Residual plastic mulch fragments effects on soil physical properties and water flow behavior in the Minqin Oasis, northwestern China

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\textbf{ABSTRACT}

The covering of complete plastic films on soil would affect physical and biochemical properties of the soil microenvironment. Residual plastic film fragments (RPFF), which is left behind after retrieving the most of plastic films, could affect the flow behavior in the arable layer. This study was designed to assess the potential effects of RPFF on soil physical properties, water infiltration and distribution in the soil. Treatments with and without residual plastic film fragments (RPFF and NRPF, respectively) were performed. A dye tracer was introduced to track the water movement, and the physical properties of the soil and the dynamic behavior of water transport in the soil column of the arable layer (0–20 cm) were determined. The initial gravimetric water content, bulk density, total porosity in 0–20 cm was significantly different between RPFF and NRPF treatment. The dark blue area in maize root and densely rooted zones under RPFF decreased by 99% and 4%, respectively, relative to that under NRPF. The sharply changing state of infiltration and outflow indicated that water flowed along a preferential path, e.g., macro-pores in NRPF and residual plastic film pieces in RPFF. After clearing the RPFF, the time of equilibrium in 0–5, 5–10, 10–15, and 15–20 cm soil columns decreased by 48%, 50%, 49%, and 45%, respectively. Our results highlighted that the presence of RPFF significantly influenced soil physical properties, altered soil water distribution, and decreased the matching degree of the flow distribution region and the maize root (densely rooted) zone. The present study demonstrated that the importance of clearing the RPFF for irrigation water management in agriculture produces.

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1. Introduction

Low temperature at seeding stage as well as insufficient precipitation and high evaporation during growth period affect the growth, development, and yield of crops in arid and semiarid regions (Beltrano et al., 1999; Boyer and Westgate, 2004). These issues have been intensified by global climate change (Zhao et al., 2014) and global population increase (Lisson et al., 2016). According to the prediction of FAO (2009), the world population would increase from 6.8 billion in 2010 to over 9.1 billion by 2050, with an expected increase in food demand of 70%. This presents a major challenge for agricultural production, especially in areas where crop production is likely to be adversely affected by unreasonable agricultural management practices.

Numerous management strategies have been adopted to solve these issues over the past decades. Recently, plastic film fully mulched ridge-furrow system has been widely adopted to significantly improve grain yield in regions where irrigation is unavailable (Gan et al., 2013); in this system, narrow ridges are alternated with wide ridges, and mulching is completed with plastic films with furrow planting (Zhao et al., 2012). Studies have shown that plastic film fully mulched ridge-furrow system exhibits several advantages. This system has reduced harvest time by up to nine days (Andrew et al., 1976) and has almost doubled grain yield (Hopen, 1965) as a result of the improved physical and biochemical properties of the soil microenvironment. This system increases the water content and temperature of the soil (Chakraborty et al., 2008; Cook et al., 2006), stabilizes the topsoil (De Silva and Cook, 2003), decreases evaporation and weed competition (Li et al., 2013a), and reduces soil compaction and erosion, enhances soil water infiltration (Gan et al., 2013), activates soil nutrients (Li et al., 2004a), collects rainwater and improves its use efficiency (Jiang and Li, 2015; Liu et al., 2016). The system also increases the water

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stability of macro-aggregates and volume of macropores (Zhang et al., 2013a); seed fertility and individual plant growth (Zhou et al., 2009); and root and shoot biomass. Moreover, the plastic film fully mulched ridge-furrow system exerts direct or indirect effects on the biochemical properties of the soil. For instance, this system alleviates the decline of soil organic carbon (Zhang et al., 2013b), increases N mineralization (Ghosh et al., 2006), reduces leaching of N fertilizers (Romic et al., 2003), improves plant nitrogen availability (Wang et al., 2015), and promotes microbial biomass C but decreases soil organic C (Li et al., 2004b). However, the disadvantages of plastic film fully mulched ridge-furrow system have attracted the attention of researchers and farmers. Grain yield decreases because of changes in the microclimate, including consistently increasing temperatures (Hou et al., 2010; Wang et al., 2009), poor soil aeration resulting from high CO₂ concentrations (Tiquia et al., 2002), excessive N mineralization (Ghosh et al., 2006), depletion of soil organic carbon (Liu et al., 2013), increased emission of two major greenhouse gases (N₂O and CH₄) (Cuello et al., 2015), accelerated decomposition of soil organic matter, and deterioration of the soil structure (Zhang et al., 2013b). Researchers and farmers have made efforts to overcome these negative factors. Overall, the benefits of mulching outweigh its disadvantages; therefore, the plastic film fully mulched ridge-furrow system has been widely applied and promoted in the arid and semiarid zones of China. For instance, the area where the plastic film fully mulched ridge-furrow system was applied reached 193 × 10⁴ ha in 2008 in Gansu Province; this area occupies about 7% of the total cropland and contributes to 20% of the total grain production (Wang et al., 2009).

