Industrial Crops & Products 109 (2017) 233–240

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Optimized nitrogen fertilizer application improves yield, water and nitrogen use efficiencies of winter rapeseed cultivated under continuous ridges with film mulching

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ARTICLE INFO

Keywords:
Continuous ridges with film mulching
Nitrogen fertilizer
Seed yield
Water use efficiency
Nitrogen use efficiency
Winter rapeseed

ABSTRACT

The continuous ridges with film mulching (CRFM) cultivation pattern has been rapidly adopted for production of winter rapeseed (*Brassica napus* L.) in northwest China due to significant improvements in soil moisture, water use efficiency (WUE) and yield. However, in many cases, the crop yield, WUE, and nitrogen (N) use efficiency (NUE) were still very low under CRFM cultivation due to the deficiency of N nutrients. The objective of this study was to investigate the response of winter rapeseed to six N application amounts: 0 (N0), 60 (N60), 120 (N120), 180 (N180), 240 (N240), and 300 (N300) kg N ha^{-1}. Aboveground dry matter and shoot N uptake at flowering and harvest, yield, oil yield, ET, WUE_Y, and WUE_{OY} were all significantly higher in N180, N240, and N300 than in N0, N60, and N120. Average WUE_Y, WUE_{OY}, N partial factor productivity and N recovery efficiency did not differ markedly between N180 and N240, but were all significantly higher than in N300. However, average seed yield and oil yield in N240 were 11.9% (427 kg ha^{-1}) and 9.7% (144 kg ha^{-1}) significantly higher than in N180. In addition, seed oil and protein content in N240 did not differ significantly from N180 and N300. These results suggest that the optimal N application amount for winter rapeseed under CRFM cultivation pattern is 240 kg N ha^{-1}. This rate simultaneously improves seed yield, oil yield, WUE_Y, WUE_{OY} and NUE.

1. Introduction

Rapeseed (*Brassica napus* L.) produces a kind of vegetable oil that is used for human consumption, and is a source for biodiesel (Zhang et al., 2012). Because of this, rapeseed is grown around the world, and the global planting area has remained stable or increased in some areas in recent years (FAOSTAT, 2016). In 2014, Canada, China, and India had the largest rapeseed planting areas globally, with about 8.1, 7.6, and 6.6 million hectares, respectively (FAOSTAT, 2016). However, the average rapeseed yields in China, Canada, and India were as low as 1947, 1926, and 1185 kg ha^{-1}, respectively (FAOSTAT, 2016), which might be due to low water and nitrogen use efficiencies, especially in arid and semi-arid regions (Jing and Dong, 2004; Gu et al., 2016a).

Mulching is an important cultivation method to improve yield, soil moisture, and water use efficiency (WUE) in rapeseed cultivation (Su et al., 2014; Gu et al., 2016a). Su et al. (2014) reported that straw mulching increased soil moisture at 0–30 cm depths by about 8.4% throughout the growth stages of rapeseed, and ultimately improved seed yield by 25.6%. Gu et al. (2016a) found that values for soil water content, rapeseed yield, and WUE in film mulching treatments were 3.1–7.2%, 20.4–70.7%, and 34.9–122.0% higher than in the conventional cultivation pattern.

Rapeseed yield is also heavily dependent on nitrogen (N) availability. In order to produce 0.1 t of seeds, rapeseed crops need to accumulate 6 kg N (Rathke et al., 2006), meaning that farmers apply large amounts of N fertilizer to produce high rapeseed yields. Adding N fertilizer can increase rapeseed yields by 1.1–2.4 t per hectare (Rathke et al., 2005; Zou et al., 2011). However, N fertilization is inefficient, and excess N in the soil is lost through leaching, gasification, and runoff (Zhu and Chen, 2002), which cause serious environmental problems. Thus, determining the optimal application rate for N fertilizer is critical for rapeseed production. Many researchers found that application of 150–180 kg N ha^{-1} could significantly increase yield and oil production, as well as maintain a high NUE of rapeseed under the conventional cultivation pattern (Barłóg and Grzebisz, 2004; Li et al., 2011; Schuster and Rathke, 2001; Zou et al., 2011). When applied at 210 kg N ha^{-1}, straw mulching significantly increased yield, N uptake, and N use efficiency (NUE) of rapeseed though more N was lost due to ammonia volatilization because of topdressing (Su et al., 2014).

Previous studies only investigated the application rate of N fertilizer

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http://dx.doi.org/10.1016/j.indcrop.2017.08.036
Received 15 June 2017; Received in revised form 9 August 2017; Accepted 18 August 2017
0926-6690/

in rapeseed cultivated under straw mulching and conventional patterns (Fismes et al., 2000; Hocking, 2001; Rathke et al., 2005; Su et al., 2014; Zou et al., 2011). However, little is known about N uptake, NUE, and how different N rates affect yield and oil production of rapeseed under the film mulching planting pattern, especially under the continuous ridges with film mulching (CRFM) cultivation method, which has been proven to be appropriate for winter rapeseed in arid and semi-arid areas (Gu et al., 2016a). The goal of the present study was to determine how N fertilization affects yield, WUE, and NUE of rapeseed grown using CRFM cultivation. Our results will be used to manage N fertilization and to improve production of winter rapeseed.

2. Materials and methods

2.1. Experimental site

A field experiment was conducted over four years (September 2012 to May 2016) at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of the Ministry of Education (34°18′N, 108°24′E; 521 m a.s.l.), Yangling, Shaanxi, China. Mean annual precipitation in this region is 632 mm, with 60–70% falling from July to September, making this a typical rainfed region. Per year in this region, soil evaporation has a mean of 1500 mm; mean air temperature is 12.9 °C; and mean sunshine duration is 2164 h. Loamy soil is present at this site, and it has a filled capacity of 24% with a dry bulk density of 1.40 g cm^{-3}. Top-soil (0–20 cm) nutrient properties at the start of each growing season are in Table 1.

