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Review

Reduced Tillage and No-Till in Organic Farming Systems, Germany—Status Quo, Potentials and Challenges

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Academic Editor: Patrick Carr
Received: 8 February 2017; Accepted: 8 April 2017; Published: 20 April 2017

Abstract: Only 34% of all German farms apply reduced tillage (RT), while approximately 1% of the arable land is under no-tillage (NT). Statistics for organic farming are not available, but the percentages are probably even lower. The development of German organic RT and NT has been strongly driven by pioneer farmers for 40 years, and supported by field trials since the 1990s. The main motive for conversion to RT is increased soil quality, followed by reduced labor costs. NT combined with high-residue cover crops plays only a very small role. Rather, German organic farmers resort to shallow ploughing, a reduced number of ploughing operations in the rotation and/or substitution of the ploughing with non-inversion tillage. In field trials, winter wheat (*Triticum aestivum* L.) yields were reduced up to 67% by using RT methods compared to inversion tillage treatments due to reduced mineralization and increased weed pressure, both of which are major obstacles that impede the wider adoption of RT and NT by German organic farmers. Improvement of NT and RT (rotations, implements, timing) in organic farming is a task of both agricultural practice and science. A number of conventional farmers who have recently converted to organic farming are already familiar with RT. These farmers will act as a thriving factor to implement their experience after conversion and contribute to further innovations of RT in organic farming.

Keywords: low disturbance tillage; non-inversion tillage; conservation tillage; direct seeding; plow; organic agriculture; cropping system; weed pressure; soil protection; soil fertility

1. Introduction

Organic farming has a long tradition in Germany, with organic farms already well established in the first half of the 20th century [1]. The number of farms increased dramatically, following a period of slow growth in the second half of the 20th century, after the implementation of the EU Regulation on Organic Food and Farming in 1992 [2]. Today, 1,078,000 ha are managed organically, amounting to over 6% of the total usable agricultural area in Germany. This represents 24,340 farms, or about 9% of all farms in the country [3]. Due to the rising demand for organic food, these numbers will likely increase in future. A high percentage of these are mixed or stockless arable farms that focus mainly on the production of cereals and grain legumes as cash crops. In addition, extensive open field production of vegetables like carrots (*Daucus carota* L.), cabbage (*Brassica oleracea* L.) and onions (*Allium cepa* L.) is done as a part of large-scale arable rotations. These rotations usually include one or two years of a perennial legume, or mixed grass/legume ley if the farm keeps ruminant livestock [4]. The perennial legume ley provides fodder, an opportunity for weed control because of frequent cutting, and biologically fixed nitrogen for subsequent crops. Stockless farms may include legume ley in rotations because of these benefits. The period for one rotation of German organic farms is approximately five to eight years, depending on farm type [5].

A strong driver for the agricultural activities of German organic farmers is the maintenance and increase of soil quality [5–7] and, more holistically, soil health [8]. The EU-Regulation on Organic Food and Farming reflects this and states that organic farming should focus on "the maintenance and enhancement of soil life and natural soil fertility, soil stability and soil biodiversity preventing and combating soil compaction and soil erosion" [9]. An important step in realizing this aim could be the widespread adoption of RT or NT practices in organic farming. RT encompasses a wide range of practices [10], even meeting the criterion of conservation tillage if, in accordance to the definition of the CTIC [11], at least 30% of the soil is covered by a vegetative mulch (e.g., crop residues). A concept which is widely used in Germany to distinguish conventional tillage from RT is whether soil inversion (conventional tillage) vs. non-inversion (RT) occurs, but RT can also indicate less aggressive inversion tillage methods (e.g., strip tillage, reduction in depth of inversion tillage) compared with the moldboard plough. Currently, organic farmers in Germany use different approaches and techniques to reduce tillage: (i) reduction of moldboard plough operations in a rotation; (ii) reduction in tillage depth while maintaining inversion tillage; (iii) non-inversion tillage at shallow soil depths and (iv) NT. For our purposes, RT includes approaches (i) through (iii), even though in some cases (e.g., for ridge systems) mulch cover is not used and our definition is therefore not in line with the one of CTIC.

The basic function of soil tillage—to control weeds and provide a suitable seedbed for rapid germination and development—is limited or eliminated entirely in RT and NT. Weed and volunteer control (e.g., volunteers from perennial legumes) without intensive inversion tillage (and without herbicides in organic farming) is one of the main challenges in RT and NT [12–14]. Yield limiting factors such as weed pressure and reduced nitrogen availability [13–17], along with environmental benefits [18] differ strongly between RT and NT on the one hand, and conventional inversion tillage on the other, influencing the level of acceptance by farmers.

There are several long-term trials on RT and NT underway in Germany. Some of these trial results are published in international journals, while others are only available in German language. To the knowledge of the authors, very limited information is available in English on the motives of German farmers who are considering the adoption of RT and NT [12]; the same is true for farmers who are using RT and NT [19]. The latter publication gives an interesting insight into the RT practices used in northwestern Europe, but, as the sample size for Germany was very small, it is unclear how this reflects the actual scope and depth of RT and NT in the country. Peigné et al. [19] detected country-specific differences in terms of peer-to-peer exchange, dissemination and extension of information on RT and NT. The experience and knowledge of German organic farmers could here initiate a novel, bottom-up approach to push the development of RT and NT. Therefore, our paper aims to (i) explore the development of organic RT and NT systems in Germany; (ii) describe the motives of German organic farmers for conversion to RT and NT; (iii) make information on the current cropping systems in RT and NT systems from "grey" non-peer-reviewed literature available to a wider audience; (iv) compile information on the on-going research on no-till and reduced tillage systems in Germany by case studies and (v) discuss the perspectives and challenges for those systems.

