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Nitrogen Use in Durum and Selected Brassicaceae Oilseeds in Two-Year Rotations

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Abstract

Brassicaceae oilseeds can serve as potential feedstocks for renewable biofuels to offset demand for petroleum-based alternatives. However, little is known about oilseed crop yield potential and N use in semiarid, wheat (*Triticum* spp.)-based cropping systems that dominate the northern Great Plains (NGP). A 5-yr study was conducted in northeast Montana to investigate the yield potential of a direct seeded system of durum (*T. durum*Desf.) in rotation with either chemical fallow or three Brassicaceae oilseeds: camelina [*Camelina sativa* (L.) Crantz], crambe (*Crambe abyssinica* Hochst. ex R.E. Fries), and canola-quality *Brassica juncea* L. Overall, results from the study indicated that seed yield in the three Brassicaceae oilseeds tested in rotation with durum was related ($P < 0.001$; $r^2 = 0.68$) to a nitrogen recovery index (NRI), indicating the importance of nitrogen use (NU) efficiency in dryland oilseed production, and that *B. juncea* generally used N more efficiently than crambe and camelina. Similarly, NRI was related ($P < 0.001$; $r^2 = 0.72$) to grain yield in durum following oilseeds. Grain yield of durum following *B. juncea* was similar to durum following fallow and greater than durum following camelina or crambe. Durum following crambe tended to use N more inefficiently than durum following camelina, *B. juncea*, or fallow. Differences in yield and N use of durum and oilseeds varied among years, which underscores the need to further develop management tools to optimize durum-oilseed cropping systems in highly variable rainfall environments typical of the NGP.

Disciplines

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Comments

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B. L. Allen,* A. W. Lenssen, U. M. Sainju, T. Caesar-TonThat, and R. G. Evans

ABSTRACT

Brassicaceae oilseeds can serve as potential feedstocks for renewable biofuels to offset demand for petroleum-based alternatives. However, little is known about oilseed crop yield potential and N use in semiarid, wheat (*Triticum* spp.)-based cropping systems that dominate the northern Great Plains (NGP). A 5-yr study was conducted in northeast Montana to investigate the yield potential of a direct seeded system of durum (*T. durum* Desf.) in rotation with either chemical fallow or three Brassicaceae oilseeds: camelina [*Camelina sativa* (L.) Crantz], crambe (*Crambe abyssinica* Hochst. ex R.E. Fries), and canola-quality *Brassica juncea* L. Overall, results from the study indicated that seed yield in the three Brassicaceae oilseeds tested in rotation with durum was related ($P < 0.001$; $r^2 = 0.68$) to a nitrogen recovery index (NRI), indicating the importance of nitrogen use (NU) efficiency in dryland oilseed production, and that *B. juncea* generally used N more efficiently than crambe and camelina. Similarly, NRI was related ($P < 0.001$; $r^2 = 0.72$) to grain yield in durum following oilseeds. Grain yield of durum following *B. juncea* was similar to durum following fallow and greater than durum following camelina or crambe. Durum following crambe tended to use N more inefficiently than durum following camelina, *B. juncea*, or fallow. Differences in yield and N use of durum and oilseeds varied among years, which underscores the need to further develop management tools to optimize durum-oilseed cropping systems in highly variable rainfall environments typical of the NGP.

Lack of soil water and N availability are the major limiting factors for growing crops in semiarid dryland cropping systems (O'Leary and Conner, 1997; Padbury et al., 2002). The traditional cropping system in the North America NGP is spring wheat (*T. aestivum* L.)–fallow, due mainly to limited soil water availability during critical growth stages of annually planted crops (Nielsen et al., 2002, 2009). The practice of summer fallow, not planting a crop for the normal cropping period, typically accrues additional soil water that can lead to crop yield increases in the subsequent year. However, the precipitation storage efficiency is typically limited to about 15 to 40% due to soil surface evaporation, transpiration by weeds, and in some cases surface runoff and deep drainage (Black and Power, 1965; Tanaka and Aase, 1987; Peterson et al., 1996). Furthermore, annualized crop yields and total economic returns are typically greater with continuous cropping than in a crop–fallow system (Aase and Schafer, 1996). During summer fallow, weeds are typically controlled by tillage (till fallow) or by application of herbicides (chemical fallow).

The practice of summer fallow can lead to detrimental impacts including increased wind- and water-induced soil erosion, development of saline seeps, and decreased C and N pools in mineralizable and organic pools (Black et al., 1981; Janzen, 1987; Campbell et al., 1990; Wienhold et al., 2006). Summer fallow area has decreased in the NGP. In Montana, for example, wheat following fallow acreage decreased 19% from 1999 to 2008 (NASS, 2009). During the same period of time alternative cropping systems have increased in the NGP. For instance pulse and oilseed acreage increased from <75,000 ha in 1990 to more than 710,000 ha in 2010 in 25 counties in northeast Montana and northwest North Dakota (Hansen et al., 2012).

Crop rotation affects the amounts of soil water and soil N available to subsequent crops. Long-term research in the NGP has shown that planting legumes (lentil, *Lens culinaris* Medikus 'Indianhead') in place of fallow does not adversely affect soil water when harvested early for green manure and increased N cycling and pre-plant soil nitrate for a subsequent spring wheat crop (Pikul et al., 1997; Allen et al., 2011). However, little is known regarding the suitability of Brassicaceae oilseeds in place of fallow in these wheat cropping systems common in the NGP. Lenssen et al. (2012) reported oilseed crops in rotation with spring wheat reduced wheat yield by 30% compared to wheat–fallow.

Interest in identifying stable energy resources has increased in recent years as alternatives to petroleum-based fuels are sought. Oilseeds such as camelina, crambe, and *B. juncea* have been proposed as feedstocks that could potentially offset the need for

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Abbreviations: NGP, northern Great Plains; NRI, nitrogen recovery index; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; NU, nitrogen use.

petroleum-based resources. The semiarid NGP has been identified as an area potentially well suited to spring planted oilseed production, where oilseeds could be planted in place of fallow in wheat-based cropping systems (Lenssen et al., 2012) or on land deemed marginal for production of traditional crops like wheat. However, cool-season oilseed production is uncommon in drier regions of the NGP due in part to stand establishment inconsistency from small seed size and limited seedling vigor compared to small grains and various pulse crops, low tolerance to heat stress at flowering (Angadi et al., 2000), and poor productivity under drought conditions (Wilson et al., 1994; Lenssen et al., 2007; Álvaro-Fuentes et al., 2009).

