

Article

Effects of Tillage Systems on the Physical Properties of Soils in a Semi-Arid Region of Morocco

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Abstract: Climate change, drought, erosion, water contamination resources, desertification, and loss of soil quality represent major environmental risks worldwide. Facing these risks is the most important issue for sustainable development. Conventional tillage (CT) practices seem to expose the soils of semi-arid regions, which are initially fragile, to degradation that is accentuated by the overuse of the environment. The benefits of conservation agriculture (CA) could mitigate the degradation of natural resources, particularly soils. The adaptation and transfer of the no-till (NT) system with mulch open new perspectives for the development of agriculture in semi-arid regions. The main objective of this study is to assess the impact of conservation agriculture, especially no-till (NT) system, on the physical properties of soil (structural stability (SS), bulk density (BD), gravimetric water content (θ_g), and soil organic matter (SOM)) compared to conventional tillage (CT). The main changes associated with the transition from a CT system to an NT system were evaluated at the experimental site, Merchouch (M13), which is typified by vertisol soil, and at the Ain Sbit (AS7) site, which is characterized by isohumic soil. Under a no-till system, most of the physical properties of the soil were improved in both sites, with a clear difference in the M13 site. Structural stability under NT showed a significant increase in both sites (fast wetting (FW), slow wetting (SW), and wet stirring (WS) improved by 88, 43, and 83% at the M13 site, respectively, against, 16, 23, and 7%, respectively, at the AS7 site). On the other hand, the SOM increased from 2.0 to 2.6% (an improvement of 28%) at AS7 and from 1.2% to 1.9% (an improvement of 52%) at M13. This research demonstrated that conservation agriculture, especially NT, improves the soil physical quality in both medium and long terms, confirming its suitability for the climatic and edaphic constraints of semi-arid areas in Morocco as well as in other parts of the world.

Keywords: conservation agriculture; conventional tillage; no-tillage system; physical properties; soil quality; vertisol



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1. Introduction

Conventional agriculture is based on intensive tillage [1], the objective of which is to obtain a soil structural state that allows crop yields to increase. Nevertheless, this idea has not persisted and has shown its limits. Intensive plowing practices, known as conventional tillage (CT), can lead to various negative effects including land erosion, water and soil pollution, and the advancement of desertification [2]. Numerous agronomic research studies, performed under different climate conditions around the world, have revealed common problems with plowed soils: compaction, erosion, the limitations of

water circulation and energy, and the financial costs of the practice [3,4]. In addition, tillage has long-term negative influences on the soil, degrading its structure, increasing wind and water erosion [5,6], and reducing the soil's organic matter content [7]. In the Moroccan context, results have shown that the physical and chemical quality of the subsoil horizons decreases under the conventional system [8]. Over the last few decades, the overexploitation of soils through increasingly intensive rotations, tilling on unfavorable dates and under high-moisture conditions, and the export of plant residues from cultivated and grazed lands has caused carbon loss and the destabilization of aggregates [9]. In addition, the strong demographic growth and the technical, environmental (water scarcity), economic, and land deficiencies pushed the farmers to exploit the available vegetation to the maximum by resorting to continuous cultivation, the use of marginal lands, and the overgrazing of rangelands [10]. In addition, water resources are becoming increasingly scarce due to the overexploitation of water reserves and prolonged periods of drought [11]. In this sense, conservation agriculture (CA), including direct seeding or the no-till (NT) of field crops (cereals, legumes, oilseeds, etc.) based on reduced tillage, appropriate rotation, and management of crop residues, is one of the technological packages that has shown its effectiveness in arid and semi-arid areas. Compared to conventional agriculture (CT), NT practices mitigate climate change's impact by reducing carbon emissions and conserving natural resources [12,13]. Indeed, NT practices improve the chemical, physical, hydric, and biochemical processes in soils [14]. They lead to the homogenization of the soil structure and the enhancement of structural stability after a period of adaptation, ultimately resulting in improved productivity while maintaining the environment [15]. NT system increase the organic matter content (SOM) of the soil, save 30–40% of labor time, labor, and fossil energy, facilitate water infiltration, and significantly reduce runoff and erosion [16]. Internationally, several studies have been conducted to investigate the effects of the NT system on the physical properties of the soil in semi-arid regions. For example, a study by Fernández-Ugalde et al. (2009) [17] found that no-till farming increased the soil organic matter and porosity, which led to better water infiltration in semi-arid regions of Spain. Similarly, a study by Kurothe et al. (2014) [18] found that NT practices improved soil structure and water-holding capacity in semi-arid regions of western India. In contrast to these results, other studies indicated that NT negatively affected the physical quality of the soil and resulted in reduced crop yields in Mollisols in the Argentine Pampas region due to the negative effects of compacted soil layers on plant root development and soil infiltration [19–21]. In Africa, a study by Mtyobile et al. (2020) [22] showed that NT farming improved the soil porosity and water-holding capacity in a semi-arid region of South Africa. Similarly, a study by Ouattara et al. (2018) found that the NT system improved soil moisture and water infiltration into the soil and reduced runoff and erosion in ferruginous soil in western Burkina Faso [23]. Despite all its advantages, the system is not yet widespread in Morocco, with only 30,000 hectares cultivated under the NT system in 2021 [24]. For this reason, the government has initiated an ambitious challenge to intensify the areas of cereals sown without plowing to reach a target of 1 million hectares of NT system by 2030 as part of the new Green Generation strategy (2020–2030) [25]. Long-term trials in different regions of Morocco have shown the importance of the no-till system in improving yields and soil stability against climatic hazards [26,27]. Several intra- and inter-annual measurements have been carried out to evaluate the effects of this cropping system on water resources, soil quality, and crop yields compared to the conventional system [28,29]. Furthermore, a study by Mekkaoui et al. (2021) [30] found that no-till systems improved the physical properties of the soil, including an increased soil structure, soil organic matter (SOM) accumulation, water-holding capacity, and reduced erosion in the Merchouch region of northwest Morocco. Our study is part of this research program and focuses on the evaluation and comparison of the effects of NT farming on the physical properties of the soil in two different soil situations: vertisol soil in M13 and isohumic soil in AS7.