However, after one or few seasons, the residual plastic fragments become problematic when the plastic films must be replaced by new ones. Soils are heavily contaminated with these films which were disposed by farmers through on-site land filling and burning (Gonzalez-Sanchez et al., 2014). This negative effect on soil will last for many years because plastic film fragments cannot decompose biologically. Moreover, plastic film fragments are discarded and buried in the arable layer. The loose characteristic of soil in this layer could lead to matrix flow. Other flow types resulting from heterogeneous structures also appear in the arable layer, including macropore flow caused by preferential paths (e.g., cracks, plant roots, worm holes, and voids between peds) (Beven and Germann, 1982) and lateral flow induced by inclined hydraulically restrictive layers, such as bedrocks (Allaire et al., 2009) and tillage pans (Jiang et al., 2015). RPPF that random appeared in the soil could not only interrupt the soil structure but also serve as a water-resistant layer or an inclined hydraulically restrictive layer. The random characteristic of RPPF induced water to either bypass the water-resistant layer or follow the laterally hydraulically restrictive layer. Thus RPPF could affect the flow behavior in the same layer. The proposed physical process and the significance of residual plastic films to soil water distribution have not been experimentally reported in the literature, although many studies have focused on the relationship between plants, soil and plastic film mulching. Therefore, in the present study a traditional method involving a dye tracer was performed on two soil plots with different management practices. This study aims to assess the effect of residual plastic film fragments on the water distribution and flow processes in the soil.

2. Materials and methods

2.1. Experimental site

Minqin Oasis, is located in the arid inland of Northwest China, whose agricultural production accounts for 80% of the gross regional domestic product (Feng et al., 2011) and 76% of its population is engaged in agricultural production (Statistical Bureau of Minqin County, 2009). From 2005 to 2010, the farmland area of the Minqin Oasis has shrunken by 12.89 km². The study area was located on Xuebai Farm in the Minqin county of Gansu Province, China (between 101°49′–104°12′E and 38°03′–39°28′N). The east, west, and north sides of Minqin County are surrounded by the Tengger Desert and Badain Jaran Desert. The area has an arid continental climate with an average annual temperature of 7.8 °C. The mean precipitation in the area is 110.5 mm yr⁻¹, and the annual average evaporation is 2 646.4 mm yr⁻¹. The soil under study was classified as “irrigated desert soil” in accordance with the Chinese Soil Classification System (Gansu Provincial Soil Survey Office, 1992) and similar to Anthropic Camborthids according to Soil Taxonomy (Soil Survey Staff, 1998).

2.2. Experimental design

2.2.1. Dye tracing

The plastic film fully mulched ridge-furrow system was applied to plant corn and sunflower by local farmers (Fig. 1A). The entire land surface was tightly covered with polyethylene film (colorless and transparent, 0.008 mm thick and 1200 mm wide) to collect rainwater and prevent heat and water loss and the perforations (around 1 cm in diameter, 30 cm apart, matches the plant spacing of 30 cm in a row) were drilled through the film by using a handheld device during sowing time. Simultaneously, we found lots of residual plastic film fragments left in the plough layer (Fig. 1B).

