Relationship between Water and Carbon Utilization under Different Straw Mulching and Plant Density of Summer Maize in North China Plain

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Abstract. To explore the relationship between water and carbon utilization and key factors to keep high water use efficiency (WUE), a 2-yr experiment was conduct by covering 0 and 0.6 kg m^{-2} straw to the surface of soil with plant densities of 1.0×10^5, 7.5×10^4, and 5.5×10^4 plants ha^{-1} in North China Plain during summer maize growing seasons of the 2012 and 2013. Results showed that straw mulching not only increased grain yield (GY), WUE, and carbon efficient ratio (CER) but also inhibited CO_2 emission significantly. WUE positively correlated with CER, GY and negative correlated with evapotranspiration (ET) and CO_2 emission. CER had the larger direct effect on WUE compared with ET and CO_2 emission. The results indicate that straw mulching management in summer maize growing seasons could make sense for inhibiting CO_2 emission.

1.   Introduction

Food security caused by water resources shortage with farmland shrinking and climatic change due to global warming results in alarming situation for the existence of life on earth, which are serious concern for scientists and researchers. One of the important causes for global warming is the uncontrolled emission of CO_2. The water use efficiency (WUE), is a primary ecosystem function characteristic that is important for the global water and carbon cycles. Improving crop WUE while maintaining or even improving grain yield (GY) may conserve water resources and maintain their economic livelihoods. Many studies combined with CO_2 emission to explore the effective way to achieve carbon emission reduction. In addition, mulching is used widely to improve soil fertility and soil moisture content. Mulching is not recommended as a method for improving water and GY of maize in northeastern China semi-humid black soil region, when the soil water content is sufficient for maize growth[1]. The mulching rate of 9.0×10^3 kg ha^{-1} with maize straw was suitable for the Loess Plateau of China where the precipitation was lower than 390 mm in the spring maize growing season[2]. But above all, the study of water and carbon utilization for maize based on straw mulching were independent and separate, comprehensive research of water and carbon utilization should be studied further. Reasonable planting density is an effective way to realize increase in GY in the case of arable land losses. Increasing effective rooting depth from 0.40 m at a density of 3.25×10^4 plants ha^{-1} to 0.60 m at a density of 4.44×10^4 plants ha^{-1} increased GY from 6.0 to 7.8 t ha^{-1} and grain WUE by 23.6%[3]. No

published research exists on the effect of summer maize plant density on water and carbon comprehensive utilization taking advantage of path coefficient analysis in North China Plain to date.

This study objectives were to (I) determine the resulting changes of soil CO_2 emission, CER, ET, GY and WUE, and (II) assess CO_2 emissions, ET, GY, and CER in the soil surface under different mulching and plant density treatments, and to investigate effect of relationship among them on WUE.

2. Materials and methods

2.1. Experimental site
Experiments were conducted at the Shandong Agricultural University Experimental Station (36°10"9'N, 117°9"03'E) in North China Plain and carried out in plots separated by concrete walls that was 25.0 cm thick and extended 1.5 m under the soil surface. The plots area was 3.0 m $\times$ 3.0 m. No signs of tillage or water erosion were observed in the experimental plots.

2.2. Experimental design
The seeding time of summer maize was on June 17th, 2012, and June 19th, 2013, respectively. Maize was harvested on October 3rd, 2012, and October 2nd, 2013, respectively. Split plots designed in randomized complete blocks with three replications. The six treatment combinations were (1) 10.0 plants m^{-2} density without straw mulching (N1); (2) 10.0 plants m^{-2} density with 0.6 kg m^{-2} straw mulching (M1); (3) 7.5 plants m^{-2} density without straw mulching (N2); (4) 7.5 plants m^{-2} density with 0.6 kg m^{-2} straw mulching (M2); (5) 5.5 plants m^{-2} density without straw mulching (N3), and (6) 5.5 plants m^{-2} density with 0.6 kg m^{-2} straw mulching (M3). Wheat straw cut into 3.0–5.0 cm was evenly over the soil surface when summer maize at 3-leaf stage. During the both summer maize growing seasons, no irrigation was applied, and other management measures were same to high-yielding field.

2.3. Measurements
Evapotranspiration was calculated as the following equation:
$$ET = P + I - R - SW - D$$
Where: ET is evapotranspiration (mm); P is precipitation (mm); I is irrigation amount (mm), there was no irrigation during experiment; R is surface runoff (mm); SW is the change of water storage in soil profile (mm); and D is downward flux under summer maize root zone (mm).
Crop water use efficiency was calculated as:
$$WUE = \frac{GY}{ET}$$
Where: WUE is the ratio of summer maize grain yield to water use efficiency of ET (kg m^{-3}), the summer maize grain yield (GY) was measured at maturity corresponding to the central lines of each plot.