The main objective of the present study is to compare the effect of conversion from a conventional (CT) system to a conservation tillage system (NT) on the physical properties of the soil in a semi-arid region.

2. Materials and Methods

2.1. Soil and Climate of the Study Sites

The present study was carried out in two no-tillage trials in the Zaer region (Figure 1). The first trial (M13) was conducted at the Merchouch research station of the National Institute of Agricultural Research (60 km south of Rabat; 33°37' N; 6°43' W; 255 m above sea level) for 13 years. The second trial (AS7) was located at a farm in the Ain Sbit area (located 80 km from the city of Rabat; 33°33'27" N; 6°31'27" W; 450 m above sea level), whose conversion to a no-till system was conducted for 7 years.

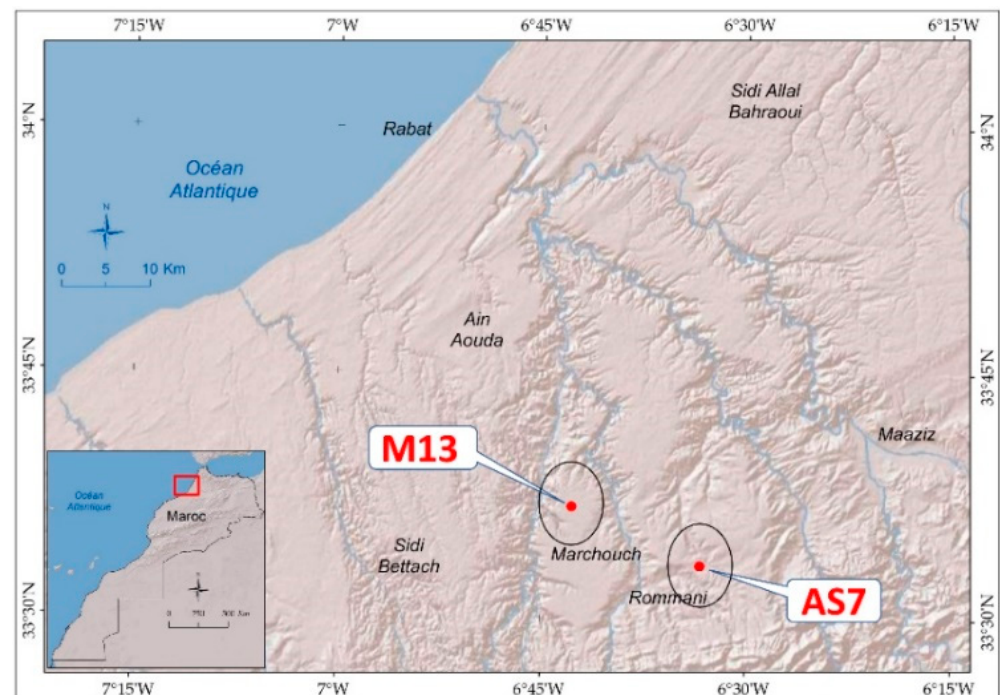


Figure 1. Location of the two study sites in the Zaer region, Morocco.

The two experimental sites were chosen for their different soil types and management conditions. The experiment reported at site M13 was initiated in 2005; the soil is vertisol, rich in clay (>50%) with possible external drainage, hydromorphic, and has shrinkage cracks that open and reclose periodically and crack when dry. Direct seeding has been installed at the AS7 site since 2011. The soil at AS7 is isohumic (based on the French soil classification (CPCS, 1967) [30]), saturated with Ca^{2+} , of a cool pedoclimate, brown, and vertic. The soil in each plot is homogeneous, and the slope is less than 1% in both sites.

