", which was launched in the 1960s, the aim of soil conservation was less visible among the efforts to reduce tillage interventions and costs. Therefore, in Hungary, cost-oriented shallow disk tillage was associated with the objectives of minimum tillage. Disking is shallow ploughless tillage, and its effect on the soil condition varies according to the tillage elements. The conventional (concave) disc leaves a low percentage of soil-protecting mulch. It became popular in Hungary due to its simplicity. However, it is potentially a soil compactor, and extreme care needs to be taken in moistened, clay, and previously compacted soils [75,76]. In the Hungarian practice, disk tillage is used at a higher than desirable proportion (approx. 10–15%) for the primary cultivation of winter cereals. It is worth considering that disk tillage can only be classified as a soil conservation method with strong doubts due to the risk of soil degradation.

4.4. Inversion Tillage—Ploughing Systems

In a tillage system based on the plough, the primary tillage treatment is ploughing itself, and the key element is inverting the soil (Figure 6). In our experiment, ploughing was mostly carried out on ploughable soil with surface consolidation. In the first years, the advantages observed in the ploughing treatments were as follows: the condition of the loosened layer, modest weed infestation, and a better yield compared to the area. The weather extremes, however, strengthened the disadvantages of ploughing [1].

Figure 6. Ploughing at JTEF (Source: Igor Dekemati).

In the results obtained in the long-term experiment and the monitoring work considering ploughing, a plough pan was formed in the third year of the experiment, has been there since, and severely limited root growth into the deeper soil layers [8,24]. The occurrence of pan compaction was found to be minimal during dry seasons, although the pan layer that formed previously lasted for the next periods. Moreover, pan compaction is only one of the several adverse phenomena associated with ploughing [54]. Blake [2] pointed out that ploughing creates an overly loosened state related to the seedbed requirement. By applying surface consolidation (with the Kverneland Packomat in our case), the number of passes in the ploughing system was sufficiently minimized.

An inverted clean surface has become more sensitive to climate threats than conservation tillage [54]. As we found, ploughing usually produces large clods (≥100 mm) in both dry and wet soils and requires secondary operations [25]. However, the creation of large clods can be avoided by adapting to the ploughable soil moisture content and applying a surface leveller. The effect of winter frost was also assessed considering the colder period's impacts on the soil structure. The size of the clods reduces, in ploughed soils after overwintering, however, a high amount of the dust (≥40–50% in a unit area) formed on the surface [24]. This frost dust was found to be an undesirable phenomenon on the bare soil surface following winters. Small soil particles are easily removable by wind, and, besides, they are exposed to surface siltation. In Hungary, the overestimation of the frost effect believed to be due to soil remediation seems unfortunate, and the damage related to the beliefs is more serious. In our case, a minimized soil surface produced less dust formation in ploughed soil [25]. The decomposition of crop residues in ploughed soil was found to be rather limited in the airless state of wet soils; however, water shortage also hindered the decomposition processes [24]. Ploughed soil may be critical due to high CO_2 emissions [54,77,78], which mainly occur in the first hours after ploughing. Madarász et al. [79] found that, under conservation tillage, the amount of eroded soil decreased by 95% and that runoff decreased by 75% as compared to ploughing on a 10% slope in Szentgyörgyvár, Hungary. A significantly greater average annual soil loss was measured for ploughing (2.8 t ha^{-1}) as compared to conservation tillage (0.2 t ha^{-1}). Dekemati et al. [29] stated that both clean surface and soil inversion create a poor habitat for earthworms. We found that it is not favourable to invert the stubble in a layer because the earthworms cannot reach their food source. However, even in this case, the soil moisture content is a determining factor. Ojha and Deepa [80] outlined that both too wet and overdried soils were unfavourable habitats for earthworms. The effect of ploughing on soil moisture transport can also be criticized. In the wet season, rainwater infiltrated the ploughed layer, but the plough pan limited normal percolation into the deeper layers. During the dry season, a large and cloddy surface was found to be the primary factor of water loss [25]. Cannell [1] noted that a cloddy seedbed, especially in dry conditions, may delay or cause very variable germination and emergence. Lal et al. [54] stated that ploughing loosens the soil, buries crop residues, and leaves a clean surface, exposing the soil to climate extremes. They noted the excess pulverization of ploughed surfaces when soil and nutrients were carried away by heavy rains. The next phase of dust siltation and the formation of the crust may hinder or impede the germination and emergence of crop seeds [54]. It often occurs that the effect of ploughing on weed infestation is overestimated [45]. Poor emergence of the weeds may be advantageous during dry seasons, although, in this case, there is no chance for effectual weed control. Earlier, soil inversion was stated to be the best weed control technique [81]. There are statements in favour of ploughing in terms of killing and burying weeds, destroying emerged weed seedlings, and restricting new seed production [82]. A plough may invert seeds deeper into the soil, where germination conditions are limited and where seed dormancy becomes longer. This seems to be a critical point, while a larger part of the buried seeds can remain viable in the soil for many years. The role of ploughing in weed control seems to have been slightly changed by the findings of recent trials [83,84]. As Kende et al. [45] outlined, weed seeds inverted to the bottom of the ploughed layer may be considered a potential source of weed infection in the future. Despite these findings, the ploughing system still represents about 30–40% of the autumnal soil tillage modes in Hungary. According to the facts described above, ploughing, with or without surface consolidation, cannot be classified as a soil-friendly tillage system. This opinion was also confirmed by the results reported in the concerned literature. The future use of ploughing may be limited mainly by the tightening of soil protection regulations. In addition, the frequency of climatic extremes may lead those who previously favoured ploughing to choose other options. A summary of the evaluation of the effects of ploughing and disk tillage in the first years after conversion and in the long term are shown in Table 3.