2. Status Quo of Reduced Tillage in Germany

According to the last official report on production methods of the German Federal Statistical Office [20], soil inversion tillage by moldboard plough is still the dominant tillage practice, and was applied in 2009/2010 to approximately 56% of the arable area in Germany (corresponding to 6.6 million ha). This number includes both conventional and organic farming systems, because separate data are not available. Only 12% of the arable farms completely abandoned the moldboard plough, and 34% applied inversion tillage (moldboard ploughing) in some years and non-inversion tillage (chisel ploughing) in other years. All in all, the chisel plough was applied to 38%

of the arable land in Germany. No-tillage is not widely used and accounted for approximately 1% of the arable land in 2010 [20].

Despite these numbers, among the countries of EU-27, Germany ranks above the European average area under RT, which is one-fifth of the EU-27's total arable area [21]. Adoption rates of RT and NT seem to be largely a question of farm size. German farms with an area > 150 ha used RT or NT on more than 60% of cropland in 2010 [21]. These farms were mainly located in the eastern part of the country: Three out of the five eastern states used conventional tillage on <40% of arable land, reflecting the lowest percentage of conventional tillage use in all of Germany [21]. In nearly all western federal states, conventional tillage was used on >50% of the arable farmland area. Approximately 30% of the farmers who apply RT or NT practices in Germany grow cereals, oil crops or protein crops, with a third of them practicing NT [21]. In summary, the relative adoption of RT or NT in Germany increases with farm size more so in eastern Germany, where agricultural cooperatives were very large in the former GDR, and is more common on farms where only a few staple crops are grown and, consequently, crop diversity is limited.

Most regions of Germany, except mountainous regions, belong to a warm, temperate, humid climate with warm summers (Cfb after the classification of Köppen-Geiger; [22]). While many studies from water limited areas show that yields can be the same or even higher under NT, as compiled by Triplett and Dick [23] and Derpsch et al. [24], this effect rarely occurs in humid climates [14,15,24,25]. Under these conditions, effects of the mulch cover on water saving are not beneficial and can even be counterproductive for yield [26]. In spite of this constraint, the need for adoption of RT or NT systems in (organic) farming in Germany clearly exists, as about 17% of the agricultural usable area is threatened by water and wind erosion [27] and drought events are expected to increase due to climate change, especially in eastern and southern parts of Germany [28].

3. Status Quo of Reduced Tillage and No Till in German Organic Farming

3.1. Development of Reduced Tillage and No Till

Historically, pioneer farmers were the main drivers for the development of innovations in the German organic sector in contrast to conventional farming, where academic research, extension services and the supply side played a major role [29]. This situation is also reflected in the development of organic RT and NT systems. In the German organic community, these farmers were perceived as the main drivers promoting RT and NT already in the 1970s and 1980s [30,31]. Some of these innovators and early adapters have remained strongly engaged, even today, in the promotion of their tillage systems by offering workshops, field trips and peer-to-peer extension programs.

As academia started to engage more in research on RT in the 1990s, German organic farming associations gave their members updates on the current research results from these trials in their publications (e.g., [32–34]). Additionally, best practice examples of farmers who apply RT in different regions in Germany are published in association media and contribute strongly to knowledge transfer (e.g., [34]). Presently, the practices used in RT systems in organic farming in Germany are diverse, just as diverse approaches towards NT exist. They include very different practices such as ridge till systems (Turiel, Kemink), use of double-layer ploughs (reduced depth of soil inversion), use of ploughs specifically designed for shallow working depths (e.g., Ecomat), shallow non-inversion tillage (rototiller, chisel plough), or specific machinery (WEcoDyn, developed by Manfred and Friedrich Wenz in cooperation with Baertschi GmbH) for simultaneous direct seeding of different species in mulch mats which comes close to conventional NT.

Data for the adoption of RT and NT among organic farmers are scarce. A first overview on tillage practices in 1990 (Werland, 1990 cited in [31]) based on interviews of 101 organic farmers revealed that 95% of them practiced inversion tillage by moldboard plough. Twenty years later, in a survey of 367 arable organic farmers in Germany (country wide random sample), 56% relied entirely on the moldboard plough, 38% used the moldboard plough and other machinery and 6% applied RT practices without inversion tillage [31]. Within this last group, the use of rototillers and chisel ploughs was widespread. In general, the farmers who applied inversion tillage tended to work at a deeper tillage depth than the other farmers. The farmers stated that the main reason for the use of the moldboard plough was weed control, followed by the incorporation of biomass and manure. High weed pressure and the challenge of terminating grass clover mixtures before seeding the following crop remain significant challenges in organic RT systems and help explain the reluctance of German organic farmers to adopt RT.

In terms of geographical distribution, most of the organic farmers using RT were located in southern Germany (Bavaria and Baden-Württemberg), reflecting the relatively high percentage of organic farms in both federal states [31]. In Rhineland-Palatia and Thuringia, the share of organic RT adopters among organic farmers was higher than expected from the total number of organic farms. In Thuringia—as part of the former GDR—organic farms are large and we therefore assume that farm size helps explain the relatively high rate of adoption of RT. Wilhelm [31] also analyzed the relation between production system and the adoption of RT and NT and found that 39% of the farmers who used RT primarily or exclusively grew forages, mainly with on-farm use, compared with 26% of farmers who grew food crops [31]. As RT in organic farming typically results in yield reductions for cereals but not legume leys and maize (*Zea mays* L.) [18], forage farmers probably are more willing to convert to RT. Cash-crop oriented, stockless arable organic farms in Germany are larger in size than mixed farms and the reduction of labor and fuel costs may be a strong driver for RT. Moreover, as the central paradigm of organic farming—the maintenance of soil fertility and soil quality by the recycling of nutrients as farmyard manure within a mixed farm [35]—cannot be realized in stockless systems, these farmers probably try to compensate for this by engaging in RT to improve soil physical and soil biological parameters. In addition, organic farmers specialized in arable crop production tend to have greater knowledge, skills and experience in redesigning rotations, modifying tillage operations and dealing with the complexity of agro-ecosystems when implementing RT, compared to organic farmers running mixed farming systems. Overall, the study [31] shows clearly that the use of RT is an exception among German farmers and NT is very rarely applied at all—even though some specialists run such systems.