The climate is semi-arid, with a Mediterranean-type rainfall regime that is characterized by a dry summer and a rainy winter. The average rainfall over 40 years was 394 mm, with a maximum of 665 mm and a minimum of 181 mm. The inter-annual monthly averages of rainfall and temperature over 40 years (1978–2018) are presented in Figure 2. Prevailing winds are strong, southwesterly, and have a low-to-medium intensity. During the 2017/2018 crop year, the two sites received 515 mm (M13) and 532 mm (AS7) of precipitation and registered mean temperatures of 17.7 °C (M13) and 16.8 °C (AS7).

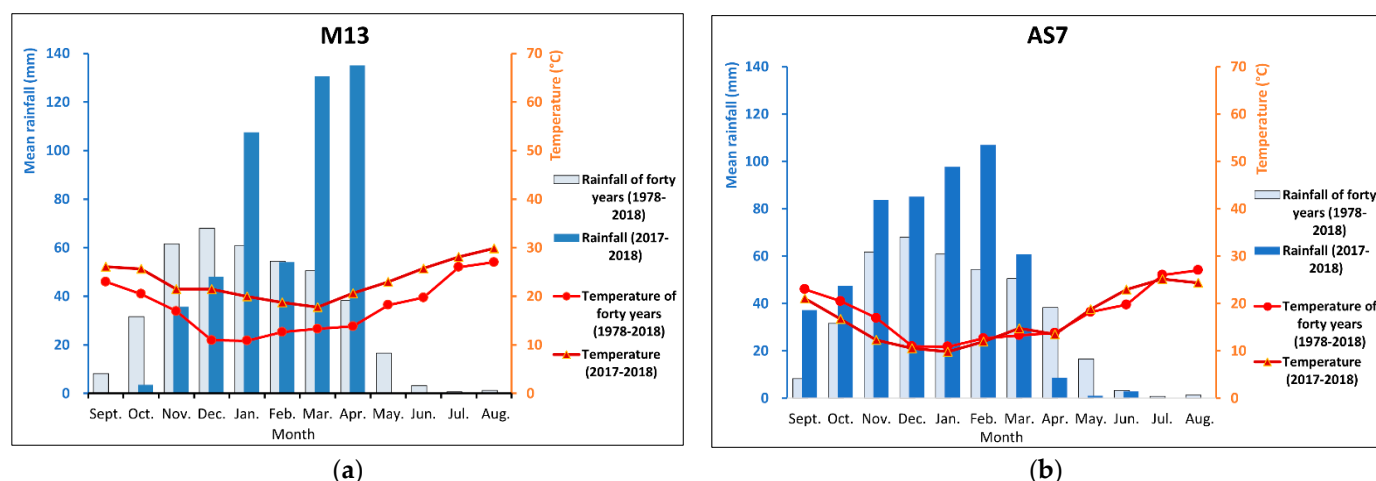


Figure 2. Precipitation and temperature of the Zaër region, recorded at the Marchouch experimental station and the Ain Sbit agricultural center during the 2017–2018 season compared to the 40-year average (1978–2018) for sites: (a) M13 and (b) AS7.

2.2. Soil Description

A granulometric analysis showed that the soil of the trial installed at the Merchouch station is a vertisol soil. At the Ain Sbit trial (AS7), the soil is a brown, isohumic soil with a vertic character (Table 1).

Table 1. The soil granulometry characteristics of the NT and CT systems.

Site	Depth (cm)	Tillage Type	Clay (%)	Fine Slit (%)	Coarse Slit (%)	Fine Sand (%)	Coarse Sand (%)	CaCO ₃ (%)	Soil Type
M13	0–13	CT	50.0	12.3	22.7	8.5	7.4	0.4	Dark brown and grey vertisol with possible external drainage
		NT	48.3	10.5	21.8	6.6	5.4	0.3	
	13–26	CT	47.7	13.0	23.2	8.7	7.7	0.5	
		NT	50.0	11.5	22.3	7.9	6.9	0.3	
AS7	0–13	CT	36.1	10.5	12.6	9.9	5.2	13.7	Isohumic and brown with a vertic character
		NT	36.4	11.2	13.2	10.4	5.6	13.7	
	13–26	CT	38.7	5.1	13.1	10.1	5.3	20.8	
		NT	39.4	5.4	12.9	10.2	5.4	19.8	

The particle size analysis results showed that the textural class of both sites is clayey, with an average of 48% clay at M13 and 38% clay at AS7 (Table 1). The isohumic soil at AS7 is uniformly calcareous (between 14 and 21%) and distinguished by a progressive accumulation with depth, whereas the soil at M13 is completely decalcified.

2.3. Experimental Design and Methodology

The experimental design consisted of two plots, each measuring one ha. The two tillage techniques (CT and NT) were adopted at the two sites, M13 and AS7 (Table 2). Since the beginning of the adoption of the no-till system at both sites, the crop rotation applied consisted of legumes, such as lentils or chickpeas, and cereals, such as soft wheat, durum wheat, or barley. The two treatments included conventional tillage (CT), involving the passage of a chisel in July and a cover crop in October, performed in plowed fields of a 0.10 to 0.15 m depth, whose objective was the preparation of the seedbeds and the burial of the residues of the culture and direct seeding; or the no-till (NT) system, which consisted of using a specific seeder that allowed for seeding and fertilization without disturbing the soil, creating an opening of 2–3 cm in the soil and sowing the seeds at a depth of 5 cm (Table 2).

