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Soil water, soil nitrogen and productivity of lucerne–wheat sequences on deep silt loams in a summer dominant rainfall environment

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ABSTRACT

The management of water and nutrients in farming systems that incorporate alternating phases of lucerne pasture with annual grain crops posses additional challenges to rotations with annual crops only. Strategies for balancing water and nutrient resources within and across rotations will be governed by local soil, climatic, skill and economic constraints. On the Loess Plateau in China, farmers have been encouraged to grow lucerne (*Medicago sativa*) to reduce soil erosion and improve soil fertility on cropping lands but with little supporting information on how to incorporate lucerne within subsistence cropping systems. Lucerne–wheat rotation experiments were established at two locations in Gansu Province and examined the yield of lucerne and wheat along with changes in soil water and nitrogen (N). Lucerne proved to be well adapted to the high water holding capacity soils and summer dominant rainfall environment of the region with annual production of around 12 t ha^{-1} at the higher rainfall site (Qingyang). An old (30 years), sparse stand of lucerne growing in the drier location (Dingxi) was much less productive, being dependent on incident rainfall. Apparent water use efficiency (WUE) of lucerne over individual harvest periods ranged from 4 to 56 kg ha^{-1} mm^{-1} at Qingyang. Lucerne was able to dry the soil to the crop lower limit (CLL) to depths of 3 m and there was clear evidence that lucerne roots were extracting water below this depth.

Wheat following lucerne is subject to low plant available soil water at sowing, unless substantial rainfall occurs, but climate variability in this region makes this difficult to predict. Rain which falls during short fallow periods after lucerne termination provides opportunity for N fertiliser responses, which may be greater after large rainfall events that lead to N leaching. In drier environments such as Dingxi, deep drainage and leaching appear unlikely under rotations which incorporate lucerne, and here evaporative water loss from the soil surface presents a more significant management challenge. The overall variability in seasonal rainfall at both sites, even within the short period of this study, indicates that an adaptive management strategy may be required, rather than fixed rotations. Systems modelling may shed further light on the most useful strategies to manage crop rotations within this variability.

1. Introduction

The integration of perennial forages, such as lucerne, with annual cropping systems has been proposed as a solution to a number of threats to the sustainability of crop production in dryland environments. In Australia, the focus on lucerne-based crop rotations has been the minimisation of deep water losses to rising groundwater systems (Latta et al., 2002; Robertson, 2006), which have been the primary cause of dryland salinity across 2 million ha of the Australian cropping belt. In the Loess Plateau in north-western China, cropping systems are dominated by dryland wheat, but extensive stubble removal, tillage and cultivation of sloping land contribute to severe soil erosion problems, declining soil fertility (Fan et al., 2005) and low or uncertain cereal grain

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yields for many farmers (Liu, 1999). To address these problems the central government introduced a revegetation campaign to encourage farmers to convert sloping cropland to forest or pasture, in exchange for cash and grain (Feng et al., 2003). Lucerne (*Medicago sativa*) is adapted to a wide range of environments in the western Loess Plateau and the forage is good for livestock production and cash income under this policy. In 2003 lucerne was grown on 1 million ha in China, a 31% increase compared to 2001 (Jia et al., 2006).

However, in rainfed environments, there are problems in integrating lucerne with the subsequent cropping phase of pasture–crop sequences, since lucerne produces residual effects on both soil water and N fertility—these problems are the topic of this paper. Lucerne can deplete soil moisture, reducing both lucerne productivity and that of subsequent annual grain crops (McCallum et al., 2001). Hence, a key challenge for rainfed cropping systems is to develop strategies that make optimal use of soil water and nutrients across rotations (Li et al., 2002; Connor, 2004). However, in lower rainfall environments when lucerne is grown in rotation with wheat, it is important to terminate lucerne growth early enough to provide opportunity for soil water accumulation prior to cereal sowing, otherwise wheat yield after lucerne may be depressed (Liu et al., 2000; Hirth et al., 2001). Soil water recharge is affected by soil type, but more so by seasonal conditions in most regions (Tennant and Hall, 2001; Li et al., 2002). In China, previous research (Zhang and Lu, 1996) demonstrated soil water deficits and lower crop yields immediately after long-term lucerne reduced following crop yields, yet the authors suggested that 5–6 years might be a suitable period for growing lucerne on slope-land in a 380 mm rainfall environment.