Currently there is limited knowledge on the rotational effects of various Brassicaceae oilseeds on subsequent crops. Lenssen et al. (2007) observed spring wheat following yellow mustard (*Sinapis alba* L.) had lower seed N and biomass N accumulation, lower N harvest index (proportion of aboveground N partitioned to grain), and lower nitrogen use efficiency (NUE) than spring wheat following fallow in semiarid northern Montana during drought conditions. In contrast, Kirkegaard et al. (1999 and 2008) reported that Brassicaceae crops in cereal rotations increased residual soil N levels in research conducted in North America, Australia, and Europe. Also, the long tap root of Brassicaceae crops can improve soil structure and infiltration (Angus et al., 1991) and use soil nitrate deeper in the profile (Guy, 1994; Kirkegaard et al., 2008). Inefficient use of N fertilizer can result in N being lost due to surface runoff, leaching, denitrification, volatization, and greenhouse gas (nitrous oxide) emissions. However, N losses to surface runoff and leaching are rare in northeastern Montana considering the semiarid environment. Growers can most likely decrease N fertilization and improve NUE by changing from cereal monocultures (i.e., spring wheat or durum) to more diversified crop rotations that include oilseeds. However, little information is currently available regarding agronomic inputs for oilseed production, including NU and NUE in long-term cropping systems in the semiarid NGP. We hypothesized that growing Brassicaceae oilseeds in place of chemical fallow would increase NUE in the subsequent durum crop compared to the traditional wheat–fallow cropping system. The objectives of this study conducted from 2007 to 2011 was to investigate crop yield potential and NU and NUE for durum and selected Brassicaceaes (camelina, crambe, *B. juncea*) in 2-yr rotations.

MATERIALS AND METHODS

This study was conducted from 2007 to 2011 at an experimental site on the USDA Conservation District Farm (48°15′ N; 104°29′ W; 660 m elevation), located 11 km north of Culbertson, MT. Yield and water use from the first 4 yr of the experiment were reported in Lenssen et al. (2012). The 30-yr average annual precipitation is 345 mm, with about 80% occurring between April and September (Table 1). The field site was mapped as Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) with 1 to 2% slope. Soil samples taken to a depth of 15 cm in Fall 2001 showed average pH of 6.1, organic C of 6 g kg^{-1}, Olsen P of 8.3 mg kg^{-1}, and ammonium acetate-extractable K of 155 mg kg^{-1} as reported by Lenssen et al. (2012).Previous cropping history included spring wheat or durum in rotation with summer fallow, millet, barley, or pea–barley.

The treatments were four crop rotations that included durum cultivar Mountrail (Elias and Miller, 2000) (2007–2010) and cultivar Divide (Elias and Manthey, 2007) (2011) in rotation with chemical fallow (and three Brassicaceae oilseed crops, *B. juncea* canola cultivar P45J10, camelina cultivar Celine (2007–2008) and cultivar Blaine Creek (2009–2010) and crambe cultivar BelAnn (2007–2008) and cultivar Meyer (2009–2010). Oilseeds always followed a previous durum crop, including the initial year of 2007. Data for durum were not collected until 2008, the first year following oilseeds and fallow. Each treatment was replicated three times in a randomized complete block design, with each phase of crop rotations present each year, for a total of 24 plots that each measured 61.0 m in length by 21.3 m in width.

Seeding dates, rates, and plot management were described in detail by Lenssen et al. (2012). Briefly, typical planting dates for camelina and *B. juncea* were in early April, durum in mid- to late April, and crambe in mid- to late May.

Aboveground biomass from oilseed and durum plots was collected from two 0.5-m^2 areas the day before combine harvest, dried at 55°C for 7 d, and weighed. Oilseed seed yield and durum grain yield was collected with a plot combine (Kincaid 8-XP, Haven, KS). Camelina was swathed in 2009–2010 to dry weeds before combine harvest. Yield samples were dried at 55°C, cleaned, and weighed. Grain and biomass data were adjusted to 100% dry matter. Biomass and grain subsamples were ground and analyzed for N with a LECO FP-2000 C-N analyzer (LECO Corp., St Joseph, MI).

Fertilizer N rates for oilseeds were based on a yield goal of 1344 kg ha^{-1}, corresponding to 87.5 kg ha^{-1} N, except for 2007 when oilseeds received 60.5, 91.9, and 125.6 kg ha^{-1} N for camelina, crambe, and *B. juncea*, respectively, while those for durum were based on a yield goal of 2350 kg ha^{-1} with 135 g kg^{-1} protein (Jacobsen et al., 2005). Oilseed crops also received 23.5 kg ha^{-1} S as ammonium sulfate. All crops received 56 and 45 kg ha^{-1} monoammonium phosphate, and potassium chloride, respectively. Fertilizer rates for oilseeds and durum were adjusted by subtracting N in applied ammonium sulfate and monoammonium phosphate fertilizer and for soil nitrate N (0–60-cm depth; kg ha^{-1}) that was

Table 1. Precipitation and air temperature at the research site near Culbertson, MT, 2007–2011.

Month	Precipitation						Temperature					
	2007	2008	2009	2010	2011	30 yr†	2007	2008	2009	2010	2011	30 yr†
	mm						°C					
April	10	12	53	33	35	22	6	5	5	7	4	7
May	137	43	24	118	172	51	14	12	11	10	10	13
June	75	58	27	69	71	71	19	16	16	17	16	18
July	21	29	100	125	42	68	24	21	18	19	21	22
August	22	21	96	83	25	34	20	21	18	19	20	21
September	18	62	23	23	17	29	15	13	17	12	14	15
Season total	283	225	323	451	362	275						
Yearly total	350	338	406	524	397	346						

† Thirty-year average (1981–2010) from Western Regional Climate Center for Culbertson, MT, located 11 km south of the research site.

determined from soil samples taken the previous fall. Fallow phase plots did not receive fertilizer applications. Fertilizers were banded at planting 5 cm below and 5 cm to the side of seed, except for urea that was broadcast to camelina plots before the 2007 planting.