Table 2. Management history of the experimental sites.

Site	Cropping System	Area (ha)	Year of NT Adoption	Previous Crop Residue Management	Plowing Technique	Current Crop	Sowing Period and Density	Basal Fertilizer NPK:14-28-14 (kg/ha)	Top Dressing Fertilizer Ammonium Sulfate 21% (kg/ha)	Pest Management
M13	NT	1	2005	30% lentil Residue retained	No ground turning; seeds were placed in a ground opening of a 5 cm depth using the Monoseed B/GP/DT Seeder.	Soft wheat: Arrihane variety	22 December 2017 150 kg/ha	150	50	Glyphosate 2 L/ha (pre-sowing)
	CT	1	-	0% lentil residue retained	Chisel passage in July; cover crop in October (15–20 cm depth) for the preparation of seedbeds and the burial of crop residues.	Soft wheat: Arrihane variety	22 December 2017 150 kg/ha	150	50	None
AS7	NT	1	2011	30% barley residue retained	No ground turning; seeds were placed in a ground opening of a 5 cm depth using the Monoseed B/GP/DT Seeder.	Chickpea: Farihane variety	15 December 2017 80 kg/ha	100	None	Glyphosate 2 L/ha (pre-sowing) + fluazifop-P-butyl 1.25 L/Ha (After sowing)
	CT	1	-	0% barley residue retained	Chisel passage in July; cover crop in October (15–20 cm depth).	Chickpea: Farihane variety	15 December 2017, 80 kg/ha	100	None	None

2.4. Measurements and Methods

The evaluation of the physical properties of the soil was achieved by adopting a simple random sampling design. At each plot, five sampling points (replicates) were installed. Soil core samples were taken from two depths: 0–13 and 13–26 cm. Sampling was undertaken on 29 March 2018 at M13 and on 5 April 2018 at AS7. The soil cores were labeled and transported to the laboratory for analysis. All analyses were conducted in the Laboratory of Soil Analysis (Lab-URECRN) of the Regional Center of Agricultural Research, INRA, Rabat, Morocco. All analyses were performed in duplicates. For each physical parameter except granulometry, a total of 80 samples (2 sites $\times$ 2 tillage types $\times$ 2 depths $\times$ 5 samples $\times$ 2 repetitions) were taken for the present study. Regarding granulometry, there was only one sample per site, tillage type, and depth.

The physical soil properties studied (Text S1) were granulometry, gravimetric soil water content (θ_g), structural stability (SS), bulk density (BD), and soil organic matter content (SOM):

- Particle size distribution was defined using Meriaux's densimetric methods [31];
- Gravimetric water content (θ_g) was determined by weight difference (Gardner, 1986) [32]:

$$\theta_g = \frac{m_{water}}{m_{soil}} = \frac{m_{wet} - m_{dry}}{m_{dry}} \quad (1)$$

With θ_g represents the gravimetric water content (%), m_{wet} represents the wet weight (g), and m_{dry} represents the weight of the dry soil obtained after drying (g);

- Structural stability (SS) is defined as the capacity of the soil aggregates to resist the degrading effects of rainfall [33]. The SS allows for determining the susceptibility of soils to degradation processes and their vulnerability to ramming and erosion [34,35]. It is determined by the method proposed by Le Bissonnais [36], which has become an ISO standard #10930 [37]. This method is applied to sieve-separated, air-dried, and dry-stored aggregates of 3.15 to 5 mm. Three aggregate tests were conducted under various climatic, hydraulic, and structural scenarios to which the soil face would be subjected:
 - Test 1: Fast wetting by immersion (FW): the aggregates are brutally immersed in a volume of water. This treatment makes it possible to test the behavior of dry soils in case of sudden humidification, such as submerged irrigation, or heavy rainfall (spring and summer storms);
 - Test 2: Slow wetting by capillary action (SW): the aggregates are slowly moistened by capillarity. This treatment allows for the testing of the performance of dry or slightly wet soils under moderate rain. It is less destructive than rapid wetting and therefore allows for the distinction of very unstable soils;
 - Test 3: Wet stirring (WS): the aggregates are saturated with ethanol, immersed in water, and manually shaken in an Erlenmeyer flask. This treatment allows us to test the behavior of wet soils (wet winter periods).