Summer maize grain by carbon (C) fixed every unit of C emissions from soil was calculated as follows:
$$CER = \frac{GY}{GHG}$$
Where: GHG is the greenhouse gas including CO_2, CH_4 and N_2O. Cumulative emissions of CO_2 in the present study was considered as background emission. Cumulative emissions of CO_2-C were calculated as follows[4]:
$$M = \frac{\sum (F_{i+1} + F_i)}{2} \times (T_{i+1} - T_i) \times 24$$
Where, M is cumulative CO_2-C emissions (mg C m^{-2}); F is the CO_2 flux of soil surface (kg CO_2 ha^{-1} h^{-1}); T is the day after sowing; and i is the sampling number.
Soil respiration rate was calculated by soil surface CO_2 flux as follows:
$$F = \rho \times \frac{V}{A} \times 100 \times \frac{P}{P_0} \times \frac{273}{273 + T} \times \frac{dC}{dt} \times 60$$
Where: F is the soil surface CO_2 flux (μg m^{-2} h^{-1}); A is the static chambers area (cm^2); V is the static chambers volume (cm^3); ρ is the CO_2 density under standard atmospheric condition (mg m^{-3}); T is the

atmospheric temperature (℃); P is the atmospheric pressure of static chambers (Pa); P_0 is the atmospheric pressure under the condition of standard atmospheric (1.013×10^5 Pa); dC/dt is change of CO_2 concentration (10^{-6} min^{-1}).

2.4. Statistical analyses
The analysis of variance was conducted by Origin 8.0 procedure. Least significant difference (LSD) at P≤0.05 was used to compare mean values of the treatments. The datasets from Experiment were tested using SPSS 20.0 (IBM SPSS statistics 20) to reveal the impact of straw mulching and plant density on WUE and CO_2 emission.

3. Results

3.1. The water-carbon factors under different treatments
In the growing seasons of 2012 and 2013, significant difference was showed between mulching and non-mulching treatments in CO_2 emission, GY, CER, and WUE, respectively (Table 1). GY, CER, and WUE of M treatments were significantly higher than that of N treatment in 2013, respectively. The CO_2 emission of M treatments was significantly lower than that of N treatments. ET was higher in 2012 than in 2013 by 185.7 mm in M treatments and by 159.21mm in N treatments.

The WUE of medium plant density treatments were significantly higher than that of high and low plant density, in 2012 but WUE were not found affected by plant density in 2013. In 2012 summer maize growing season, the significant decrease in ET of medium plant density treatments compared to high plant density treatments and significant improvement in grain yield compared to low plant density treatments result in the higher improvement in WUE of medium plant density treatments than others. In the both growing seasons, the highest CO_2 emission were showed in medium plant density treatments which had a significant difference in 2012 and no significant in 2013 compared to other treatments. The significant decrease in CER of medium plant density treatment compared to low plant density treatments was mainly cause by the increase in CO_2-C emission of medium plant density in 2013.

GY, CER and WUE between M and N treatments under three plant density conditions exhibit a consistency trend in both growing seasons. CER and WUE were significantly higher in the straw mulching treatments than in non-mulching treatment under three different plant density conditions. Meanwhile, mulching treatment didn't have effect on yield under high plant density condition.

Table 1. The water-carbon factors in 2012 and 2013 summer maize growing seasons

Year	Treatment	ET	CO_2-C emission	GY	CER-CO_2	WUE
2012	M	287.14a	8.3b	1157.44a	1.39a	40.71a
	N	314.44a	12.85a	1021.06b	0.8b	32.57b
	1	325.61a	10.61a	1113.72a	1.1a	34.25b
	2	289.68b	10.64a	1149.49a	1.16a	39.85a
	3	287.08b	10.48a	1004.54b	1.04a	35.81b
2013	M	472.84a	12.94b	1156.19a	0.9a	24.45a
	N	473.65a	15.66a	918.01b	0.6b	19.35b
	1	476.9a	14.18b	1054.87a	0.76ab	22.12a
	2	475.85a	15.45a	1037.55a	0.68b	21.74a
	3	466.98a	13.26b	1018.89a	0.81a	21.85a

a.   Each year, the same letter following values in the same column, show no significant (*LSD, P <* 0.05) standard deviation.

