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Forage production, quality and water-use-efficiency of four warm-season annual crops at three sowing times in the Loess Plateau region of China

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ABSTRACT

Increasing demand for livestock products is driving development of livestock systems worldwide. That requires improved and new forage production options. The Loess Plateau region in central-northern China is an important area for livestock production, as it supports11% and 19% of the country's cattle and sheep, respectively (China statistical yearbook 2014). The rain-fed semi-arid environment of the Loess Plateau means that maximizing the water-use-efficiency (WUE) of forage production is vital to guarantee enough fodder supply the livestock demand. A three-year field experiment in north-west Loess Plateau compared forage production, water use and water-use-efficiency as well as crude protein (CP) content of forage maize, Sudan grass, foxtail millet and Japanese millet sown at three sowing dates according to the opening rain during 2011–2013. On average, forage maize produced the highest biomass (12.1 t ha^{-1}) and had the highest WUE (43.4 kg DM ha^{-1} mm^{-1}). This was followed by Sudan grass (7.8 t ha^{-1}; 26.5 kg DM ha^{-1} mm^{-1}), Japanese millet (6.7 t ha^{-1}; 26.2 kg DM ha^{-1} mm^{-1}) and foxtail millet (6.7 t ha^{-1}; 24.6 kg DM ha^{-1} mm^{-1}). Optimizing sowing date played an important role in maximizing forage production and WUE of all tested forages. Compared to the earliest sowing date, a delay of two weeks reduced forage production by 17% in maize, 35% in foxtail millet, and 16% in Japanese millet. A delay of four to six weeks reduced biomass yield by 58% in maize, 57% in foxtail millet, and 56% in Japanese millet. Late sowing also greatly reduced WUE of forage maize and foxtail millet by 33% and 42%, respectively, when compared to early sowing. The middle sowing date maximized forage production and WUE of Sudan grass in two of the three growing seasons, which was 20% and 38% higher than the early and late sowing, respectively. Late sowing in all forages reduced crop water use by 42–57 mm compared to the early sowing. Among four test crops, CP of Sudan grass (7.9%) and forage maize (7.7%) was higher than foxtail millet (6.8%) and Japanese millet (6.7%). Compared with early sowing, CP_f in late sowing significantly increased in Sudan grass and decreased in Japanese millet, in contrast, no evident sowing date effect was found in forage maize and foxtail millet. This study showed that all four warm-season annual grasses had high forage production potential, forage maize was the most reliable and efficient option. Forage maize and the millets could easily be integrated into existing cropping systems and provide opportunities as both grain and forage-producing crop to provide added flexibility for farmers.

1. Introduction

Sustainable development of animal production systems is defined as balancing the needs of animal production of the current generation and those of future generations and securing what is biologically and physically achievable in the long run (Gamborg and Sandøe, 2005). Population growth is increasing the demand for food and animal products worldwide. To meet this increased demand and to maintain a steady growth in animal numbers, while ensuring sustainable development of animal production, forages well adapted to the local environments with high yielding and rich nutrition are needed. Arid and semi-arid zones take up approxi-

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mately 30% of the world's land surface. They are also important world sources of animal and crop production (Saco et al., 2007).

The Loess Plateau region of north-western China is an important livestock production base (Squires and Limin, 2010). It produces 11% (12,311,000) and 19% (56,525,000) cattle and sheep of China, respectively (China statistical yearbook 2014). However, limited water constrains forage yield in this area. Scientists attempted to use conservation tillage practices, rainfall harvesting and mulching technologies to improve water use and increase yield (Su et al., 2007; Wang et al., 2009). Rotation and intercropping were also conducted to raise the production (Lu et al., 2003; Xu et al., 2008). However, systematic and scientific forage management methods are still lacking, and forage options are very limited. Because of poor management, unpredicted rainfall often leads to failed establishment.

The Gansu region of north-western Loess Plateau is a typical semi-arid region, dominated by rain-fed cropping systems [accounts for 99% of 3,546,800 ha arable land (Gansu province development yearbook 2015)], with highly variable seasonal rainfall, which is mainly concentrated from June to September. The average annual rainfall ranges from 300 to 600 mm (Ao et al., 2007). There are 4,546,000 cattle and 19,605,000 sheep while only 1,350,229 ton fodders were produced (China fodder industry yearbook 2014). Much of the highly erodible arable land has been seriously degraded by continuous farming and over-grazing (Zhang et al., 2007). To solve these problems, the Chinese government introduced the Grain-for-Green Program that commenced in the 1990s. This program promoted pen feeding of livestock, banned open grazing, and provided financial incentives to encourage the return of marginal cropping land on the high slopes to grassland and forest (Qu et al., 2011,). A result of the grazing bans combined with the increasing demand for livestock production in the cropping systems of northwestern Loess Plateau, is the need to access more diverse forage sources. However, with limited land, to increase livestock production, forage production must complement the existing cropping systems and not compete significantly with the subsistence grain production that is vital to the survival of communities within this region (Komarek et al., 2015).