After each of these tests, the evaluation of the proportions of the size classes of the aggregates was performed by sieving using a column of six sieves. The expression of the results in terms of the mean weight diameter (MWD) was carried out after the process of disaggregation, and the calculation was performed using the following formula [30]:

$$\text{MWD (mm)} = \sum \bar{X}_i \times W_i, \quad (2)$$

with $\bar{X}_i$ represents the average diameter between two consecutive sieve classes and W_i represents the proportion of the total residual, aggregate mass in each sieve (ranging from 2 mm to 0.05 mm).

$$\text{MWD} = 3.5 \times [\% > 2 \text{ mm}] + (1.5 \times [\% 1\text{--}2 \text{ mm}]) + (0.75 \times [\% 0.5\text{--}1 \text{ mm}]) + (0.35 \times [\% 0.2\text{--}0.5 \text{ mm}]) + (0.15 \times [\% 0.1\text{--}0.2 \text{ mm}]) + (0.075 \times [\% 0.05\text{--}0.1 \text{ mm}]) + (0.025 \times [\% < 0.05 \text{ mm}]) / 100. \quad (3)$$

- Soil bulk density (BD) was measured with the calibrated cylinder method, using cylinders with a volume of 1140 cm³ and following the procedure described by Grossman and Reinsch (2002) [38]. The measurements were made at two soil depths (0–13 and 13–26 cm), with five replicates for the two treatments (CT and NT). The principle of the cylinder method is based on the determination of the apparent specific weight of a volume of soil sampled, using a metal cylinder, so that the weight sampled is evaluated by weighing before and after passage in an oven at 105 °C for 24 h, using a precision balance [39]. Bulk density can be expressed in g·cm^{−3} using the following equation [40]:

$$\text{BD} = \text{Ms} / \text{V}_T \quad (4)$$

with BD representing the bulk density (g·cm^{−3}), Ms representing the mass of dry soil (g), and V_T representing the total soil volume (cm³).

- Soil organic carbon (SOC) content was assessed indirectly through the oxidation of organic carbon using the classical Walkley and Black method [41]. The soil organic matter (SOM) content is calculated by multiplying the soil organic carbon (SOC) content by a correction factor of 1.724.

$$\text{SOM} (\%) = \text{SOC} (\%) \times 1.724 \quad (5)$$

2.5. Statistical Analysis

An analysis of variance (ANOVA) was carried out using the IBM SPSS Statistics 23 software to compare the differences between the mean values ($p < 0.05$) of the two tillage systems and the two depths and, eventually, their interaction for each physical parameter.

3. Results and Discussion

3.1. Soil Physical Parameters

Table 3 highlights the average values with the standard deviations of the physical properties for the two depths (0–13 cm and 13–26 cm) and the two tillage types (NT and CT) used at each site.

It is noted that for the two sites, AS7 and M13, the averages of the physical measurements obtained under the NT system generally exceed the averages achieved using the CT system. The exception was the gravimetric water content at AS7, for which the average was equal to the value for the CT. This overshoot was established at an average of 46% at M13 and 14% at AS7. Variations are represented in Table 3.

It should be noted that, among the eight physical properties of the soil, the fast wetting (FW) factor at site M13 was the most impacted by the type of tillage, with an average variation of 89%. However, for AS7, the soil organic matter (SOM) was the most impacted factor, with a variation of 28% if there was a conversion from CT to NT.

3.1.1. Effect of Tillage Type (NT and CT) and Depth on the Physical Properties of the Soil

For Site M13, there were significant differences between the two tillage types (NT and CT) for all physical properties of the soil except the bulk density (Table 4), which had a p -value well above the 5% significance level with higher means for the NT type (Table 3). Therefore, tillage type exerts an influence on θ_g , FW, SW, WS, and SOM. Regarding the effect of depth on the studied parameters, it should be noted that all p -values were below the significance level except for gravimetric water content and slow wetting. Therefore, we can conclude that after 13 years of NT, the tillage system and soil depth have a significant effect on the soil's physical properties.

Table 3. Physical characteristics of M13 and AS7 (mean $\pm$ standard deviation).

