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Research article

Towards Conservation Agriculture systems in Moldova

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Abstract: As the world population and food production demands rise, keeping agricultural soils and landscapes healthy and productive are of paramount importance to sustaining local and global food security and the flow of ecosystem services to society. The global population, expected to reach 9.7 billion people by 2050, will put additional pressure on the available land area and resources for agricultural production. Sustainable production intensification for food security is a major challenge to both industrialized and developing countries. The paper focuses on the results from long-term multi-factorial experiments involving tillage practices, crop rotations and fertilization to study the interactions amongst the treatments in the context of sustainable production intensification. The paper discusses the results in relation to reported performance of crops and soil quality in Conservation Agriculture systems that are based on no or minimum soil disturbance (no-till seeding and weeding), maintenance of soil mulch cover with crop biomass and cover crops, and diversified cropping s involving annuals and perennials. Conservation Agriculture also emphasizes the necessity of an agro-ecosystems approach to the management of agricultural land for sustainable production intensification, as well as to the site-specificity of agricultural production. Arguments in favor of avoiding the use of soil tillage are discussed together with agro-ecological principles for sustainable intensification of agriculture. More interdisciplinary systems research is required to support the transformation of agriculture from the conventional tillage agriculture to a more sustainable agriculture based on the principles and practices of Conservation Agriculture, along with other complementary practices of integrated crop, nutrient, water, pest, energy and farm power management.

Keywords: no-till; mouldboard plough; crop rotation; soil tillage; ecosystem and societal services

1. Introduction

As the world population and food production demands rise, keeping agricultural soils and landscapes healthy and productive are of paramount importance to sustaining local and global food security and the flow of ecosystem services to society. The global population, expected to reach 9.7 billion people by 2050, will put additional pressure on the available land area and resources for agricultural production. Sustainable production intensification for food security is a major challenge to both industrialized and developing countries. The paper discusses the results from long-term multi-factorial experiments involving tillage practices, crop rotations and fertilization to study the interactions amongst the treatments in the context of sustainable production intensification in relation to reported performance of crops and soil quality in Conservation Agriculture (CA) systems that are based on no or minimum soil disturbance (no-till seeding and weeding), maintenance of soil mulch cover with crop biomass and cover crops, and diversified cropping systems involving annuals and perennials.

The discussions on whether "to mechanically till the soil or not" have been going on for at least a hundred years in Moldova. In Basarabia (the former territory of present day Republic of Moldova) a book entitled "The new system of agriculture" was published in 1909 written by Ovsinschi [1] suggesting that agricultural production systems could use less intensive tillage than the mouldboard plough. The book was translated from Polish to Russian. As an agronomist, Ovsinschi [1] was consulting with farmers in the north of Basarabia and stated that soil tillage should be done no deeper than 5 cm. He also reported on achieving stable yields in the range of 4.2–4.9 t ha^{-1} for cereal crops for a period of 30 years under such reduced soil tillage conditions.

In the same historical period, conventional research on soil tillage had been conducted at the Ploti Experimental Station in Ribnita district across the river Dnister (Transnistria) under the leadership of Trubetchoi [2]. The research reports emphasized the importance of mouldboard ploughing to 25 cm every year in agricultural production systems. While there were large differences in opinion among scientists at that time, it only took a short period of time of mouldboard ploughing to cause visible soil erosion and degradation. The annual reports written in three languages by researchers from the Ploti Experimental Station can be found in the Odessa State University Library, Ukraine [2].

A sensation was created with the publication of Faulkner's book "Plowman's Folly" in 1943, which considered that mouldboard plough caused more damage for humanity than all wars together, and that there was nothing wrong with our soils except our interference [3]. Nevertheless, farmers have continued to plough, and with greater intensity particularly after the end of the World War II when motor engines with greater horsepower capacity from armoured vehicles and tanks became widely available. Even the concept of the "Green Revolution" agriculture was, and continues to be, based on the assumed need for intensive tillage with mouldboard ploughs and other forms of intensive tillage equipment for land preparation for sowing and crop establishment, and for weed control. Indeed, intensive tillage is considered to be an integral and necessary part of a set of measures for increasing crop productivity and agricultural output [4], and any accompanying damage to the land or soil in the form of land degradation and soil erosion seems to be accepted as being unavoidable co-lateral consequences that must be accepted by the farmers and the society.

Over the last 10,000 years, humankind has been building its "modern" tillage agriculture production systems on the ruins of the "old" tillage and monoculture concepts at its peril [4-6]. Mechanical soil disturbance with tillage and the complementary practices of maintaining exposed bare soil surfaces, reduced cropping system diversity and monocropping, and heavy dependence on excessive applications of agrochemicals for plant nutrition and plant protection are the causes of wind and water soil erosion and of agro-ecosystem degradation that continues to increase due to droughts and floods associated with climate extremes. In such degrading agricultural environments, production systems that lose top soil faster than the rate at which it can be replaced by Mother Nature are not sustainable ecologically but also economically.