Soil samples (5-cm diam.) were taken in spring 2009 to 2011 and fall 2006 to 2011 to a depth of 120 cm in 15-cm increments for the surface 30 cm and in 30-cm increments thereafter. Soil was dried at 25°C, extracted with 2 M KCl, and analyzed for nitrate and ammonium (Mulvaney, 1996) by flow injection with a LACHAT QuickChem 8000 analyzer (Hach Company, Loveland, CO). Soil bulk density was determined from samples taken in fall 2010 and was 1.41, 1.46, 1.49, 1.63, and 1.63 Mg m^{-3} for the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm sampling depths, respectively.

Key indicators of NUE included NU, NUE for biomass, NUE for grain, nitrogen harvest index (NHI), nitrogen recovery index (NRI), and a N mass balance approach. The NU is available N at planting (spring soil nitrate plus fertilizer) minus fall soil nitrate to a 60-cm depth, with the assumption that N loss to the environment was negligible based on weather data. The NUE for biomass is aboveground biomass yield divided by NU. The NUE for grain or seed is grain or seed yield divided by NU. The NHI represents the proportion of grain N in total aboveground biomass N, and the NRI represents the proportion of grain N relative to total N inputs (fertilizer N and preplant nitrate to a 60-cm depth). The N mass balance was calculated by subtracting inputs (fertilizer, spring soil nitrate, and ammonium) from outputs (crop N removal from biomass and seed or grain, residual fall soil nitrate, and ammonium), such that a negative value signifies net N gain while a positive value signifies net N loss from the system.

Statistical Analysis

Data were analyzed using Proc GLIMMIX (SAS Institute, 2003) for a split-plot design. Oilseed entry (or rotation for durum) was the whole-plot factor, year the subplot factor, and their interaction considered fixed effects. Rep and rep × entry (or rotation for durum) were considered random effects. Mean separation tests were conducted using Tukey's honest significant difference. Unless otherwise noted, treatment differences are reported at the 5% level of significance. Regression analysis using PROC REG (SAS Institute, 2003) was used to determine relationships between crop yield and N use.

RESULTS AND DISCUSSION

Weather

Precipitation and air temperature for 2007 to 2010, previously reported by Lenssen et al. (2012), in addition to that for 2011 are shown in Table 1. In summary, total precipitation during the 2007 cropping season was slightly higher than the 30-yr average, marked by an unusually wet period in May and relatively dry period during July to September. Air temperature during the 2007 growing season was close to the 30-yr average, with the exception of a warmer than normal period in July. The 2008 cropping season was notably dry and cool compared to the 30-yr average. The 2009 cropping season had above normal precipitation, especially during April, July, and August, and was cooler during most of the season compared to the 30-yr average. The 2010 growing season was characterized by an unusual abundance of precipitation, especially during May, July, and August, and was relatively cooler than normal. Noticeable damage was observed in crops from hail that occurred on 20 and 28 July 2010. The 2011 growing season was also very wet overall, with above normal precipitation during the early growing months and less than normal levels during the last 3 mo. Air temperatures during the 2011 growing season were consistently below the 30-yr average.

Oilseeds

Oilseed biomass and seed yields for 2007 to 2010 were reported by Lenssen et al. (2012) and are included in Table 2. Crop biomass from 2007 to 2011 differed ($P < 0.05$) among oilseeds and was on average 50% greater in *B. juncea* and crambe than camelina (Table 2). Seed yield also was on average 50% greater ($P = 0.087$) for *B. juncea* than camelina, while crambe yield was similar to the other oilseeds (Table 2). The comparatively lower biomass and seed yield of camelina compared to other oilseeds could be attributed in part to the variable stand establishment and maturity within plots reported by Lenssen et al. (2012). The crop × year interaction was not significant ($P < 0.05$) for seed yield or crop biomass (Table 2). Biomass and seed yield differed ($P < 0.001$) among years and followed similar trends. The relatively low yields in 2008 and 2010 were most likely related to drought conditions and hail damage, respectively. Greatest yield for oilseeds was in the relatively wet year of 2009, where timely rainfall during the growing season increased yields compared to previous years. Moderate yields in 2007 and 2011 were likely related to relatively hot and dry conditions during reproductive periods (July 2007) and delayed planting dates from excessive rainfall (spring 2011). Smith et al. (2013) reported average canola yields of 1030 kg ha^{-1} in a Saskatchewan, Canada, rotation study with *B. napus* and wheat, similar to the 940 kg ha^{-1} seed yields of *B. juncea* in the current study (Table 2).

Pre-plant and post-harvest soil nitrate (0–60-cm depth) were similar among oilseeds and averaged 50.5 and 46.3 kg ha^{-1}, respectively, but did differ ($P < 0.01$) among years (Table 2). The relatively greater soil nitrate in fall 2008 and spring 2009 was likely due to limited crop N uptake during the drought year of 2008, where rainfall during May to July was 68% of normal (Table 1). The crop × year interaction was not significant ($P < 0.05$) for pre-plant or post-harvest soil nitrate (0–60-cm depth) or total available N (Table 2).

Total available mineral N was similar among oilseeds and averaged 116.9 kg ha^{-1}, but did differ ($P < 0.001$) among years (Table 2). The greater available N in 2007 compared to other years was a result of higher than normal rates of N fertilizer applied during that particular year. Beginning in 2008, fertilizer N rates were based on university recommendations that accounted for pre-plant nitrate N at the 0- to 60-cm depth (Jacobsen et al., 2005). Available N in 2009 was greater than that for 2008, 2010, and 2011, largely a result of relatively greater pre-plant soil nitrate resulting from decreased crop N uptake during the dry 2008 growing season. Harker et al. (2012) reported a positive relationship between N supply and *B. napus* seed yield in a Canada study, though an inverse relationship with N supply and seed oil concentration was observed when N was 1.5 times greater than the recommended rate.