Given the spatial heterogeneity, two contacting fields (10 m × 20 m) were chosen as research fields. In each research field, 0.8 kg polyethylene film was used to cover soil during sowing; the crops for these two fields were alternated in a maize-wheat rotation from 2000 to 2015. From 2012 to 2015, these two fields exhibited several common agricultural management practices after harvesting. The large pieces of polyethylene films (about 0.5 kg in one field) were cleared and removed and the small pieces of polyethylene films (about 0.3 kg were left behind in one field) were randomly broken into fragments with different sizes when the arable layer (0–20 cm) of research fields was plowed using a rotary cultivator. The difference in agricultural practice was that the residual plastic film fragments in the first field were retained, whereas those in the second field were picked and cleared during plowing. Agricultural practices (e.g., irrigation, plowing, sowing) conducted on the two fields before harvesting in the second year was expected to reduce the effect of the picking and cleaning process on soil. Generally, besides the picking and cleaning process of residual plastic film fragments in the second field, other agricultural practices were conducted in the two fields. Namely the two treatments in this study were residual plastic film fragments (RPPF) and no residual plastic film fragments (NRPF).

Notice that the experiments were conducted from October 6th to 15th, 2015 before the maize was harvested. Three plots were randomly selected as replicates in each field. The dye-stained test plots were prepared by carefully removing the polyethylene film and a thin layer of the soil (less than 2 cm) to ensure a levelled horizontal surface. Each replicate plot was surrounded by a PVC quadrant (height = 0.3 m, diameter = 0.25 m). The bottom edges of the PVC quadrats with water-tight sidewalls and edges were inserted 0.05 m into the soil. All eight plots were irrigated with 4.1 L of water dye solution containing 3.0 g L⁻¹ Brilliant Blue FCF (Flury and Flühler, 1995). The infiltrated area was covered with a vinyl film to prevent evaporation and dilution by rainfall (Jiang et al., 2012) between the end of the infiltration and the beginning of excavation. The eight dye-stained soil vertical sections of 40 cm
(length) × 35 cm (width) were carefully excavated from the center of the ring by using a spatula (Weiler and Flühler, 2004) 24.0 h after the infiltration. The calibrated frames for soil vertical sections were placed in the soil profile to assist subsequent image correction. The entire pit area was placed beneath a black umbrella to provide soft light conditions. All soil sections were photographed using a digital camera (Canon EOS Rebel T3, Japan) under daylight conditions. The distance from the camera to the center of the vertical sections was 25 cm, whereas that to the lower boundary of the soil sections was 20 cm. Six dye-stained soil vertical sections were photographed. Five dye calibration patches were prepared and photographed for the soil horizons in our previous study to define the concentration categories for dye-stained soil regions (Jiang et al., 2015).

Image processing was conducted using ERDAS IMAGINE version 9.0 (Jiang et al., 2015), following the procedures developed by Forrer et al. (2000) and described in detail by Cey and Rudolph (2009). Images were developed with the following procedure: geometric correction, background subtraction, color adjustment, histogram stretching, dye classification, and final visual checking. The resulting images were grouped into dyed and non-dyed regions, with the dyed regions further divided into three relative classes based on the intensity of dye staining. Dye-stained soil calibration patches were used to determine the concentration categories for the three dye-stained soil classes (0.05–0.5, 0.5–2.0, and >2.0 g L−1). The maximum dye-stained depth (cm) and width (cm) in the soil vertical sections was measured using a tapeline when photographing. To elucidate the effect of water infiltration and distribution on maize growth, we assumed that the maize root (and densely rooted) zone (fan-shaped, below the surface) on the soil section had a radius of 10 (and 5) cm, with the location of seed placement (5 cm in depth) as the center. Under this premise, the areas (cm²) of the different concentration categories (light, dark blue) in the maize root (and densely rooted) zone of each photographed soil vertical section were estimated (Jiang et al., 2012). Applying these two parameters, we intended to illustrate the effect of residual plastic film fragments on water distribution.