Research should therefore compare other methods of cropping with minimum soil disturbance and no-till; however, data on impacts of soil tillage on yield is generally sparse in Moldova. The starting point, in the new qualitative level of research, should focus on the capacity of the whole farming system in providing all the ecosystem and societal services efficiently and with resilience, and not just crop yield. Experimental work should be oriented towards comparison of different farming systems with improved agro-technical measures rather than one-sided comparisons oriented to one or another factor, including soil tillage. This aspect will be discussed later in this article.

The objectives of this review are to: (i) report on the research results from the long-term multi-factorial experiments on the influence of different systems of soil tillage in different crop rotations with different systems of soil fertilization at the Selectia Research Institute of Field Crops; (ii) compare the research findings with those from global research on CA systems; and (iii) elaborate on the long-term importance of CA for Moldova.

The three key interlinked components in CA systems are: (1) continuous no or minimum mechanical soil disturbance through no-till seeding and weeding; (2) maintenance of soil mulch cover with crop residues, crop stubbles and cover crops; and (3) diversified cropping system with annuals and perennials including legumes, in rotations, and/or sequences, and/or associations. Conservation Agriculture aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with lower external inputs. Every farm and farmer reflects a unique combination of multiple management decisions. There is a need for another "complimentary/support component" to enable the incorporation of comprehensive agronomic and management practices to fine-tune the functional system [7-9]. Conservation Agriculture practices and systems require site specific adaptation to the different agro-ecologies to benefit farmers and to allow informed choices of technology tailored to local conditions, and taking into account the trade-offs and externalities associated with technology choice in the short and long-term. CA systems have been shown globally to be much more sustainable than conventional tillage agriculture systems, and CA will be used throughout the paper to describe the intended sustainable production system [10,11].

2. Materials and methods

Data from the long-term field experiments at the Selectia Research Institute of Field Crops (47°45'44.92"C; 27°51'59.09"B), Balti, Moldova, have been used to review and discuss about crop rotations and permanent (continuous) cropping (the duration is more than 50 years), and multi-factorial experiments with interactions among crop rotations, soil tillage systems and fertilization in crop rotations.

The long-term field experiments are located in the Balti steppe in the north of Moldova. The soil is typical chernozem: heavy clay with 4.5–5.0% soil organic matter; pH water 7.3; pH $CaCl_2$ 6.2; total NPK of 0.20–0.25, 0.09–011 and 1.22–1.28%, respectively.

The annual precipitation is in the range 450–500 mm, with high variability. In dry years, precipitation is in the range 270–350 mm and in wet years 720–903 mm.

The annual average air temperature is 9.0–10.0 °C, but in the coldest years 7.2–8.3 °C and in warmest years 10.8–12.1 °C.

The long-term multi-factorial experiment was established in 1995. The experiment includes two seven-field crop rotations, one with and the other without a mixture of perennial legume and grasses (alfalfa + ryegrass). There are two systems of soil tillage in the crop rotations: *system 1* was non-inversion tillage, and *system 2* was alternation of non-inversion tillage with tillage using the mouldboard plough which inverts the topsoil. This means that during the rotation of crops different amount of non-inversion tillage and moldboard ploughing can be made.

Three systems of fertilization being studied in the experiment are: (1) control (without fertilizers); (2) composted farmyard manure; and (3) composted farmyard manure + mineral NPK fertilizers. The same amount of manure (10 t ha^{-1}) is used in both crop rotations, but the amount of mineral fertilizers is different ($N_{12.8}P_{21.8}K_{24.2}$ kg active ingredient ha^{-1} in the rotation that includes perennial legumes and grasses; $N_{38.6}P_{24.2}K_{24.2}$ kg active ingredient ha^{-1} in the other crop rotation). No chemicals are used for weed, insect and disease control.

Standard randomized block design was used for the multi-factorial experiment. Crops in each rotation have been sown on larger plots (main or first order plots). These plots have been divided into two subplots with different soil tillage practices (sub-plots or second order plots), which in turn have been subdivided into three sub-plots with different fertilization practices (third order plots). The size of each third order plot is 264 m^2. The experiment includes three replicates.

The total experimental area is 8.7 ha. Simultaneously, trials are conducted with permanent cropping (continuous monoculture) of winter wheat, winter barley, sugar beet, maize for grain and sunflower under the two systems of soil tillage and three systems of soil fertilization, but without replications. The main reasons for separating monocultures from crop rotations were difficulties connected with high levels of infestation with insects, pathogens and weeds, especially in monocultures since the experiment was conducted without chemical applications for crop protection.

The other long-term field experiment on crop rotations was established in 1962 and on continuous monocultures in 1965.

The experiment with crop rotations includes eight rotations, each of them on ten fields with different proportions of row crops—from 40 up to 70%, including 10–30% of sugar beet, 10–20% of sunflower and 20–40% of maize. All crop rotations have 30% winter wheat, but the wheat is sown, after different preceding crops: in one field after early-harvested preceding crops (spring vetch and oats for green biomass; alfalfa and alfalfa + ryegrass for green biomass on the third year after first cutting), in the second field after maize for silage, and in the third one after maize for grain. The systems of fertilization are different for different crop rotations.

Each plot in the crop rotation is 283 m^2, with three replicates, and in the continuous monocultures 450 m^2 without replicates.

When discussing the results in the following section, reference is made to CA system performance based on the data from published international literature.

