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Soil nitrogen fractions under long-term crop rotations in the Loess Plateau of China

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ABSTRACT

Long-term crop rotation may influence soil N storage, mineralization, and availability. We studied the 30 yr effect of crop rotations on soil N fractions at 0–15 and 15–30 cm depths in the Loess Plateau of China. Crop rotations were continuous winter wheat (*Triticum aestivum* L.) (W), corn (*Zea mays* L.)-winter wheat-winter wheat-millet (*Eleusine coracana* L.) (CWWM), pea (*Pisum sativum* L.)-winter wheat-winter wheat-millet (PWWM), and sainfoin (*Onobrychis viciifolia* Scop.)-winter wheat-winter wheat-sainfoin (SWWS); pea-winter wheat-winter wheat-corn (PWWC); alfalfa (*Medicago sativa* L.) (4 yr)-potato (*solanum tuberosum* L.) (1 yr)-winter wheat (3 yr) (A4PoW3), and fallow (F). Nitrogen fractions were soil total N (STN), particulate organic N (PON), microbial biomass N (MBN), potential N mineralization (PNM), NH_4–N, and NO_3–N. The STN and PON at 0–15 cm were greater in CWWM and at 15–30 cm were greater in A4PoW3 than F and W. The PNM at both depths was greater in A4PoW3 than other crop rotations, except SWWS and CWWM. The MBN was greater in CWWM, PWWM, SWWS, and A4PoW3 than other crop rotations. The NH_4-N content was greater in F than other crop rotations, except PWWC. The NO_3-N content at 0–15 cm was greater in CWWM and at 15–30 cm was greater in PWWM than F. Most soil N fractions were correlated with each other and also with the length of the crop rotation. Diversified crop rotations with increased root biomass N returned to the soil and longer year rotations enhanced soil N storage, mineralization, and availability compared with monocropping and fallow.

1. Introduction

Nitrogen is a major limiting nutrient for achieving sustainable crop yields in dryland cropping systems (Janzen et al., 2003; Lenssen et al., 2007; Sainju et al., 2009). Nitrogen fertilization can enhance crop yields and quality, but excessive fertilization can reduce soil and environmental quality by increasing soil acidification, N leaching, and greenhouse gas (N_2O) emissions (Ross et al., 2008; Sainju et al., 2016). As crops can remove about 40 to 60% of applied N from inorganic N fertilizer, manure and other N amendment, the residual soil N (NO_3-N + NH_4-N) after crop harvest can be lost to the environment (Janzen et al., 2003; Ross et al., 2008). Because soil residual and potentially mineralizable N can also contribute N to crops during the growing season, it is necessary to adjust N fertilization rates so that crop production can be optimized and potential for N losses minimized (Sarker et al., 2015; Akhter et al., 2016; Sainju et al., 2016). While some of the residual N is immobilized by microorganisms into soil organic N, unharvested N in crop residue (stems and leaves) and roots recycle to form the core of soil N storage. By increasing N-use efficiency, enhancing N storage, and reducing N fertilization rate through improved management practices, N losses to the environment can be minimized compared with traditional practices (Janzen et al., 2003; Ross et al., 2008; Sainju et al., 2012, 2016). By understanding soil N cycling, N fertilization to crops can be managed efficiently for sustaining crop yields and quality and reducing the potential for N loss (Sarker et al., 2015; Akhter et al., 2016; Sainju et al., 2016).

