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Nitrogen fertilization to malt barley enhances pea yield and quality, regardless of cover cropping, in the malt barley–pea rotation

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Abstract

Cover crop and N fertilization rate to malt barley (*Hordeum vulgare* L.) (NRMB) can affect soil residual NO_3-N that may alter pea (*Pisum sativum* L.) growth, yield, and quality in the malt barley–pea rotation. The effect of cover crop (oat [*Avena sativa* L.) cover crop vs. none) and NRMB (0, 40, 50, 60, 70, and 80 kg N ha^{-1}) were examined on soil residual NO_3-N and pea growth, yield, and quality in the malt barley–pea rotation from 2014 to 2019 in the US northern Great Plains. Soil residual NO_3-N content increased with increasing NRMB. Cover crop biomass yield was 33%–393% greater with than without NRMB in 2015 and 2016. Pea grain yield and N uptake were 40%–41% greater for 40 than 60 kg N ha^{-1} of NRMB in 2015 and 45%–167% greater for 70 than 0 kg N ha^{-1} in 2018. Grain test weight was 27% greater with than without NRMB in 2014 and 2019. Harvest index was 22%–29% greater for 70 than 40, 60, and 80 kg N ha^{-1} in 2014, but 18%–33% greater for 0 than 50 or 80 kg N ha^{-1} in 2017 and 2019. Nitrogen harvest index was 13%–14% greater for 0 than 50 and 60 kg N ha^{-1} in 2015 and 2019. Straw yield, N concentration, N uptake, and grain protein concentration were 10%–34% greater with than without NRMB. Nitrogen fertilization to malt barley enhanced pea yield and quality, regardless of cover cropping, in the malt barley–pea rotation in the northern Great Plains.

Plain Language Summary

Legume–nonlegume rotation is getting popular to replace fallow–nonlegume rotation in dryland cropping systems in the US northern Great Plains because it increases crop yields and farm income for producers. In this rotation, nonlegumes receive nitrogen fertilizers, but legumes do not because they fix nitrogen from the atmosphere. The effect of nitrogen fertilization rate to nonlegumes on yield and quality of legumes in the legume–nonlegume rotation is not well known. An ARS researcher in Sidney, MT, evaluated the effect of winter cover cropping and nitrogen fertilization rate to malt barley on pea growth, yield, and quality in the malt barley–pea rotation from

Abbreviation: NRMB, nitrogen fertilization rate to malt barley.

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2014 to 2019. He reported that nitrogen fertilization to malt barley enhanced pea yield and quality compared with no nitrogen fertilization, regardless of cover cropping, in the malt barley–pea rotation. Cover cropping was less effective in pea performance. Producers can benefit the enhancement of pea yield and quality by applying nitrogen fertilizer to malt barley in the malt barley–pea rotation.

1 | INTRODUCTION

Rotation of legumes, such as pea (*Pisum sativum* L.), with nonlegumes, such as malt barley (*Hordeum vulgare* L.), is getting popular in dryland cropping systems of arid and semiarid regions because of their numerous benefits on ecosystem services compared to monocropping. These benefits include enhanced soil water conservation, reduced weed and pest infestations, decreased N fertilization rates to nonlegumes, greater crop yields (Krupinsky et al., 2002; Stevenson & van Kissel, 1996), lower risk of crop failure, and increased economic returns (Chen et al., 2012; Lafond et al., 2011; Miller et al., 2015). Furthermore, environmental benefits associated with legume–nonlegume rotations include reduced N leaching and greenhouse gas emissions compared with nonlegume monocropping (Lafond et al., 2011; Sainju et al., 2020). Pea matures earlier than nonlegumes, such as spring wheat (*Triticum aestivum* L.) and barley, resulting in more soil water available for following crops and enhancing their yields in the semiarid region of the US northern Great Plains where growing season precipitation is limited (Lenssen et al., 2018). Because of these benefits, the fallow system in crop–fallow rotations is now being replaced by pea, resulting in small grains–pea rotations, thereby enhancing crop yields and farm income in this region (Chen et al., 2012; Huang et al., 2017; Koeshell et al., 2022; Miller et al., 2015).

In legume–nonlegume rotations, N fertilizer is usually applied to nonlegumes to enhance their yields and quality, but not to legumes because of their N fixing ability (Sainju & Pradhan, 2024). Such N fertilization to nonlegumes usually results in the accumulation of soil residual NO_3-N content (Sainju & Pradhan, 2024) because of the crops' inability to remove 100% of the applied N fertilizer (Eickhout et al., 2006; Ross et al., 2008). Excessive accumulation of soil residual NO_3-N content can result in negative consequences on soil health and environmental quality by increasing soil acidity, N leaching, and N_2O emissions, a potent greenhouse gas that contributes to global warming (Eickhout et al., 2006; Ross et al., 2008). The accumulation of soil residual NO_3-N content can also affect succeeding legume growth, yield, and quality in the legume–nonlegume rotation, which needs to be explored, as few information exists in the literature.