2.2.2. Water infiltration and outflow of soil column

After the dye tracer infiltration twelve undisturbed soil columns of the arable layer (prepared at the interval of 5 cm from the surface to 20 cm soil depth, three replicates in each soil layer) were extracted from each plot by using cutting rings (inner diameter = 50.46 mm, height = 50 mm). These twelve undisturbed soil columns were used to measure the soil physical properties (e.g., gravimetric water content, soil bulk density, total porosity, and saturated hydraulic conductivity). The procedures of obtaining bulk soil samples and determining soil physical properties in NRPFF were following the methods described by Chen (2005). It is worth noting that when the bulk soil samples in RPFF were obtained, the attached plastic film was cut off from the samples by a sharp scraper. According to the abovementioned method, another twelve undisturbed soil columns of the arable layer were obtained and then the columns were used to measure the infiltration and outflow of water from falling head (height = 50 mm) and constant head (height = 50 mm) permeameter measurement. This measurement was also used to measure the saturated hydraulic conductivity. A simple apparatus was designed for this experiment. The top cover of the cutting ring (containing the soil column) was removed and replaced by a circular wire mesh (diameter = 50.46 mm). A hollow cutting ring was spliced on the top of the cutting ring that contained the soil column and poured with distilled water. A burette was used to ensure that the water level was as high as the height of the cutting ring, and a filter cup was placed on the bottom of the cutting ring containing the soil column to collect the outflow. The volume of infiltration and outflow was recorded using a burette and a measuring cylinder, respectively, for every 2.0 min until steady-state conditions were reached. In this experiment, infiltration refers to the flow of water into a soil section, outflow refers to the water flow out of the soil section, and permeation means water flow through a soil column. The rate of infiltration and outflow was calculated using the following formula:

\[ V = \frac{Q}{T} \]
where $V$ is the rate of infiltration and outflow (mm min$^{-1}$), $Q$ is the volume of infiltration and outflow (mm$^3$), $T$ is the time interval (min), and $S$ is the area of soil section (mm$^2$).

### 2.3. Statistical analysis

One-way analysis of variance (ANOVA) was used to assess the effect of different treatments on the dyed parameters (e.g., maximum dye-stained depth and area of each concentration category), as well as the measured soil physical properties based on the average values of three replicates. Significant differences between means were detected using the least significant difference (LSD) at $P < 0.05$. All statistical procedures were performed in SPSS 17.0.

### 3. Results

#### 3.1. Soil physical properties

Soil physical properties that could determine soil water flow and distribution were more affected by RPFF compared with that by NRPFF from two perspectives (Table 1). First, the emergence of RPFF in the same soil layer significantly changed soil physical properties at different depths. Under RPFF, the initial soil water content (%) in 5–10 and 15–20 cm columns, bulk density (g cm$^{-3}$) in 10–20 cm column, and saturated hydraulic conductivity (10$^{-3}$ cm s$^{-1}$) in 5–10 cm column were significantly decreased, whereas total porosity (%) in 10–20 cm column significantly induced compared with those under NRPFF. Second, as observed from the same soil section, the RPFF in the soil resulted in physical properties (except saturated hydraulic conductivity) sharing the same change tendency from the soil surface to the 20.0 cm column. For instance, the soil bulk density consistently increased from 1.36 g cm$^{-3}$ at the soil surface to 1.66 g cm$^{-3}$ at 20.0 cm depth in the column, whereas the total porosity (%) consistently decreased from 48.55% on the soil surface to 37.11% in 20.0 cm column in the RPFF plots. In summary, the initial gravimetric water content, bulk density, total porosity in 0–20 cm was significantly different between RPFF and NRPFF treatment. Higher CV (coefficient of variation) indicated that these parameters largely varied under RPFF treatment because the residual plastic film fragments were randomly distributed in the soil.

#### 3.2. Flow distribution patterns

The water flow paths and distributions were directly interpreted from the six classified vertical dye-stained patterns of 30.0 cm (length) × 25.0 cm (depth) (Fig. 2). The corresponding stain characteristics (e.g., maximum dye-stained depths, widths, and areas) are summarized in Table 2. The dark blue areas, light blue areas, and green areas were heavily, slightly, and very slightly stained with Brilliant Blue FCF dye, respectively.