Biomass N concentration and yield differed ($P < 0.05$) for oilseed crop, year, and the crop × year interaction (Table 2). In the relatively dry years of 2007 and 2008 camelina had as great or greater biomass N concentration than crambe or *B. juncea*, while in the relatively wet years of 2010 and 2011 that for crambe was as great or greater than other oilseeds (Table 3). Biomass N concentration

Table 2. Treatment means and analysis of variance for crop biomass, seed yield, soil preplant nitrate N (PreNO$_3$), post-harvest residual nitrate N (PostNO$_3$), total available N , biomass N, seed N, N harvest index (NHI), N recovery index (NRI), N balance (NBal), N use (NU), biomass N use efficiency (NUE bmas), and seed nitrogen use efficiency (NUE seed) for three Brassicaceae oilseeds following durum near Culbertson, MT, 2007–2011.

Parameter	Biomass	Seed	PreNO$_3$†	PostNO$_3$‡	Available N§	Biomass N		Seed N		NHI	NRI	NBal¶	NU#	NUE bmas††	NUE seed‡‡
	kg ha^{-1}						kg ha^{-1}	g kg^{-1}	kg ha^{-1}				kg ha^{-1}	kg kg^{-1} ha^{-1}	
Oilseed															
Camelina	2977b§§	639b	47.0	38.5	101.5	22.9a	69.2b	46.2a	30.8b	0.43ab	0.30	30.6	62.4	54.2	10.4
Crambe	4414a	835ab	54.1	49.0	122.3	23.1a	104.8a	40.3b	33.3ab	0.29b	0.26	37.0	73.2	74.1	12.6
B. juncea	4375a	940a	50.5	51.5	126.9	19.3b	90.2ab	46.4a	44.2a	0.50a	0.40	–0.6	81.6	75.0	16.5
Year															
2007	4379b	776b	–	43.1b	184.5a	22.0b	93.8b	46.7ab	36.4b	0.39ab	0.22b	–	140.4a	42.7b	7.4bc
2008	2344c	323c	–	76.4a	92.2c	21.6b	49.4c	48.2a	17.2c	0.32b	0.19b	12.3	26.2b	50.2b	6.1c
2009	5600a	1704a	105.2a	33.6b	140.7b	26.8a	147.5a	45.3b	76.9a	0.53a	0.58a	30.0	107.1a	63.0b	19.4ab
2010	3210c	383c	23.0b	36.1b	80.8c	16.7c	57.9c	38.4d	14.6c	0.36ab	0.19b	30.6	44.7b	70.8ab	9.0bc
2011	4174b	831b	23.3b	42.6b	86.4c	21.7b	91.7b	42.9c	35.5b	0.43ab	0.42a	16.3	43.8b	112.1a	23.9a
Significance						*P* value									
Rotation (R)	*	0.087	ns¶¶	ns	ns	*	*	**	0.085	0.063	ns	ns	ns	ns	ns
Year (Y)	***	***	***	**	***	***	***	***	***	*	***	ns	***	0.051	*
R × Y	ns	ns	ns	ns	ns	***	***	*	ns	0.051	ns	ns	ns	ns	ns

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$

*** Significant at $P \leq 0.001$.

† Soil pre-plant nitrate N, 0- to 60-cm depth, 2009 to 2011.

‡ Post-harvest residual nitrate N, 0- to 60-cm depth.

§ Total available N, preplant nitrate N + fertilizer N, 2009 to 2011; post-harvest nitrate N from previous year + fertilizer N, 2007–2008.

¶ N balance, preplant nitrate, ammonium, and fertilizer N– postharvest nitrate, ammonium, and seed N, 2008 to 2011.

N use, total available N–Fall soil nitrate, 0- to 60-cm depth.

†† Biomass N use efficiency, biomass yield/NU, 0- to 60-cm depth.

‡‡ Seed N use efficiency, seed yield/NU, 0- to 60-cm depth.

§§ Means followed by different lowercase letter within a column are significantly different.

¶¶ Not significant.

Table 3. Interaction between crop and year for biomass N concentration and yield, and seed N concentration for three Brassicaceae oilseeds in rotation with durum near Culbertson, MT, 2007–2011.

Crop	2007	2008	2009	2010	2011
			Biomass N concentration, g kg^{-1}		
Camelina	23.2a†	22.6a	27.6	18.4a	22.2b
Crambe	21.3b	22.6a	26.9	18.7a	25.9a
B. juncea	21.3b	19.7b	25.6	12.5b	16.9c
			Biomass N yield, kg ha^{-1}		
Camelina	74.7	39.8b	118.0b	28.3	90.5ab
Crambe	95.6	40.7b	184.7a	78.2	125.0a
B. juncea	110.0	67.8a	146.3ab	63.9	59.6b
			Seed N concentration, g kg^{-1}		
Camelina	47.8b	47.3	48.9a	41.4	46.1a
Crambe	41.9c	44.6	38.9b	35.0	41.1b
B. juncea	50.8a	52.6	48.2a	38.9	41.4b

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

ranged from 16.7 to 26.8 g kg^{-1}, somewhat greater than the 10.4 to 14.6 g kg^{-1} range reported by Urbaniak et al. (2008) for camelina grown in the Maritime Provinces of Canada. Biomass N yield favored *B. juncea* in the drier years of 2007 and 2008, while that for crambe was as great or greater than other oilseeds in the wetter years of 2009 to 2011 (Table 3). Differences were detected for seed N concentration ($P < 0.01$) and nearly so for N yield ($P = 0.085$) among oilseeds and for differences among years ($P < 0.001$). Seed N concentration also showed a significant ($P < 0.05$) crop × year interaction (Table 2). In general, seed N concentration was as great or greater in *B. juncea* during the dry years of 2007 and 2008, while that for camelina was as great or greater than other oilseeds during the wet years (Table 3). May et al. (2010) reported seed N concentration of *B. juncea* canola (cultivar Dahinda) grown at four locations in southern Saskatchewan ranged from 39.5 to 41.0 g kg^{-1}, somewhat lower than the 46.4 g kg^{-1} average observed in the current study (Table 2). Lemke et al. (2009) reported seed N concentration of *B. napus* canola grown for 12 site-years in southern Saskatchewan ranged from 29.1 to 48.5 kg ha^{-1}. Seed N yield was 44% greater in *B. juncea* than camelina, due mainly to the greater yield of *B. juncea*, as seed N concentration was similar (Table 2). Seed N yield for crambe was similar to that of the other oilseeds. Differences among years for seed N yield followed trends similar to those described previously for seed yield and crop biomass (Table 2).

