Effect of tillage methods on oxygen diffusion rate (ODR), power and fuel requirements, some soil physical properties and wheat grain yield

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Abstract: Three types of tillage implement including moldboard plow (conventional tillage), heavy disk (tandem disk harrow) and chisel plow (minimum tillage), is common in Iran and widely used by farmers for plowing and preparing the land for both rain-fed and irrigated wheat production. A lot of chemical and physical properties of the soils are influenced by the type of tillage. Tillage methods are usually evaluated by the amount of oxygen in the soil and distribution of organic matter. On the other hand, using the cropping operations program can significantly affects the amount of oxygen diffusion rate (ODR), fuel consumption and energy efficiency. Prediction of the accurate amount of fuel requirements for tillage operation of the soil is difficult. Therefore, in the current research, the effects of abovementioned tillage methods on the amount of power required, fuel consumption, oxygen diffusion rate and some soil physical properties including bulk density, and organic carbon contents in a randomized complete block design was studied. The results showed that minimum tillage methods increase the amount of organic matter, reduces fuel consumption and needed less power. Highest fuel consumption of 49.6 liters per hectare and the lowest 21.3 liters per hectare, related to the moldboard plow and heavy disk, respectively. The experimental results showed that the highest ODR was recorded at the moldboard plow, (53.6×10^{-8} g cm^{-2} min^{-1}) and the lowest (35×10^{-8} g cm^{-2} min^{-1}) measured by heavy disk. This value was equal to 42.5×10^{-8} g cm^{-2} min^{-1} for chisel plow. Mean values of soil organic carbon related to the moldboard plow, chisel plow and heavy disk were 0.38, 0.43 and 0.48 percent, respectively. It can be concluded that by considering the land conditions in Iran, the current research findings recommend the use of chisel plow or heavy disk for rainfed or irrigated wheat production.

Keywords: conventional tillage, fuel consumption, organic carbon, oxygen diffusion rate, tillage methods

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1 Introduction

Agriculture is the most important sector in the production of food and consequently is a big consumer of energy in in Iran, most of them for plowing operations (Farahmandpour et al., 2008). Plowing with moldboard plows leads to the formation of many hard and large lumps in the soil. The formation of lumps is mainly due to plowing operations in improper climatic conditions and subsequent unsuitable humidity, which causes the disk to be used several times to crush or pulverize the lumps. Therefore, it not only increases the

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cost of preparing the seedbed, but also causes excessive dusting of the soil and complications such as clogging and soil erosion. The moldboard plow has soil pulverization greater than chisel plow by 32.57% (Nassir, 2017). Low soil moisture content can make the stronger cohesive force between soil particles and consequently uses a lot of energy in tillage processes. However, the higher soil moisture content, the less effectiveness of tillage equipment expected (Ahmadi and Mollazade, 2009). Seedbed preparation is an important operation to achieve uniform crop emergence, plant growth, and high yield under different soil and climatic conditions in dry lands crop production (Bayhan et al., 2005; Younesi Alamooti and Hedayatipoor, 2019; Hedayatipoor and Alamooti, 2020).

In conventional tillage practices, plant residues are buried in soil, which contributes to higher carbon contents and losses more organic nitrogen. Intensive farming by degradation of soil aggregates and prone to erosion, extensively enhance soil organic carbon decomposition. Also, the tillage practice can affect soil aggregate stability (Lampurlanés et al., 2001). The proper tillage operations provide sufficient soil moisture and prepare appropriate environment for seed germination, and longer root development by suppressing weeds and controlling soil erosion (Ehsanullah et al., 2013; Younesi Alamouti and Navabzadeh, 2007), while conservation tillage can increase the weed density (Younesi Alamouti et al., 2015). In general, conservative tillage system compare to the traditional system produce the higher diameter of soil aggregates (Martinez et al., 2008; Fuentes et al., 2009). The research findings also indicated that no-tillage cropping system had stronger soil structure, more soil water holding capacity, and better root development at the soil depth of 0-15 cm. (Acharya and Sharma, 1994; Acar et al., 2017). Abouhamed (2004) studied the effects of three field preparation methods (i.e. moldboard plow, chisel plow, and disc plow) on soil permeability and bulk density in irrigated farming.