3.2. Motives for Conversion to Reduced-Tillage and to Till Among German Organic Farmers

A fundamental motivation for conventional German farmers to adopt RT or NT is the management of a large acreage, which is difficult to do by using a moldboard plough because of high time, labor, and fuel costs. In total, farm sizes are still relatively small in Germany with about 70% of all farms < 50 ha [36]. Nevertheless, due to structural changes in the agricultural sector, the average acreage of German farms is increasing, and average farm size currently amounts to 59 ha (in the year 2013; [36]). A continued increase of farm size will probably support the need for saving time and labor costs via RT or NT.

Farm economics drive the acceptance of RT or NT in conventional farming in Germany [37]. Reduced tillage reportedly is up to 60% more profitable than conventional tillage [38], mainly because of cost savings, which more than compensate for the lower yields that occur under German climatic conditions. Mal et al. [37] indicate that the risk of soil erosion is another factor that explains the acceptance of RT. The importance and development of RT methods are supported by governmental and EU regulations for soil protection, such as the cross compliance system for direct payments of the EU [39,40], which regulates the timing of moldboard ploughing in vulnerable areas, among other things. A group of conventional farmers from the upper Rhine valley (16 German and 21 French farmers) identified fuel, labor and time savings, improvement of the hydrologic balance, and trafficability as the main reasons for non-inversion tillage [41]. For conventional farmers, the intrinsic motivation for soil protection cannot be distinguished from the financial motivation through payments by the EU. For organic farmers, the situation is different: they receive subsidies from the agro-environmental programs of the EU for organic management but are not eligible for additional payments for NT or RT, in contrast to their conventional colleagues.

A few studies exist that explore the motives for conversion to RT and NT for German organic farmers. Casagrande et al. [12] surveyed 159 organic farmers applying RT, NT and green manure systems in 10 European countries, including Germany. They found that the main motivation for conversion to RT and NT was the improvement in soil fertility (biological soil quality, soil structure and organic matter content) followed by the aim to minimize costs. Significant differences between countries could not be detected, so we assume that this study reflects the main drivers of conversion to RT and NT in Germany as well. Our assumption is supported by a study of Schmidt [42], which documented the motives of 15 organic farmers indicating that soil quality related motives (e.g., improvement of soil structure, promotion of soil organisms) were by far more prominent than time and cost savings and even protection from erosion. Interviews with three organic RT and NT pioneers revealed that the maintenance and enhancement of soil life, the minimization of soil compaction and the increase of soil quality were the key motives for conversion to RT or NT [31]. Experiences with NT in conventional farming helped two of the famers in adopting organic RT or NT systems. Personal exposure to erosion problems prior to conversion to organic farming was another important driver to change tillage practices. Moreover, labor optimization for cost reduction and personal well-being were also important. The pioneers faced declining yield levels in cereals, but they adjusted their cropping system to higher value crops (seed production for clover, seed production for wild flowers and herbs) to compensate for financial losses.

To conclude, the maintenance of soil quality seems to be the main motive for German organic farmers adopting RT and NT, followed by the optimization of workflows and cost savings, contrary to the findings of Mirsky et al. [43] who assumed that reducing time and labor requirements were the main drivers for organic farmers in the US. In addition, German farmers seem to develop strategies to maintain RT and NT despite yield reductions by diversification of their cropping system towards high value crops.

4. Tillage Systems Used for RT and NT in German Organic Farming

4.1. Ridge Systems

The Kemink- and Turiel-systems are based on loosening the subsoil with a wing share, ridge formation, packing and then seeding in the ridges. The ridges are maintained during the growing season and re-ridging is done again for the following cash crop/cover crop. The system is flexible in ridge width and distance and can be adapted to different working widths. From a conceptual point of view, one may ask if a system that relies heavily on ridging and re-ridging of the topsoil can be considered RT. However, the system is perceived as such because deep conventional inversion tillage by ploughing is not done. Contrary to other RT systems, perennial weeds like Canada thistle (*Cirsium arvense* (L.) Scop.) can be controlled easily via tillage operations and ridging, so the system has been adopted by farmers who had existing problems with Canada thistle before converting to the Turiel system [42]. Apart from Schmidt's [42] case study collection of on-farm-experiences, scientific results on the Turiel-System in Germany are scarce. Only Müller [44] and Brandt et al. [45] compared the Turiel-System ridge system to conventional tillage and RT using the double layer plough. In this case, the Turiel-System showed higher temperatures in the ridges, higher CO_2 emissions per product unit of harvested goods, lower numbers of earthworms and 23% lower yields compared to ploughing in the first two years of implementation [44]. Despite these results, which might be strongly affected by adverse climatic conditions and the short trial duration, the system is used by organic farmers with good results [42].

4.2. Reduced Tillage

For the cultivation of row crops (mostly maize and potatoes (*Solanum tuberosum* L.), and for the incorporation of cover crops, the moldboard plough is quite frequently replaced by other non-inversion implements [42]. The current experiences from farmers and data from field trials (e.g., [46]) show that a reduction in deep ploughing is possible without negative effects on yield and even contributes to soil quality. Kainz et al. [46] used the moldboard plough (20 cm depth) three times in a 7-year rotation to break a two-year clover grass ley and for the cereals winter wheat (*Triticum aestivum* L.) and winter rye (*Secale cereale* L.). This system was compared to a non-inversion tillage system (rototiller, rotary hoe and a chisel plough, 10 cm depth) and to a control where deep moldboard ploughing (28 cm) was done every year. Reducing moldboard ploughing operations and ploughing depth led to the lowest yield reduction, to the lowest production costs and improved soil parameters compared to the deep moldboard plough. Therefore, a reduction in the frequency of moldboard ploughing in the rotation by organic farmers [31] seems possible.