Nitrogen harvest index differed among years ($P < 0.05$), and nearly so among oilseeds ($P < 0.063$), and for the crop × year interaction ($P < 0.051$) (Table 2). Across years, NHI was on average 72% greater for *B. juncea* than crambe, while that for camelina was similar to the other oilseeds. The NHI was greater in 2009 than 2008, corresponding to years with the highest and lowest crop and biomass yields (Table 2). No other difference among years was detected for NHI.

Nitrogen recovery index differed ($P < 0.001$) among years, but not among oilseeds or for the crop × year interaction (Table 2). The NRI average for oilseeds was 0.32. The NRI was 150% greater for the wet years of 2009 and 2011 compared to the dry years of 2007 and 2008 or hail-impacted year of 2010 (Table 2). Regression analysis indicated that seed yield across oilseeds was significantly related to NRI ($r^2 = 0.68$; $P < 0.001$; seed yield, kg ha^{-1} = 2263 × NRI + 94). These results are similar to those reported by Allen et al. (2010) where wheat yield was highly related ($P < 0.001$; $r^2 = 0.89$) to NRI in a long-term rotational study near Sidney, MT.

Nitrogen balance for oilseeds ranged between −0.6 for *B. juncea* to 37.0 for crambe, though this difference was not significant ($P < 0.113$). Differences for year and crop × year interaction also were not significant (Table 2).

Nitrogen use did not differ among oilseeds and averaged 72.4 kg ha^{-1} (Table 2). The NU differed with year and was greater in 2007 and 2009 than 2008, 2010, or 2011. Differences for the crop × year interaction were not significant (Table 2).

Nitrogen use efficiency for biomass did not differ among oilseeds and averaged 67.8 kg kg^{-1} ha^{-1} (Table 2). The NUE for biomass

Table 4. Soil nitrate N sampled to 120 cm in five depth increments during fall and spring for three Brassicaceae oilseeds in rotation with durum near Culbertson, MT, 2007–2011.

	0–15 cm		15–30 cm		30–60 cm		60–90 cm		90–120 cm	
Parameter	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
					kg ha^{-1}					
Oilseed										
Camelina	8.1	15.2	8.3	9.8	30.6	13.6	37.7	20.7	31.0	24.5
Crambe	9.8	26.5	11.5	8.3	32.7	14.2	42.2	26.3	48.2	34.4
B. juncea	8.4	25.2	9.2	8.6	33.0	17.6	37.0	47.1	32.2	24.8
Year										
2007	–	23.8ab†	–	5.2b	–	14.2ab	–	21.8bc	–	29.5b
2008	–	31.5a	–	19.6a	–	25.0a	–	62.6a	–	28.2b
2009	13.2a	10.4c	19.2a	6.2b	72.8a	16.9ab	58.9a	51.9ab	35.7b	49.9a
2010	4.3c	18.4bc	5.3b	7.1b	13.5b	10.6b	31.2b	8.9c	21.0b	16.6b
2011	8.8b	27.4ab	4.5b	6.4b	10.0b	8.8b	26.9b	11.6c	54.6a	15.2b
Significance						*P* value				
Rotation (R)	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	***	**	***	***	***	*	*	*	**	***
R × Y	ns	ns	ns	0.082	ns	ns	ns	ns	ns	ns

* Significant $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

‡ Not significant.

nearly differed ($P < 0.051$) with year and was greater in 2011 than 2007 to 2009, with 2010 being similar to all years. Differences for the crop × year interaction were not significant (Table 2).

Nitrogen use efficiency for seed did not differ among oilseeds and averaged 13.2 kg kg^{-1} ha^{-1} (Table 2). The NUE for seed differed ($P < 0.05$) with year and was greatest in 2011, lowest in 2008, and intermediate for other years. Differences for the crop × year interaction were not significant (Table 2).

Soil nitrate measured in the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths did not differ ($P < 0.05$) among oilseeds or for the crop × year interaction, but was significant among years (Table 4). In general, spring soil nitrate measured in the surface 90 cm was greater in 2009 than 2010 or 2011, likely due to the relatively low crop N removal during the drought conditions of 2008. Spring soil nitrate for the 90- to 120-cm depth was greater in 2011 than 2009 or 2010, which could be related to leaching of N from higher than normal rainfall in 2010 and early spring 2011. Fall soil nitrate for the surface 90 cm was as great or greater for 2008 than other years, attributable to drought conditions that limited crop N uptake in that year. Fall soil nitrate for the 90- to 120-cm depth was greater in 2009 than other years, and could be evidence of N leaching and/or greater than normal nitrification as a result of higher than normal levels of late-season rainfall that year.

Soil ammonium in the surface 15 cm sampled in fall was on average 58% greater ($P < 0.091$) for crambe than camelina, while that for *B. juncea* was similar to the other oilseeds (Table 5). No other differences were detected among oilseeds for soil ammonium sampled in spring or fall to a 120-cm depth. Soil ammonium at the 15- to 30-cm depth was greater ($P < 0.094$) in 2009 than 2010 (Table 5). No other differences were detected among years or for the crop × year interaction for soil ammonium sampled in spring or fall to a 120-cm depth.