The appearance of preferential flow was induced by RPFF in the plough layer; thus, the number, distribution characters and connectivity of preferential flow paths were directly illustrated from the three vertical soil sections. In a similar soil section of RPFF, the dye stained patterns had more or less difference between any two tests. The dye was less uniformly distributed, as evidenced by an unstained fraction within the staining area. Moreover, the dark blue regions were broken up into separated and isolated patches. The RPFF in the soil appeared randomly and destroyed the soil structure. As a water-resistant layer, the RPFF in the soil would obstruct the initial orientation of water flow; simultaneously, if the RPFF in the soil served as an inclined hydraulically restrictive layer, it would induce the appearance of lateral flow. This random characteristic caused the water to either bypass the water-resistant layer or follow the inclined hydraulically restrictive layer. These basic postulated flow phenomena caused the matching area of the flow distribution region and maize root (densely rooted) zone to shrink abruptly. After removing the RPFF, the soil structure was restored to its loose and macropore-rich characteristic. Therefore, matrix flow was the dominant flow type in the NRPFF plot. Furthermore, the matching degree of the flow distribution region and the maize root (densely rooted) zone was improved.

The maximum dye-stained depths between RPFF and NRPFF were not significantly different. However, maximum dye-stained widths significantly differed between RPFF and NRPFF treatments; in particular, the entire stained area was significantly less in RPFF-treated (271.54 cm$^2$) than that in NRPFF-treated soil (368.15 cm$^2$) (Table 2). The removal of the residual plastic film not only significantly decreased the green and light blue areas but also significantly increased the dark blue area. For instance, the light blue area decreased by 24%, and the dark blue area increased by 101% under NRPFF compared with those under RPFF treatment. Maize root distribution range increased from the maize densely rooted zone to the maize root zone along with maize growth.

### Table 1

Soil physical properties (mean ± SE, $n = 3$) of the two sites.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Treatments</th>
<th>Initial gravimetric water content</th>
<th>Bulk density</th>
<th>Total porosity</th>
<th>Saturated hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Value (%)</td>
<td>CV (%)</td>
<td>Value (%)</td>
<td>CV (%)</td>
</tr>
<tr>
<td>0–5</td>
<td>RPFF</td>
<td>(7.66 ± 0.08)a</td>
<td>1.84</td>
<td>(1.41 ± 0.06)a</td>
<td>7.79</td>
</tr>
<tr>
<td></td>
<td>NRPFF</td>
<td>(8.03 ± 0.01)a</td>
<td>0.26</td>
<td>(1.36 ± 0.01)a</td>
<td>1.12</td>
</tr>
<tr>
<td>5–10</td>
<td>RPFF</td>
<td>(8.51 ± 0.07)b</td>
<td>1.35</td>
<td>(1.37 ± 0.06)a</td>
<td>6.96</td>
</tr>
<tr>
<td></td>
<td>NRPFF</td>
<td>(8.75 ± 0.01)a</td>
<td>0.23</td>
<td>(1.41 ± 0.01)a</td>
<td>1.78</td>
</tr>
<tr>
<td>10–15</td>
<td>RPFF</td>
<td>(8.99 ± 0.07)a</td>
<td>1.41</td>
<td>(1.42 ± 0.05)b</td>
<td>6.68</td>
</tr>
<tr>
<td></td>
<td>NRPFF</td>
<td>(9.15 ± 0.02)a</td>
<td>0.29</td>
<td>(1.60 ± 0.01)a</td>
<td>0.95</td>
</tr>
<tr>
<td>15–20</td>
<td>RPFF</td>
<td>(7.43 ± 0.07)b</td>
<td>1.63</td>
<td>(1.45 ± 0.05)b</td>
<td>6.23</td>
</tr>
<tr>
<td></td>
<td>NRPFF</td>
<td>(9.62 ± 0.01)a</td>
<td>0.10</td>
<td>(1.66 ± 0.01)a</td>
<td>0.92</td>
</tr>
<tr>
<td>0–20</td>
<td>RPFF</td>
<td>(8.23 ± 0.07)b</td>
<td>1.55</td>
<td>(1.41 ± 0.03)b</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>NRPFF</td>
<td>(8.89 ± 0.01)a</td>
<td>0.26</td>
<td>(1.51 ± 0.00)a</td>
<td>0.34</td>
</tr>
</tbody>
</table>

CV, coefficient of variation.

RPFF, residual plastic film fragments. NRPFF, no residual plastic film fragments.