In Germany, shallow inversion tillage by double layer ploughs (inversion of the upmost soil layers, soil loosening in deeper horizons) is comparatively widespread among RT adopters and is normally combined with non-inversion tillage (e.g., chisel plough, rototiller). In different field trials, systems based on double layer ploughs generally had slightly lower yields compared to conventional tillage (e.g., [16,47]), though in one instance, similar or even higher yields occurred [48]. Another option is the use of machinery developed from traditional skimmer ploughs and specifically adapted for shallow inversion tillage (Ecomat, skimmer plough, and others). These tillage implements can be used on large areas and are best suited for fine-textured and/or shallow soils [42]. For these systems, slight yield differences to conventional tillage are documented [42,44]. These slightly lower yields may be offset by the ability to cover a larger area more quickly and with lower power inputs and thus lower fuel and labour requirements. In addition, there was less weed pressure from perennial weeds, which, under German climate and soil conditions, were lower than in non-inversion tillage systems.

Non-inversion tillage, using chisel ploughs and rototillers or rotary hoes, is applied in German organic RT farming practice. Typically, soil is disturbed to roughly a 10-cm depth using these implements, though the depth can vary depending on the location. The highest weed pressure and lowest yields usually occurred in RT treatments in field trials, particularly when cereals and grain legumes were grown [13,46,47], even though cover crops and undersown crops were frequently included in these treatments to reduce weed pressure

4.3. Direct Seeding, No-Till

Direct seeding systems in organic farming that come close to conventional no-till systems in terms of soil disturbance exist in Germany, but are used only rarely compared to the other RT approaches described previously. These organic no-till systems rely heavily on cover crops and the improvement of soil quality by improving biological soil parameters like soil organic matter content, number of earthworms or increasing soil microbial activity. Their core element is the maintenance of an almost permanent soil cover provided by cover crops, undersown crops, living mulches and high-residue biomass mulches. Inversion tillage and intensive non-inversion tillage of the topsoil are not done, and conventional direct seeding equipment is often not suitable for use in these systems because of the large amounts of soil cover, improper seed placement, poor germination, and low yields that have resulted when used [33]. Instead, these systems generally rely on WEcoDyn direct seeding equipment developed by Manfred and Friedrich Wenz, which was developed to ensure proper seed placement in such high soil cover systems. WEcoDyn equipment consists of goose-foot blades and direct seeding equipment. Generally, the WEcoDyn systems have a very shallow working depth of the blades (approximately 5 cm) across the entire working width of the machine and resembles conventional direct seeders.

Organic farmers wanting to perform NT with the WEcoDyn must completely rethink the cropping system, including crops and crop sequence [42], which can be very demanding and impede a widespread adoption of the system. In particular, the maintenance of an almost continuous soil cover—the key element of organic NT—demands specific adaptions in rotation design and timing of operations. As these adaptions are specific to the environmental conditions of each location and organic NT is very rarely used, best-practice examples for farmers and peer-to-peer extension are missing. Moreover, only very few field trials with this equipment exist. A few organic farmers started only recently to use high-residue cover crops, which are killed by a roller crimper, in grain legume production in Germany, much like in North America [49,50], e.g., direct seeding of soybean (*Glycine max* (L.) Merr.) into cover crop residues produced by winter rye [50]. Compared to a rolled-crimped system, which usually relies on cereals as cover crops, the diversity of cover crops is much higher in the WEcoDyn NT systems because of the frequent use of legume living mulches (e.g., white clover, *Trifolium repens* L.), cover crop mixtures, and/or companion cropping in the cash crops (see case studies of 42) and Wilhelm [31]. A satisfying establishment of such living mulches—directly sown or undersown—is very challenging, as weed problems will emerge if living mulches do not grow well. WEcoDyn-based NT is a very knowledge intensive cropping system that requires high levels of risk tolerance, dedication and flexibility as the cropping systems are complex and have to be adapted to the local climatic and soil conditions. For this reason, WEcoDyn systems are usually not used in research trials, as the rigidity of the experimental set up does not fit the demands in flexibility.

5. Long-Term Experiments on Reduced Tillage and No Till in Germany

5.1. Research Aims and Trial Design

Field experiments that systematically explored the impact of RT and NT on biomass production, crop yield, product quality, and other agronomic parameters began much later in Germany than the activities of the pioneer farmers. More recently, research was initiated to determine the impact of the RT and NT on environmental parameters like soil organic matter, aggregate stability, greenhouse gas emissions, soil erosion, and water infiltration. In some cases, labour requirements, fuel costs and machinery costs were assessed. The first experiment was established at Scheyern Technical University of Munich, in 1992. Today, several long-term field experiments on RT exist in Germany in different climatic regions on diverse soil types and with a high diversity of tillage and rotation systems (Table 1). The field trials are designed either as randomized complete blocks or in a split-plot design. In most cases, the experiments were established at research stations in fields that had been managed according to organic standards previously, but using conventional tillage. Different tillage systems (inversion tillage at shallow depths, non-inversion tillage) and/or NT treatments are being compared with a standard deep plough treatment. At some locations (e.g., Frankenhausen), different mechanization methods (Turiel ridge system, Ecomat for shallow inversion tillage, conventional moldboard plough) are being used [44]. Some field experiments compare not only the impact of varying tillage depths, inversion versus non-inversion tillage (e.g., moldboard plough, double layer plough, chisel plough or rototiller) but also rotation adaptation in RT systems that emphasize increases in soil cover to reduce weed pressure (e.g., [51]), while others maintain the rotations that were designed for plough based cropping systems and only vary tillage (e.g., [13]). In general, yield levels are reduced under RT, but there is a wide variation among trial sites, years and plant species (Table 1).