Results showed that the tillage method had a significant effect on these two characteristics. Chisel plows require less time to prepare the fields than moldboard plows, due to their faster forwarding speed and higher working width. Also, chisel plows use less energy than the moldboard plows due to less time consumed per unit area and relatively lower retaining power consumption and so have less fuel consumption (Rouzbeh et al., 2002). Bonari et al. (1995) studied the effect of various tillage methods under different conditions, on the energy consumption, the yield of crop and soil physical properties. They reported that reduced tillage resulted in 55% less fuel consumption than the max tillage, without a significant difference in the yield of crop.

Adequate oxygen in the soil increases the mineralization of organic matter, the release of nutrients for consumption by plants, and soil microorganisms and animals' activities. Diffusion is defined as the random movement of particles due to kinetic energy (Hillel, 2003). Gas diffusion is conditioned by the physical properties of the soil, among which soil porosity is one of the most important. Compaction and water saturation of soils are the main barriers to soil oxygen transport, water being a more effective barrier (Papendick and Runkles, 1965; Moldrup et al., 2000; Neale et al., 2000). Singh et al. (2015) studied the effects of tillage and straw management on soil aggregation and soil carbon sequestration in a 30-year split-plot experiment on clay soil in southern Finland. They concluded that the chances to increase topsoil carbon sequestration by reduced tillage or straw management practices appear limited in cereal monoculture systems of the boreal region. Soil organic carbon storage can be higher under no-till management in some soil types and climatic conditions (Ogle et al., 2019). The results of some researches also indicate the presence of more organic carbon in the surface layers and its drastic reduction in more soil depths (Sidhu and Sur, 1993; Sidhu and Beri, 1989). The recent findings of the soil and water research institute indicated that due to improper plowing methods in the country agricultural land, the farmer faced with several problems for better crop production such as: reduction in organic carbon, hardening of the soils, losing the soil structure. The cope with these constraints, the current study was designed and conducted to explore the effects of three types of primary tillage implements including moldboard plow (conditional tillage), heavy duty disk, and chisel plow (minimum tillage) on grain yield, the amount of power required, fuel consumption, oxygen diffusion rate, and some important physical and chemical properties soil including bulk density, and organic carbon contents of soil.

2 Materials and methods

The current study was conducted during 2017 to 2019 in the research farm of Karaj Agricultural Higher Education Center, located in Alborz province of Iran which is located at Latitude of 35°46'11.8" N, and Longitude of 50°56'51.0" E. A three factors experiment was performed in a completely random block design (CRBD) with three replications. Experimental factors were: three plowing methods at three levels: 1- Moldboard plow (MP) with a depth of 25 cm (conditional tillage), 2- heavy duty disk or tandem disk harrow (HD) with a depth of 15 cm and 3- chisel plow (CP), with a plowing depth of 25 cm (minimum tillage). The tillage treatment was performed based on the machines mentioned in Table 1, for primary tillage and the secondary tillage operations for breaking the larger lumps and leveling the land in all treatments included, disc harrow and land leveler. Tillage operations were performed in September each year. Before plowing, a disturbed and undisturbed composite soil samples were collected and their physical and chemical properties was measured in the laboratory The measured characteristics were: texture, bulk density, particle density organic carbon to a depth of 40 cm, as well as permeability and soil moisture were measured (Table 2). Plowing was done using a Massey Ferguson tractor (MF399), with 110 hp engine power in mid-September. The crop was planted in early October each year and harvesting were done annually in early July. After plowing and preparing the field, autumn wheat seeds were sown.