2.2. Experimental design

Six application rates of N (as urea) were used in this experiment: 0 (N0), 60 (N60), 120 (N120), 180 (N180), 240 (N240), and 300 (N300) kg N ha^{-1}. The N fertilizer was applied as a basal dressing to all plots. Four replicates of each rate were used (24 total plots), and the experiment was designed as a randomized block. Plots were 4 m × 5 m in size, and were spaced 1 m apart. Calcium superphosphate (P_2O_5 = 16%), potassium sulphate (K_2O = 51%), and borax (B = 11%) at rates of 90 kg P_2O_5 ha^{-1}, 120 kg K_2O ha^{-1}, and 15 kg B ha^{-1} were also used as basal fertilizers in each plot. No additional fertilization was used during the growth period.

The continuous ridges with film mulching (CRFM) method was used to plant winter rapeseed. Ridges were 20 cm high and 50 cm wide (Fig. 1). In each growing season, we ploughed the field and separated it into plots; applied fertilizers; and formed ridges. After these steps, a transparent plastic film (0.8 m wide and 0.008 mm thick) containing small holes every 0.3 m for rainwater infiltration, was laid manually over the ridge layer at the soil surface (Fig. 1). Shaanyou No. 107 seeds were planted by hand in plot furrows on 15 September 2012, 12 September 2013, 21 September 2014, and 16 September 2015. At the three leaves stage, seedlings were thinned manually, and at the five leaves stage, we determined that the plant density was 120 000 plants ha^{-1}.

Table 1
Nutrient properties in the 0–20 cm soil layer at the start of each growing season at the experimental site.

Soil property	Growing season			
	2012–2013	2013–2013	2014–2015	2015–2016
pH (water)	8.12	8.14	8.14	8.13
Organic matter (g kg^{-1})	12.35	12.78	12.18	12.57
Total N (g kg^{-1})	0.95	0.98	0.94	0.97
Alkali hydrolysable N (mg kg^{-1})	75.31	72.54	76.01	73.93
Available P (mg kg^{-1})	25.34	24.26	25.22	24.8
Available K (mg kg^{-1})	131.92	135.32	132.97	133.62

Each plot received 60 mm (at each irrigation) of irrigation water in the first season on 15 January and 5 April 2013, because of severe drought; 30 mm in the second season on 15 September 2013 to ensure seedling emergence, and none in the third and fourth seasons. Weed control was also performed in order to reduce yield loss. Plants were harvested on 20 May 2013, 22 May 2014, 23 May 2015, and 20 May 2016, and the plastic film was recycled.

2.3. Measurements and methods

2.3.1. Weather conditions

Daily rainfall and air temperatures during the winter rapeseed growing seasons were measured at Yangling National Meteorological Observing Station, which is located 50 m away from the experimental field. The monthly total rainfall and monthly mean air temperatures were calculated using these data.

2.3.2. Aboveground dry matter and shoot N uptake

Ten representative plants from each plot were cut at ground level at three growth stages: seedling (78 DAS in 2013–2014, 75 DAS in all other seasons); flowering (215 DAS); and harvest (247, 252, 244, and 246 DAS in 2012–2013, 2013–2014, 2014–2015, and 2015–2016, respectively). Plants were separated into leaves, stems, pod walls, and seeds. Plant tissues were first oven-dried to deactivate enzymes (30 min at 105 °C), and then dried to a constant weight (75 °C). The weights of dry leaves, stems, pod walls, and seeds were added together to obtain aboveground dry matter, and then these plant tissues were ground and digested with H_2SO_4-H_2O_2 (Bao, 2000). We used an automated continuous flow analyser (AA3, Seal, Norderstedt, Germany) to determine the N concentration in different tissues. Finally, we calculated shoot N uptake by multiplying the dry weight by the N concentration in different tissues.

2.3.3. Seed yield and oil and protein contents

To determine seed yield, plants at a size of 1 m^2 (1 × 1 m) from the middle of each plot were chosen at harvest, and were then sun-dried and threshed. Then, near-infrared reflectance spectroscopy (NIR System 5000, Foss, Denmark) was used to measure seed oil and protein content. Oil yield was calculated by seed yield × oil content.

2.3.4. Evapotranspiration (ET) and WUE

Soil moisture contents at depths between 0 and 200 cm were determined before planting and after harvest in order to calculate changes in soil water storage during the winter rapeseed growth period. Coring at 10 cm depth intervals was done manually between two plants in the same row. Soil moisture content was then calculated using the oven dry weight method (samples were dried at 105 °C).

Soil water storage was calculated using Eq. (1):

$$SWS = 10\Sigma g_i \times h_i \times \omega_i \quad (1)$$

Where *SWS* (mm) is soil water storage, γ_i (g cm^{-3}) is soil dry bulk density in each different soil layer, h_i (cm) is the soil thickness, ω_i (%) is gravimetric water content in each different soil layer, and i = 10, 20, 30,…, 200.

The soil water balance equation (Eq. (2)) was used to calculate the evapotranspiration of winter rapeseed (Heerman, 1985):

$$ET = I + P - D + SWS_0 – SWS_1 \quad (2)$$

Where *ET* (mm) is the evapotranspiration of winter rapeseed; *I* (mm) is the amount of irrigation; *P* (mm) is precipitation; *D* (mm) is deep drainage into the lower boundary of 200 cm (which was assumed to be negligible in this study because no heavy rains or irrigation occurred during the rapeseed growing seasons); and SWS_0 and SWS_1 (mm) are the soil water storages before sowing and after harvesting, respectively.