Catena 158 (2017) 413–420

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Assessment of implement efficiency and soil structure under different conventional tillage implements and soil moisture contents in a silty loam soil

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ARTICLE INFO

Keywords:
Soil structure
Implement efficiency
Moisture content
Plastic limit

ABSTRACT

Farmers' use of tillage implements under extremely dry soil conditions, ignoring optimum soil moisture conditions, results in low field efficiency, high fuel consumption and ultimately poor soil structure. Accordingly, the effect of tillage, applied under a range of near-plastic-limit soil moisture contents, on the efficiency of conventional tillage implements and subsequent soil structure, was investigated. Two conventional tillage systems: (i) moldboard plough followed by two cultivator passes and (ii) disk plough followed by two cultivator passes, were factorially combined with four soil moisture contents (θ) at tillage: dry soil, $\theta = 5.0\%$ w/w, and at 70, 80 and 90% of the moisture content at the soil's plastic limit ($0.7\theta_{\text{pl}}$, $0.8\theta_{\text{pl}}$ and $0.9\theta_{\text{pl}}$, respectively). The lowest field efficiency was observed under dry conditions, with a significant increase in efficiency at $0.7\theta_{\text{pl}}$, a further increase at $0.8\theta_{\text{pl}}$, and a subsequent decrease, compared to $0.7\theta_{\text{pl}}$ and $0.8\theta_{\text{pl}}$, at $0.9\theta_{\text{pl}}$. Similarly, fuel consumption was greatest under dry conditions, decreasing at $0.7\theta_{\text{pl}}$ and $0.8\theta_{\text{pl}}$, only to increase again at $0.9\theta_{\text{pl}}$. Overall, the lowest fuel consumption occurred at $0.8\theta_{\text{pl}}$. Under dry soil conditions the proportion of large aggregates ($>$ 8 mm) was the lowest and that of small aggregates ($<$ 0.5 mm) the greatest, whereas at $0.9\theta_{\text{pl}}$ the converse was the case. At $0.7\theta_{\text{pl}}$ and $0.8\theta_{\text{pl}}$, the proportions of large and small aggregates were low, while the proportion of desirable aggregates was greatest. At $0.8\theta_{\text{pl}}$ the proportion of medium aggregates was greater than that at $0.7\theta_{\text{pl}}$. Therefore, in terms of post-tillage soil structure $0.8\theta_{\text{pl}}$ was deemed the optimum θ for tillage of a silty loam soil. The aggregate stability of soil was higher under dry conditions and $0.7\theta_{\text{pl}}$, and lower at $0.8\theta_{\text{pl}}$ and $0.9\theta_{\text{pl}}$ under both moldboard and disk ploughing. A somewhat similar trend was observed under both conventional tillage implements; however, the disk plough followed by two cultivator passes offered a better performance in terms of field efficiency and soil properties than did the moldboard plough followed by two cultivator passes.

1. Introduction

Soil structure arising from tillage holds a vital, but often neglected role in sustainable food production. It is crucial for the germination and growth of crops (Pirmoradian et al., 2005), as well as modulating soil moisture content (θ) status, nutrient dynamics and soil tilth (Oades, 1984). Better soil structure corresponds to better soil tilth (Christopher and Mokhtaruddin, 1995).

Soil structure is strongly affected byθ (Keller et al., 2007). If the soil is too wet to be tilled, it will produce large clods, thereby damaging soil structure; likewise, if the soil is too dry to be tilled, a great deal of energy will be required to till the soil and large clods will also be produced (Dexter and Bird, 2001). In contrast, tilling soil under optimal soil conditions will not only minimize the required number of tillage operations, but also reduce the total energy input for a given tillage system (Keller et al., 2007). Nayanaka and Mapa (2014) demonstrated this by showing that soils tilled at θ levels exceeding the optimum, not only produced large clods, but also suffered structural damage. Therefore, knowing a soil's optimum θ for tillage is beneficial in managing power requirements during tillage and minimizing post-tillage damage to the soil's structure.

