Effect of Aeration and Soil Water Redistribution on the Air Permeability under Subsurface Drip Irrigation

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While subsurface drip irrigation supplies water to meet crop needs with high water use efficiency, it might cause low O_2 levels around crop roots and affect plant growth and yield. A modified flow apparatus was used in the laboratory to investigate the impact of aeration following subsurface drip irrigation on transient air permeability. Disturbed samples from two soils from China, a Brown Forest soil (sandy loam) and Lou soil (silty clay loam), were repacked to construct soil columns with various bulk densities (1.3, 1.35, 1.4, 1.45, 1.5, and 1.55 g cm^{-3}). Subsurface drip irrigation (350 mL) was performed at the 17-cm soil depth. Aeration (1050 mL) was conducted through the emitter of the subsurface drip irrigation system for 5 min. The results showed that air permeability was affected by soil texture and bulk density. The measured air permeability from the modified apparatus was comparable to that from the classical apparatus. Soil air permeability after irrigation was reduced by 88.2, 70.1, and 42.5% for the Brown Forest soil with a bulk density of 1.3, 1.4, and 1.5 g cm^{-3}, respectively, and 71.2, 65.4, and 54.3%, respectively, for the Lou soil. A short-period aeration following irrigation quickly improved soil air permeability, however. The air permeability level within 10 min after aeration was 3.7, 2.0, and 1.5 times that before aeration for the Brown Forest soil with a bulk density of 1.3, 1.4, and 1.5 g cm^{-3}, respectively, and 3.0, 2.5 and 2.0 times, respectively, for the Lou soil. It seems a feasible and economical approach to improve soil air permeability by aerating the soil through a subsurface irrigation system following irrigation.

Subsurface drip irrigation is a high-efficiency water-use system that has been widely adopted in arid and semiarid areas with limited water supply. By providing small amounts of water frequently, subsurface drip irrigation can enhance crop growth and yield, and improve plant health. Compared with surface irrigation systems, drip irrigation has more efficient water use by reducing surface soil evaporation and deep percolation, allows more precise control of the irrigation position, and produces fewer water quality hazards (Lamm and Camp, 2007).

While irrigation supplies water to meet crop needs, it causes some problems associated with irrigation agriculture. One of these problems is the inadequate air in the root zone due to irrigation. During and following irrigation events, air in the soil pore space is replaced by water, resulting in poor soil air around crop roots (Poysa et al., 1987; Heuberger et al., 2001; Chen et al., 2009). The occurrence of soil air displaced by irrigated water often results in the temporal decrease of O_2 levels in wetted soil. A linear correlation between O_2 level and matric potential after trickle irrigation was found for the 20-cm depth (Meek et al., 1983). When the O_2 level in soil is relatively low and the CO_2 level is relatively high, aerobic respiration is inhibited by the inadequate O_2 around crop roots, which thereby adversely affects the plant growth and yield (Boru et al., 2003; Bhattarai et al., 2006; Niu et al., 2011).

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Under subsurface drip irrigation, crop roots are mainly distributed in wetted soil; as a result, it is important to improve O_2 levels under the relatively wet condition. It has been recognized that the limiting of O_2 in the root zone could be improved by soil aeration (Busscher, 1982; Huang et al., 1994). By forced injection of air into the soil through a subsurface irrigation system, aeration reduces the water in the soil pore space and therefore increases the O_2 level in the root zone. Aeration at a certain soil depth has been found to increase crop yields in both field and greenhouse experiments (Busscher, 1982; Bhattarai et al., 2006). Vyrlas and Sakellariou-Makrantonaki (2005) documented improvements in sugarbeet (*Beta vulgaris* L. ssp. *vulgaris*) yield and quality due to root zone aeration through subsurface drip irrigation. Changes in the soil air status due to aeration following irrigation needs to be further investigated, however, such as how long it takes to improve the aeration status to the level comparable to pre-irrigation. Such questions could be answered, at least in part, by measuring the soil air permeability.

