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Effect of integrated reservoir tillage for *in-situ* rainwater harvesting and other tillage practices on soil physical properties

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ABSTRACT

There is a need for *in-situ* soil moisture conservation in arid and semi-arid regions due to insufficient rainfall for agriculture. For this purpose, a combination implement [integrated reservoir tillage system (RT)] comprised of a single-row chisel plow, single-row spike tooth harrow, modified seeder, and spiked roller was developed and compared to the popular tillage practices, *viz.*, minimum tillage (MT) and conventional tillage (CT) in an arid Mediterranean environment in Egypt. The different tillage practices were conducted at tillage depths of 15, 20, and 25 cm and forward speeds of 0.69, 1, 1.25, and 1.53 m s^{-1}. Some soil physical properties, runoff, soil loss, water harvesting efficiency and yield of wheat were evaluated. The different tillage practices caused significant differences in soil physical properties as the RT increased soil infiltration, producing a rate of 48% and 65% higher than that obtained in MT and CT, respectively. The lowest values of runoff and soil loss were recorded under RT as 4.91 mm and 0.65 t ha^{-1}, whereas the highest values were recorded under CT as 11.36 mm and 1.66 t ha^{-1}, respectively. In conclusion, the RT enhanced the infiltration rate, increased water harvesting efficiency, reduced runoff and achieved the highest yield of wheat. The best tillage operating parameters appeared to be at a tillage depth of 20 cm and speed between 1.00 and 1.25 m s^{-1}.

1. Introduction

Water scarcity in arid and semi-arid regions due to low rainfall and uneven distribution throughout the season makes rainfed agriculture in such areas a precarious enterprise. In recent decades, there has been increased interest in the evaluation of traditional water management techniques (Prinz and Wolfer, 1999), such as rainwater harvesting for drylands agriculture, which aims to ease future water scarcity in many arid and semi-arid regions of the world.

Of the various methods of rainwater harvesting, "*in-situ*" systems are the simplest and cheapest approaches that can be practiced in many farming systems including those in arid and semi-arid regions. Also known as soil and water conservation systems, *in-situ* systems increase the amount of water stored in the soil profile by trapping or holding the rainwater where it falls (Stott et al., 2001), which eliminates the separation between the collection and storage areas. The *in-situ* systems may be close to micro-catchment techniques, but they provide an alternative in arid and semi-arid regions, where precipitation is low or infrequent during the dry season. Additionally, there is a need to store the maximum amount of rainwater during the wet season for use at a later time, especially for agricultural and domestic water supply (OAS, 1997). The common *in-situ* rainwater harvesting techniques in arid and semi-arid regions are mulching, deep tillage, contour farming and ridging (Hatibu and Mahoo, 1999).

Soils in the Mediterranean region typically have low organic matter content, which often entails weak structure. For this reason, conventional intensive tillage systems for rainfed crops often lead to soil quality deterioration (Hernanz et al., 2002). This increases the soil's potential for erosion and also induces carbon loss, which weakens the soil's production capacity and stability. These concerns gave rise to the invention of conservation tillage practices that improve physical and biological soil properties.

Conservation tillage has several positive effects on water productivity (Rockstrom et al., 2001) compared to traditional soil and water conservation systems. Besides enhancing infiltration and soil moisture storage (Kahlon et al., 2013; Liu et al., 2013),

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it reduces runoff which is then available for plant uptake during dry periods. The main limitation in stabilizing grain yields in rainfed farming systems is crop water stress caused by inefficient use of total available seasonal rainwater (McHugh et al., 2007). Therefore, technologies that use rainwater more efficiently are needed.

An alternative method to *in-situ* rainwater harvesting and conservation tillage is reservoir tillage, which has been defined as a system in which numerous small surface depressions are formed to collect and hold water during rainfall or irrigation to prevent surface runoff (Hackwell et al., 1991; Rochester et al., 1994; Patrick et al., 2007; Salem et al., 2014). This approach was developed under the consideration that tillage can provide increased levels of surface storage and may represent one of the most effective means of controlling both runoff and soil erosion. A large body of research has been conducted on reservoir tillage with variations in equipment and terminology including: basin tillage, micro-basin tillage, furrows diking, furrow blocking, soil pitting, and tied-ridging (Hackwell et al., 1991; Wiyo et al., 2000; Brhane et al., 2006; Nuti et al., 2009).

This study used Egypt as the focus region because it lies in the heart of the water scarcity problem. Egypt's rainfed agriculture is mainly concentrated in the north-western coastal zone, which extends approximately 500 km from the western city of El-Saloum on the border with Libya, to Alexandria in the east. It is bounded by the Mediterranean Sea on the north and the Sahara Desert, about 60 km on the south.