Small letters a and b within a column of the same depth indicate significant difference at the 0.05 level.
Fig. 2. Flow distribution patterns in the vertical soil sections of plough layer as visualized by Brilliant Blue FCF dye-tracing under two different treatments 24.0 h after the infiltration of dye tracer. RPFF, residual plastic film fragments; NRPFF, no residual plastic film fragments. Three profile sections in each sample plot are shown by tests 1, 2, and 3. As water infiltrated the soil, flow paths were stained with different concentrations of Brilliant Blue FCF dye. The dark blue areas, light blue areas, and green areas were heavily, slightly, and very slightly stained with Brilliant Blue FCF dye; the associated concentration was >2.0, 0.5–2.0, and 0.05–0.5 g L−1, respectively. The maize root (and densely rooted) zone was encircled in each of the six pictures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>LBA (cm²)</th>
<th>DBA (cm²)</th>
<th>GA (cm²)</th>
<th>ESA (cm²)</th>
<th>Area of LBA in MRZ (cm²)</th>
<th>Area of LBA in MDRZ (cm²)</th>
<th>Area of DBA in MRZ (cm²)</th>
<th>Area of DBA in MDRZ (cm²)</th>
<th>MDS (cm)</th>
<th>MDSW (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPFF</td>
<td>(94.38 ± 1.09)</td>
<td>(120.32 ± 2.97)</td>
<td>(56.84 ± 2.32)</td>
<td>(271.54 ± 2.13)</td>
<td>(78.05 ± 0.90)</td>
<td>(42.13 ± 0.50)</td>
<td>(115.51 ± 2.86)</td>
<td>(56.61 ± 3.11)</td>
<td>(18.89 ± 0.45)</td>
<td>(21.28 ± 0.40)</td>
</tr>
<tr>
<td>NRPFF</td>
<td>(76.28 ± 2.45)</td>
<td>(241.95 ± 1.28)</td>
<td>(49.93 ± 1.33)</td>
<td>(368.15 ± 4.59)</td>
<td>(35.85 ± 1.15)</td>
<td>(3.34 ± 0.70)</td>
<td>(229.85 ± 1.22)</td>
<td>(58.66 ± 0.26)</td>
<td>(18.19 ± 0.26)</td>
<td>(26.80 ± 0.11)</td>
</tr>
</tbody>
</table>

RPFF, residual plastic film fragments. NRPFF, no residual plastic film fragments. Small letters a, b, and c within a column indicate a significant difference at the 0.05 level.
LBA, light blue area; DBA, dark blue area; GA, green area; ESA, entire stained area; MRZ, maize root zone; MDRZ, maize densely rooted zone; MDS, maximum dye-stained depth; MDSW, maximum dye-stained width.

Therefore, the matching degree of water distribution range and maize root distribution region was important for maize growth and development. The light blue area in the maize root and the densely rooted zone decreased by 54% and 92%, respectively, whereas the dark blue area increased by 99% and 4%, respectively, under NRPFF compared with those under RPFF.

3.3. Dynamic behavior of water transport

Dye tracer in the field could track water distribution in the soil. Experiments on water infiltration and outflow of soil columns were conducted on each column in the laboratory to characterize the dynamic behavior of water transport. Fig. 3 shows the common features between NRPFF and RPFF involving infiltration and outflow trend in soil columns. First, infiltration rates decreased rapidly as classical theory predicted. Second, water started to drain from the columns soon after the start of infiltration (16–20 min in NRPFF and 22–34 min in RPFF). The sharply changing stages of infiltration and outflow indicated that the water flow along a preferential path, e.g., macropore in NRPFF and fragments in RPFF. The steady state of infiltration and outflow implied that the water exchanged between the preferential path and the soil matrix arrived at a stable or equilibrium condition when the soil columns were saturated by water. Third, the outflow rate from the column remained smaller than the measured infiltration rate most of the time during the measurement period. Furthermore, the outflow rates measured from the columns in NRPFF and RPFF increased slowly with time and exhibited fluctuations before the emergence of equilibrium flow. The fluctuation indicated that the exchange of water between macropore and soil matrix, slowly faded when the equilibrium flow arrived.