Cover crop based NT/direct seeding systems for grain legumes were tested in several short-term projects (e.g., [48,52,53]), and continue to be studied in several ongoing experiments. The objective of these projects is to improve grain legume production and local protein supply for organic farming, rather than develop RT or NT systems. These projects focus on the production of grain legumes (faba bean, *Vicia faba* L.; pea, *Pisum sativum* L.; soybean, lupines, *Lupinus angustifolius* L.) in two to three cropping seasons. Yield levels of cereals and other crops following the legume species in a rotation are often not assessed and, if so, then only for the first crop following the grain legume. Still, these projects are generating useful information on organic NT and direct seeding of grain legumes as cash crops, feed crops, and rotational sources of biologically fixed N.

Table 1. Overview of organically managed long-term field trials on reduced tillage in Germany.

Trial Site	Trial Duration	Systems Compared	Source
Klostergut Scheyern, Technical University of Munich	1992–2002	Deep moldboard plough (28 cm), reduced number of moldboard plough operations, non-inversion tillage (chisel plough and rototiller max. 20 cm)	[46]
Eichenhof, Stiftung Ökologie und Landbau	1994–2004	Deep moldboard plough (30 cm), Double layer plough (15–15 cm) *, non-inversion tillage chisel plough 30 cm	[51]
Bernburg, State Institute for Agriculture, Forestry and Horticulture, Saxony-Anhalt	1994–2008	Different ploughing depths with moldboard plough (26 cm–16 cm), non-inversion tillage with chisel plough (16 cm)	[54]
Roda and Spröda, State Office for Environment, Agriculture and Geology, Saxony	1997–2006	Deep moldboard plough (25 cm), Double layer plough (15 cm + 10 cm) *	[55]
Güterfelde, State Office for Consumer Protection, Agriculture and Farm Land Consolidation, Brandenburg	1998–2007	Deep moldboard plough, non-inversion tillage (chisel plough + disc harrow 16 cm), stockless, with animal husbandry	[56]
Kleinhohenheim, University of Hohenheim	Since 1998	Deep moldboard plough (25 cm), double layer plough (15 cm + 10 cm) *, shallow moldboard plough (15 cm), chisel plough (15 cm)	[13]
Köln-Ahrweiler, Chamber of Agriculture North Rhine-Westphalia	1998–2006	Deep moldboard plough (35 cm), chisel plough (10 cm–15 cm)	[57]
Gladbacher Hof, University of Gießen	Since 1998	Deep moldboard plough (30 cm), double layer plough (15 cm + 15 cm) *, plough or chisel plough (15 cm), chisel plough (30 cm) and rototiller (15 cm)	[58]
Bad Lauchstädt, Martin-Luther University Halle-Wittenberg	1998–2006	Deep moldboard plough (25 cm), Double layer plough (15 cm + 10 cm) * stockless, with animal husbandry	[48]
Frankenhausen, University of Kassel	Since 2003	Deep moldboard plough (25 cm), Ecomat (skimmer plough, 15 cm), Turiel ridge system Several new trials with NT systems for grain legumes	[44,45]

* For double layer plough: The first depth in parentheses refers to the depth to which the soil is inverted, and the second to the depth to which the soil is additionally loosened by a chisel.

5.2. Trial Results

Even though these trials cover a wide range of crops, most of them include the most important cash crops for arable organic systems in Germany: winter wheat and potatoes. In addition, mixtures of grass with clover and/or alfalfa (*Medicago* spp.), or pure stands of clover (all of them often as perennial leys, or sometimes as annual leys) are usually present in the rotations, as well as peas, faba beans or lupines as typical grain legumes for German organic cropping systems. All crops react differently to the growing conditions induced by RT and NT in organic cropping systems, e.g., higher weed pressure and/or the lack of adequate mineralization (Table 2).

Cash crop yields were reduced to about 80% of the yield level of the conventional tillage system in most of the trials (Table 2), but in some cases, yields in RT reached those of the moldboard plough systems. For winter wheat, relative yields of shallow non-inversion treatments compared to deep moldboard plough ranged from 67% to 101%, with absolute yield levels ranging from 3.7 to 7 t ha^{-1}, depending on the environment. The yield differences were smaller for potatoes than for winter wheat, ranging from 83% to 100% of the conventional tillage system (Table 2). In general, the potato yield ranged from 21 to 29 t ha^{-1}. Grain legumes seemed especially sensitive to the increased weed pressure in RT systems, with yields as low as 39% compared to those of the moldboard plough treatment (Table 2). However, legume yield depression varied by species, with yield reductions ranging from 18% [47] to 61% [16] for faba bean, while lupine yields were unaffected by tillage system.

Table 2. Relative Yield (%) of Shallow Non-Inversion Tillage Compared to Deep Inversion Tillage.

Wheat	Potatoes	Grain Legumes	Legume Species	Location	Source
79	-	39	*Vicia faba* L.	Kleinhohenheim	[16]
89	83	89	*V. faba* L.	Bernburg	[54]
81	-	97	*V. faba* L.	Köln-Auweiler	[57]
88	98	82 (95)	*V. faba* L. (*Pisum sativum* L.)	Gladbacher Hof	[47]
101	99	101	*P. sativum* L.	Bad Lauchstädt	[48]
-	101	101	*Lupinus angustifolius* L.	Güterfelde	[56]
67	-	-		Scheyern	[46]

Relative yield of wheat, potatoes and grain legumes based on results of German organic long-term field trials with reduced tillage; yield of moldboard plough treatment (20 to 30 cm depth) is set as 100% and compared to shallow non inversion tillage with rototiller or chisel plough (6 to 10 cm depth), depending on the experiment mean of yields for multiple years.

Under German conditions, yield reductions are not necessarily problematic under RT for farmers if they can be compensated with labour and fuel cost savings [57]. However, yield depression might prevent adoption if lower yields are accompanied with greater yield instability. For instance, the three pioneer farmers in the study by Wilhelm [31] reported an unwanted yield variation in winter wheat of 4.5–7 t ha^{-1}, 3.5–6 t ha^{-1} and 2.0–6.0 t ha^{-1}, for their respective farm after adoption of RT, a range that might be unacceptable and daunting for many farmers.