Soil air permeability is an important physical property reflecting the ability of gas to permeate through the soil pore space. It pertains to the amount of gas per area and unit time in the soil and is the overall indicator of the effect of soil characteristics on the soil air exchange rate. Soil air permeability is affected by various factors, including texture, bulk density, water content, and soil porosity (Roseberg and McCoy, 1990; Jury and Horton, 2004; Sakaguchi et al., 2005; Chief et al., 2008; Chamindu Deepagoda et al., 2011; Hamamoto et al., 2011). Numerous methods have been proposed to measure the soil air permeability (Shan et al., 1992; Springer et al., 1998; Jalbert and Dane, 2003; Poulsen and Moldrup, 2007; Poulsen et al., 2008). Those methods are often conducted in saturated or unsaturated soil with a uniform distribution of water within the tested soil volume. In subsurface drip irrigation, however, the soil water is generally not uniformly distributed but is greater around the orifice.

There is a great need to better understand the change in aeration status caused by subsurface drip irrigation. To our knowledge, there are few studies that have compared soil air permeability before and after irrigation, and there is very limited information on how post-irrigation aeration affects air permeability. In this study, a modified flow apparatus was used in the laboratory to measure the air permeability of soils with uneven soil water distribution. The impact of subsurface drip irrigation on the soil air permeability of two soils with distinct soil textures (sandy loam and silty clay loam) was investigated using the transient flow apparatus. The influence of forced aeration following irrigation on soil air permeability was also examined.

Table 1. Particle size distribution of the tested soils.

Soil	Sampling location	Clay	Silt	Sand	Soil texture
			%		
Brown Forest soil	Yantai, Shandong	6.4	48.6	45.0	sandy loam
Lou soil	Yangling, Shaanxi	29.5	53.9	16.6	silty clay loam

MATERIALS AND METHODS

Two soils were used in this study: a Brown Forest soil (sandy loam) from Yantai, Shandong, and Lou soil (silty clay loam) from Yangling, Shaanxi. The Brown Forest soil is classified as an Alfisol and Lou soil is classified as an Inceptisol based on the U.S. Soil Taxonomy. The particle size distribution of each soil is shown in Table 1. Soil samples were air dried, ground, and screened through a 2-mm sieve before use.

Flow Apparatus for Measuring Soil Air Permeability

Soil air permeability was measured using a flow apparatus (Grover, 1955), which consisted of an air pump, air chamber, soil test box, and pressure gauge (Fig. 1). The experiments were conducted in a room where the temperature was controlled within the range of 23 to 25°C. Therefore, the impact of temperature variations on soil air permeability measurements was negligible in this study. The soil test box was made of a cylindrical Plexiglas container, with a diameter of 20 cm and a height of 32 cm. A 6-cm hole was drilled into the soil box at a distance of 17 cm from the top of the box. This hole was used for later subsurface drip irrigation experiments and was otherwise sealed with tape. Approximately 1000 straight 1-mm holes were drilled at the bottom of the soil box for drainage. For each of the two tested soils, six boxes of soil with varying bulk densities (1.3, 1.35, 1.4, 1.45, 1.5, and 1.55 g cm^{-3}) were constructed. To achieve a relatively uniform bulk density for the whole soil column, the soils were packed in the Plexiglas box layer by layer, with a 5-cm thickness for each layer.

To measure the transient air permeability, air was injected on the top surface of the soil column and discharged from the bottom of the soil box. Air was applied using a pressure pump until the liquid height difference in a U-tube manometer reached 10 cm. Time was recorded with a stopwatch for every 1-cm drop in the liquid height (H) of the manometer until the liquid height difference dropped to zero. Then the pressure values corresponding to different heights were calculated, and the air pressure function $f(t)$ was determined as a function of time (t) according to