Durum

Crop biomass and durum yields for 2008 to 2010 were reported by Lenssen et al. (2012) and are included in Table 6. Crop biomass from 2008 to 2011 differed ($P < 0.05$) in durum rotations and was on average 35% greater in durum following fallow than durum following crambe or *B. juncea* (Table 6). Biomass for durum following camelina was similar to the other durum rotations. Grain yield also was on average 55% greater ($P < 0.05$) for durum following fallow than durum following camelina or crambe, while durum following *B. juncea* yield was similar to the other durum rotations (Table 6). The comparatively greater biomass and grain yield of durum following fallow compared to other durum rotations in the study could be attributed to the greater pre-plant soil water for the durum–fallow rotation reported by Lenssen et al. (2012). The durum rotation × year interaction was not significant ($P < 0.05$) for grain yield or crop biomass (Table 6). Biomass and grain yield differed ($P < 0.001$) among years (Table 6). Most notably, durum biomass was greatest in 2010 and lowest in 2008, following trends in growing season precipitation (Table 1) described previously. Durum grain yields were greatest ($P < 0.05$) in 2009 where timely rainfall during the growing season increased yields compared to other years. Durum in the 2010 and 2011 cropping seasons would likely have yielded more had it not been for the two instances of hail (2010) and the delayed planting date from excess spring rainfall (2011) described previously.

Pre-plant soil nitrate (0–60-cm depth) was similar among oilseeds and averaged 52.8 kg ha^{-1}, but did differ ($P < 0.05$) among years (Table 6). The relatively greater soil nitrate in spring 2009 compared to that in 2011 was likely related to limited crop N removal during the drought year of 2008, where precipitation during May–July was 68% of normal (Table 1). The durum rotation × year interaction was not significant ($P < 0.05$) for pre-plant soil nitrate (0–60-cm depth). Post-harvest soil nitrate differed with durum rotation ($P < 0.05$), year ($P < 0.001$), and durum rotation × year interaction ($P < 0.05$) (Table 6). The durum rotation × year interaction for post-harvest soil nitrate is shown in Table 7 where the most notable difference was the much greater levels in 2008 durum following *B. juncea* than durum following crambe or fallow.

Total available N was similar among oilseeds and years and averaged 120.0 kg ha^{-1} (Table 6). The durum rotation × year interaction for total available N was not significant at the 0.05 level.

Biomass N concentration and yield differed ($P < 0.05$) among years, but not for durum rotation or the durum rotation × year

Table 5. Soil ammonium N sampled to 120 cm in five depth increments from fall and spring for three Brassicaceae oilseeds in rotation with durum near Culbertson, MT, 2007–2011.

	0–15 cm		15–30 cm		30–60 cm		60–90 cm		90–120 cm	
Parameter	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	kg ha^{-1}									
Oilseed										
Camelina	8.6	6.9b†	8.8	5.9	7.5	6.0	9.9	10.1	10.3	12.9
Crambe	15.9	10.9a	7.4	7.9	7.2	7.5	8.6	10.0	11.4	13.0
B. juncea	7.8	7.5ab	6.3	5.9	6.8	7.1	7.9	11.0	9.8	13.3
Year										
2007	–	10.0	–	7.2	–	8.7	–	12.0	–	14.0
2008	–	7.5	–	5.2	–	5.8	–	9.2	–	12.4
2009	9.3	8.4	9.3a†	7.2	7.1	7.2	8.2	10.8	8.8	14.4
2010	11.9	9.0	5.2b	7.4	6.2	6.3	7.8	11.2	11.2	13.3
2011	11.2	7.3	8.1ab	5.8	8.2	6.3	10.2	8.7	11.4	11.3
Significance					P value					
Rotation (R)	ns‡	0.091	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	ns	ns	0.094	ns	ns	ns	ns	ns	ns	ns
R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

† Means followed by different lowercase letter within a column are significantly different at $P \le 0.10$.

‡ Not significant.

Table 6. Treatment means and analysis of variance for crop biomass, grain yield, soil preplant nitrate N ($PreNO_3$), post-harvest residual nitrate N ($PostNO_3$), total available N , biomass N, grain N, N harvest index (NHI), N recovery index (NRI), and N balance (NBal), N use (NU), biomass N use efficiency (NUE bmas), and grain N use efficiency (NUE seed) for durum in rotation with three Brassicaceae oilseeds and fallow near Culbertson, MT, 2008–2011.

Parameter	Biomass	Grain	$PreNO_3$†	$PostNO_3$‡	Available N§	Biomass N		Grain N		NHI	NRI	NBal¶	NU#	NUE bmas††	NUE grn‡‡
			kg ha^{-1}				kg ha^{-1}	g kg^{-1}	kg ha^{-1}				kg ha^{-1}	kg kg^{-1} ha^{-1}	
Durum in rotation															
Durum–camelina	4584ab§§	1517b	49.2	49.0ab	118.6	15.7	70.5	28.1	40.9ab	0.59	0.36ab	35.6	70.8	98.0	36.1
Durum–crambe	4262b	1278b	57.3	33.0b	123.1	17.0	69.9	30.2	37.6b	0.57	0.32b	57.1	90.1	63.4	19.9
Durum–*B.juncea*	4317b	1627ab	62.0	60.4a	127.2	18.3	77.3	29.7	47.9ab	0.63	0.39ab	18.9	66.8	82.2	42.8
Durum–fallow	5792a	2163a	42.6	34.2ab	111.0	15.7	89.1	26.8	56.8a	0.63	0.54a	27.0	76.8	117.9	46.0
Year															
2008	3533c	1250b	–	91.9a	115.4	19.2a	66.6bc	32.1a	38.8b	0.58ab	0.35b	–7.2b	24.7b	148.2	63.4
2009	4900b	2424a	75.5a	33.4b	126.7	19.6a	96.1a	26.3c	63.1a	0.66a	0.55a	34.9ab	93.3a	95.1	48.1
2010	6647a	1543b	49.5ab	24.8b	127.8	13.3b	87.8ab	27.0c	41.3b	0.48 b	0.34b	66.5a	103.0a	71.1	16.6
2011	3875bc	1367b	33.8b	26.5b	110.0	14.6b	56.2c	29.5b	40.0b	0.69a	0.37b	44.4a	83.5a	47.2	16.7
Significance						*P* value									
Rotation (R)	*	*	ns¶¶	*	ns	ns	ns	ns	*	ns	*	ns	ns	ns	ns
Year (Y)	***	***	*	***	ns	***	***	***	***	**	**	**	***	ns	ns
R × Y	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Soil preplant nitrate N, 0- to 60-cm depth, 2009 to 2011.