In the last 15 years there has been an increase in our quantitative understanding of the productivity of lucerne and crops in integrated systems, in relation to biomass productivity, water use and crop–soil nitrogen dynamics (e.g. Angus et al., 2001; Ward et al., 2006). However, much of this understanding is based on Australian experience in agro-climatic zones and on soil types that do not apply elsewhere in the world. Australian crop–lucerne systems are based on Mediterranean-type winter-dominant rainfall patterns (Connor, 2004). In addition, soils are often shallow or possess significant subsoil constraints to both lucerne and crop root systems (Tennant and Hall, 2001; Latta and Lyons, 2006), with consequences for soil water and nitrogen balances (Dunin et al., 2001; Dolling et al., 2005a,b). In environments, such as those encountered on the Loess Plateau, rainfall patterns are summer dominant (Huang et al., 2003) and soils are deep silt loams (Zhu et al., 1983) with no known constraints to root system penetration. Consequently, it is difficult to extrapolate the quantitative understanding from the Australian experience to these contrasting circumstances.

In order to address this limitation two field experiments were established on the Loess Plateau, one in a winter wheat growing area (Qingyang) and one in a drier environment where spring wheat is grown (Dingxi). Measurements of soil water, pasture and crop biomass, water use efficiency (WUE), and grain yield of wheat were undertaken from 2000 to 2004. Results are compared and contrasted with those from other global environments. A specific hypothesis we tested was that an earlier terminated perennial pasture (forage lucerne) should result in significantly more stored soil water and mineralised nitrogen, and a higher grain yield for following wheat crops.

2. Materials and methods

Two contrasting environments where the soil is benign for crop growth were chosen in Gansu Province, China, to examine the resource use efficiency of perennial lucerne–crop rotations. The environments differed in their position in the Loess landscape, with Qingyang (35° 40′N, 107° 51′E, elev. 1298m a.s.l.) on tableland in eastern Gansu, and Dingxi (35° 28′N, 104° 44′E, elev. 1971m a.s.l.) occupying loess hills in central Gansu. Winter wheat is grown in Qingyang but this is not possible in Dingxi where there is less snow cover and more severe radiation frosts in winter. Instead spring wheat is grown in Dingxi where it is considerably drier than in Qingyang. We first detail experimental protocols for Qingyang, and then highlight differences at the Dingxi experimental site. Field experiments were conducted at the two sites from 2001 to 2004.

2.1. Qingyang

Qingyang Experimental Station (35° 40′N, 107° 51′E; elevation, 1298 ml) Lanzhou University, is in the rainfed agricultural production zone of the western Loess Plateau. Average annual long-term precipitation is 561 mm, varying from 320 to 820 mm over the past 43 years. The mean number of frost-free days is 255, which approximates the length of the annual crop growing season. Daily rainfall, solar radiation and temperature were recorded during the period of study using an automatic weather station on site.

The soil at Qingyang is a Heilu soil (see Zhu et al., 1983) (Entisol of US classification), being an infertile sandy-loam with 70% silt, and represents the major cropping soil of the district. Soil properties (Table 1) show a uniform profile with high pH, and low organic carbon and low total nitrogen. Although total phosphorus is high (0.08% at the surface), available P (Olsen) was low at the start of the experiment. Soil bulk density, determined by inserting thin-walled cylinders horizontally into the wall of a soil pit, is moderate and constant down the profile at about 1.3 g/cm^3. Bulk density was used to convert gravimetric soil water to volumetric soil water, and inorganic nitrogen concentration to mass of inorganic nitrogen in each soil layer.

2.1.1. Experimental design

An existing lucerne ley (*Medicago sativa*, local landrace Longdong) established in the spring of 1997 was used as the basis for the experiment at Qingyang. Plant density was 7–8 plants/m^2. In 2001 a completely randomised block design was imposed over the lucerne ley, with plot sizes of 20 by 4 m and four replicates of the following treatments over the next 3 years (Fig. 1):

- Continuation of the established lucerne stand (L),
- winter wheat cropping phase initiated after 4 months of fallow following lucerne removal in May 2001 (4fW),
- winter wheat cropping phase initiated after 1 month of fallow following lucerne removal in August 2001 (W),
- and finally a 2-year fallow initiated in May 2001 which was not sown to winter wheat until August 2003 (FW).

All winter wheat (cv Xifeng No. 24) was sown under conventional tillage (one working before sowing and one after harvest), at a rate of 187 kg/ha, a depth of 2.5 cm and in rows 15 cm apart. Sowing dates were 14th September 2001, 17 September 2002, and 24 September 2003. Phosphate was applied at sowing of each wheat crop at 46 kg P/ha. Wheat plots were split for N as detailed in Fig. 1, with di-ammonium phosphate being the source of N in the first year of wheat and urea fertiliser thereafter. There were no significant pests or diseases evident and weeds were controlled by hand in both the lucerne, wheat and fallow plots. Lucerne removal was achieved by hand hoeing.

2.1.2. Soil water and nitrate measurement

The volumetric soil water content (SWC) was measured using a neutron moisture meter (NMM, Campbell Pacific, CPN 503). In