Table 1 Characteristics of the machines* used in the study

Tillage implements	Working width (cm)	Specifications
Moldboard plow	96	3- bottom, mounted type, working width of each bottom (32 cm)
Heavy disk harrow or tandem disk	300	Mounted, 28 number of discs, 49 cm disc diameter, notched disc in front and smooth disc in rear
Chisel plow	300	Mounted type, 9 shank (4 in front and 5 in rear)

Note: Three types of tillage implement which are common in Iran and widely used by farmers for plowing and preparing the land for wheat planting

2.1 Power required for tillage implements

Power required for tillage implements was measured directly by a dynamometer connected to a three-point hitch of a Massey Ferguson 399 tractor and the required data were collected with a Campbell CR23X data stabilization system.

2.2 Fuel consumption

Fuel consumption was also measured by the fuel metering system installed on the tractor board (Table 2).

2.3 Oxygen diffusion rate

Oxygen diffusion rate was measured averagely 5 points per plot in the early stage of farming and after the crop were cultivated and also in spring (mid-May). The soil pore oxygen concentration in experimental plots was monitored using an oxygen-sensitive Fibox-3 oxygen meter (PreSens GmbH, Germany). The sensors were placed at soil depth of 0-15 cm. The soil oxygen measurement was measured at about 23% soil moisture content (approximately at field capacity).

Table 2 The most important physical and chemical properties of soil ofthe research field before treatments application(depth, 0-40 cm)

OC% (organic carbon percentage)	0.45
ODR (oxygen diffusion rate, g cm^{-2} min^{-1})	28.2×10^{-8}
Particle density (g cm^{-3})	2.61
Bulk density (g cm^{-3})	1.48
Soil infiltration (cm hr^{-1})	0.98
Texture	Silty clay loam (SiCL)
Soil moisture at the time of oxygen measurement	23% (about field capacity)

2.4 Permeability or soil infiltration measurement

The permeability or soil infiltration was measured by the double ring method. Also, the cumulative infiltration was determined using the Equation 1. Finally, the arithmetic mean of water infiltration into soil was measured with field apparatus in cm h^{-1}.

$$I=aT^{-n} \quad (1)$$

where, I = Cumulative infiltration (cm.min^{-1})

a = Is a constant for a soil type (cm)

T = Time of cumulative infiltration (min)

n = Infiltration slope.

2.5 Soil bulk density

To measure soil bulk density, soil samples were taken at multiple points in each plot (at least 3 samples) using an undisturbed sampling cylinder (diameter = 76 mm, height = 42 mm). Then selected samples were dried in an oven. The bulk density ($B.D$, g. cm^{-3}) measurement using Equation 2 (Gunder, 1986).

$$B.D=\frac{M_2-M_1}{V} \quad (2)$$

where, M_1 = Mass of empty cylinder (g)

M_2 = Mass of full cylinder with dry soil (g)

V = Volume of cylinder (cm^3)

2.6 Statistical analysis

The normality of collected data was checked with the Kolmogorov Smirnov test. The SAS, and MSTATC programs were used to analysis of variance (ANOVA) and the mean comparison through LSD (0.05), respectively.

3 Results and discussion

The most important physical and chemical properties of soil of the studied research field before treatments application (depth, 0-40 cm) summarized Table 2. The soil of studied plots had a silty clay loam texture and naturally prone to lower field capacity and infiltration rate. The organic carbon is lower than its optimum level for agricultural crop growing system (2%).

In order to investigate the effects of tillage methods, before the first plowing, the soil of the field was examined and analyzed in the laboratory and some of its properties including the texture, bulk density, particle density organic carbon to a depth of 40 cm, as well as permeability and soil moisture were measured (Table 2). The results of analysis of variance (Table 3) showed that the effect of tillage methods on soil bulk density was not significant. Effects of tillage methods on the soil infiltration rate and Soil organic carbon were significant at the level of 5%. The effects of tillage methods on the required power and fuel consumption was significant at the level of 1%, and on oxygen diffusion rate at the level of 5%. Effects of tillage methods on crop yields were not significant (Table 4).