3. Results and Discussions

The fundamental question is: why do discussions about soil management still continue and what approach and recommendations should farmers follow?

First, we would like to consider some of the methodological aspects of soil tillage. Faulkner [3] pointed out that agricultural science does not offer a convincing theory about the need for soil tillage.

The diversity and contradictory nature of the data collected about the effect of tillage on short-term crop productivity and on soil quality and functions is not surprising, because soils, cropping systems and weather conditions are different in different geographical areas. Also, given the biological nature of production systems, the use of soils in tillage agriculture brings about further changes in soil functions over time, depending on the type and intensity of tillage and the rate of turnover of soil organic matter. In general, over the past many centuries, tillage and poor understanding and management of soil health have been shown to be the root causes of land degradation and ecological unsustainability [1]. That is one reason why zonality or site-specific character of agriculture production is a very important determinant of performance and must be taken into consideration in any kind of meta-analysis along with the need to ensure that data sets are properly characterized, which is often not the case [12]. Often soils and weather conditions are quite different even within the boundaries of one farm. Izmailski [13,14] wrote that "as there is no way to use one size of boots for the legs of different people, because the feet of people are different, there is no way to find one method or system of soil tillage suitable for all conditions". Docuceaev [15] found that by studying the chernozems and steppe conditions, including chernozems of Basarabia, the steppe region under chernozems requires improvement in physical properties—structure and hydrological regime and geographically, the upper regions with the domination of forest soils need improvement in chemical properties, and lower regions with greezioms soils need improved hydrological properties. However, such conclusions have been drawn within the conventional tillage agricultural paradigm, and not within the framework of the CA paradigm.

The modern industrial model of agricultural intensification is based on conventional tillage-based agriculture referred to as the "Green Revolution" agriculture. It has overemphasized the importance of soil chemical properties as the basis for enhancing crop productivity everywhere. Liebigh in his book "Chemistry as the attachment to agriculture and crop physiology" recognized his overestimation of the NPK thinking in agriculture. We will come back to this point latter.

The other important methodological aspect under any agricultural paradigm is the necessity of a systems (holistic) approach to farm management, instead of a reductionist (narrow) one where each component of the farming system, including soil tillage is studied separately and over very short periods. Narrow specialization in science and desire to obtain quick results or draw general conclusions from short-term experiments have often led to fragmentation of the whole-farm thinking and to deeply divided studies of different components which may create a basis for the first step in the process of analysis for cognition, but this is often not followed by the second step which is synthesis for system development. Frequently, the assumption is that the whole is the sum of each component, but in reality this is often not the case. Within the conventional tillage-based agricultural paradigm, the roles and the influences of soil tillage practices are quite different in different farming systems with different crop rotations and systems of fertilization [16].

A sustainable farming system is more than a good cropping system, because restoration of soil fertility requires integrated crop husbandry, or integrated crop and animal husbandries, where livestock is part of farming system. The negative influence of tillage with mouldboard plough or with any tillage implement and of bare soil surface cannot be compensated in an unbalanced crop rotation. This is because of the extensive soil degradation and biological and structural disruption that occurs with tillage and the associated exposed soil surfaces which are subjected to erosion. On the other hand, the idea of avoiding soil tillage and the transition to no-till system and its potential benefits can be compromised if not done with simultaneous development and maintenance of good soil mulch cover with biomass from crop residues, stubbles and cover crops as well as with good fertility management. We know many examples from history when the importance of one or the other component of the farming system was overestimated or underestimated. Today, we are witnesses to the yield stagnation for many crops in the majority of industrialized countries as a result of neglecting the importance, in crop production, of the many inter-linked biodiversity properties of soil health upon which depend its fertility and response to application of plant nutrients. A major concern is the overestimation of the importance of mechanical soil disturbance through intensive tillage for crop establishment and of industrial agrochemical inputs based on the use of fossil fuels and the importance of nonrenewable energy and their derivatives [17,18].

In general, agricultural activities and support services have been oriented mainly on increasing crop yields. This has led to the neglect of the biological and ecological aspects of agro-ecosystem processes that have a positive impact on crop phenotypic performance and total farm output as well as for the environment and ecosystem services.

Agriculture everywhere needs more structural changes at the production system and service provision level for better adaptation through the application of ecologically and biologically based methods that can also help minimize inputs required. Otherwise, the current dependence on technological methods based on an ideology that more production output can only be obtained from applying more production inputs, including mineral fertilizers, pesticides for pest, disease and weed control, genetically modified seeds (GMOs and non-GMOs), etc., will continue to degrade all agro-ecosystems globally. This is a topic for another discussion.