Table 3. Evaluation of ploughing and disk tillage in the first years and in the long term based on Birkás [17].

Assessed Characteristics	Time after Conversion	Ploughing	Disk Tillage
Soil state	1st yr 2–3rd yr After 6–8 yrs	Good Plough pan occurrence Deterioration	Loosened top layer Disk pan occurrence Disk pan extension
Soil structure	1st year After 6–8 yrs	Good Deterioration	Medium crumb ratio High dust ratio
Soil surface	In years	Bare	Moderately covered
Weed infestation	1st year After 6–8 yrs	Low Reflects weed management	Faced former weed control High, hardly manageable
Earthworm abundance	1st year After 6–8 yrs	Medium Low	Reflects the water content and stubble residues Medium to high
Yield	1st year After 6–8 yrs	Acceptable Variable	Moderate Decreasing
Adaptability to dry seasons	1st year After 6–8 yrs	Moderate Poor	Low Critical
Adaptability to wet seasons	1st year After 6–8 yrs	Moderate Poor	Moderate, sometimes low Critical

5. Soil Tillage at Extreme Climate Conditions

The intensity of precipitation and the number of heavy rain occasions will presumably increase, while the intensity of light rainfall occasions will decrease [85]. According to Láng [86], the amount of precipitation will not increase in Hungary in the future; moreover, it will be less erratic than it is currently. Regarding the National Climate Change

Strategy [87], the annual mean temperature in Hungary and in the Carpathian Basin will probably increase by 1–2.5 °C. Classical authors suggested the importance of creating a good site for crops and that of improving the soil's fertile layer to make it suitable for cropping [1,88]. Consequently, the period of several centuries dominated by this approach is referred to as the era of crop-oriented tillage [5]. The overestimation of the believed crop requirements resulted in the damage of the soils, which inevitably led to the recognition, in the mid-1960s, of the need to preserve the soil quality; hence, that was the era of soil-oriented tillage [5]. Any crop requirements can be met by soil kept in a good physical and biological condition through soil-preserving tillage, with the added benefits of causing less damage and cutting costs. As the new trends have raised concerns since the first years of climate change, tillage must be turned into a climate-focused effort to reduce climate-induced losses by improving the soil quality [3].