$$f(t)=\ln\left[\frac{c(P-P_{\text{atm}})}{P+P_{\text{atm}}}\right] \qquad [1]$$

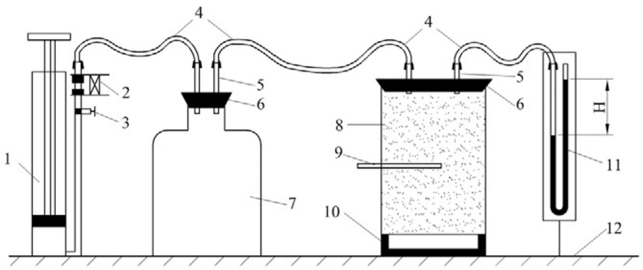

Fig. 1. Apparatus for measuring the transient soil air permeability: air pump (1), inflating valve (2), air switch (3), flexible pipe (4), air hard tube (5), rubber plug (6), air chamber (7), soil test box (8), drip irrigation pipe (9), support (10), pressure gauge (11), floor (12).

where $c = [P(0) + P_{atm}]/[P(0) - P_{atm}]$, $P(0)$ is the initial pressure in the air chamber (Pa); P_{atm} denotes the atmospheric pressure (Pa); and P is the air pressure (Pa) in the air chamber at time t. It should be noted that the experiment was performed under uncovered conditions, i.e., the soil surface was open to the atmosphere during the entire period of the experiment.

The soil air permeability was calculated according to the one-dimensional transient soil air permeability model (Li et al., 2004):

$$K_a = -\frac{\mu V Z s}{A P_{atm}} \qquad [2]$$

where K_a is the soil air permeability (m^2); μ is the air dynamic viscosity, which is equal to $(1717 + 4.8T) \times 10^{-8}$ Pa s, where T (°C) is the soil temperature; V denotes the volume of the air chamber (m^3); Z is the thickness of the soil column (m); A represents the cross-sectional area of the soil column (m^2); and s is the air permeability characteristic parameter (s^{-1}), which is determined by the slope of the best-fit line between $f(t)$ and t.

Following the same procedure, a total of 12 soil air permeability measurements were done for the Brown Forest soil and Lou soil with six different bulk densities for each soil.

Air Permeability under Subsurface Drip Irrigation

A modified flow apparatus was used to measure the air permeability in subsurface drip irrigation. In the modified apparatus, instead of forced injecting air on the soil surface, air was applied through a drip irrigation emitter (when the water head was 10 m, this emitter's flux was 3.1 L h^{-1} in air and the index of flow state was 0.53) to simulate aeration via the subsurface irrigation system. A 6-mm hole was drilled 17 cm below the top of the box and a single emitter was installed in the middle of the soil box through the hole for drip irrigation (Fig. 2). Following the same procedure as above, the air pressure functions were obtained and air permeability was calculated for the Brown Forest soil and Lou soil with six different bulk densities without drip irrigation. The measured air permeabilities of the classical flow apparatus and modified apparatus were then compared for the corresponding bulk densities.

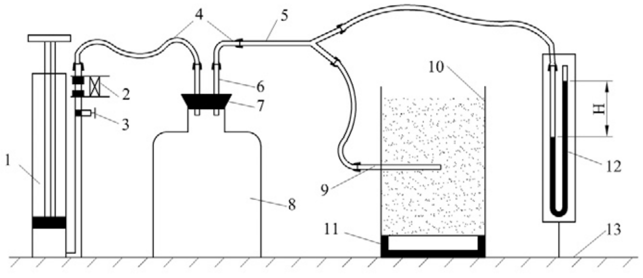

Fig. 2. Apparatus for measuring soil air conductivity characteristic parameter under subsurface drip irrigation: air pump (1), inflating valve (2) air switch (3), flexible pipe (4), tee joint (5), air hard tube (6), rubber plug (7), air chamber (8), drip irrigation pipe, (9), soil test box (10), support (11), pressure gauge (12), floor (13).

