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Plastic film mulch promotes high alfalfa production with phosphorus-saving and low risk of soil nitrogen loss

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ABSTRACT

Plastic film mulch and phosphorus (P) fertilization usually increase alfalfa (*Medicago sativa* L.) forage yield in semi-arid regions by improving soil moisture and P availability. However, this does not always occur. The present study explored the P level for highest forage yield under film mulch and the mechanism underlying yield decrease at high P levels. A six-year study was conducted with randomized blocks of split-plot design with and without plastic film mulch as main plots: M0, no film mulch with flat planting; and M1, film mulching with ridge-furrow field regimes. Four P rates were applied in sub-plots: P0, P1, P2 and P3 with 0, 9.73, 19.3 and 28.9 kg P ha^{-1}, respectively. Film mulch greatly increased forage yield, resulting in 14% higher yield in M1P0 than in M0P3. Forage yield under mulching decreased for 19.3 and 28.9 kg P ha^{-1}. The P rate for maximum yield was 16.1 kg P ha^{-1}. Soil total nitrogen (N) and inorganic-N decreased at 19.3 and 28.9 kg P ha^{-1} with mulching compared with 9.73 kg P ha^{-1}, and the latter was about 90% lower than that of alfalfa lands in semi-humid region. Soil microbial biomass carbon (C) and C/N ratio in microbial biomass in mulched P2 and P3 subplots were significantly lower than for P1. With mulching, soil organic C mineralization was significantly less for P3 than for P1 and P2. Shoot N/P ratio decreased with increasing P with mulching. Thus shoot N uptake for P2 and P3 mulched plots was associated with low soil N availability. It is concluded that the highest forage yield was obtained with mulching, P-saving and low risk of N loss on the semiarid Loess Plateau.

1. Introduction

Alfalfa (*Medicago sativa* L.) is a high-quality forage legume and the market demand for forage has been increasing in recent years (Zhang et al., 2009). Alfalfa is beneficial to sustainable development of agro-ecosystems by increasing soil carbon (C) and nitrogen (N) stocks and conserving soil and water resources, thus reducing environmental risk (Fan et al., 2011; Zhang et al., 2009; Jia et al., 2006a). However, alfalfa forage yield in semiarid regions is usually low due to poor soil conditions and limited rainfall (Fan et al., 2016; Jia et al., 2006a).

Plastic film mulch and phosphorus (P) fertilization are two main management practices for improving crop growth and yield in semi-arid regions (Li et al., 2018; Wang et al., 2018; Fan et al., 2016; Jia et al., 2006b). Plastic film mulch can increase soil temperature in the upper 5 cm by 2.9 °C during the first 20 days of mulching (Li et al., 1999). The use of film mulch has greatly contributed to grain yield increase of wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and flax (*Linum usitatissimum* L.) by improving soil properties (Luo et al., 2018; Mo et al., 2018; Zhou et al., 2012; Li et al., 1999). Furthermore, the ridge-furrow system mulched with plastic film increased alfalfa forage yield in this region by improving soil water and temperature conditions, reducing soil water evaporation and absorbing more water from the deep soil (Jia et al., 2006b).

Fertilization with P has been used widely in the Loess Plateau since 1980s and has increased crop yield by a large margin due to low concentration and mobility of available P in the soil (Jia et al., 2006b; Li et al., 2004). It has increased shoot P concentration, P uptake and forage yield in both young and old alfalfa stands (Fan et al., 2016). A long-term alfalfa study showed that 26 kg P ha^{-1} applied annually significantly increased cumulative dry matter yield over 24 years by 7.78 Mg ha^{-1} on the Loess Plateau of northern China (Fan et al., 2011). Griffiths et al. (2012) reported that P application increased soil microbial C, N and P and altered microbial community structure in a grazed grassland, resulting from increased net primary production. P

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addition also increased soil microbial activities and altered the microbial community composition in upland grasslands (Rooney and Clipson, 2009).

Nutrient limitation to plant productivity and other ecological processes is widespread in terrestrial ecosystems, and N and P are the most common limiting elements, either individually or in combination (Liu et al., 2012; Han et al., 2005). Alfalfa has the ability to fix atmospheric N to biologically-available forms through its symbiotic relationship with specific rhizobia (Fan et al., 2016). Soil nutrient limitations can affect N fixation by reducing the growth of N-fixing bacteria, nodule formation and function, as well as affecting host plant growth (Rashid et al., 2016). Soil P limitation decreases nitrogenase activity in N-fixing bacteria because both autotrophic and heterotrophic bacteria require high amounts of ATP for cellular N fixation (Rashid et al., 2016). Soil microbes, consisting largely of a consortium of bacteria and fungi, act as both a source and a sink of available nutrients (Li et al., 2015). Most of the annual nutrient requirements of plant production are supplied via decomposition of soil organic matter by soil fungi and bacteria (Cleveland et al., 2002). However, microbial utilization of C substrates can be limited by soil nutrients (Liu et al., 2012). The microbial biomass contains the largest part of the biologically active N in soil, and N incorporation into soil microbes is strongly affected by soil N availability (Joergensen et al., 1995) and soil microbial N limitation increases soil organic matter decomposition (Craine et al., 2007). Under low soil N availability, soil microbes meet their N demand by increasing decomposition of organic sources (Li et al., 2017). Thus, soil nutrient limitations will severely affect plant growth, N fixation and soil organic matter decomposition. The ratio of N to P concentration (N/P ratio) in plant biomass has been proposed as a diagnostic tool for nutrient limitation (Güsewell, 2004; Koerselman and Meuleman, 1996). An alfalfa field experiment investigating N and P fertilization showed that lower relative forage yield was more likely with shoot N/P ratio > 17, and P addition was required to boost forage yield (Fan et al., 2016).