3.2. The path -correlation analysis of water-carbon factors
CER had the largest direct effect on WUE which followed by ET and CO_2 emission. The correlation coefficient was larger than direct action, direction action was the main reason for the correlation between CER and WUE, which suggested that it was very signality in achieving high water use

efficiency by improve CER directly. By analyzing the various indirect path coefficients, we found that ET had a negative indirect action on WUE by the interaction with CO_2 emission. Although ET had a positive indirect action on WUE by the interaction with CER, the negative direct action of ET and negative effect of ET by the interaction with CO_2 emission on WUE play a more important role, which resulted in the negative action of ET on WUE.

Table 2. The direct and indirect functions analysis of WUE factor impact on WUE

Independent variable	Correlation coefficient	Direct action	Indirect effect			
	r_{iy}	P_{iy}	Total	ET	CER	Amount of CO_2 emission
ET	-0.904	-0.744	0.057		0.493	-0.55
CER	0.842	0.953	1.535	-0.632		-0.903
CO_2 emission	-0.818	0.637	0.132	0.471	-0.603	

3.3 The determination coefficient and total R^2 contribution of WUE

In the present study, determination degree of ET together with CER to WUE was 0.923 ranking first place among all determination coefficient, and the contribution of CER to R^2 was 0.802426 taking the first among all index, which declare the importance of CER to WUE. The mount of ET was also necessary to be considered. Meanwhile, the determination degree of ET together with CO_2 emission was list second among all determination coefficients.

Table 3. The coefficient of determination and total R^2 contribution of each factor impact on WUE

Name	Coefficient of determination	$r_{yi}P_{y.i}$	Total contribution to R^2 of variable
$d_{y.12}$	0.923	$r_{y1}P_{y.1}$	0.672576
$d_{y.13}$	0.867	$r_{y2}P_{y.2}$	0.802426
$d_{y.1}$	0.818	$r_{y3}P_{y.3}$	-0.52107
$d_{y.2}$	0.802		
d_{y23}	0.713		
d_{y3}	0.669		

a. y, 1, 2 and 3 represent WUE (dependent variable),ET (independent variable), CER(independent variable) and CO_2 emission (independent variable), respectively.

4. Discussion

The result of no significant difference in ET between M and N treatment was consistent with the conclusion of Lu Xianju, et al（2015）[5]. Decreasing the water consumption of soil surface plays an important role for water saving agriculture and water management schemes. The mulching practice determines soil cover and consequently influence non-productive evaporation. To take a clear understanding of farmland moisture loss, a further study in transpiration is still need. Our experiment revealed that GY, WUE, CO_2 emission and CER in mulching treatments were significantly higher than that in non-mulching treatment in general. The improvement in GY will be efficient based on the biological yield. Increase in GY and WUE by straw mulching mainly caused by improvement in soil moisture content[6]. Straw mulching could keep more residues on soil surface to make SOC concentration higher than conventional tillage[7]. Straw mulching had benefit in curbing CO_2 emission, even CO_2 fluxes showed delays before reaching their lowest levels in autumn in mulching treatments[8]. GHG (CO_2, CH_4, N_2O) produced as a result of agricultural production could enhance the natural greenhouse effect. Therefore, straw mulching management for summer maize growth period could make sense for conversion of SOC and alleviation of greenhouse effect. ET was positively correlated

with CO_2 emission in our study. Gas production and transport are regulated by water submergence to a large extent and result in an indirect positive retroaction to gas emissions[9].CER had the larger direct effect on WUE compared with ET and CO_2 emission which indicated that the key to realize high WUE was to elevate CER, even WUE was calculated by GY and ET in this study. GY was got rid of the factors of WUE in multiple regression analysis showed that it is beneficial and worthiness to study WUE by combine GY with CO_2 emission. There was strong correlation between net primary productivity and ET appeared in global century simulations[10]. Primary production needs nitrogen to create organic matter which satisfy critical C / N ratios for roots, foliage and wood. It is important for the increase of production to study the relationship between C and N cycle in future study.

5. Conclusions

Straw mulching not only increase GY, WUE and CER but also inhibited CO_2 emission effectively in general. Under three plant density condition，straw mulching treatments have significant advantage in improve WUE and CER. WUE positively correlated with CER, yield and negative correlated with ET and CO_2 emission in this study. The stepwise regression analysis indicated that the contribution of independent variables to WUE were ET, CER and CO_2 emission, respectively.CER had the larger direct effect on WUE compared with ET and CO_2 emission.

Acknowledgment

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