Only three bulk densities (1.3, 1.4, and 1.5 g cm^{-3}) were tested for each soil in the subsurface drip irrigation experiments. For each bulk density, two soil boxes were constructed, one for subsurface drip irrigation only and the other for aeration following irrigation. A total of 350 mL of water was irrigated in all the subsurface drip irrigation experiments using a Marriotte bottle (Fig. 3). The average irrigation times were 100, 150, and 600 min for the Brown Forest soil with bulk densities of 1.3, 1.4, and 1.5 g cm^{-3}, respectively, and 120, 270, and 590 min for the Lou soil with bulk densities of 1.3, 1.4, and 1.5 g cm^{-3}, respectively. After irrigation, the same procedure was followed as described above to obtain the air pressure function and air permeability under subsurface drip irrigation using the modified apparatus.

In the aeration experiments, the irrigated soil was aerated with an air pump through the emitter immediately after irrigation. The volume of aeration air was approximately three times (1050 mL) the volume of the irrigated water. The whole aeration process lasted <5 min. The corresponding air pressure function and air permeability were then determined following the same procedure as described above.

To investigate the impact of the soil water content on soil air permeability after irrigation, the air pressure function and air permeability were measured repeatedly after irrigation and aeration using the modified flow apparatus. The initial manometer liquid height difference started at 25 cm and the time for every 1-cm drop of liquid height was recorded. For a single test, it took <5 min for the liquid height difference to drop to zero. The air pressure function was obtained every 10 min for the eighth to 22nd tests. The tests were resumed the next day and were taken every 2 h due to the reduced rate of change in the air permeability with time.

RESULTS AND DISCUSSION

Impact of Soil Texture and Bulk Density on Soil Air Permeability

A good linear relationship existed between the air pressure function, $f(t)$, and time (t), with R^2 values being >0.99 (Table 2). The results showed that the soil air permeability was dependent on both soil type and bulk density. Overall, the Brown Forest soil

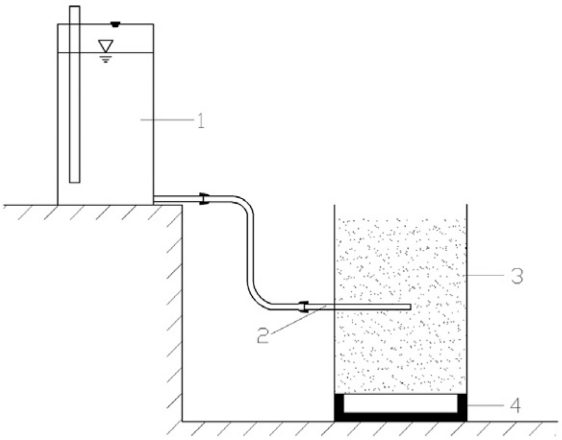

Fig. 3. Apparatus for subsurface drip irrigation: Marriotte bottle (1), drip irrigation pipe (2), soil test box (3), support (4).

Table 2. Air permeability characteristic parameter (*S*) estimated from the best fit of the air pressure function and the coefficient of regression (R^2).

Bulk density	Brown forest soil		Lou soil	
	S	R^2	***S***	R^2
g cm^{-3}	s^{-1}	w	s^{-1}	
1.30	−0.2878	0.9946	−0.0853	0.9996
1.35	−0.2487	0.9997	−0.0375	0.9959
1.40	−0.1712	0.9991	−0.0301	0.9967
1.45	−0.1325	0.9981	−0.0292	0.9916
1.50	−0.1022	0.9984	−0.026	0.9926
1.55	−0.1012	0.9983	−0.0251	0.9964

(sandy loam) had higher air permeability than the Lou soil (silty clay loam) (Fig. 4), probably due to more coarse pores in the sandy loam. Based on measurements in three Danish soils with textures from sand to sandy loam, Schjønning (1986) found that the percentage of coarse pores increased with increasing sand content and air permeability was lognormally distributed. Bulk density also had a great impact on air permeability, which generally decreased as the bulk density increased. Air permeability was less sensitive to the change in bulk density for the Lou soil compared with the Brown Forest soil, varying within a narrow range (0.223–0.735) for bulk densities between 1.30 and 1.55 g cm^{-3}. Previous research has suggested that soil compaction more than soil texture is the major control on air permeability, based on a total of 150 undisturbed soil samples (Chamindu Deepagoda et al., 2011).