Parameter	Tillage	M13			AS7		
		0–13	13–26	Mean	0–13	13–26	Mean
θ_g (%)	CT	17.31 $\pm$ 0.75	17.48 $\pm$ 0.42	17.39 $\pm$ 0.58	22.52 $\pm$ 0.76	21.71 $\pm$ 0.76	22.12 $\pm$ 0.83
	NT	19.34 $\pm$ 0.70	19.20 $\pm$ 0.61	19.27 $\pm$ 0.62	22.04 $\pm$ 0.54	22.23 $\pm$ 0.55	22.14 $\pm$ 0.52
	Variability (%)	12	10	11	–2	2	0
BD (g cm ^{–3})	CT	1.41 $\pm$ 0.05	1.60 $\pm$ 0.04	1.51 $\pm$ 0.11	1.20 $\pm$ 0.07	1.37 $\pm$ 0.08	1.29 $\pm$ 0.11
	NT	1.46 $\pm$ 0.02	1.60 $\pm$ 0.05	1.53 $\pm$ 0.08	1.34 $\pm$ 0.05	1.50 $\pm$ 0.06	1.42 $\pm$ 0.09
	Variability (%)	4	0	1	12	9	10
SOM (%)	CT	1.33 $\pm$ 0.15	1.10 $\pm$ 0.11	1.22 $\pm$ 0.17	2.23 $\pm$ 0.04	1.82 $\pm$ 0.07	2.03 $\pm$ 0.22
	NT	1.96 $\pm$ 0.04	1.75 $\pm$ 0.02	1.85 $\pm$ 0.11	2.68 $\pm$ 0.06	2.50 $\pm$ 0.07	2.59 $\pm$ 0.11
	Variability (%)	47	59	52	20	37	28
FW (mm)	CT	0.47 $\pm$ 0.01	0.64 $\pm$ 0.00	0.55 $\pm$ 0.09	0.35 $\pm$ 0.01	0.43 $\pm$ 0.01	0.39 $\pm$ 0.05
	NT	0.97 $\pm$ 0.05	1.12 $\pm$ 0.05	1.04 $\pm$ 0.09	0.37 $\pm$ 0.01	0.57 $\pm$ 0.02	0.47 $\pm$ 0.10
	Variability (%)	106	75	89	6	33	21
SW (mm)	CT	0.81 $\pm$ 0.01	1.02 $\pm$ 0.05	0.92 $\pm$ 0.12	0.49 $\pm$ 0.01	0.73 $\pm$ 0.02	0.61 $\pm$ 0.13
	NT	1.42 $\pm$ 0.02	1.20 $\pm$ 0.02	1.31 $\pm$ 0.12	0.63 $\pm$ 0.01	0.90 $\pm$ 0.03	0.76 $\pm$ 0.14
	Variability (%)	75	18	42	29	23	25
WS (mm)	CT	0.88 $\pm$ 0.03	1.03 $\pm$ 0.03	0.95 $\pm$ 0.08	0.66 $\pm$ 0.01	0.80 $\pm$ 0.02	0.73 $\pm$ 0.07
	NT	1.87 $\pm$ 0.02	1.60 $\pm$ 0.05	1.74 $\pm$ 0.15	0.71 $\pm$ 0.01	0.88 $\pm$ 0.01	0.80 $\pm$ 0.09
	Variability (%)	113	55	83	8	10	10

Table 4. ANOVA for the effect of tillage type (NT and CT) and depth on the physical properties of the soil at site M13.

Site	Soil Property	Effect of Tillage System		Effect of Soil Depth		Tillage Type * Depth	
		F	Sig.	F	Sig.	F	Sig.
M13	Bulk density (g/cm ³)	1.383	0.257 ns	73.650	<0.001 ***	1.980	0.178 ns
	Gravimetric water content (%)	43.879	<0.001 ***	0.004	0.952 ns	0.305	0.588 ns
	SOM (%)	228.690	<0.001 ***	27.622	<0.001 ***	0.073	0.791 ns
	Fast wetting (mm)	885.014	<0.001 ***	99.244	<0.001 ***	0.713	0.411 ns
	Slow wetting (mm)	1013.928	<0.001 ***	0.243	0.629 ns	307.839	<0.001 ***
	Wet stirring (mm)	2306.756	<0.001 ***	14.360	0.01 **	164.023	<0.001 ***
AS7	Bulk density (g/cm ³)	23.292	<0.001 ***	32.595	<0.001 ***	0.014	0.909 ns
	Gravimetric water content (%)	0.005	0.947 ns	1.105	0.309 ns	2.880	0.109 ns
	SOM (%)	413.568	<0.001 ***	114.812	<0.001 ***	17.212	0.01 **
	Fast wetting (mm)	346.574	<0.001 ***	1180.378	<0.001 ***	168.739	<0.001 ***
	Slow wetting (mm)	1863.704	<0.001 ***	4941.530	<0.001 ***	14.238	0.01 **
	Wet stirring (mm)	106.454	<0.001 ***	555.199	<0.001 ***	4.408	0.052 *

* Significant at $p < 0.05$, ** significant at $p < 0.01$, and *** significant at $p < 0.001$; ns: not significant.

The ANOVA (Figure S1) showed that there was only an interaction between the tillage type and the soil depth for the two structural stability tests: slow wetting (SW) and wet stirring (WS). The weighted mean diameter of the two NT tests was higher at the surface (1.42 and 1.87 for SW and WS, respectively) than at depth (1.20 and 1.60). These results are explained by the high clay content of the vertisol (47% clay) and the presence of cracks in the deep horizon, which were observed during the cropping season [42].

For site AS7, we observed significant differences between the two tillage types (NT and CT) and the effect of depth for all physical properties of the soil except for gravimetric water content, for which the p -value was well above the 5% significance level (Table 4). The ANOVA showed that there was an interaction between the tillage type and the soil depth for all physical parameters except bulk density and gravimetric water content. Therefore, we conclude that the tillage type and depth exert an influence on the FW, SW, WS, and SOM. Thus, the tillage system type and depth have an impact on the physical properties of the soil. These results show that conventional tillage breaks up clods, but the no-till system

increases organic matter and maintains the soil structure at the surface. This increases the soil performance when the soil is exposed to sudden moisture (e.g., heavy rains or spring and summer thunderstorms), moderate rainfall, or moisture during winter periods.