Nowadays, the extreme alternation of dry and wet seasons has become a factor that hinders or complicates the implementation of soil conservation tasks [44]. During harvest and tillage operations, damages that are hard to improve can be created during the rainy autumn periods. In the winter, soil structure remediation does not occur as opposed to the general beliefs [24]. When the spring is dry, fewer failures occur during seedbed preparation and sowing, but there is no chance of repairing the damage caused in the autumn. If a drought occurs in the summer and early autumn, there is a chance to repair the damage of the previous year if the soil remains arable by utilizing adequate stubble management [89]. When mid-autumn is rainy, no repair is possible, only to reduce the tillage-induced damages are possible. We consider it important to evaluate the currently applied tillage systems from a soil conservation perspective to move forward.

The advantages and considerations of the soil tillage systems are found in Table 4. It may be noted that the main reasons for adaptability should comply with the site and local conditions.

Table 4. Advantages and considerations of soil tillage systems in relation to Hungary based on Birkás [17].

Tillage Systems	Main Advantages	Main Considerations
No-till farming	Low disturbance	Soil state improvement in long term
Strip tillage	Deep loosened layer	Precedent factors require more attention
Subsoiling	Deep loosened layer	Soil moisture content
Tine tillage	Complex benefits	Chance for soil quality improvement
Disk tillage	Good mixing	Depth of loosened layer
Ploughing	Inverting (?)	Short- and long-term consequences

While looking at the progress of Hungarian tillage and presenting the factors that hinder and promote it, we can see that there is a chance to broaden the soil conservation approach. The difficulties of tillage include rapid changes between dry and wet periods, the occurrence of unexpected weather events, and the removal of stubble residues that can be used as mulch. The factors that help the progress of cultivation include knowledge of soil conditions, site adaptation, and the possibility of improving soil conditions. Regarding the variability of soils and the variation in soil conditions, a tillage system adapted to the site and soil seems to be the most effective at present. Maintaining crop safety requires complex solutions based on soil quality preservation and improvement. The increase in weather extremes will prioritize the possible methods both in general and for a given site. The solutions that were previously considered to be good, especially ploughing, are becoming less and less safe.

6. Conclusions

The history of Hungarian soil tillage provided several lessons that offered significant progress and improvement, even if several difficulties arose in the meantime as well. Among the lessons, the recognition of soil degradation had significant importance, and the experience of finding the solutions has contributed to progress. The benefits experienced in the first decades of ploughing (fewer weeds, greater yield) led to an overestimation of the process over time. The questioning of the need for ploughing began with the recognition of the deterioration of the soil quality. Nowadays, continuously decreasing rainfall is forcing soil cultivators to look for other solutions. Further progress can only be expected if it is recognized that ploughing is the least suitable tillage method to retain the rainwater entering the soil.

Since the 1970s, soil conservation tillage has been well accepted in Hungary. The number of farmers who apply conservation tillage is constantly increasing due to the results achieved in soil protection. In the progress of Hungarian soil tillage, the broadening of the soil-centred approach has brought about favourable changes in the soil quality at the expense of the plant-centred approach. In addition to the real evaluation of the previously used cultivation methods, the results of the tillage research also drew attention to the difficulties, which were gradually overcome, related to the new methods, which are no-till farming, strip-till farming, and mulch tillage. The increase in weather extremes nowadays necessitates the use of cultivation systems that lose the least amount of moisture and maintain crop safety in which the role of stubble residues is becoming more important. The soil conservation systems provide higher topsoil protection, greater water content in the subsoil, and favourable physical soil circumstances indicated by generally lower compaction as compared to uncovered ploughed soils. Based on this study, we can conclude that the use of the conservation tillage methods is more beneficial in terms of soil moisture retention and decreasing soil temperature as compared to conventional ploughing. The amount of cover residues in conservation tillage provides higher soil biodiversity and improves soil health.

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