Air Permeability from the Modified Apparatus

Based on the experiments for soil columns with various bulk densities, a relationship between the air permeability from the classical flow apparatus (Fig. 1) and the air permeability characteristic parameter from the modified apparatus (Fig. 2) was established for each soil type. The air permeability from the transient soil air permeability approach was negative correlated with the characteristic parameter from the modified transient soil air permeability model. The soil air permeability (K_a) measured by the modified apparatus can be estimated using the soil air permeability parameter (S) by $K_a = -10.93S + 0.025$ with $R^2 = 0.99$ for the Brown Forest soil and $K_a = -25.65S - 0.42$ with $R^2 = 0.95$ for the Lou soil (Fig. 5). This suggests that the soil air permeability under subsurface irrigation conditions could be indirectly calculated by using the regression function between the soil permeability characteristic parameter and soil air permeability after the soil permeability characteristic parameter has been determined.

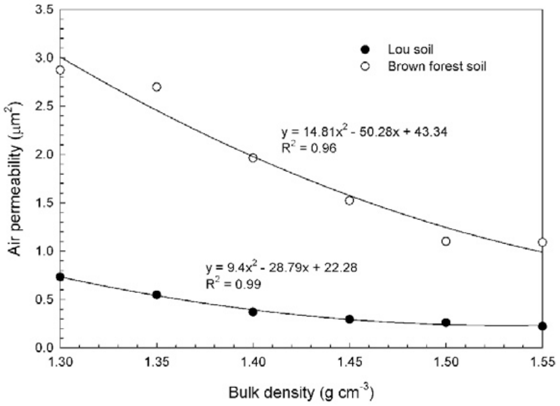

Fig. 4. The impact of bulk density on soil air permeability.

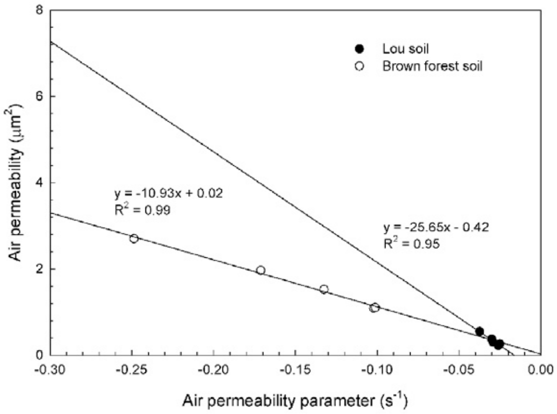

Fig. 5. The relationship between air permeability from the transient approach and the air permeability characteristic parameter from the modified transient approach.

Impact of Drip Irrigation on Soil Air Permeability

The soil air permeability was high before irrigation and dramatically dropped once irrigation started (Fig. 6a–6f). During irrigation, the soil water content around the emitter rapidly approached saturation. Many soil pore spaces, especially macropores that are the main air conductors, in those temporally saturated pockets were probably filled with water, thereby resulting in a rapid decrease in soil air permeability (Rolston and Moldrup, 2002). At the end of the irrigation, the air permeability levels were reduced by 88.2, 70.1, and 42.5% for the Brown Forest soil at bulk densities of 1.3, 1.4, and 1.5 g cm^{-3}, respectively, and 71.2, 65.4, and 54.3% for the Lou soil, respectively. Lower air permeability with increasing moisture content was also observed in a compost study by Das and Keener (1997). Soil air permeability of the Brown Forest soil (sandy loam) decreased more rapidly than that of the Lou soil (silty clay loam). This contradicts previous findings by Schjønning et al. (1999), who found that the air permeability of disturbed soils decreased more rapidly with increasing water content for soils with higher clay content. They attributed this to the structural development of clay soils. In this study, disturbed soil samples were used in the soil column experiment; therefore, the soil structure might have been destroyed. Overall, the air permeability after subsurface drip irrigation was similar for the same soil with different bulk densities, and the impact of irrigation on air permeability was more notable for the low-bulk-density soil (Fig. 6a–6f). The difference in soil air permeability between pre-irrigation and post-irrigation decreased gradually with decreasing bulk density. Research has suggested that crops irrigated by subsurface drip systems could suffer from low O_2 levels when the evapotranspiration rate is less than the irrigation rate, particularly in heavy clay soils (Camp, 1998).