Table 3 ANOVA of studied factors: soil bulk density, soil infiltration rate and organic carbon contents of soil

Sources of variation	df	Mean squares (MS)		
		Soil bulk density (g cm^{-3})	Soil infiltration rate (cm hr^{-1})	Soil organic carbon (%)
Replication	2	0.018 ^{ns}	0.321*	0.021 ^{ns}
Tillage method	2	0.012 ^{ns}	15.20*	0.79 *
Experimental error	4	0.008	3.85	0.39

Note: ns = No significant; * and **= significant at 5 and 1 percent confidence level

Table 4 ANOVA of studied factors: power requirements, fuel consumption, oxygen diffusion rate and crop yields

Sources of variation	df	Mean squares (MS)			
		Power requirements (kN m^{-1})	Fuel consumption (Lit ha^{-1})	ODR (g cm^{-2} min^{-1})	Crop yield (t ha^{-1})
Replication	2	1.59 *	36.35 ns	1.66 ns	131.136 *
Tillage method	2	141.126 **	1335.22 **	108.90*	1.49 ns
Experimental error	4	0.35	21.12	0.970	0.30

Note: ns = No significant; * and **= significant at 5 and 1 percent confidence level

3.1 Soil bulk density

The results of analysis of variance (Table 3) showed that the effect of tillage methods on soil bulk density was not significant. However, the decreases values of soil bulk density associated with moldboard plow were generally higher than that of other tillage implements, but the difference was not significant (Table 4). The mean value of three years measurements for investigation of the effects of the tillage methods, on bulk density are shown in Table 5. Although the effect of plowing methods were not significant but numerically was considerable. The highest decrease in soil bulk density was observed in conventional tillage with the moldboard plow (1.25 g cm^{-3}) and the lowest decrease in soil bulk density was observed in HD treatment and plowing the field by heavy disk or tandem disk harrow (1.32 g cm^{-3}). The amount of soil bulk density for chisel plow treatment was less than the heavy disk treatment (1.28 g cm^{-3}). This is due to the higher depth of plowing depth and so higher soil agitation caused by the moldboard plow and the chisel plow than the disc harrow, which in turn reduced the soil bulk density. The values of soil bulk densities below the 30 cm depth were not more different between the three methods of plowing. The greatest value of bulk density observed from 30 to 40 cm depth on conventional tillage and may have been due to plow pan of moldboard plow. The trend for lower soil bulk density is found in deep tillage rather than in other tillage treatments, as seen in this study, agrees with the findings by others, who measured greater bulk density values in moldboard plow and reduced bulk density with conventional tillage, after plowing (Erbach et al., 1992; Håkansson et al., 1988; Lowery and Schuler, 1991). Higher soil BD in subsurface layer than in surface layer for soils in no-tillage systems occurs due to the concentration of loading by farm machinery traffic and absence of soil tillage (Reichert et al., 2009).

Table 5 Effects of tillage methods on soil bulk density, soil infiltration rate, organic carbon contents of soil, power requirements, fuel consumption, oxygen diffusion rate (ODR) and crop yields

Factor	Moldboard plow	Heavy disk or tandem disk harrow	Chisel plow
Bulk density (g cm^{-3})	1.25 b	1.32 a	1.28 ab
Soil infiltration rate (cm hr^{-1})	0.12 a	0.82 b	0.98 ab
OC (%)	0.38 c	0.48 a	0.43 b
Power requirements (kN m^{-1})	22.35 a	6.23 c	11.12 b
Fuel consumption (Lit ha^{-1})	49.6 a	21.3 c	37.2 b
ODR (g cm^{-2} min^{-1})	53.6×10^{-8} a	35×10^{-8} c	42.5×10^{-8} b
Crop yields (t ha^{-1})	5.45 a	5.23 a	5.36 a

Note: Values followed by different letters within a column (a-c), are significantly different at the 5% level of probability.