Water is particularly important in this region, as it is inhabited by an indigenous Bedouin population, 85% of which lives off of an extensive dryland production system, where barley and wheat are the main crops. Human settlements and land use are entirely dependent on rainfall and on various forms of water harvesting (Mamdouh, 1999) to increase the efficiency of runoff water use for human and animal consumption and cultivation and to minimize soil erosion.

The area's geography and hydrology are ideal for effective use of water harvesting systems. In this region, soil water management techniques must retain the maximum possible rainfall by methods that reduce storm-water runoff, improve infiltration and boost the water storage capacity of the soil. The system must also be cost effective for acceptance by the farmers.

Currently, most farmers in the northwestern coastal zone of Egypt still utilize old-fashioned crop production systems. Some farmers have switched to mechanization systems, but these systems have resulted in several problems. Some of the most common problems include added costs related to buying or renting agricultural machines, difficulties in using and maintaining these machines, crumbling of cultivated land, and the necessity for multiple machines to fulfill all agricultural processes. This last problem has been the most decisive, as farmers have often been unable to obtain all of the necessary machinery. Additionally, some farmers who own tractors as sources of power still even broadcast seeds because the region only receives rainfall during a short period of time, and so the farmers must utilize the little moisture available before it dries out.

These problems indicate a need to design integrated technologies to increase agricultural water use efficiency through rainwater harvesting while conserving the soil in rainfed areas. Researchers in this region recognized the need to develop an alternative system that was energy, water and labor efficient that could also help sustain soil and environmental quality and produce more at a lower cost. Specifically, there has been a need to produce a combination implement (integrated reservoir tillage system) to simultaneously perform multiple processes including tilling and planting in order to decrease the number of machines traveling on soil surface, which mitigates soil compaction problems (El-Saied, 2000; Rohit and Hifjur, 2006), and consequently increases crop yields, and lowers the total cost for mechanization processes by decreasing fuel consumption, labor, maintenance cost and the cost of owning or renting machines (Tuhtaku-Ziev and Utepbergenov, 2002; D'aene et al., 2008).

The long-term effects of conservation tillage have been well documented; however less information is available regarding the immediate effects, particularly when switching to conservation tillage from conventional tillage in such soil conditions, limited crop root development due to compaction and poor water infiltration are the major initial obstacles (Chen et al., 2005). The long-term benefit from conservation tillage cannot be achieved easily, unless producers see that the system works in a short term (Chen et al., 2005). This is a very important topic from an agronomic point of view where the adoption of conservation tillage particularly no-tillage has led to difficulties in soil workability, forcing farmers to switch to other systems (López-Garrido et al., 2014). In these cases it would be desirable that farmers initially opt for other alternatives of conservation tillage that are different from no-tillage, such as reservoir tillage (Salem et al., 2015).

There is limited documentation on the immediate effects of reservoir and minimum tillage practices compared to conventional tillage on soil conditions in the north-western coastal zone of Egypt. In this region farmers frequently only consider traditional tillage with soil inversion to avoid compaction and eliminate weeds. However, less aggressive tillage practices, such as reservoir tillage and minimum tillage, could solve the problem and increase agricultural water use efficiency through rainwater harvesting without losing the advantages of conservation agriculture. Therefore, the objectives of this work were: (i) to develop and manufacture a combination implement suitable for conserving rainwater *in-situ* within the root-zone using a reservoir tillage tool and mechanical seeding; (ii) to increase soil moisture storage, reduce runoff, and improve infiltration of harvested water through reservoir tillage; (iii) to optimize various operating parameters that affect the performance of tillage practices; and (iv) to compare the influence of the combination implement and other popular tillage practices on soil physical properties, water harvesting efficiency, and yield of wheat.

2. Materials and methods

2.1. Site description and meteorological conditions

Field experiments were carried out in Wadi Madwar located at the El-Qasr region, which lies approximately 10 km Southwest of the Marsa Matruh city and 3 km from the Mediterranean sea in Egypt's northwestern coastal zone (latitude: 31°21′08″N, longitude: 28°08′40″E, and an altitude of 30 m above sea level). The location of the study area is presented in Fig. 1. The soils of Wadi Madwar are mainly sandy loam in texture, and the average slope is between 4 and 6% in South–North direction. The climatic conditions from the Marsa Matruh meteorological station (latitude 31°20′N, longitude: 27°13′E, and an altitude of 28 m above sea level) were used to determine the meteorological data of the study area. The arid Mediterranean climatic conditions are characterized as short rainy seasons during October–March; about 85% of the total annual rainfall is recorded between December and February. During the growing season of wheat (2012–2013), the average temperature, relative humidity and total precipitation were 15 °C, 64.2% and 161.2 mm, respectively.

2.2. Combination implement [integrated reservoir tillage system (RT)]

The combination implement (Figs. 2 and 3), used in this study was manufactured from local materials to overcome the problems associated to the imported machines like cost and power