Crop rotation can enhance crop yield and quality by efficiently utilizing water and N compared with monocropping in water-limited dryland farming systems (Sainju et al., 2012). Legumes, such as pea, in rotation can not only reduce N fertilization rates to successive crops by

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Abbreviations: A4PoW3, alfalfa (4 yr)-potato (1 yr)-winter wheat (3 yr); CWWM, corn-winter wheat-winter wheat-millet; F, fallow; MBN, microbial biomass N; PNM, potential N mineralization; PON, particulate organic N; PWWC, pea-winter wheat-winter wheat-corn; PWWM, pea-winter wheat-winter wheat-millet; STN, soil total N; SWWS, sainfoin-winter wheat-winter wheat-sainfoin; W, continuous winter wheat

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supplying N from their residues due to higher N concentrations, but also utilize soil water more efficiently than nonlegumes, such as wheat and barley (*Hordeum vaularis* L.) (Sainju et al., 2012; Lenssen et al., 2007, 2014; Hossain et al., 2016; Jahan et al., 2016). Deep-rooted perennial legume forages, such as alfalfa, can also scavenge residual soil N and reduce N leaching (Karlen et al., 1994; Sainju and Lenssen, 2011). After termination of such crops, more N becomes available to successive crops from residue decomposition due to higher N concentrations in legumes than nonlegumes (Hossain et al., 2016; Jahan et al., 2016). Some rotations, however, may temporarily reduce plant available N by increasing N immobilization when crops with higher C/N ratio are included in the rotation (Zhang et al., 2007). Perennial legume forages can also enrich soil N storage by increasing N inputs from root biomass because of their extensive root systems compared with annual crops (Summers, 1998; Zentner et al., 2011).

Because of a large pool size and inherent spatial variability, changes in soil total N (STN) due to management practices are often slow (Franzluebbers et al., 1995; Sainju et al., 2011). As a result, changes in STN do not adequately reflect soil productivity and N status (Franzluebbers et al., 1995; Sainju et al., 2009; 2011). The microbial biomass N (MBN), as a measure of N immobilization, and potential N mineralization (PNM), as a measure of N mineralization, are labile soil N fractions that change rapidly during a crop growing season (Sainju et al., 2009). The particulate organic N (PON), a measure of N storage in coarse organic matter, is an intermediate fraction between slow and labile fractions that also changes rapidly during a growing season and is an important substrate for soil microorganisms (Zhang et al., 2007). The soil mineral N (NO_3-N and NH_4-N) is the available N fraction that can either be taken up by the crop or loss to the environment (Wood et al., 1990; Sainju et al., 2012, 2016). Increased soil residual N (NO_3-N and NH_4-N) accumulation after crop harvest can reduce water and air quality by increasing the potential for N leaching in the groundwater and increasing greenhouse gas (N_2O) emissions (Janzen et al., 2003; Ross et al., 2008; Sainju et al., 2012, 2016).

Continuous monocropping under conventional tillage with high N fertilization rates for the last several decades has resulted in soil fertility loss and erosion in the Loess Plateau of China (Huang et al., 2003; Jiang et al., 2015). In this region, winter wheat monocropping under rainfed condition accounts for 70–80% of the total crop production, however, often has low yields (Huang et al., 2003; Jiang et al., 2015). Crop rotations that can efficiently utilize soil water and N, reduce N fertilization rates, and sustain crop yields are urgently needed. Diversified crop rotations that include legumes and forages with winter wheat have been initiated in the last few decades to enhance soil fertility and crop yields (Guo et al., 2008; Cai and Hao, 2015; Jiang et al., 2015). The effect of such rotations on soil N storage, mineralization, and availability as well as N balance compared with monocropping and fallow, however, is lacking in this region.

We evaluated the long-term (30 yr) effect of diversified crop rotations that included cereals, legumes, tuber crops, and forages on soil N fractions and N balance compared with monocropping and fallow in the Loess Plateau of China. Our objectives were to: (1) quantify the impact of crop rotations of various rotation lengths on STN, PON, MBN, PNM, NH_4-N, and NO_3-N at 0–15 and 15–30 cm depths, (2) examine relationships between root biomass N input, crop rotation length, and soil N fractions, (3) evaluate N balance based on N inputs, outputs, and soil retention, and (4) determine crop rotations that enhance soil N storage, mineralization, and availability and reduce N balance compared with monocropping and fallow. We hypothesized that crop rotations with high root biomass N returned to the soil and greater rotation lengths would increase soil N fractions and reduce N balance compared with monocropping and fallow.