Several differences between NRPFF and RPFF were also observed from the infiltration and outflow rate in the columns. The fluctuations before the steady state under NRPFF exhibited a smaller range and shorter time compared with RPFF (Table 3). In addition, the time of outflow in 0–5, 5–10, 10–15, and 15–20 cm soil
column under NRPF decreased by 18%, 38%, 47%, and 41%, respectively, relative to that under RPFF (Table 3). After clearing the RPFF, the time of equilibrium in 0–5, 5–10, 10–15, and 15–20 cm soil columns decreased by 48%, 50%, 49%, and 45%, respectively (Table 3).

4. Discussion

This study implied that the presence of RPFF in soil caused differing soil physical properties and water flow phenomena, which confirmed the results of previous reports from other places of China. Although different places exhibited different soil texture, the effect of residual plastic film on soil shared some common features. As early as 1992, in research conducted in Changji City of Xinjiang, China, Wen et al. (1992) found that residual plastic film mulch affected soil physical properties by reducing soil bulk density and increasing soil porosity. Results from potted plant simulations and field experiments in Shanxi province also showed that residual plastic film fragments not only increased soil bulk density but also reduced the velocity of soil water flow (Xie et al., 2007). A result from Inner Mongolia (Li et al., 2013b) reported that RPFF changed the path of water transport, reduced the rate of infiltration, and increased both transport velocity and distance of wetted volume. Besides, in Qinyang City of Gansu, China, Zhang et al. (2014) reported that the gravitational movement of water was blocked when soil pore continuity was altered or cut off by the residual plastic film fragments. In the present study, the residual plastic film fragments in the soil enlarged the CV of soil physical properties (gravimetric water content, soil bulk density, total porosity, and saturated hydraulic conductivity) and induced the emergence of heterogeneous water infiltration in the soil column. More important, the residual plastic film fragments not only reduced the dye-stained region but also remarkably decreased the matching degree of water distribution region and maize root (densely rooted) zone. The unevenly distributed dye-stained patterns in the present study were equivalent to the wetted volume in other studies. We noticed that the distribution of the wetted volume in the vertical directions was much larger in the NRPF treatments than in RPFF treatments. The wetted front was uneven and irregular, and the size of the wetted volume was reduced because some water bypassed the border of the RPFF and redistributed in the soil; the extent of unevenness and irregularity increased along with the amount of RPFF. In addition, soil water content was affected by the water distribution, namely the vertical downward flow which was affected by the residual plastic film caused water to spread unevenly across the vertical soil section. Such flow characteristics became more complicated, although the location of RPFF and the contact extent of RPFF and soil were difficult to confirm. It is worth noting that the water unevenly distributed in the wetted volume and water content exhibited different values. This result disagreed with the finding of Li et al. (2013b). Their results showed that there was no difference of water content inside the wetted volume. Thus we concluded that the greater the amount of residual plastic film fragments, the lesser was the rate and amount of infiltration into soil. Such predicament would be worse for crops with fibrous root systems. This finding implied that a preferred irrigation strategy should consider root development status and distribution characteristics, i.e., taproots...
or fibrous roots. The taproot system of cotton can reach deep soil layers to absorb water and nutrients by penetrating or bypassing the residual film plastic mulch fragments. However, the fibrous roots of wheat and corn could only be distributed to shallow parts of the soil where residual film plastic mulch fragments are left. The production and the planted survival rate were much lower for undeveloped root species than for developed root species when field soil was contaminated with RPFF, although they belonged to one species of cotton. The water exchange between the preferential path and the soil matrix was an important water flow phenomenon in soil (Cey and Rudolph, 2009). In the present study, water was supplied by a constant head permeameter. As long as water infiltrated into soil matrix (matrix flow) and part of water migrated in the preferential flow path (macropore flow), there would be water exchange between the preferential path and the soil matrix. The outflow water was the water that was transported in preferential flow paths while bypassing the soil matrix. Some water infiltrated from those preferential paths into the soil matrix before the soil column was saturated. Thus, the outflow rate remained smaller than the infiltration rate during the measurement period. Water exchange would reach an equilibrium condition when the soil column was saturated, thus the outflow rate equal to the infiltrated rate. Besides, we speculated that different preferential paths (macropores in NRPPF and residual plastic film pieces in RPFF) were responsible for the temporal fluctuations of water infiltration and outflow. Water transport in soil under RPFF exhibited the more dominant temporarily heterogeneous flow behavior, which could affect the exchange of water and nutrient elements between preferential flow path and soil matrix. For instance, RPFF destroyed the path for migrating water and nutrients and reduced the water and nutrients use efficiency, ultimately affecting the crop growth. One problem that involves the methodology used in the study is that the process of cleaning the plastic fragments in NRPPF could disturb the soil sample and create some voids within the soil profile and further increase the void ratio and macropores in the soil, however this negative effect was restrained to the lowest degree by some agriculture practices (e.g., irrigation, plowing, sowing). Another insufficiency was that the cutting ring was not big enough to obtain the precise mass and volume of plastic fragments, so that the mass and volume of plastic fragments was not measured. Our future work will focus on the relationship between soil physicochemical properties (total nitrogen, available P, microbial biomass carbon, etc.) and specified plastic existence percentage.

