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Effect of experimental warming on nitrogen uptake by winter wheat under conventional tillage versus no-till systems

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ABSTRACT

Despite the perceived importance of nitrogen (N) to growth and production of wheat, few studies have attempted to examine the effect of warming on wheat N uptake or its preference for NO_3^--N vs. NH_4^+-N, especially under different tillage systems. In the North China Plain, an experimental warming (2 °C increase in soil during the jointing stage) study was conducted using in situ ^{15}N labeling under till and no-till systems. We aimed to investigate the uptake of NO_3^--N, NH_4^+-N, and glycine-N by winter wheat. Warming strongly enhanced wheat biomass (14.7% and 13.2% for till and no-till, respectively) and N content in biomass (11.1 and 7.4 g N m^{-2} for till and no-till, respectively). Total N uptake rates increased by 47% and 40% under till and no-till treatments, respectively. Warming changed the uptake pattern for the three N forms by significantly increasing the contributions of NO_3–N by 16% and glycine-derived N by 5%, while decreasing the contribution of NH_4^+-N by 20% under the two tillage systems, on average. Collectively, high soil temperatures accelerated N uptake in winter wheat and improved the preferential contribution of NO_3^--N and glycine-N due to the increase in soil glycine and NO_3^- content. Our findings suggest that enhanced N uptake improved growth of wheat and could reduce N losses through increased uptake of NO_3^- under till and no-till systems in the North China Plain under the warmer conditions that are likely in future.

1. Introduction

The challenge to agro-ecosystems in future is two-fold. Securing sufficient food for the world's estimated 9 billion humans by 2050 requires doubling global agriculture productivity (Foresight, 2011). In addition, global warming, which is projected to increase the global temperature by 3.7 °C by the end of the 21st century (IPCC, 2013), will affect crop growth and yields in varied ways. As the efficiency of nutrient uptake by crops is one of the most important determinants of crop biomass and yield, improving nutrient acquisition and thus crop productivity under climate change conditions can help address the challenge (Garnett et al., 2009; Kraiser et al., 2011; Rimski-Korsakov et al., 2012). As the main limiting nutrient to crop growth and yield, nitrogen (N) uptake by crops is determined by the N availability in the soil, which is strongly affected by tillage practices (Thomsen and Sørensen, 2006). Tilling significantly affects the soil N cycle, N uptake by crops, and microbial activities, which results in different responses of crop yield and soil properties to experimental warming (Hou et al., 2014; Ruisi et al., 2016; Zuber and Villamil, 2016). As a "win-win" measure, the no-tillage (no-till) agricultural system, which has rapidly spread worldwide during the last two decades, enhances agricultural sustainability concomitant with mitigating global warming (Johan et al., 2004; Powlson et al., 2016). Numerous studies show that the two dominant tillage systems cause differences in soil N availability (Ruisi et al., 2016). Elucidating the relationship between increased temperature and N uptake by crops growing under different tillage systems will improve our understanding of the effect of climate change on agriculture.

Wheat growth and yield are very sensitive to temperature (Chowdhury and Wardlaw, 1978; Darwinkel, 1978; Sofield et al., 1977). Previous studies have shown that a higher temperature notably decreases both vegetative growth duration and grain-filling duration (Batts et al., 1997; Porter and Gawith, 1999) and decreases grain weight while decreasing the number of kernel per ear (Sofield et al., 1977; Thorne and Wood, 1987). Studies have reported mixed results regarding the effects of temperature on yield; some have reported declining yield (Lobell et al., 2011; Wheeler et al., 1996), while others have noted increased or unchanged yield (Hatfield et al., 2011).

It remains unclear how warming affects plant N uptake in croplands.

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Warming often results in a decline of plant N use efficiency (NUE), because higher temperatures increase plant-microbial competition for N and lead to more N becoming immobilized in microorganisms (Kuzyakov and Xu, 2013; Rütting et al., 2010). This in turn leads to a reduction of N utilization by crops and depresses yields (Rathke et al., 2006). Higher temperatures can also increase the risk of N losses by increasing N_2O efflux (Kallio et al., 1997; Rankinen et al., 2013) and decreasing NUE and crop biomass (Cai et al., 2016; Liu et al., 2013). In contrast, numerous studies have demonstrated that warming may accelerate N delivery to the root surface by improving transpiration in well-irrigated croplands (Pregitzer and King, 2005). Further, warming may enhance N uptake by plants by increasing the availability of soil N (Bai et al., 2013; Rustad et al., 2001). Numerous studies have suggested that higher temperature increases crop biomass and yield. (Hou et al., 2012b; Tian et al., 2012). Warming could thus improve crop N uptake by increasing N mineralization (Rustad et al., 2001).

Because of the variable influence of warming on plant N uptake, crops may show different preferences for different N forms under warming conditions. Inorganic forms of N (NO_3^--N and NH_4^+-N) have long been recognized as the dominant forms of N available to plants, especially in croplands (Chapman et al., 2012; Wang et al., 2015). Higher temperatures can significantly change the availability of these forms of N in the soil by increasing nitrification and by drying the soil (Bai et al., 2013; Carrillo et al., 2012). As a result, crops may need to alter their intake of the two dominant N forms during growth. Several studies have shown that crops are able to uptake organic N in the form of amino acids in cropland (Ge et al., 2009; Reeve et al., 2009; Xu et al., 2008). The availability of soil organic N may increase with more intensive soil organic matter (SOM) decomposition (Carrillo et al., 2012; Rustad et al., 2001) in croplands. As a result, the contribution of organic N to crop N uptake could be increased under warming. A better understanding of the effects of warming on the three forms of N is important to estimate the growth and yield of winter wheat under increased temperatures.