The optimum θ for tillage is defined as the θ at which tillage produces the greatest proportion of small aggregates and the lowest number of large aggregates (Dexter and Bird, 2001). The optimum θ for

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http://dx.doi.org/10.1016/j.catena.2017.07.017
Received 7 March 2017; Received in revised form 18 July 2017; Accepted 24 July 2017

tillage generally falls in the range of 70% to 90% of the plastic limit (θ_{pl}, i.e., the lower Atterberg or plastic limit) (Müller et al., 2003; Barzegar et al., 2004 and Keller et al., 2007), as friability reaches a maximum at θ values approaching but lower than the θ_{pl} (Watts and Dexter, 1998), namely the minimum θ at which soil can be crumbled (Lal and Shukla, 2004).

In contrast, farmers in developing countries, particularly Pakistan, apply tillage implements under extremely dry conditions without considering the optimum θ for tillage, thereby forming large clods and requiring excessive energy for tillage. Indeed, Sharma (2001) showed that dry soils were difficult to till, broke into hard large clods, and required excessive energy to do so. Cloddy soil tilth is unfavorable for crop production and affects seed emergence due to poor seed-soil contact.

While it is very important to apply tillage implements at the optimum θ for tillage, the knowledge of this optimum does not guarantee a specific fineness or cloddiness of the resulting soil structure (Dexter, 2004). Moreover, it is quite difficult to predict the field efficiency of tillage implements under varying soil conditions. To establish the optimum θ for tillage under different conventional tillage implements, the present study assessed conventional tillage implements' effects on in-tillage implement efficiency and post-tillage soil structure under different θ levels near the θ_{pl}.

2. Materials and methods

The study was conducted at the Latif Experimental Farm of Sindh Agricultural University, Tandojam, Pakistan. Under the two conventional tillage systems, soil was first ploughed to a depth of 0.25 m by either a moldboard plough or disk plough, then both received two passes of a cultivator to a depth of 0.15 m. The cultivation in both cases being identical, the tillage treatments are hereafter simply referred to as moldboard plough or disk plough. These tillage protocols were implemented at four θ levels: 5% w/w moisture content (dry conditions), and at 70, 80 and 90% of the θ at the soil's plastic limit ($0.7\theta_{pl}$, $0.8\theta_{pl}$, and $0.9\theta_{pl}$, respectively). The 5% θ was selected on the basis of pre-surveys, farmer interviews and soil sampling of various fields under cultivation at Tandojam.

The treatments were arranged in a randomized complete block design (RCBD) with three replications. The experimental field (48 m × 168 m) was divided into 24 plots (15 m × 20 m each). To achieve the desired θ, the plots were saturated and θ determined thrice a day after irrigation (Barzegar et al., 2004). Tillage was carried out when a plot's θ level reached the desired level, according to the particular θ treatment under study.

2.1. Physico-mechanical properties of soil

To determine pre-tillage soil moisture content, soil texture and organic matter, soil samples ($n = 288$) were procured at depths of 0–0.15 m, 0.16–0.30 m and 0.31–0.45 m from four randomly selected locations in each plot with the help of a soil auger. The samples were mixed to produce a composite soil sample for each plot and then stored in aluminum containers, labeled and brought to the laboratory. A core sampler was used to take a further similar set of soil samples for determination of dry bulk density. The θ and dry bulk density (ρ) were determined by the gravimetric method (Blake and Hartge, 1986). In addition, a further 288 undisturbed soil samples were taken using rings of 63 mm internal diameter and 25 mm height to determine soil shear strength properties. The plastic limit was determined as the θ at which the soil crumbled as it was rolled into a thread of 3 mm in diameter (Sowers, 1965).