3.2 Soil infiltration

The ANOVA results indicated that regardless of type of applied treatments, the soil infiltration rate significantly influenced by tillage method at 5% confidence level. The effect of tillage on soil infiltration was significant in the three tillage methods (Table 3). Infiltration rate was greater for moldboard plow tillage (mean of 0.12 cm h^{-1}), medium for chisel plow treatment (0.98 cm h^{-1}) and lower for HD treatment (0.82 cm h^{-1}). The increase in infiltration rate with moldboard plow and chisel plow probably reflects the decrease in soil bulk density shown in Table 5. Higher infiltration rate in moldboard plow due to increasing plowing depth, agrees with the findings by others, who measured greater infiltration values in deep tillage (Erbach et al., 1992; Croissant et al., 1991).

3.3 Soil organic carbon

Soil organic carbon (SOC) was significantly affected by tillage methods and total SOC content of deep tillage was lower than the other methods (Table 5). So, the SOC decreased as tillage intensity increased and the greatest decreases were observed in deep tillage by moldboard plow. This reflects the increasing level of crop residue returned to the soil with increasing tillage intensity. Organic carbon content for heavy disk (HD) method was higher than chisel plow and moldboard plow tillage by 12% and 26%, respectively (Table 5). Primary tillage's with heavy disk (HD) appear to have distributed OC, concentrated at the soil surface and creating a more uniform OC distribution. As tillage intensity increases, crop residue-soil contact is increased and incorporated residues are placed into moister conditions than those left on the soil surface. Higher amounts of SOC content for heavy disk method than the chisel plow and moldboard plow tillage, agrees with others who measured lower SOC as the tillage intensity increased (Doran et al., 1998; Davidson and Ackerman, 1993; Wang et al., 2020). Singh et al. (2015) studied the effects of tillage and straw management on soil aggregation and soil carbon sequestration in a 30-year split-plot experiment on clay soil in southern Finland. They concluded that the chances to increase topsoil carbon sequestration by reduced tillage or straw management practices appear limited in cereal monoculture systems of the boreal region. Our results showed impact of minimum or reduced tillage on the organic carbon content in the arable soil. Similarly, Ogle et al. (2019) concluded based on their extensive literature review that SOC storage can be higher under no-till management in some soil types and climatic conditions. It should be noted that SOC improves the water holding capacity of soil, which is an important feature under drought conditions.

3.4 Power requirements

The effects of tillage methods on the required power were significant at the level of 1% confidence level. The average required power, were changed by changing the tillage methods. The average power required for moldboard plow was 22/35 kN m^{-1}, which by changing the tillage methods, this value sharply decreased and reached to the 11.12 kN m^{-1} and 6.23 kN m^{-1}, for plowing with the chisel plow and heavy disk respectively. The power required for plowing the land with a chisel plow and a heavy disk was much less than the moldboard plow and was 49% and 28%, respectively (Table 5). A review of the works of other researchers also shows that same results for lees power requirements and energy consumption for same tillage implements (Loghavi and Hosseinpoor, 2002; Bonari et al., 1995; Tabatabaeefar et al., 2009; Craciun et al., 2004). All of them indicated that requires less tractor traction for plowing with a chisel plow and heavy disk because of the less plowing depth or reduced plowed soil surfaces, was expected due to the reduction of the soil disturbed surface and less mixing, stirring and turning the soil.