In general, comparison between mouldboard plough, which inverts the soil, and other methods of soil tillage, which do not, is not strictly correct. This is because soil tillage equipment with different working tools performs different soil disturbance operations such as: cutting of soil and cutting of weeds; loosening of soil; inversion of soil; fracturing of soil; mixing of soil; settling (compacting) of soil; leveling of soil; creation of micro-relief (ridges, dishes); keeping the straw on soil surface after harvesting [19]. For example, mouldboard plough does a high amount of soil disturbance relative to other soil tillage equipment: cutting the soil and weeds; loosening with simultaneous inversion of the soil; and mixing and fracturing of soil. Chisel plough loosens the soil, but without cutting weeds and without complete soil inversion etc. Similarly, rotavators and power tillers do the same to the top 10 to 15 cm soil layer but by fracturing, pulverizing and mixing the soil. Chisel plough, if deep enough, can break the plough pan created by years of tillage with a mouldboard plough. Each soil tillage tool has shortcomings in that they all over time destroy soil structure, aggregate stability and porosity, soil health and biota, habitats and food webs in the soil and above the soil surface, debilitate soil in-situ ecosystem functions and disrupt landscape level ecosystem functions, reduce soil organic matter and therefore soil life. Such serious shortcomings cannot provide solutions for sustainable intensification of agriculture. Therefore, when we are comparing different soil tillage systems, we are in fact comparing apples with oranges, and not apples with apples [5].

The problem with any form of soil tillage is that it does not add anything to the soil nor does it contribute to maintaining soil biological, physical, chemical and hydrological health when compared with crop rotation and soil fertilization. Tillage can only fracture, mix or redistribute soil, and incorporate crop residues and fertilizers in the soil for plant nutrients to be utilized by crops [20]. The mouldboard plough, disc and chisel ploughs, harrows and rotavators are the most soil destructive methods of tillage. They increase the speed of soil organic matter decomposition, making soils lose their structure and aggregate stability, and function as well as their fertility, making them more vulnerable to wind and water erosion and to droughts.

The main objectives of soil tillage have been different in different stages of agricultural development [21]. Three primary objectives are: preparation of the seedbed; control of weeds, insect pests and diseases; and temporary alteration or improvement of soil physical conditions for increased mobilization of soil nutrients, and accumulation and conservation of soil moisture. By destroying weeds, insect pests and pathogens, it is possible to more efficiently use nutrients and soil moisture.

However, with mineral fertilizers for plant nutrition and herbicides and pesticides for weed, pest and disease control, and with the use of irrigation, the need for the above-mentioned objectives of soil tillage has been significantly reduced or eliminated. The majority of the experimental data obtained in different regions of the world, including in Moldova, have shown that tillage can be avoided altogether. We will discuss below some of the arguments in favor of no or minimum mechanical soil disturbance by avoiding the application of any form of tillage.

3.1. Contribution of soil tillage to yield

Data obtained from the multi-factorial long-term field experiment show that contribution of soil tillage to yield is relatively low or not significant when compared to the contribution of crop rotation and soil fertilization (Table 1).

Yield increase was higher under crop rotation in both systems of soil fertilization across the soil tillage treatments for winter wheat, 1.18–1.21 t ha^{-1} (39–40%) and 0.50–0.54 t ha^{-1} (13–14%), respectively. Yield increase with fertilization was higher in crop rotation without mixture of perennial legumes and grasses, 0.74–0.88 t ha^{-1} (24–29%) and lower in crop rotation with the mixture of perennial legumes and grasses, 0.10–0.17 t ha^{-1} (2–4%).

Sugar beet, a root crop, was more responsive to soil tillage relative to other crops, and there was an increase in yield in the crop rotation on unfertilized and fertilized plots, especially in the crop rotation without the mixture of legumes and grasses. The influence of the mixture of perennial legumes and grasses was significantly greater than the influence of soil tillage. However, non-inversion tillage reduced the yield of sugar beet which normally has a deep root system on chernozem soil.

Maize yield was influenced to a lesser extent by crop rotation, soil tillage and soil fertilization. Similar response has been reported for a number of other geographical areas with different types of soils in Moldova [22-26].

Data from Table 1 shows the interactions amongst the three basic components of each cropping system. The expenditures related to the application of mineral fertilizers and inversion soil tillage can be reduced by the type of crop rotation chosen and by using different sources of fresh organic matter in the mixture of perennial legumes and grasses.

Reducing soil tillage or avoiding it altogether does reduce the production cost for fuel and labor, and can decrease emissions of greenhouse gases, crop water requirements and soil erosion, and environmental degradation. In the long-term field experiments, the average fuel consumption with mouldboard ploughing for all 7 crops in a 7-year crop rotation was 30 L ha^{-1}, but it was only 16 L ha^{-1} when non-inversion tillage tools had been used. The input of labour was 2.8 and 1.1 man-hours ha^{-1}, respectively [23].

Table 1. Yields of crops in rotations with and without a mixture of perennial legumes and grasses under different systems of soil tillage and fertilization, average for two full rotations (1996–2009), t ha^{-1} [22].