‡ Post-harvest residual nitrate N, 0- to 60-cm depth.

§ Total available N, pre-plant nitrate N + fertilizer N, 2009 to 2011; post-harvest nitrate N from previous year + fertilizer N, 2008.

¶ N balance, pre-plant nitrate, ammonium, and fertilizer N–postharvest nitrate, ammonium, and grain N.

N use, total available N–fall soil nitrate, 0- to 60-cm depth.

†† Biomass N use efficiency, biomass yield/NU, 0- to 60-cm depth.

‡‡ Grain N use efficiency, grain yield/NU; 0- to 60-cm depth.

§§ Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

¶¶ Not significant.

Table 7. Interaction between crop and year for fall residual soil nitrate N for the 15- to 30-, 30- to 60-, 90- to 120- and 0- to 60-cm depths for durum following three Brassicaceae oilseeds and fallow near Culbertson, MT, 2008–2011.

Durum in rotation	2008	2009	2010	2011
		Fall soil nitrate, 15–30-cm depth, kg ha^{-1}		
Durum–camelina	46.3ab†	7.8	5.8b	4.1
Durum–crambe	23.5b	4.0	5.6b	6.3
Durum–*B. juncea*	64.6a	5.0	10.1a	4.8
Durum–fallow	35.0b	4.1	4.3b	4.1
		Fall soil nitrate, 30–60-cm depth, kg ha^{-1}		
Durum–camelina	15.0b	25.1	10.5	4.9b
Durum–crambe	8.2b	14.3	11.3	8.7a
Durum–*B. juncea*	44.3a	25.9	15.0	5.1b
Durum–fallow	13.2b	18.0	9.2	5.0b
		Fall soil nitrate, 90–120 cm depth, kg ha^{-1}		
Durum–camelina	37.6	76.5	55.2	8.5 c
Durum–crambe	39.5	27.4	115.2	12.9a
Durum–*B. juncea*	31.0	56.3	104.5	10.3b
Durum–fallow	45.5	36.8	22.0	12.0a
		Fall soil nitrate, 0–60-cm depth, kg ha^{-1}		
Durum–camelina	89.6ab	50.5	23.7	32.3
Durum–crambe	55.9b	21.2	21.8	33.0
Durum–*B. juncea*	145.7a	35.9	35.7	24.1
Durum–fallow	76.3b	25.9	18.0	16.5

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

interaction (Table 6). Biomass N concentration and yield averaged across durum rotations was 16.7 g kg^{-1}and 76.7 kg ha^{-1}, respectively. Biomass N concentration in durum was greater in 2009 than 2008 and 2011, while biomass N yield was 39% greater for 2008 and 2009 than for 2010 and 2011 (Table 6).

Grain N yield, but not grain N concentration, differed ($P < 0.05$) among durum rotations (Table 6). Grain N yield and N concentration differed ($P < 0.001$) among years, but not for the durum rotation × year interaction. Durum grain N concentration was similar across rotations and averaged 28.7 g kg^{-1}, but in the drought year of 2008 was 9% greater than that in 2011 and 20% greater than that in 2009 and 2010 (Table 6). Grain N yield was 51% greater in durum following fallow than durum following crambe, due mainly to the greater impact of grain yield than grain N concentration (Table 6). Grain N yield for durum following camelina or *B. juncea* was similar to other durum rotations. Grain N yield was 58% greater in 2009 than that for other years, following the same trend described previously for durum grain yield (Table 6). Compared to the 57 kg ha^{-1} grain N yield for durum following fallow in the current study, Lenssen et al. (2010) reported a somewhat

Table 8. Soil nitrate N sampled to 120 cm in five depth increments during fall and spring for durum in rotation with three Brassicaceae oilseeds and fallow near Culbertson, MT, 2008–2011.

	0–15 cm		15–30 cm		30–60 cm		60–90 cm		90–120 cm	
Durum in rotation	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
					kg ha^{-1}					
Durum–camelina	7.7	19.1	12.3	16.0ab†	29.2	13.9b	37.9	38.3	26.5	44.5
Durum–crambe	8.6	12.5	12.0	9.9b	36.6	10.6b	40.6	30.9	25.5	48.8
Durum–*B. juncea*	9.3	16.7	12.6	21.1a	40.1	22.6a	79.0	51.8	34.7	50.5
Durum–fallow	7.4	11.0	10.9	11.9b	24.4	11.3b	20.8	25.1	23.9	29.1
Year										
2008	–	29.3a	–	42.4a	–	20.2a	–	38.0ab	–	38.4bc
2009	9.3	7.4b	14.3	5.2b	51.9a	20.8a	52.8	57.7a	26.7ab	49.2ab
2010	7.5	6.9b	12.6	6.5b	29.3ab	11.5ab	65.2	40.3ab	38.5a	74.2a
2011	8.0	15.7b	8.9	4.8b	16.5b	6.0b	15.7	10.0b	17.8b	10.9c
Significance						*P* value				
Rotation (R)	ns‡	ns	ns	*	ns	*	ns	ns	ns	ns
Year (Y)	ns	***	ns	***	*	***	ns	*	**	***
R × Y	ns	ns	ns	***	ns	*	ns	ns	ns	*

* Significant at $P \leq 0.05$.

** Significant $P \leq 0.01$.

*** Significant $P \leq 0.001$.

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

‡ Not significant.

greater grain N yield of 82 kg ha^{-1} for durum following fallow in an experiment located at the same research farm in northeastern Montana during 2002 to 2006.

Nitrogen harvest index for durum differed ($P < 0.01$) among years, but not among durum rotations or for the durum rotation × year interaction (Table 6). The NHI for durum rotations averaged 0.61. The NHI was 41% greater for durum in 2009 and 2011 than durum in 2010, while that in 2008 was similar for all durum rotations (Table 6).