In most of the trials, the high weed pressure in the treatments with shallow, non-inversion tillage was described as the main reason for yield reduction, while skimmer plough treatments and double layer plough treatments often performed similarly to the moldboard plough [16,47]. Weeds having the greatest impact on yield were perennial weeds like *C. arvense* L. [13], and direct seeding resulted in complete yield loss of the cash crop in some years due to excessive weed pressure [59]. Reduced N availability in RT and NT in the spring was another important factor that led to yield loss under German climatic conditions. Recent results indicate that deficiencies in plant-available N can be compensated for by planting legume cover crops, like common vetch (*Vicia sativa* L.), prior to growing a cereal cash crop [59]. For soil parameters, the German long-term trials confirm the benefits of RT and NT in organic farming which have been found elsewhere (e.g., [60]): higher earthworm biomass [61], enrichment of soil organic matter in the top soil [62] or even to deeper soil horizons [16], higher microbial respiration [57], higher microbial carbon and aggregate stability in the top soil [17,62].

6. Crop Rotation and Residue Management

The most important tool to control or prevent weeds, improve soil parameters and provide N in organic farming is rotation design. Crop rotation design is of particular importance in RT and particularly NT systems because it is one of the few tools available for controlling weeds and volunteers. Other non-mechanical weed control measures are limited in terms of efficacy or costs, for example, adjustment of crop density or flaming. Contrasting crop rotations used on three German organic farms employing RT and NT are provided in Figure 1 [42]. These rotations reflect the practices used on these farms following adjustment to specific site conditions and the constraints and opportunities of the different farm types. In addition, the rotations and the associated machinery and tillage operations represent a sequence from moderate RT to NT/direct seeding. Farm 1 uses shallow inversion tillage by a skimmer plough combined with frequent applications of a rototiller. On farm 2, RT involves only non-inversion methods with fewer passes than those used on farm 1. The direct seeding system on farm 3 reduces tillage to a minimum and operates with a very high amount of soil cover (strip till in living mulches, undersown crops, bi-cropping, and cover crops).

All three rotations start with a grass clover ley, which is typical for cropping sequences in Germany, no matter which tillage system is used. Farmers usually have site-specific experience for the establishment of these mixtures (e.g., underseeding in spring or autumn depending on water availability for germination) and can easily introduce them into their RT and NT systems. This practice seems to frequently be applied by organic farmers using RT and NT over all of northern Europe [19]. In some cases, the vigorous growth of undersown crops results in harvest problems and reduced yields of the cereal cash crop [34]. Generally, weed suppression is greater in perennial leys than annual leys, but perennial leys generally are limited to mixed farms with ruminant livestock where forage is needed as feed (farm 1). On arable, stockless farms (e.g., farm 2; Table 3), this is usually not an option, since no commercial use of the grass clover exists, even though this practice could improve weed control. The weed controlling effect of annual and perennial leys used for forage is based on the frequent cutting (up to four times per year) which directly destroys annual weeds, and which moreover exhausts perennial weeds that re-grow from persistent root systems. A lower share of annual or perennial legume ley, or grass clover, respectively, in the crop rotation can therefore lead to high occurrences of *Convolvulus arvensis* L. that can develop into problem weeds on certain fields [42]. For farm 3, direct seeding of a perennial grass clover ley appears to be the best option to combat perennial weeds by frequent cuttings, because tillage operations that would mix the topsoil for weed control are not applied; the blades of the WEcoDyn cut beneath the soil surface, but the weed controlling effect is limited.