Soil tillage	Control (without fertilizers)			Farmyard manure + NPK			Farmyard manure + NPK relatively to control	
	1	2	±/%	1	2	±/%	1	2
a) Winter wheat, LSD = 0.32 t ha^{-1}								
Moldboard plough	3.04	4.22	+1.18/39	3.78	4.32	+0.54/14	+0.74/24	+0.10/2
Non-inversion tillage	3.01	4.22	+1.21/40	3.89	4.39	+0.50/13	+0.88/29	+0.17/4
Difference (±/%)	−0.03/1	0		+0.11/3	+0.07/2			
b) Sugar beet, LSD = 2.59 t ha^{-1}								
Moldboard plough	28.9	35.2	+6.3/22	40.2	40.4	+0.2/0.5	+11.3/39	+5.2/15
Non-inversion tillage	27.4	32.1	+4.7/17	36.4	38.3	+1.9/9	+9.0/33	+6.2/19
Difference	−1.5/5	−3.1/9		−3.8/9	−2.1/9			
c) Maize, LSD = 0.34 t ha^{-1}								
Moldboard plough	4.81	5.16	+0.35/7	5.13	5.37	+0.24/5	+0.32/7	+0.21/4
Non-inversion tillage	4.75	5.01	+0.26/6	4.96	5.19	+0.23/5	+0.21/4	+0.18/4
Difference	−0.06/1	−0.15/3		−0.17/3	−0.18/3			

The legend: 1, rotation without mixture of perennial legumes and grasses; 2, rotation with mixture of perennial legumes and grasses.

According to Soane and coauthors [27], the fuel costs and the working time for crop establishment are 6.5 and 5 times higher for mouldboard ploughing than for no-till. Some researchers report that no-till is economically acceptable even with a yield decrease of up to 12–28% on a 500 ha farm, or with a yield decrease of 10–15% on a 100–150 ha farm [28].

Taking into consideration the negative impact of the mouldboard ploughing and other forms of tillage on soils and their relative low contribution to yield, the best approach for the future should be to replace mechanical tillage with what can be termed "biological tillage" [26] with deep-rooted cover crops and diversified crop rotations that are economically and environmentally appropriate, as recommended for CA systems.

In order to make the large-scale transition from the unsustainable tillage-based agriculture to CA requires structural changes beyond technological modernization. Such an objective can be achieved when all stakeholders understand and respect ecological principles for effective and efficient farm management. Before going to these principles, we would like to point out the crucial importance of soil organic matter and soil health for modern farming systems because soil organic matter represents the best integral index of soil fertility. Consequently, the restoration of soil health and fertility creates a smooth transition to a more sustainable agriculture. Healthy soils provide better conditions for plant growth, and decrease the negative influence of weeds, insect pests and pathogens. This is why even when using optimal rates of mineral and organic fertilizers in crop rotation, the share of soil fertility based on soil organic matter in yield formation is very high, as seen from the data collected from the long-term field experiment [29] (Table 2).

Table 2. The contribution of soil fertility to yield formation on fertilized plots (manure + NPK) for different crops in crop rotations and in continuous monocropping, average for 1991–2011, % [29].

Crops	Unfertilized	Crop rotations		Continuous monocropping
		With mixture of perennial legumes and grasses	Without mixture of perennial legumes and grasses	
Winter wheat	100	93.7	90.9	34.9
Sugar beet	100	31.7	51.2	0
Maize	100	81.8	91.4	57.0
Winter barley	100	51.8	65.2	20.9
Sunflower	100	-	90.3	90.3

The largest contribution of soil fertility to yield formation on fertilized plots was in the crop rotation without the mixture of perennial legumes and grasses for: winter wheat, sunflower and maize (90.3–91.4%) and the lowest for sugar beet and winter barley (51.2–65.2%). On unfertilized plots yields of crops are assumed to be 100%. So, even for crops such as sugar beet and winter barley the contribution of soil fertility in yield formation was more than 50%.

The share of soil fertility in yield formation was lower in crop rotation with the mixture of perennial legumes and grasses. It means that including perennial leguminous crops and grasses in the crop rotation reduces the mineralizational losses of soil organic matter and consequently contributes to more carbon storage in the soil profile. This is proven by the experimental data from this long-term field experiment (Table 2).

The contribution of soil fertility to yield formation was significantly higher in crop rotation than in continuously monocropped crops, with the exception of sunflower. It would seem that reduced soil functionality in continuously monocropped crops has to be compensated by higher inputs of mineral fertilizers for crop nutrition and of pesticides for insect pest, disease and weed control. However, the stocks of soil moisture and nutrients in the soil under continuously monocropped crops are not considered to be limiting the yield potential, which is confirmed by our experimental data. Soil health is the key soil quality issue for increasing soil productivity and for decreasing the dependency of agriculture on expensive chemical inputs. In this regard, there are real possibilities for providing environmental, ecosystem and societal services from agriculture based on CA. However, many questions still exist regarding the relations between CA and the provisioning of ecosystem and societal services [11,12,30,31].

3.2. Soil moisture under different soil tillage methods

The results of the long-term field experiment using three full rotations of crops with different systems of soil tillage (excluding no-till) at the Selectia Research Institute of Field Crops showed no difference in the water content in the soil profile and no difference in yields independent of the methods, depth and frequency of different methods of soil tillage in crop rotation [23]. Both moldboard ploughing and non-inversion soil tillage in crop rotations contributed to losses of soil organic matter, but the mineralization of soil organic matter was 50% higher in soil under the moldboard plough than under non-inversion tillage. Thus, over 14 years, in the crop rotation with 57.2% of row crops and 5.7 t ha^{-1} of manure, the total loss of soil organic matter in 0–30 cm soil layer was 2.3 t ha^{-1} under the moldboard plough and 1.4 t ha^{-1} for non-inversion tillage. Reduction in the intensity of soil tillage in this study does not compensate for the annual mineralization losses of soil organic matter in the upper layers of soil.