After irrigation, the soil water was redistributed, moving from the high-moisture area to the low-moisture regions, and the measured soil air permeability increased. Soil air permeability showed a large increase at the initial stage of post-irrigation and a gradual

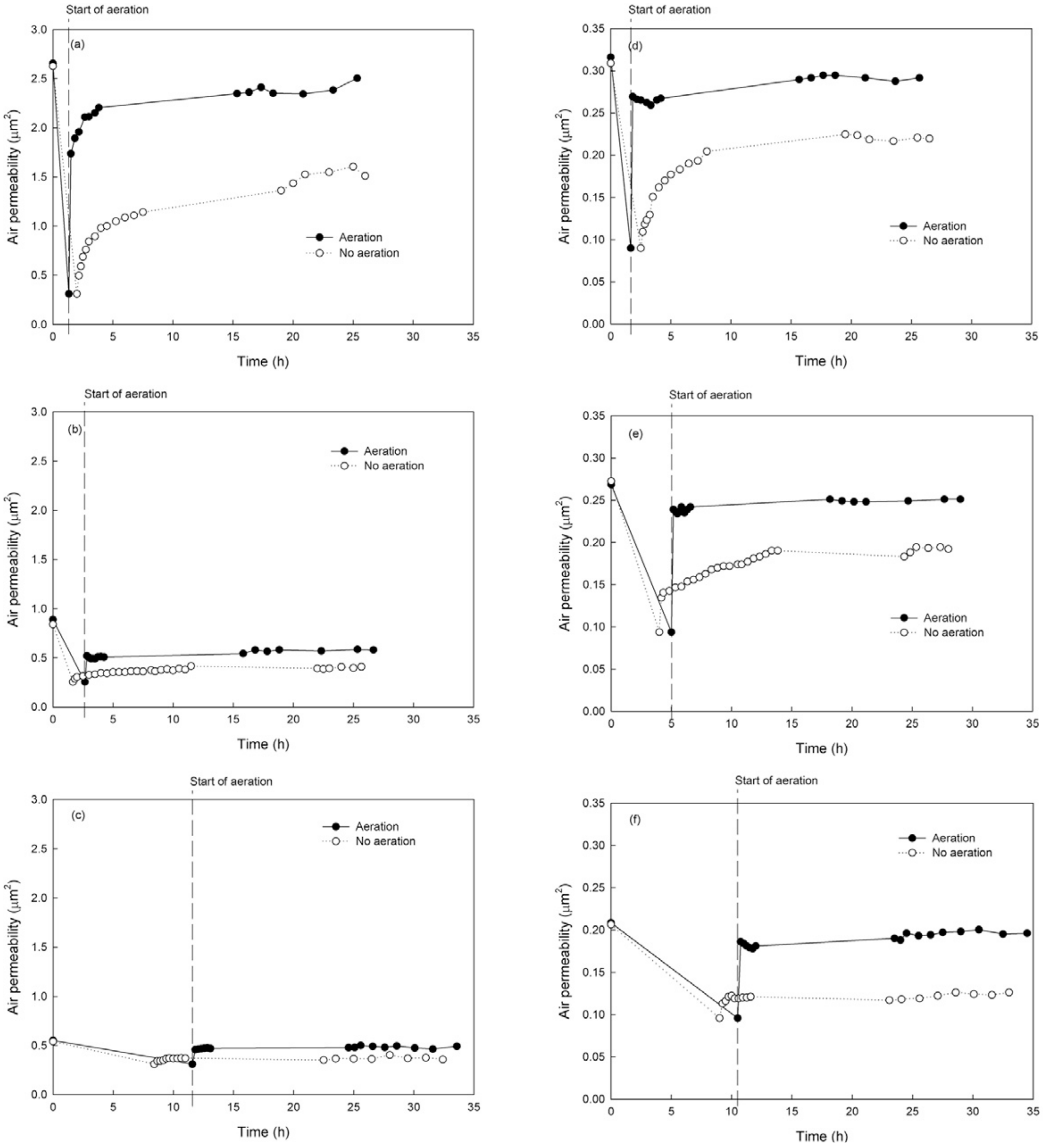

Fig. 6. Change in air permeability after subsurface drip irrigation or aeration for (a) Brown Forest soil with bulk density of 1.3 g cm^{-3}; (b) Brown Forest soil with bulk density of 1.4 g cm^{-3}; (c) Brown Forest soil with bulk density of 1.5 g cm^{-3}; (d) Lou soil with bulk density of 1.3 g cm^{-3}; (e) Lou soil with bulk density of 1.4 g cm^{-3}; (f) Lou soil with bulk density of 1.5 g cm^{-3}.

change afterward. Again, soil air permeability during post-irrigation was affected by soil texture and bulk density. The Brown Forest soil (sandy loam) had higher soil air permeability than the Lou soil (silty clay loam), probably due to its higher sand content. As expected, the increase in bulk density decreased the soil air permeability because of the reduced pore space in the soil with a high bulk density. The soil air permeability after irrigation increased more slowly for high-bulk-density soils. This might be because the soil hydraulic conductivity generally decreases as bulk density increases, therefore slowing down water redistribution.

Impact of Aeration following Drip Irrigation on Soil Air Permeability

Our results indicated that a short-period aeration after irrigation quickly improved the soil air permeability. The measured soil air permeability within 10 min after aeration into wetted soil was enhanced rapidly to just slightly lower than the pre-irrigation permeability level (Fig. 6a–6f). The average air permeability after aeration was about 70% of that before irrigation for the Brown Forest soil and 88% for the Lou soil. In comparison, the average air permeability at 24 h after irrigation without aeration was only 54.8% of that before irrigation for the Brown Forest soil and 67.6% for the Lou soil. After drip irrigation, the soil water content increased and many coarse pores were filled with water, which led to poor aeration. With aeration, air flow could force soil water redistribution from the wet area to a relatively dry area; as a result, water in the soil pore spaces was replaced by air and consequently the pore continuity was probably increased, which could greatly increase air permeability and improve the aeration status. For example, the air permeability level within 10 min after aeration was 3.7, 2.0, and