Long-term no-till agriculture is known to change the properties and biological functions of soil and therefore affects soil carbon (C) and N cycling, especially in the upper layer of the soil (Bayer et al., 2015; Gregorich et al., 2006). Between no-till and till systems, N mineralization from the soil and plant residues and the status of mineral N are affected by soil temperature and water changes (Sainju et al., 2009, 2012) via changing microbial activity (Bremer and Kessel, 1992). Our previous study showed that warming-induced changes to soil temperature or water content fluctuate less under no-till than under conventional tilling (Hou et al., 2014). In addition, an increase in the extracellular enzyme activities and their sensitivity has been reported with increased temperature in no-till systems alone (Hou et al., 2016). This effect may threaten N uptake by roots by increasing competition for N (Kuzyakov and Xu, 2013).

To clarify how warming affects N uptake by winter wheat under the two types of tillage systems, the uptake of three forms of N (NH_4^+, NO_3^-, and glycine-N) was examined using in situ ^{15}N labeling under warm conditions in fields that have followed till and no-till systems since 2003 in the North China Plain. We aimed to test two hypotheses: 1) warming could increase N uptake by wheat, especially for organic N, and 2) under warm conditions, no-till, in contrast to till, could decrease the total N uptake by wheat due to stronger microbial competition.

2. Materials and methods

2.1. Study site

This study was conducted in a long-term (since 2003) conservation tillage experiment located in the North China Plain (NCP, 36°50′N, 116°34′E, elevation: 20 m a.s.l.). The set-up of the field experiment is described in detail in a previous study (Hou et al., 2012a). Briefly, the site is located in a temperate semi-arid climate, with mean annual temperature of 13.1 °C and mean precipitation of 561 mm during the past 32 years (from 1985–2016). Approximately 70% of the annual precipitation occurs between June and September. The soil is classified as Calcaric Fluvisol according to the World References Base for soil resources (WRB, 2014). Soil surface texture is silty loam (sand, 12%; silt, 66%; clay, 22%) and uniform in our experimental area, with a pH of 7.1. Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) were double cropped according to a common practice in the NCP.

For tillage treatment, standing crop stubble of each treatment was cut to approximately 10 cm and all other residues were removed after the harvest of the maize crop. A rotary tiller was used with a tillage depth of about 10–15 cm, which fully incorporated standing stubble into the soil before winter wheat planting. For the no-till treatment, maize residues were chopped into pieces (about 5 cm length) by hand and retained on the soil surface. The residue mass retained for no-till was about 10 Mg ha^{-1} yr^{-1} with 4 Mg ha^{-1} yr^{-1} of wheat and 6 Mg ha^{-1} yr^{-1} of maize.

According to the experiential application rate of fertilization in the study region (Ju et al., 2007; Zhen et al., 2006; Zheng et al., 2017), the total N application rate for no-till and till treatments was 285 kg N ha^{-1} yr^{-1} for wheat. The base fertilizer, along with phosphorus (P) and potassium (K), was applied as a compound inorganic chemical fertilizer containing N (as urea), P (as P_2O_5), and K (as K_2O) at a ratio of 12:19:13 and with application rates of 116 kg ha^{-1} of N, 178 kg ha^{-1} of P, and 122 kg ha^{-1} of K as the base fertilizer for the crop in both tillage systems each year. Considering residue N (50 kg ha^{-1} of N), the inorganic N input was 66 kg ha^{-1} of N for no-till. For topdressed N, during the re-greening stage, the remaining 169 kg ha^{-1} yr^{-1} of N was applied as urea for both till and no-till systems. The base fertilizer application of all treatments was the same as for topdressing: October 6 and March 3. There was a one-time irrigation on April 1, 2014, and the amount of irrigation was about 30 mm. All other management procedures were identical for the two systems with spraying of herbicide (2,4-D butylate) and insecticide (40% dimethoate) in May.

2.2. Experimental design

Experiments were based on four treatments: Till with, and without warming (TW and TN, respectively), and no-till with, and without warming (NW and NN, respectively). We used split-plot design with tillage system (no-till or till) in the main plots and warming (with or without warming treatment) in subplot. Eight randomly ranged plots were chosen, comprising 4 till treatments and 4 no-till treatments. Each plot is 7.5 m × 40 m (300 m^{-2}). Four subplots were chosen in each plot and each subplot size is only 2 m × 2 m (4 m^{-2}) (Fig. 1). Each treatment was replicated four times. There was a 5 m border between adjacent plots and at least 10 m between treatments. The warmed soil was continuously heated (since February 4, 2010) using an MSR-2420 infrared heater (Kalglo Electronics, Inc., Bethlehem, PA, USA) placed 3 m above ground. The control (without warming) plots were the same shape and size as the warmed ones and included a "dummy" infrared heater suspended 3 m above ground to simulate shading effects of the infrared heater. The heater increased the soil temperature by 2 °C relative to the control treatment.

Temperature of the canopy was measured by a thermal imager (Model SC2000 ThermaCAM; Flir Systems, Danderyd, Sweden) at 09:00, 15:00, and 21:00 each day from April 22 to 28, 2014. The wave band of the thermal imager was 8–14 l m. According to the thermal radiation balance equation, the measured radiance includes a reflection term from the environment. Thus, to correct for heater radiation and sky radiation reflected off the crop canopy, we used the methods described specifically in our previous study (Hou et al., 2012b).

2.3. ^{15}N injection and biomass measurements

To determine uptake of different N forms (NO_3^-, NH_4^+ and