In general, there are no advantages in water accumulation for the soil profile up to 2 m deep between different tillage methods within the same cropping system. A majority of researchers have reported increased soil moisture under non-inversion soil tillage in drought years, especially for winter cereal crops [32]. Correspondingly, the yields of crops also show a tendency to increase in drought conditions under non-inversion tilled soil.

In soils that are under conventional tillage agriculture for many years, the capacity of tilled soil to accumulate and retain soil moisture is determined not so much by the methods of soil tillage, but by soil structure and mulch (crop residue) on the soil surface. Docuceaev [15], Rotmistrov [33], Costicev [34], and Izmailski [13,14] in their classical works with tillage of chernozem soils have pointed out the limited importance of the methods and depth of soil tillage, but more important are the timing and the quality of soil tillage. In other words, soil tillage in conventionally tilled soils can have a higher negative influence on crop yields when it is done at the wrong time and of poor quality. Mouldboard ploughing can be temporarily efficient in accumulation of soil moisture, especially in deeper soil layers, when it is done together with the application of composted farmyard manure [14,34,35].

The recent data from the long-term field experiments with different fertilization and irrigation in crop rotations indicates that the organic matter losses in the 40–100 cm soil layer are greater than in 0–40 cm soil layer [36]. Managing soil organic matter in the soil profile is one of the crucial sustainability issues for modern farming, including no-till farming.

Future research should quantify water and nutrients up-take by crops from the different soil layers in the soil profile, especially with regards to global warming as shown from the experimental data obtained from the State Agricultural University in Chisinau, Moldova [19,37]. The soil horizons ABC have been modeled to monitor the root distribution of grain maize. By placement of soil horizons in a natural sequence ABC, the 0–25 cm soil layer contains 53.4% of the root system. By placement of soil horizons in the order AAA in the same soil layer, only 36.8% of roots were found. In the soil layers 25–50 cm by ABC sequence 24.6% of the roots were found, and in the second case (AAA) 39.4%. Krauze [35] and Wolny [38] also showed a higher yield level on soil with improved soil structure and thicker layers as a result of better water and nutrients accumulation. That is why the majority of researchers studying reduced tillage agree that production efficiency can be increased on soils that have deeper and more fertile soil layer available for the root system [25].

However, in no-till CA soil, water retention and availability is greater throughout the crop season due to improved infiltration and soil pore volume. A healthy untilled soil generally tends to maintain 50–60% pore volume, and half of this space can be used to store moisture. Under tillage conditions, the destruction of structure and porosity leads to compaction and a significant decrease in infiltration, and in soil pore volume, often down to 20% or less. The arguments in favour of avoiding the use of moldboard plowing are also: optimal agrophysical parameters and differentiation of soil layers on their soil fertility.

3.3. Important parameters of soil physical properties

For soils with optimum bulk density (1.1–1.2 g cm^{-3}), tillage of any type makes little sense, especially if the field is not infested with weeds. For agricultural soils that are compacted due to tillage over many years, the necessity of continuing with soil tillage is evident. Otherwise, effective rooting zone will be reduced and crops will have smaller, abnormal root systems that may decrease their yields.

Degraded and compacted soils in conventional tillage agriculture require higher energy input, higher level of fertilizer and seed rates, and can make crops more susceptible to water stress, pests and disease attacks, and increased the level of weed infestation [16,39]. This means that part of the strategy for effective transition from conventional tillage system to a CA system in heavy or compacted and degraded soils may need to include the preliminary improvement of soil health (soil quality) by planting of deep-rooted cover crops to open up the soil and initiate improvement of soil structure, which over time can reduce or prevent the occurrence of the above mentioned problems.

Higher bulk densities in soils under CA transition do not necessarily correspond to high soil compaction if improved soil structure is accompanied by better aggregate stability and improved network of biopores of different sizes. What is important for soil health and productivity is not the lowering of bulk density but the improvement in infiltration rate, soil water and nutrient retention and availability, soil structure and porosity, soil organic matter content and soil biodiversity [40].

3.4. Differentiation of soil layers in the upper horizons of the soil profile

The surface layers of agricultural soils are more fertile and contribute relatively more to yields as demonstrated at the Ploti Experimental Station, Ribnita district, in Basarabia (former name of Moldova) from 1896 to 1912 and confirmed later by the Agricultural University Experimental Station in Chisinau, Moldova [19,37]. Fifty percent of the nutrient requirements of cereal crops were extracted from the 0–20 cm soil layer. The thicker the upper soil layer (up to 50 cm) the higher was the yield of corn. Increasing the thickness of the upper soil layer up to 75 cm did not increase the maize grain yield, relative to 50 cm soil layer. If the yield of maize grown in the top soil layer of 25 cm is considered as 100, then decreasing the thickness of the surface layer to 15 cm reduced the grain yield of maize by 22.6%, to 10 cm, by 35.4% and to 5 cm by 48.5% [19].