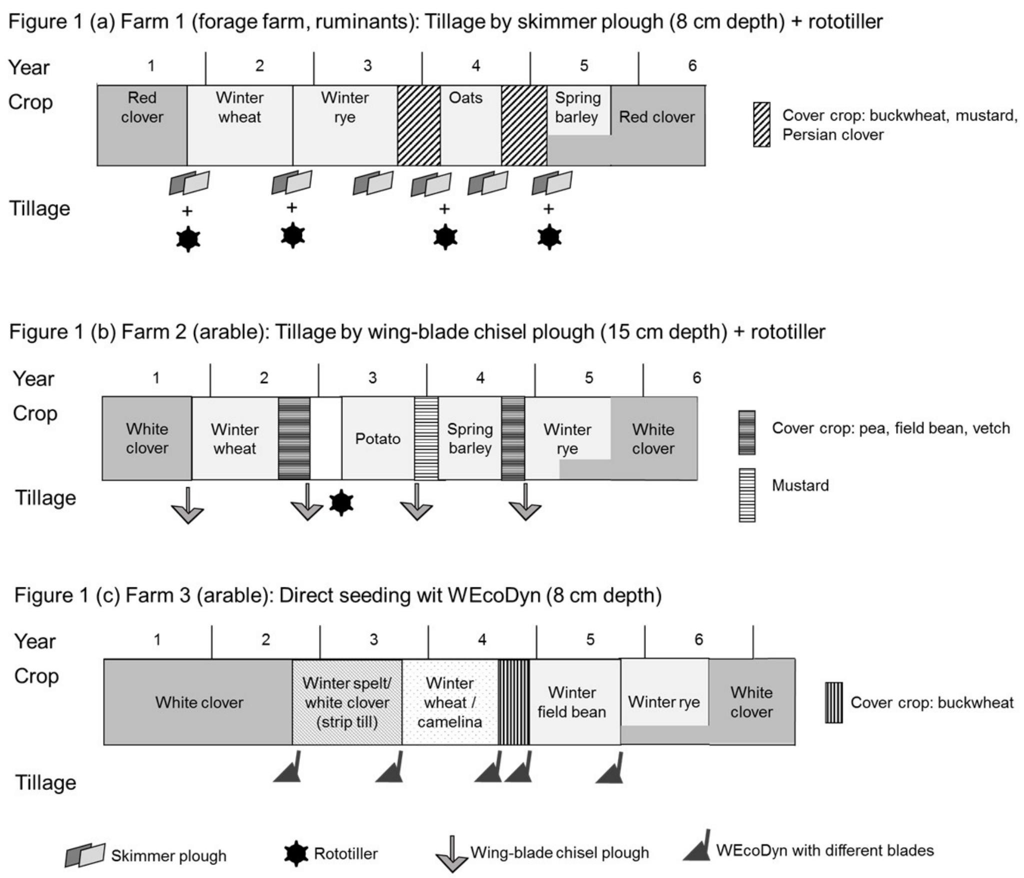

Figure 1. (**a**–**c**) Rotation design and machinery use for three different, practice-related systems of reduced tillage and no-till in Germany ([31], modified).

The RT systems used on three contrasting German organic farms create different challenges in terms of crop management and weed control (Table 3). Farm 1 uses inversion tillage and faces few challenges in breaking the perennial legume (red clover; *Trifolium pratense* L.) ley. A different strategy is required to destroy and incorporate the ley biomass on farm 2, which is accomplished with several passes using a chisel plough without the need of a rototiller (Figure 1). Farmers using RT often break perennial legume leys during dry spells in autumn in order to kill off the plants, but this method can be risky due to weather uncertainties. Moreover, breaking a perennial legume ley in autumn followed by the seeding of winter cereals (which do not develop much before winter) increases N leaching during winter [63]. Whether or not a farmer really manages to reduce costs by RT partially depends on the number of passes [42], and in this regard farmer 1 may have room for improvement since he performs several soil inversion passes, though at a comparatively shallow depth.

Table 3. Overview of weed infestation problems in the model rotations and possible management solutions.

Model Farm	Weed Infestation	Perennial Legume Ley	Destruction of Clover Grass Ley	Measures to Improve Weed Control
Farm 1	Medium to high weed pressure	Ruminant husbandry; ley needed for feeding, N fixation and weed control	Easily done by inversion tillage	Cover crops; alternation of winter and spring crops
Farm 2	Problems with perennial weeds (*C. arvense* L.) + monocot weeds	Stockless farm; ley needed for biological N fixation and weed control	Several passes with different tools necessary	Wide row system in cereals for hoeing; intensification of cover crop use
Farm 3	Very high weed pressure for all crops in the rotation	Stockless farm; ley needed for biological N fixation and weed control	Transformed to strip till, then destroyed by shallow non-inversion tillage; difficult for management of following crops	Intensification of the mulch system: High biomass residue cover crops and living mulches, nurse crops

All three farms use cover crops whenever possible to reduce weed pressure, to reduce erosion during autumn and winter rains and to fix N. Species like buckwheat (*Fagopyrum esculentum* Moench), spring types of faba bean and peas, vetch, Phacelia (*Phacelia tannacetifolia* Benth.), mustard (*Sinapis alba* L.), and Persian clover (*Trifolium resupinatum* L.) die off during winter and provide a mulch with a low C/N ratio to cover the soil surface. Farms 1 and 2 use leguminous cover crops, and it can be assumed that this results in high NO_3-N availability in spring. All three farms include winter rye in their rotation, which usually performs well under RT practices [17,64]. Alternating summer and winter crops help reduce weeds (Table 3). Farmer 2 always used a mixture of field beans, peas and vetches as cover crops—together with the clover grass, this might increase the risk of diseases [5].

Farm 3 faces unique challenges since direct seeding is done in a NT system. The WEcoDyn machinery allows seeding into thick mulches and even into living mulches. The competitiveness of living mulches can be reduced by intensive cutting of the living mulch prior to seeding and strip tilling of the cash crop into the living mulch. Use of living mulches and of cover crops should be alternated in this rotation. In agricultural practice, this system showed the highest weed pressure and the lowest yields, compared to farm 1 and 2 for several reasons [42]. As the clover strips (remnants from the prior clover grass ley) were maintained for several years, they allowed the establishment of perennial weeds (e.g., dandelion, *Taraxacum officinale* (L.) Weber ex F.H. Wigg). This weed infestation prevented a proper seedbed preparation for the living mulches substituting the initial clover strips. Moreover, after several years of NT, there was a build up of annual weeds (grasses, and *Vicia hirsuta* (L.) Gray), which subsequently became a problem after germination of the main crop. The cover crops described above failed to produce enough biomass to suppress weeds in the following cash crops, and management of the living mulches was not optimized. The use of high residue biomass cover crops, prior to seeding spring crops like soybean and maize, could be an option to combat weeds for this farm. Silage maize performed very well in an RT trial in Switzerland despite high weed infestations [65]. In Germany, for a stockless farmer in favourable climatic conditions, growing grain maize would be a good option in terms of weed control and as a cash crop, in particular with a leguminous cover crop providing additional N (Table 3). Another option could be the seeding of winter legumes into the mulch of the cover crop as this reduced plant losses resulting from low temperatures [42].

7. Discussion

The results of the long-term field experiments indicate that RT approaches involving non-inversion tillage and NT presently are not viable options for organic farmers in Germany because of yield depression coupled with yield instability. However, recent studies in Switzerland and other European countries contradict this and suggest that RT methods can result in similar [66,67] or even higher yields than inversion tillage methods [65]. Some of the field experiments used in our evaluation may still be in the transition period from conventional tillage to RT or NT, since this can last for a number of years before new equilibria in soil characteristics and weed populations are established [68]. In long-term experiments with adapted rotations, yield reductions seem to decline in RT systems over time [69].