We previously found that plastic film mulch and P fertilization could increase alfalfa forage yield by improving soil water conditions, P availability and microbial processes (Gu et al., 2018). We also found an interesting phenomenon of decreased forage yields at moderate and high P application levels under film mulch. A large amount of N in soil is removed by aboveground forage harvest without any form of N input. Moreover, Fan et al. (2016) showed in the similar area to the present study that alfalfa was not inoculated and no nodulation was observed in the top 20 cm of the soil profile. Thus, we hypothesize that alfalfa forage yield may be limited by low soil N availability when using plastic film mulch and P fertilization. The present study aimed to (1) identify the threshold of P application beyond which forage yield decreased under film mulch, (2) explore soil N availability influenced by film mulch and P fertilization, and (3) investigate why forage yield decreased at moderate and high P application levels under film mulch.

2. Material and methods

2.1. Site description and experimental design

A six-year field experiment was initiated in 2011 at the Semi-arid Ecosystem Research Station (36°02′N, 104°25′E, above sea level 2400 m) at Zhonglianchuan, Yuzhong County, Gansu Province, China (Fig. 1). The site has a medium temperate semi-arid climate, with mean annual air temperature of 6.5 °C, mean monthly maximum temperature of 19.0 °C (July) and mean monthly minimum temperature of –8.0 °C (January). The monthly mean precipitation, annual precipitation and growing season of alfalfa are shown in Fig. 2. The annual precipitation in 2011, 2015 and 2016 was lower than the mean annual precipitation (315 mm) but higher than that in 2012, 2013 and 2014. The soil at the study site is classified locally as Calcic Kastanozem (Siltic) (IUSS Working Group WRB, 2015) or rusty dark loessial soil according to the Chinese soil taxonomy, with field water-holding capacity of 19.6% (gravimetric) (Shi et al., 2003). The soil properties prior to the establishment of the experiment were displayed in Table 1.

The experiment was in randomized blocks of split-plot design with and without plastic film mulch as main plots: M0, no film mulch with flat planting; and M1, film mulching with ridge-furrow field regimes. Four P application levels were assigned to sub-plots P0, P1, P2 and P3 with 0, 9.73, 19.3 and 28.9 kg P ha^{-1} respectively. Additional details are provided in Fig. 1. The highest rate for P application was based on the P fertilizer level applied to maize for maximum above-ground biomass in the local area. As the quality of the P fertilizer ($CaP_2H_4O_8$) sourced from the market was unstable, we measured the P content in the P fertilizer applied each year, and the actual content of applied P is displayed in Table 2. Before sowing in 2011, 34.5 kg N ha^{-1} and half of each corresponding P level was distributed and plowed to 20 cm depth for each plot. No fertilizers were applied to the soil except for P in the following years. From 2012 to 2013, the P fertilizer was applied to ridges to avoid harming root systems of young alfalfa in furrows. However, from 2014 to 2016, the P fertilizer was applied in furrows, close to root systems of alfalfa. The ridges were 30 cm wide and 15 cm high, and acted as rainwater harvesting zones. The furrows were V-type as alfalfa planting zones. The ridges were formed and covered with plastic film (0.008 mm thick polyethylene film) on 29 June 2011, and at the same time, local alfalfa cultivar ‘Longzhong’ was sown at 15 kg ha^{-1}. Each year after 2011, when alfalfa returned to green (mid-April), the plastic film of the previous year was removed. New film was mulched on the ridges by hand with two adjacent plastic films jointed in the furrow; the joint was fixed by placing soil on the top of the film. Each plot was 10 m long and 3 m wide, and each treatment was replicated three times. Before 2011, the experimental field was farmland cultivated with maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), flax (*Linum usitatissimum* L.) and other crops in rotation.

2.2. Sampling and measurements

2.2.1. Alfalfa forage yield and shoot N and P concentrations

Each year, aboveground forage was harvested at the full-bloom stage twice (mid-July and mid-October, respectively). At each harvest, plants from a randomly selected 2 m section of a row were sampled at ground level except for the edge rows. This was repeated three times for each plot. The fresh weight of each forage sample was then measured. About 200 g of forage was weighed and oven-dried at 105 °C for 0.5 h (de-enzyme) and then at 75 °C for a minimum of 72 h (Luo et al., 2018; Fan et al., 2016) to calculate the dry weight/fresh weight ratio. The forage yield of alfalfa (kg ha^{-1}) was determined by land area on a dry mass basis, and the yearly forage yield was the sum production of mid-July and mid-October. At each harvest, the remaining alfalfa not used for forage samples was cut also at ground level and removed from plots immediately after alfalfa sampling.

The oven-dried forage samples were ground to a fine powder using an Ultra centrifugal mill (ZM 200, Retsch Gmbh., Düsseldorf, Germany) to measure shoot N and P concentrations. Shoot N and P concentrations were respectively determined using the Auto-Kjeldahl and the molybdenum-antimony anti-spectrophotometry methods (Xu et al., 2016) after H_2SO_4–H_2O_2 digestion (Thomas et al., 1967). Shoot N uptake (kg ha^{-1}) was the product of shoot N concentration (g kg^{-1}) and forage yield (kg ha^{-1}).

2.2.2. Soil samples

In each plot, three sub-samples from ridge soils and three from furrow soils (each 8 cm in diameter and 20 cm in depth) were taken randomly and bulked to form a composite soil sample. Each treatment had three replicate plots. The times of sampling in April and P fertilization were 8 April and 10 April respectively. Root fragments and plant debris were removed from the soil samples before screening with a 2 mm sieve. Each soil sample was divided into two parts: one was stored at 4 °C for determination of soil inorganic-N (nitrate-N + ammonium-