This is contrary to what has been proposed by Williams [41] who stated the necessity of annual ploughing for inverting the 0–10 and 10–20 cm soil layers, because in his opinion soil structure and soil fertility were better in the 10–20 cm soil layer. However, the microbiological studies have shown a decrease in soil biological activity from upper to lower soil layers [42]. At the Rothamsted Experimental Station in England, Russel [43] found a sharp decrease in earthworms in soils under the mouldboard plough. It was concluded by some scientists that “worn out soils” lose their productivity not because of nutrient deficiency, but because of increased loss of soil organic matter, deterioration of soil structure and higher level of infestation by weeds [39,44].

3.5. Conservation Agriculture (CA)

Conservation Agriculture is based on ecological principles that emulate agroecological processes that are central to the normal functioning of natural ecosystems [31,45,46]. CA constitutes an alternative productive and profitable systems approach to sustainable production intensification developed globally, especially in last three decades or so. In this approach, harnessing sustainability requires paying attention to the ecological processes that underpin land and crop production potentials, soil health, biodiversity below and above ground, ecosystem services and protecting environmental quality. CA is considered to be a "climate-smart" approach to agriculture around the world, indicating that many rural communities are already successfully making the transition to new forms of locally adapted CA systems that are better suited to cope with climate change. CA holds the promise of sparking agricultural renewal and economic development in rural areas in the developing world where hunger and poverty are most prevalent [7].

The data obtained in the long-term field experiments with different crop rotations and monocropping at Selectia Research Institute of Field Crops show annual losses of 0.45 t ha^{-1} soil organic matter in the crop rotation with 30% of alfalfa and 4 t ha^{-1} of composted farmyard manure. This "energy balance deficit" is a unique way of evaluating the system. If we equate energy = carbon, the analysis then becomes a balance of carbon in verses carbon out of the soil. To illustrate this, we have calculated the balance of energy for different crop rotations and continuously monocropped crops. More details about these experiments can be found in the recently published book "Soil as World Heritage" edited by Dr. David Dent [36].

The data presented in Table 3 show annual energy deficit, because the amount of energy taken up by the above ground biomass and uncompensated deficit of soil organic matter, of 83.6% on fertilized plots of the "black" bare fallow (without any crop during the vegetation period, but ploughed annually); 64.6–72.9% on plots with the continuously monocropped winter wheat and maize, and 39.2–52.9% for crop rotations. The lowest annual energy deficit was determined for the crop rotation with perennial legumes. So, even 30% of perennial legumes in crop rotation cannot compensate for the energy deficit, which results in the reduction of soil organic matter. The energy in composted farmyard manure is considerably lower than the energy in crop residues, yet the role of composted manure is very important in the reduction of uncompensated soil organic matter deficit. Even avoiding mouldboard ploughing in this experiment will not compensate for the above mentioned deficit unless there is an adequate supply of crop biomass to help build soil organic matter.

In natural ecosystems, the amount of energy taken up by the above ground biomass is equal to the amount of energy returned to the soil, which maintains an equilibrium in the balance of the soil organic matter [47,48]. The vegetation in natural ecosystems is primarily of perennial type with abundant root systems, compared to the root system of annual crops. Malitev T. cited by Kononova [49] and Licov [50], who was the pioneer in promoting non-inversion tillage in the former USSR, noted that annual crops have the same ability to restore soil fertility as perennial crops by using a non-inversion system of soil tillage. The experimental data from the Selectia Research Institute and other institutions did not confirm this statement [24,51,52]. Apparently, the rate of humification for straw left on the surface of the soil is significantly lower than the rate of humification for composted farmyard manure. In tillage-based systems, the rate of humification is increased when there is incorporation of crop residues in deeper layers of the soil. The intensity of decomposition of straw depends also on its amount. Using ^{14}C marked straw of spring barley, it was found that during the first year of decomposition of 1.25 t ha^{-1}, the contribution of the products of decomposition to humic substances was in the range 7–15%, but for a higher rate of return of straw (1.88 t ha^{-1}), it was only 4–6% [53]. In one year the amount of ^{14}C in humic substances decreased 2–3 times, but the tendency has remained the same. The deeper incorporation of straw provides a higher humification. The coefficient of humification for composted farmyard manure is 25–30%, which is determined by the lower C:N ratio and better soil quality [49,50,53]. As a result, the potential to restore soil organic matter is higher with composted manure. In any case, the most important consideration is to regularly add fresh organic matter, which has many beneficial effects. Use of a diverse mix of 8 to 15 species cover crops and diverse rotations enable regular additions of soil carbon and all of the associated benefits in CA systems [54]. Integration of forage crops in rotations together with animals in the farming system is one of the best solutions for recycling of nutrients and restoration of soil organic matter and for rational use of by-products from crop husbandry [55].

Table 3. The annual energy balance in different variants of the long-term field experiment at Selectia Research Institute of Field Crops, average for 1962–1991, thousand MJ ha^{-1} [18].