3.5 Fuel consumption

The effects of tillage methods on the fuel consumption were significant at the level of 1% confidence level. The average amount of required Fuel for plowing with moldboard plow was 49.66 Lit ha^{-1}, which decreased with the change of tillage methods. These amounts in plowing with chisel plow by 25% decrease, reached, 3702 Lit ha^{-1} and in plowing with heavy disk by 57% decrease, reached 21.3 Lit ha^{-1} (Table 5). The reduction of the average fuel consumption values was expected due to the reduction of the soil disturbed surface and less mixing, stirring and turning the soil. Some other researchers also shows that the same results for lees fuel consumption, power requirements and energy consumption for same tillage methods (Loghavi and Hosseinpoor, 2002; Bonari et al., 1995; Tabatabaeefar et al., 2009; Craciun et al., 2004; Akbarnia and Farhani, 2014).

3.6 Oxygen diffusion rate

The average amount of oxygen diffusion rate (ODR) for plowing with moldboard plow was 53.6×10^{-8} g cm^{-2} min^{-1}, which decreased with the change of tillage methods. These amounts in plowing with chisel plow by 21% decrease reached 42.5×10^{-8} g cm^{-2} min^{-1} and in plowing with heavy disk by 35% decrease reached 35×10^{-8} g cm^{-2} min^{-1} (Table 5). Oxygen transport in soils occurs mainly by diffusion, a process that depends upon physical characteristics of the soil such as texture, structure, porosity, and water content. These factors affect oxygen transport; organic matter acts positively on some of these physical factors, usually by increasing the aggregate stability and changing the pore size distribution of the soil. As mentioned, in this study (Table 5), due to the greater depth of plowing with moldboard plow, the values of soil specific gravity were lower and the amount of permeability was higher than the other two methods. Therefore, the higher amounts of oxygen diffusion rate (ODR) by moldboard plow can be due to the lower specific gravity of the soil in the plowing method with moldboard plow. However, the values of SOC for moldboard plow at shallow depths of soil (0 to 20 cm) were lower than other methods. Some other researchers also shows that the same results for negative effects of soil compaction and soil specific gravity on ODR (Neale et al., 2000; Hillel, 2003; Dexter, 2004; Ellies et al., 2005; Grosbellet et al., 2011; Hamamoto et al., 2012; Uteau et al., 2013).

3.7 Crop yields

Although the yield of the crop in the conventional tillage (moldboard plow) method was slightly higher than other methods, however, the yield of the crop in different tillage methods was not significantly different. Crop yield by the moldboard plow tillage were 5.45 tons ha^{-1}, while the heavy disk tillage and chisel plow methods were 5.23 tons ha^{-1} and 5.36 tons ha^{-1}, respectively. Comparing the moldboard plow, heavy disk tillage and chisel plow methods decreased wheat yield by 4% and 2%, respectively (Table 5). The distribution of organic carbon may be a factor in the yield increases seen in the moldboard plow tillage treatments and may be due to the placement of plant nutrients at a greater soil depth was more accessible to where plant roots growing.

4 Conclusion

The current research findings emphasized that by changing the type of plowing methods from lower tools or moldboard plow (conventional method), to lighter tools such as chisel plow or heavy disks and consequently lesser soil incorporation, we can save the soil bulk density and soil organic matter, and can harvest higher crop yields. Also, plowing with safer tools can significantly decreased power required and fuel consumption that increase farmers' income. The results also showed that the higher infiltration rate was recorded by chisel plow about 0.98 cm h$^{-1.}$ Organic carbon content for heavy disk (HD) method was higher than chisel plow and moldboard plow tillage by 12% and 26%, respectively. The best power required was obtained about 6.23 kN m^{-1} for heavy disk. The heavy disk was the best plowing methods to reduce the amount of required compared to other methos and decreased it by about 57% decrease. The most effective plowing method to save the oxygen diffusion rate was moldboard plow (53.6×10^{-8} g cm^{-2} min^{-1}). The higher crop yield was harvested by the moldboard plow tillage were 5.45 t ha^{-1}, while the rest with no significant differences reduced it. Therefore, it can be concluded that for both the power requirements and fuel consumption, and also the amount of crop yields per hectare using chisel plow and heavy disk was an effective alternative for the moldboard plow tillage on agricultural lands in Iran.

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