There are inconsistencies in the impacts of tillage equipment used in RT and NT systems that complicate comparisons with conventional tillage systems. For example, the double-layer plough performed well in reducing weeds and stabilizing cash grain yield in some instances [13,16], but not in others. For example, a higher incidence in weeds and subsequent yield reduction was associated with double layer ploughing in a meta-analysis of studies across Europe, Canada, and the USA [69]. Variations in climate, soils and rotations confound analyses of RT and conventional tillage. It seems that specially tailored RT and NT systems can work in some environments, but we do not yet know under which conditions these systems are most appropriate.

More studies demonstrating the economic profitability of RT and NT are needed before larger numbers of German organic farmers will be motivated to adopt these methods, even if cost savings are not the most important reason for converting [12]. The ability of cost savings in labor and fuel to off-set yield losses following the adoption of RT is dependent on various factors (e.g., the number of passes, acreage performance of machinery, machinery costs, etc.), but until now, no systematic assessment of these aspects on organic farms has been made.

Reduced tillage systems are very knowledge intensive and demanding and, at the current stage of development in Germany, readily accessible information on these systems is lacking and best-practice examples are still scarce. A step-wise, site-dependent approach encouraged by organic farmers' associations and farmers' networks for peer-to-peer extension may be an option for knowledge dissemination. Reducing the number of inversion tillage operations and inversion tillage depth can be the first steps towards adoption of RT systems, and this should be economically feasible for the farmer since they might reduce labor and fuel costs without compromising yields too much [46]. The farmer can gain experience with the crops for which RT and NT work at a specific location, the optimum placement of those crops in a rotation, and the environmental benefits that result following the adoption of RT and NT.

Current data show that profits for organic farmers in Germany rise while they decrease for conventional farmers due to low commodity prices [3]. This leads to a growing number of farms converting from conventional to organic farming. As the number of farms applying NT in conventional farming has risen in recent years, we assume that a considerable number of the "organic newcomers" are (i) large in size and (ii) already familiar with NT approaches. Therefore, we assume that these farmers will modify their tillage practices to fit organic systems but, most likely, will not resort to inversion tillage again. For these farmers, "thinking outside the box" may be easier than long-time organic farmers and we anticipate new ideas in cropping system design as well as in the design of adapted tillage equipment as a result of the interaction these groups.

In this context, the role of weeds warrants special attention from an agro-ecological point of view. Farmers may experience increased weed problems following the adoption of RT and NT [12], but since biodiversity in agro-ecosystems declines despite efforts to stop this tendency [70], greater weed abundance may lead to greater biodiversity (e.g., pollinators, ground beetles, birds). This enhancement in biodiversity may have financial value in the future due to changes in agricultural policies, even if economic incentives do not presently exist.

In addition to the positive site-related effects on the environment offered by RT and NT, more global benefits may exist. For instance, Cooper et al. [69] found increasing C-stocks following adoption of shallow inversion tillage accompanied by yield losses of only 5.5% in a meta-study of data from 12 long-term trials from the US and Canada and 28 from Europe, including 6 of the German field trials described previously. Even if it was unclear whether this will really lead to C-sequestration or mere stratification of C in the soil profile [71], higher C-stocks in the topsoil would have many benefits for soil conservation, in addition to improving soil biological and soil physical parameters [72]. This would contribute to meeting a central paradigm of organic farming: maintaining or even enhancing soil quality and soil life. As results of field research have demonstrated, hurdles remain, particularly related to weed control, which must be overcome before widespread adoption of RT and NT will occur. In addition, research with models, as done with NDICEA, elsewhere in Europe [73], should be used to better understand the N dynamics of organic RT and NT systems in German long-term trials.

Climate change will alter rainfall patterns and lead to an increased occurrence of drought in some regions in Germany (e.g., in the North-East), resulting in increased water stress and reduced yields [74]. As RT and NT have a high potential to improve water infiltration, reduce evaporation and improve soil structure, we assume that acceptance for these systems will rise in the future. With changing climate patterns, yield levels in conventional inversion tillage systems might also decline, leading to greater relative economic profitability of RT and NT. Climate models additionally predict a higher frequency for extreme weather events—lower rainfall during the summer and higher rainfall during the winter for Germany [28]—suggesting, in this context, that RT and NT may offer a strategy for increasing the resilience of organic farming systems and a means for adaption to climate change. In response to these challenges, a project was launched to develop specific RT and NT solutions for organic farming in an action research approach [75] in the German federal state of Brandenburg (Northeast Germany), one of the regions where highest impacts of climate change on agriculture are expected [74]. The increasing annual temperatures in Germany due to climate change, and the anticipated extension in the growing season length, suggest that there may be opportunities to grow crops that could not be grown in the past. For example, it may become possible to grow soybeans in southern Germany, again allowing for new cropping sequences that fit RT or NT systems.

8. Conclusions

Organic farmers in Germany are reluctant to convert to RT and NT systems because of increased weed pressure and yield reductions of cash crops following adoption. In spite of this, a rising awareness among organic farmers of the need to maintain and even enhance soil quality, the transitioning of conventional farmers with RT and NT experience to organic production, a predicted narrowing of the yield gap between conventional-tillage and RT systems as progress in academic and on-farm research lead to better designed cropping systems. Improvements in the transfer of knowledge about RT and NT through peer-to-peer extension and farmer networks suggest great potential for increased adoption of RT and NT methods among organic farmers. We speculate that the wide spread use of RT and NT practices among organic farmers will enhance the ecosystem services delivered by organic agriculture and make it more resilient to the effects of climate change. The approaches for RT and NT developed in organic farming can also serve as a blue print for conventional RT and NT in order to reduce herbicide use while continuing with soil conservation measures.

Acknowledgments: We thank all organic farmers in Germany who apply RT and NT and who made it possible that the researchers to gain helpful insights in their cropping systems and motives for conversion. Moreover, we acknowledge the work of our colleagues running the field trials on RT and NT for many years as well as their efforts in data collection and assessment.

Author Contributions: The work is a product of the intellectual environment of the authors who have both substantial contributed to the concept of the manuscript, to the acquisition and interpretation of data.

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

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