Nitrogen recovery index differed among durum rotation ($P < 0.05$) and among years ($P < 0.01$), but not for the durum rotation × year interaction (Table 6). The NRI was 69% greater for durum following fallow than for durum following crambe, while that for durum following camelina or *B. juncea* was similar to the other durum rotations (Table 6). The NRI was 56% greater for durum in 2009 compared to other years, reflecting trends described previously for durum grain yield and grain N yield (Table 6). Lenssen (2010) reported a 0.68 NRI for durum following fallow, somewhat greater than the 0.54 NRI for durum flowing fallow reported here (Table 6). Regression analysis indicated that durum grain yield was significantly related to NRI ($r^2 = 0.66$; $P < 0.001$; Grain yield, kg ha^{-1} = 3497 × NRI + 281).

The N balance differed ($P < 0.01$) among years, but not among durum rotation or for the durum rotation × year interaction (Table 6). The average for N balance in durum was 34.7 kg ha^{-1}. The negative value for N balance in the drought year of 2008 indicated a net return of N to soil, and differed significantly from that in 2010 and 2011 (Table 6). The N balance for 2009 durum was similar to other years.

Nitrogen use, NUE for biomass, and NUE for grain did not differ among rotations for durum following oilseeds and averaged 76.1 kg ha^{-1}, 90.4, and 36.2 kg kg^{-1} ha^{-1}, respectively (Table 6). The NU differed with year and was greater in 2009 to 2011 than the relatively dry year 2008. Differences for the crop × year interaction were not significant (Table 6).

Soil nitrate differed among durum rotations, among years, and for the durum rotation × year interaction, but the effects varied depending on the sampling depth and sample season (Table 8). Soil nitrate sampled in the spring was similar for durum rotations at all sampling depths, and averaged 8.3, 12.0, 32.6, 44.6, and 27.7 kg ha^{-1} for the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths, respectively. Soil nitrate sampled in fall was similar for sampling depths, except for the 15- to 30-cm and 30- to 60-cm depths where durum following *B. juncea* had as great or greater levels of nitrate than other durum rotations. Soil nitrate differed among years for 0- to 15- and 60- to 90-cm depths in fall and for 30- to 60- and 90- to 120-cm depths in spring (Table 8). Nitrate generally was greatest in 2008 fall and 2009 spring samples due to limited N uptake from 2008 growing season drought conditions, and lowest in 2011 due to previously described wet conditions that year. The durum rotation × year interaction was significant for fall soil nitrate at the 15- to 30-, 30- to 60-, and 90- to 120-cm depths (Table 8). Most notably, fall soil nitrate at the 15- to 30-cm depth was as great or greater for durum following *B. juncea* in 2008 and greatest for durum following *B. juncea* in 2010 compared to other durum rotations (Table 7). Fall soil nitrate at the 30- to 60-cm depth was greatest in durum following *B. juncea* in 2008 and greatest for durum following crambe in 2011 (Table 7). Fall soil nitrate at the 90- to 120-cm depth was 21 and 46% greater for durum following crambe and fallow than durum following *B. juncea* or camelina, respectively (Table 7).

Soil ammonium was similar across durum rotations, differed ($P < 0.05$) in one instance for year, and did not differ for the durum rotation × year interaction (Table 9). Across durum rotations, soil ammonium averaged 8.0, 8.2, 6.9, 8.3, and 10.3 kg ha^{-1} for spring and 6.9, 6.0, 6.6, 9.6, and 12.6 kg ha^{-1} for fall samples at the 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths, respectively. The one instance where soil ammonium differed was for the 90- to 120-cm depth sampled in spring that was 40% greater ($P < 0.05$) for 2010 than for 2009 (Table 9).

Table 9. Soil ammonium N sampled to 120 cm in five depth increments during fall and spring for durum in rotation with three Brassicaceae oilseeds and fallow near Culbertson, MT, 2008–2011.

	0–15 cm		15–30 cm		30–60 cm		60–90 cm		90–120 cm	
Durum in rotation	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	kg ha^{-1}									
Durum–camelina	8.5	6.5	9.5	7.0	10.2	7.0	10.9	9.1	10.8	12.2
Durum–crambe	9.1	7.2	6.2	6.0	5.7	6.1	7.2	8.6	10.3	12.0
Durum–*B. juncea*	7.4	8.6	7.7	5.4	5.8	8.0	7.2	11.7	9.5	12.9
Durum–fallow	6.9	5.4	9.4	5.6	5.9	5.4	7.7	9.0	10.5	13.2
Year										
2008	–	8.9	–	4.8	–	5.5	–	8.4	–	12.3
2009	8.2	6.5	8.7	6.2	6.7	6.3	7.9	9.8	8.6 b†	14.9
2010	8.6	6.2	6.7	5.3	5.8	4.8	7.9	7.2	12.0a	10.7
2011	7.2	6.1	9.2	7.6	8.2	10.0	8.9	12.9	10.3ab	12.4
Significance					*P* value					
Rotation (R)	ns‡	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
R × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at $P \leq 0.05$.

† Means followed by different lowercase letter within a column are significantly different at $P \leq 0.05$.

‡ Not significant.

CONCLUSION

Oilseeds can diversify dryland cropping systems, reduce incidence of fallow acreage, and serve as a potential feedstock for biofuels to offset demand for petroleum-based alternatives. Our study shows that NUE was significantly related to seed yield in the three Brassicaceae oilseeds tested in rotation with durum and that *B. juncea* generally used N more efficiently than crambe and camelina. Similarly NUE was related to grain yield in durum following oilseeds. Grain yield of durum following *B. juncea* was as great as that for durum following fallow and greater than that for durum following camelina or crambe. Durum following crambe tended to use N less efficiently than durum following camelina, *B. juncea*, or fallow. Differences in yield and N use of durum and oilseeds varied significantly among years, underscoring the need to further develop management tools that optimize cropping system N utilization despite the highly variable rainfall typical of the NGP.

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