Annual forages grown in rotations with grain crops or crops that could be used for a dual purpose (Tian et al., 2012) could be effective options for increasing forage production in mixed cropping system and provide fodder and grain for pen feeding of livestock (Waldron et al., 2007). This would also benefit local households by reducing livestock feed deficits and therefore supplementary feeding costs, and benefit overall economic returns for local households (Komarek et al., 2015).

Currently, alfalfa (*Medicago sativa* L.) is the major forage sown in the Loess Plateau region and contributes a large proportion of all forage used by livestock producers (Robertson et al., 2015). However, alfalfa normally consumes more water than local annual rainfall, and water-use-efficiency (WUE) is less than from annual forage-based systems (Jia et al., 2009), and therefore its production varies yearly with the highly variable rainfall (Li, 2002). Furthermore, the production of alfalfa is insufficient to consistently meet the demand of increasing livestock numbers (Komarek et al., 2012). To supplement alfalfa supply, forages with good protein value, high yield potential, and high efficiency of water use are urgently needed. Annual forages that can be grown in crop rotations provide an alternative to perennial pastures and offer high forage yields, are low cost and easy to manage. Forage maize (*Zea mays*), foxtail millet (*Setaria italica*), Sudan grass (*Sorghum sudanense* Stapf., S) and Japanese millet (*Echinochloa crus-galli var. frumentacea*) are four annual warm-season forages with wide spread use in China and could be easily implemented within the cropping systems to produce forage.

Forage production under rain-fed cropping system are associated with limited planting opportunities and highly variable rainfall during the crop cycle. Forage sown early may be at risk of poor establishment due to the frost; however, those sown late may suffer from frost during flowering or grain filling (Muchow et al., 1994). Therefore, quantifying the effect of sowing date on yield is critical for farmers to make planting decisions, which maximizes crop growth, quality, water capture and hence WUE (Ding et al., 2016; Kirkegaard et al., 2016; Reta-Sánchez et al., 2015).

Water use (WU) and WUE are two key indicators used to evaluate crop responses to water limited environments (Steiner and Hatfield, 2008). Crude protein content (CP) is the most important nutrient for livestock. WUE and CP are important characteristics when determining the management of annual forages in water limited environments. Agronomic management, such as planting date can greatly improve WUE of many grain crops in the north-west Loess Plateau region (Deng et al., 2006; Su et al., 2007; Wang et al., 2009). However, this is only well documented for maize (Zhang et al., 2014), and little information exists for Sudan grass, foxtail millet and Japanese millet.

In the north-west Loess Plateau, rain-fed crop production and pen fed animals are main agricultural components of the local economy (Shan and Chen, 1993; Shi and Shao, 2000). Maize (*Zea mays* L.), sorghum (*Sorghum* spp.), wheat (*Triticum* spp.) and soybean (*Glycine max*) are the major crops in the cropping system (Huang et al., 2011; Yang et al., 2014; Zhang et al., 2013). However, local farmers generally harvest grains for food and use the low quality straws as forage, which cannot satisfy the nutrition demand of animals. Therefore, we selected a local forage (foxtail millet) and introduced three new forages (forage maize, Sudan grass and Japanese millet) to diversify annual forages and provide more food for animals. Forages are normally planted around the end of April or the beginning of May by farmers in Loess Plateau. But the variable planting date, results from the uncertainty of the rainfall, restricts crop production and increases the potential risk of poor yield. Therefore, the objectives of this experiment were: 1) to compare biomass production and water use efficiency of four annual warm-season grasses which could be used as forage crops, forage maize, Sudan grass, foxtail millet and Japanese millet; 2) to quantify water consumption changes during the growing season amongst the forages; and 3) to investigate the effect of sowing date on the forage production, WUE and CP for the four annual forage grasses.

2. Materials and methods

2.1. Site details

The field experiments were conducted at Lanzhou University Quzi experimental station near the township of Huanxian, Gansu, China (36°20′N; 107°21′ E) over three consecutive years, 2011, 2012 and 2013. The soil type was a typical Huangmian soil (Zhu et al., 1983) (Entisol of US classification) and represents the major cropping soil of the Loess Plateau. The soil is an infertile sandy loam, and was sampled pre-planting at a depth of 0.2 m or 0.1 m (bulk density) using an auger. The organic carbon content was 4.9 g kg^{-1}, total N 0.67 g kg^{-1}, available P 11.6 mg kg^{-1}, available K 143 mg kg^{-1}, pH 8.5, and bulk density 1.3 g cm^{-3}. The soil characteristics were determined according to methods detailed in Page et al. (1982).

The experimental site had previously grown maize and wheat. No differences in soil water status were measured between these various plots at the initiation of this experiment. Rainfall (mm), incoming solar radiation (MJ m^{-2}), maximum and minimum temperature (°C) were recorded daily by PC200W automatic mete-