3.1.2. Structural Stability

The stability of the soil structure refers to the soil's ability to retain its arrangement of solid particles and voids when subjected to various stressors such as the erosive effect of rain or wetting [36]. The results of the soil structural stability test for the M13 site indicated a significant difference between the no-tillage (NT) and conventional tillage (CT) systems for all three tests and at both depths (0–13 and 13–26 cm). The results of the water test revealed that the M13 vertisol was still more capable of resisting the breakup of aggregates during rapid wetting (FW).

According to the results of Table 5, the Merchouch vertisol under NT in this study is stable. Indeed, its good structural stability on the surface helps to limit the risks of sealing and erosion [43], which demonstrates that the no-till technique is a soil-conservative system.

Table 5. Stability, sealing, and erosion classes are based on MWD values (average of three tests), as per the standards established by Le Bissonnais, 1995 [44].

Site	Tillage Type	Depth (cm)	MWD (mm)	Class	Stability	Sealing	Runoff and Erosion
M13	NT	0–13	1.42	1.3–2.0 mm	Stable	Occasional	Limited risk
	CT	0–13	0.72	0.4–0.8 mm	Unstable	Very frequent	Frequent risk
AS7	NT	0–13	0.57	0.4–0.8 mm	Unstable	Very frequent	Frequent risk
	CT	0–13	0.50	0.4–0.8 mm	Unstable	Very frequent	Frequent risk

For the mechanical disaggregation test of agitation after rewetting (WS), the soil under the NT system showed an MWD value of 1.87 mm for the 0–13 cm depth, which is significantly higher than that of the soil under the CT system (0.88 mm) (Table 3). Similarly, for the test of slow wetting with ethanol (SW), the stability of aggregates was greater in the no-tillage (NT) system compared to the conventional tillage (CT) system, and the results indicated that the non-plowed plots had an MWD value of 1.42 mm, significantly higher than for soils in the conventional tillage system (0.81 mm). This indicates that the presence of residues in the no-tillage system enhances soil strength during slow wetting, which simulates the effect of moderate rainfall. The average MWD values for the three stability tests were significantly higher under NT than under CT. Therefore, it can be deduced that plots in the conventional tillage system have a low and unsteady surface structural stability (MWD < 0.8 mm), whereas plots in the no-tillage system have a stable structure (MWD > 0.8 mm).

These findings support those obtained by Laghrour et al. (2016) [45] in the same trial under a no-tillage period of 10 years. In contrast, Laghrour et al. (2015) [46] revealed that there is a significant distinction between the slow and fast wetting tests; however, there is no significant difference in the mechanical disintegration test (WS). Conversely, the findings obtained by Moussadek et al. (2011) [47] in the same location revealed a significant difference in the slow-wetting test but no significant differences in the other two tests. By comparing these results with our own, we can deduce that the improvement in structural stability due to a no-tillage system only becomes evident after several years. After 13 years of no-tillage in the semi-arid conditions of Morocco, the vertisol of M13 remains more resilient to different pedoclimatic challenges when compared to conventional tillage.

The structural stability test results for the second site (AS7) indicated a significant difference between the two tillage systems for all three tests at both depths. However, the results, obtained for the isohumic soil of Ain Sbit in accordance with the method of classification of structural stability described by Le Bissonnais et Le Souder (1995) [44] (Table 5), allowed us to conclude that, despite the remarkable improvement in structural

stability under the NT system compared to the CT system, the MWD values were low ($MWD < 0.8$ mm). As a result, the isohumic soils of AS7 are prone to degradation processes, particularly erosion, runoff, and crustability. This may be due to an insufficient accumulation of soil organic matter (SOM) on the surface [48]. It appears that it takes longer under the semi-arid conditions of Morocco for the isohumic soil under an NT system to accumulate sufficient SOM to withstand the various mechanical stresses to which the soil is continuously subjected.

Our findings at site M13 are consistent with those obtained by Mrabet et al. (2001) [8] on a Calcixeroll soil for 11 consecutive years in an NT system, which showed that aggregate stability was improved by a significantly larger MWD under an NT system (3.8 mm) than under a CT system (3.2 mm) at the soil surface. These results are consistent with the findings of Moussadek et al. [47] on clayey soils, which reported that after seven years in an NT system, the soil quality (MWD and SOM) was improved compared to a CT system and that the soils under the NT system had a more stable structure (MWD) than under the CT system.

3.1.3. Bulk Density

The bulk density serves as a measure of the soil compaction and the amount of void space in the soil [49]. The bulk density of the M13 site under a no-tillage system was slightly higher than the bulk density under a conventional tillage system at a depth of 0–13 cm, but was the same at a depth of 13–26 cm.

These results align with those of Moussadek et al. (2011) [47] but contradict the findings of Laghrour et al. (2015) [46] and Laghrour et al. (2016) [45], who reported a significant difference between the two systems with a bulk density of less than 1.34 g/cm^3 . A one percent decrease in bulk density was observed at the NT level from 2011 (1.51 g/cm^3) to May 2018 (1.44 g/cm^3) (Table S1).