2. Materials and methods

2.1. Experimental site

The long-term crop rotation experiment began in September 1984 at the Changwu Agroecological Station (107°44′E, 35°12′N; 1220 m elevation) in Changwu County, Shaanxi Province, China (Guo et al., 2008; Cai and Hao, 2015; Fu et al., 2017). The experimental site has a continental monsoon climate, with mean annual temperature of 9.1℃and the frost-free period of 194 d. The long-term (1984–2008) average annual precipitation is 580 mm, half of which occurs during July to September. The soil is a Heilutu silt loam (Calcarid Regosol according to the FAO classification system or Ultisol according to the U.S. soil taxonomy), with 45 g kg^{-1} sand, 656 g kg^{-1} silt, 309 g kg^{-1} clay, 8.4 pH, 105 g kg^{-1} $CaCO_3$, 10.5 g kg^{-1} organic C, 1.0 g kg^{-1} total N, and 1.4 Mg m^{-3} bulk density at the 0–30 cm depth at the beginning of the experiment.

2.2. Treatments and crop management

The experiment design has been described in detail by Fu et al. (2017). In brief, seven crop rotations with rotation lengths of 1–8 yr (Table 1) were arranged in a randomized complete block design with three replications. Each phase of the crop rotation was present in every year. As a result, the number of plots in each crop rotation was also proportional to the length of the crop rotation. Each plot had 10.3 m by 6.5 m size separated by 0.5 m strip, and each block was separated by 1 m strip.

Crops were planted by hand under conventional tillage using animal-drawn (first 16 yr) and hand tractor-drawn (second 14 yr) plows to a depth of 10 cm. Crops were planted at 20 cm row spacing, except for corn and potato which were planted at 70 cm spacing. Plant populations were 2.23, 0.60, 0.04, and 0.50 million plants ha^{-1} for winter wheat, pea, corn, and potato, respectively, and seeding rates were 28, 9, and 38 kg ha^{-1} for millet, alfalfa, and sainfoin respectively. At planting, chemical fertilizers were broadcasted to winter wheat, corn, millet, and potato using urea (46% N) and monoammonium phosphate (11% N, 23% P) at rates of 120 kg N ha^{-1} and 20 kg P ha^{-1}. Pea, sainfoin, and alfalfa also received N and P from monoammonium phosphate at 10 kg N ha^{-1} and 20 kg P ha^{-1}, respectively. Because of high soil K content, no K fertilizer was applied. Weed management was done by hand before, during, and after crop growth. Pesticides were applied as needed to control pests.

Winter wheat, pea, corn, and millet were harvested by hand from the entire plot by cutting plants at a height of 2 cm above the ground. A portion was oven dried at 70 °C for 7 d to determine the dry matter weight which was used as a conversion factor for calculating total biomass (grain + leaves + stems) yield. Grain yield was determined after separating grains from straw or stubble by threshing plants and oven drying a portion of the grain at 70 °C for 7 d. Biomass (stems + leaves) yield was determined by deducting grain yield from total biomass yield. Potato yield was determined by hand harvesting potato tuber from the entire plot at field moisture content after separating the aboveground biomass, a portion of which was oven-dried at 70 °C for 3 d to determine dry weight. After grain harvest, aboveground biomass (stems and leaves) of all crops were removed. Sainfoin and alfalfa were harvested by hand one to two times a year for forage from the entire plot, depending on precipitation and biomass growth. A portion was oven-dried at 70 °C for 3 d to determine dry weight, from which biomass yield was determined. Total biomass yield was determined as the sum of individual cuttings. Annualized biomass and grain yields for a rotation were calculated by dividing total biomass and grain yields of all crops by the number of crops within the rotation in a year and mean annualized biomass and grain yields were calculated by averaging annualized biomass and grain yields of all crops for a rotation across years. For grain yields in SWWS and A4PoW3, only grain yield of winter