Soil physical conditions could indirectly influence the biochemical properties of the soil. For instance, Dong et al. (2013) found that poor ambient conditions reduced the available phosphate and nitrogen in the soil by 55% and 60%, respectively. Poor physical and biochemical soil properties had negative impact on crop growth; Zhang et al. (2014) found that the yields of wheat, corn, and cotton were heavily reduced by 1–22%, 2–27%, and 1–8%, respectively. More seriously, more than 1 million ton of plastic film was still used to promote agricultural production in arid and semiarid zones in China each year, and larger parts remained in fields as fragments. These residual mulching plastic films fragments will continue to release phthalate esters into the soil environment (Chen et al., 2013), and could persist in the soil for hundreds of years (up to 200–400 years). In summary, the residual mulching plastic films fragments have negative effects on the soil which may result in poor physical and biochemical soil properties. And this would introduce harmful pollutants into the agroecosystem. One of the ways to mitigate the effects of this problem is to incinerate the fragments under controlled conditions. However, from an environmental and sustainable point of view, Gonzalez-Sanchez et al. (2014) advised that mechanical recycling of agricultural plastic film wastes would be a better solution. Simultaneously, he stated that agricultural plastic waste could be used as matrix for composite materials. Although such methods seem preferable, recycling agricultural plastic film fragments from fields is challenging, especially those from the arable layer. From the point of view of plant productivity and disease management, plastic mulches are critical tools for weed suppression, soil moisture retention, and soil temperature control. The sustainability of agricultural practices in the long run requires not only agricultural but also economic and ecological benefits. Minqin Oasis located adjacent to the Badanjilin Desert in the west and Tenger Desert in the east, caused it to be an ecological fragile region. Related agricultural measures (water saving irrigation, drip irrigation project, etc.) on water resources should prefer comprehensive agricultural management measures. Agricultural sustainable development should prefer the whole development of agriculture, economy, ecology, and society. Brodhagen et al. (2015) recently proposed that biodegradable plastic mulch films are an exciting option for sustainable development if a perfect collaboration among polymer engineers, microbiologists, agricultural scientists, toxicologists, and soil ecologists could be reached.

In general, quantitatively and qualitatively analyzing soil physical properties, water distribution and transport in soil columns demonstrated the importance of clearing RPFF for soil quality. Notwithstanding that the way RPFF affects soil biochemical properties and agricultural production requires further investigations, the present study has shed light on the effect of residual plastic film fragments on soil physical properties, water distribution and transport. The findings from the present study have the following implications for soil quality and agricultural management: 1) To ensure crop growth and development, soil quality must be optimized to favorable physical and biochemical properties. Any impurities and foreign materials that would disturb water flow and mass transport in soil must be cleared out. 2) The characteristic of root systems should be associated with the distribution of water and nutrient elements. Taproot systems can reach deeper soil layers while fibrous root systems only reach shallower soil layers. The best strategy of water irrigation, is to use little amount of water that could saturate the crop root zone, rather than using plenty of water which may infiltrate into deeper soil and become unavailable for plants. 3) The favorable exchange of water and nutrient elements between preferential flow path and soil matrix could promote the use efficiency of water and nutrients.

5. Conclusion

This study demonstrated that the presence of RPFF in the soil significantly changed the soil physical properties, altered soil water distribution, caused heterogeneous water infiltration, and remarkably reduced the matching degree of flow distribution region and the maize root zone.

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