This improvement in the surface bulk density (0–13 cm) was not observed until 13 years after the adoption of the no-till system at Site M13. According to Table 3, the bulk density under the NT system, was high, with values exceeding 1.40 g cm^{-3} , reaching a maximum of 1.60 g cm^{-3} in the 13–26 cm depth under the no-till system. The soil surface bulk density (0–13 cm) was slightly greater with the no-till system (1.46 g cm^{-3}) compared to the conventional tillage system (1.41 g cm^{-3}). This result aligns with the conclusions drawn by several previous studies [50,51], which demonstrated that the bulk density is higher in the upper 0.75 m of the soil profile under a no-till system compared to conventional tillage.

For the second site (AS7), Tables 3 and 5 show that the BD was significantly higher in the no-till system (1.34 and 1.48 g cm^{-3}) than the BD obtained from conventional tillage (1.20 and 1.38 g cm^{-3}) at the two depths (0–13 and 13–26 cm), respectively. The results of Chellappa et al. (2021) [43] are contrary to our findings at AS7, in which the CT system had a higher BD compared to the NT soils at all three study sites. However, our findings concur with the results reported by Jabro et al. [52], who found a substantial distinction between the two tillage systems in sandy loam soil, with BD values in the 0–30 cm layer that were lower in the CT system (1.56 and 1.58 g cm^{-3}) than in the NT system (1.63 and 1.64 g cm^{-3}) under corn and soybeans, respectively. The increase in soil bulk density, however, was less in the tillage systems than in the no-till systems [53], but it stabilized over the long term (after ten years of installing these techniques) [54,55].

The no-till system results in a higher soil compaction [56], especially for clayey soils, but some authors suggest that this compaction under a NT system decreases with time as biological activity and soil biodiversity increase [57]. This supports the idea that the no-till system provides a habitat for abundant biological activity and the growth of the soil's biomass [58].

3.1.4. Soil Organic Matter

The content of soil organic matter (SOM) is a crucial factor in determining the quality of the soil [59]. Conventional tillage (CT) reduces the organic matter content of the soil [60]. In addition, tilled soils are very susceptible to water erosion because of their low organic matter content, which makes the aggregates more susceptible to erosion [61]. On the other hand, conservation agriculture (CA) increases the content of organic matter in the soil [62]. According to Table 3, the SOM content was significantly higher under the NT system (1.85 and 2.59% at M13 and AS7 sites, respectively) than the SOM content obtained under the CT system, (1.22 and 2.03%) at both soil types, especially in the surface horizon (0–13 cm), with a variation of 28% at the AS7 site and 52% at the M13 site. The significantly higher variation at site M13 can also be explained by the duration of use of the NT technique, which is in agreement with works that have shown that the increase in SOM content depends on the duration of NT adoption [63].

There was also a decrease in SOM under the NT system with depth at both sites, as crop residues remain on the surface and undergo decomposition. Soil organic matter (SOM) in the 13–26 cm horizon of the conventional tillage (CT) systems was consistently lower than for the no-tillage (NT) systems, which can be attributed to the greater biological activity that takes place under a no-till system and the existence of shrinkage cracks specific to soils with vertic character. These cracks can move the SOM directly at a depth from the soil surface. The result of SOM accumulation under an NT system is in line with most studies conducted on no-till systems. Indeed, a recent study by Mekkaoui et al. (2021) [30] confirmed that plots under a NT system with residues have a significantly higher SOM content than those under a CT system at five depths: 0–5, 5–10, 10–20, 20–40, and 40–60 cm. These results show the positive effect of an NT system on SOM accumulation in different soil horizons. This is in agreement with the results obtained by other authors [64–66].

4. Conclusions

This study very clearly confirms that conservation agriculture, and the no-till (NT) system in particular, is an unavoidable alternative for field crops in arid and semi-arid environments in Morocco. This system allows for an increase in the soil organic matter content, soil stability, and coherence improvement, making it more resistant to erosive processes. The impact of the no-till system on the physical properties of the soil was investigated in two different soil situations in the Zaer region: the Merchouch vertisol (M13) and the Ain Sbit isohumic soil (AS7). The transition from a conventional tillage system (CT) to a conservation agriculture system (CA) based on a no-till (NT) system resulted in a significant improvement in SOM and a very highly significant increase in structural stability. Thus, a no-till system is a winning alternative for improving the physical properties of the soil and reducing the risk of erosion in semi-arid areas. Overall, the results of this study have implications for farmers and land managers in semi-arid regions, as they suggest that the adoption of an NT system can help improve the physical properties of the soil and enhance land use sustainability, which can help improve the resilience of these areas to climate change and improve the farmers' livelihoods.

The encouraging results obtained through this study need to be extended and verified in other pedoclimatic zones of the country and in other parts of the world. In addition, it is appropriate to proceed to the evaluation of the conversion from a conventional tillage system to a no-till system on the chemical properties of soil and its fertility.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture13030683/s1>, Figure S1: PP-Plot normal, Text S1: Measurements and methods, and Table S1: Effect of the two cultivation practices over time on bulk density [67,68].

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