Soil texture was determined by the Bouyoucos hydrometer method (Bouyoucos, 1927). In this method 50 g of oven-dry soil, sieved through a 2 mm sieve, was added to a dispersing cup bearing 400 mL of distilled water. After the addition of 100 mL of sodium hexametaphosphate solution (50 g L^{-1}), the overall volume in the cylinder was brought up to 1.0 L with distilled water. Readings were taken after 40 s and 2 h. The shear strength properties were determined using a direct shear box apparatus (Fredlund and Vanapalli, 2002) and the desired parameters calculated based on Coulomb's formula (Arora, 1988):

$$\tau_{\max} = C + \sigma_n \tan\varphi \tag{1}$$

where, $\tau_{\max}$ — is the shear resistance of soil at failure, C — is the apparent cohesion of soil, σ_n — is the total normal stress on the failure plane, and φ — is the angle of shearing resistance of soil (angle of internal friction).

The cone index (penetration resistance) was measured using a cone penetrometer (CN-973). Organic carbon content was determined using the Walkley and Black (1934) method: in a 500 mL flask, 10 mL of 1 N $K_2Cr_2O_7$ was added to 1 g of sieved soil, and the flask swirled. 20 mL of conc. H_2SO_4 was then rapidly added, and the flask swirled again for 1 min. The flask was allowed to stand on an insulating (asbestos) sheet for 30 min, after which deionised water (200 mL) was added to the flask, followed by three to four drops of o-phenanthroline indicator solution. Titration was conducted with a 0.5 M $Fe\,(NH_4)_2\,(SO_4)_2$ solution. The organic carbon content in the soil was then calculated as:

$$O.\,C\,(\%) = \frac{(B - S) \times N \times 0.003 \times 100}{Wt\ of\, soil\ in\ g\,(Oven\ dry)} \tag{2}$$

where: B is the volume of standard 0.5 N ferrous ammonium sulphate required to titrate the blank (mL), S is the volume of standard 0.5 N ferrous ammonium sulphate required to titrate the soil sample, and N is the normality of the std. ferrous ammonium sulphate solution (0.5 N). The organic carbon was then converted to soil organic matter content by multiplying by a factor of 1.72 (Mattingly, 1974). Table 1 shows the physical and mechanical properties of the experimental soil.

After tillage practices were imposed a further set of 288 soil samples were collected at depths of 0–0.15 m, 0.16–0.3 m and 0.31–0.45 m from four randomly selected locations (0.5 m^2 each) in each plot. The samples were mixed to produce a composite soil sample and were stored in aluminum containers, labeled and brought to the laboratory. The litter, rock fragments and surface crust were removed and the soil left to air dry at room temperature for 15 days. The air-dried soil samples were passed through a nest of sieves with apertures of 32, 25, 12.5, 8, 2, 1.2, 0.5, 0.25, 0.15, and 0.015 mm, respectively. The mass of

Table 1
Soil conditions, moisture content at plastic limit (θ_{pl}), moisture content under different soil conditions (θ), particle size distribution, textural class, dry bulk density (ρ), cohesion (C), internal friction angle (ϕ), cone index (CI) and organic matter (OM) content.

Soil condition	θ_{pl} (g hg^{-1})	θ (g hg^{-1})	Particle size distribution (g hg^{-1})			Textural class	ρ (Mg m^{-3})	C (kPa)	ϕ (°)	CI (MPa)	OM (g hg^{-1})
			Sand	Silt	Clay						
Dry	20.05	5	29.6	56.7	13.7	Silty loam	1.21	127.5	15.8	1.41	0.59
70% θ_{pl}		14	34.8	53.0	12.2	Silty loam	1.28	30.4	18.1	1.19	0.57
80% θ_{pl}		16	29.3	55.5	15.2	Silty loam	1.29	25.5	17.2	0.95	0.51
90% θ_{pl}		18	27.8	57.6	14.6	Silty loam	1.32	21.6	14.3	0.83	0.49