1.5 times that before aeration for the Brown Forest soil with bulk densities of 1.3, 1.4, and 1.5 g cm^{-3}, respectively, and 3.0, 2.5, and 2.0 times, respectively, for the Lou soil.

The impact of aeration following subsurface drip irrigation on soil air permeability for the Brown Forest soil was greater than for the Lou soil. The air permeability level barely changed after the initial increase, however, indicating that improvement of the aeration status by forced air injection was probably accomplished within a very short period after aeration. Our findings suggest a potential for using existing subsurface drip systems to aerate irrigated soils for a short period and prevent possible negative impacts associated with the reduced O_2 levels caused by irrigation. Although the use of subsurface irrigation systems for soil aeration is still limited, it would be expected that more attention might be paid to its potential, considering the benefits and relatively low lost. Compared with forced air injection on the soil surface, aeration through subsurface drip irrigation systems does not require additional perforated hose, and the volume of injected air is less. Another side benefit of soil aeration through the drip irrigation infrastructure is the reduced risk of emitter clogging (Lemos Filho et al., 2011).

CONCLUSIONS

The soil air permeability under subsurface irrigation conditions was estimated by using the regression function between the soil permeability characteristic parameter and soil air permeability using a modified flow apparatus. The air permeability was strongly influenced by the soil water content. It decreased dramatically to near zero after subsurface drip irrigation. A short period of aeration after irrigation quickly improved the soil air permeability to pre-irrigation levels. This is a feasible and economical approach to improving the soil air permeability using subsurface drip irrigation infrastructure to aerate the soil after irrigation. Further experiments with undisturbed structured soils need to be conducted.

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