Variants			Taken up by the above ground biomass	Uncompensated deficit of soil organic matter	Total	Crop residues	Composted manure	Total	± MJ/ha	Annual deficit of energy, %
Crop rotations with different saturation by row crops, %		40	99.3	10.4	109.7	64.8	1.9	66.7	–43.0	39.2
		50	95.2	12.4	107.6	50.4	0.3	50.7	–56.9	52.9
		60	116.9	11.5	128.4	60.2	3.7	63.9	–64.5	50.2
		70	112.6	11.5	124.1	63.6	2.4	66.0	–58.1	46.8
Continuously monocropped crops	Maize	Unfert.	100.4	20.0	120.4	35.8	-	35.8	–84.6	70.3
		Fert.	141.0	16.8	157.8	51.1	4.4	55.5	–102.3	64.8
	Winter wheat	Unfert.	57.4	20.0	77.4	21.0	-	21.0	–56.4	72.9
		Fert.	80.3	15.2	95.5	29.4	4.4	33.8	–61.7	64.6
Black fallow		Unfert.	-	32.7	32.7	-	-	-	–32.7	100.0
		Fert.	-	26.9	26.9	-	4.4	4.4	–22.5	83.6

Crop rotation is the key to a more sustainable farming system. It includes the alternation of crops with roots of different depths, with different amounts and quality of crop biomass (mainly C:N ratio), with different capacity to suppress weeds, including varieties and hybrids of each crop, to prevent (instead of control) pests, diseases, to restore soil fertility in the whole profile, to use water, especially from deeper layers of soil, more efficiently. A good crop rotation will decrease the dependence on external production inputs. Each crop rotation should provide a non-deficit balance of soil organic matter.

Estimations of C and N balance can be done for each crop rotation taking into consideration the achieved yields and inputs from different sources.

Mulvaney et al. [56] have generalized data from long-term field experiments from all over the world and found that mineral fertilizers, especially nitrogen, in tillage-based cropping, increase the rates of soil organic matter mineralization. This means, that by using only mineral fertilizers in tilled systems without adding enough fresh sources of organic materials, it is not possible to maintain the content of soil organic matter [46,56].

Many of the above mentioned issues are complex and appear to be contradictory and sometimes difficult to solve under the framework of one type farming system. Overestimation of the effect of soil tillage, but also its underestimation can complicate the transition to a more sustainable farming system, which should be flexible under different field conditions. More research is required under different conditions, for different systems, including CA, especially taking into consideration the associated ecosystem services [29,57,58].

With CA systems, residues are retained on the soil surface and become incorporated into the soil over time with the help of microorganisms and mesofauna, some of whom are able to fix atmospheric nitrogen. The buildup of soil organic matter under many CA systems is a well-established fact as the review by Corsi et al. shows [8].

4. Conclusions

The results from the long-term field experiment on different tillage practices, crop rotation and fertilization systems show that it is necessary to keep searching for best options in terms of various combinations of farming practices. The experimental results obtained here are evidence of clear justification to reduce tillage intensity. It is also clear from the global research that tillage-based systems, even with reduced intensity, are simply unable to offer the kind of sustainable production intensification needed by all farmers which combines maximum productivity, efficiency, resilience and ecosystem services with minimum of production inputs. This is due to the fact that mechanical soil disturbance of any kind and not maintaining soil mulch cover and diversified cropping, over time degrades soil health and ecosystem functions. Lack of holistic approach to farm management has led in different historical periods of time to overestimation of mechanical and/or chemical methods for increasing crop productivity and for restoring soil fertility.

Conservation Agriculture shows that maintaining soil health, including aggregate stability and soil biology is significantly more efficient than mechanical means or excessive chemical inputs. Microorganisms in the soil have coevolved with crops and livestock over time, and they have many symbiotic relationships amongst them that support efficient and resilient crop and livestock performance. More research is required to better understand these relationships and to explain how they improve efficiency and resilience in CA production systems. Consequently, no-till CA research was initiated in 2014 at the Selectia Research Institute. This research will be extended in the future by including a larger diversity of cover crops in the crop rotation. The existing experimental data obtained in the long-term field experiments at Selectia Research Institute of Field Crops demonstrate that the systems of soil tillage, including no-till, should be integrated in the agricultural systems with a higher level of economic crop diversity and cover crops in the system, allowing a more effective recycling of carbon energy and nutrients in each system.

A high deficit of carbon energy in modern farming systems cannot be compensated by higher rates of application of mineral fertilizers and reduced systems of soil tillage. They will only increase soil degradation and decrease soil health and fertility along with many other negative consequences.

Globally, conventional tillage agriculture has been shifting to CA systems at the annual rate of some 10 Mha, and already in 2013 some 11% of the global annual cropland (some 157 Mha) was applying the CA approach to farming in more than 50 countries, involving small, medium and large farms in the topics, sub-tropics and temperate agroecologies [56]. There is additional CA area not included in this total of 157 Mha, and this area is covered by mainly perennial CA systems such as CA-based orchards, plantations, agroforestry and permanent pasture systems. Further spread and success of CA will continue to depend to a great extent on the cooperation between all stakeholders but particularly among farmers, and between farmers and input service providers and processors and consumers of agricultural products. This can help to return a bigger share of the profit back to the farming community, which can enhance the sustainability of farms and the stability of rural communities, create opportunities to improve land stewardship and provide global social stability.

Conflict of interest

This is to declare that there are no conflicts of interests involved with this article.

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