Sainju and Pradhan (2024) reported that N fertilization to small grains increased pea yield and N uptake in the small grains–pea rotation in the semiarid US northern Great Plains. In contrast, Mohr et al. (2007) found that N fertilization to spring wheat did not affect pea yield in the spring wheat–pea rotation in the semiarid region of western Canada. Pea yield and quality can be enhanced by applying starter N fertilization rate of 15–40 kg N ha^{-1} compared to no N fertilization (Lafond et al., 2011; McKenzie et al., 2001; Raja et al., 2022) because rhizobium inoculation to enhance biological N fixation sometime becomes ineffective (Huang et al., 2017). As 35% of total N requirement for pea is taken up from the soil, supplemental N fertilization in small amounts is sometime needed to boost pea yield and quality (Herridge et al., 2008; Huang et al., 2017). When soil residual NO_3-N content is <20 kg N ha^{-1}, N fertilization can enhance pea yield and protein concentration compared with no N fertilization (McKenzie et al., 2001), but not so when soil residual NO_3-N content is >44 kg N ha^{-1} (Huang et al., 2017). Nitrogen fertilization can inhibit nodule development and N fixation, thereby decreasing pea yield and quality compared with no N fertilization (Bollman & Vessey, 2006; Clayton et al., 2004; Zhao et al., 2020). Small N fertilization rates (<30 kg N ha^{-1}) enhanced pea yield, but higher rates decreased pea yield and quality (Podgorska-Lesiak & Sobkowicz, 2013; Raja et al., 2022). Higher N fertilization rates can promote pea straw yield instead of grain yield (Clayon et al., 2004; Lopez-Bellido et al., 2003; Rutkowska & Pikula, 2016).

Winter cover cropping is a popular management option to cover soil during the fallow period and to enhance soil and environmental quality in regions with mild winter and adequate precipitation (Daryanto et al., 2018; Poeplau & Don, 2015; Wang et al., 2018). There are numerous benefits of cover cropping compared with no cover cropping, such as enhanced soil structure and erosion control (Blanco-Canqui & Lal, 2004; Kaspar & Singer, 2011), increased C sequestration (Poeplau & Don, 2015) and water infiltration (Basche et al., 2016), decreased nutrient leaching (Gabriel et al., 2012) and greenhouse gas emissions (Tonitto et al., 2006), superior weed and pest controls (Damien et al., 2017; Schipanski et al., 2014), and improved wildlife habitat and biological diversity (Elhakeem et al., 2019). Although precipitation is limited in the semiarid region of the US northern Great Plains, there is an opportunity for winter cover cropping immediately after pea harvest, because pea uses less soil water than malt barley, in which autumn-planted cover crops can use the remaining

soil water to enhance their biomass yield (Lenssen et al., 2018; Sainju et al., 2020; Zhang et al., 2022). Performance of such cover crops, however, depends on the precipitation amount received during the cover crop growing season when little precipitation can result in modest cover crop biomass yields (Antosh et al., 2022). The effect of such cover cropping on pea growth, yield, and quality in the malt barley–pea rotation needs to be examined.

A narrow range of N fertilization rates to malt barley (NRMBs) from 40 to 80 kg N ha^{-1} (40, 50, 60, 70, and 80 kg N ha^{-1}) in the malt barley–pea rotation was evaluated to determine the exact N fertilization rate for enhanced malt barley yield and quality in this research because previous study revealed that N fertilization rate between 40 and 80 kg N ha^{-1} can sustain malt barley yield and quality in the malt barley–pea rotation (Sainju & Pradhan, 2024). This study evaluates pea growth, yield, and quality as affected by such narrow ranges of NRMB and winter cover cropping in the malt barley–pea rotation. It was hypothesized that pea growth, yield, and quality would be enhanced with moderate rates of NRMB (40–60 kg N ha^{-1}) as well as cover cropping compared with no N fertilization and cover cropping in the malt barley–pea rotation. The objective of the study was to evaluate the effect of cover cropping and NRMB on pea growth, yield, and quality in the malt barley–pea rotation from 2013 to 2019 in dryland cropping systems of the US northern Great Plains.

Core Ideas

- Soil residual NO_3-N content increased with increasing N fertilization rate to malt barley in the malt barley–pea rotation.
- N fertilization to malt barley increased pea yield, protein, and test weight compared to no N fertilization.
- Cover cropping had less effect on pea performance.
- N fertilization to malt barley can enhance pea yield and quality in the malt barley–pea rotation.

2 | MATERIALS AND METHODS

2.1 | Field experiment

The dryland field experiment was conducted from 2013 to 2019 at a research station, 11 km west of Sidney (48° 33′ N, 104° 50′ W), MT. The mean annual air temperature and average total annual precipitation (30-year average) for the study site were 7.1°C and 341 mm, respectively. About 77% of the total annual precipitation was covered by the crop growing season precipitation (April–August) (Figure 1). The periods when monthly total precipitation exceeded the 30-year average were April–June and August 2013; April, May, and August 2014; June and September 2015 and 2019; April, July, and September 2016; and May 2018. The growing season precipitation was 3–180 mm greater in 2013, 2014, and 2016 than the 30-year average (Figure 2). The growing season precipitation was lowest in 2017 when only 104 mm occurred. The site had Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustoll) soil, with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, and pH 7.2 at the 0- to 20-cm depth. The site was previously cultivated with continuous spring wheat (*Triticum aestivum* L.) under conventional tillage for 10 years.

Treatments were two winter cover cropping (oat [*Avena sativa* L.] cover crop vs. no cover crop) and six NRMBs (0, 40, 50, 60, 70, and 80 kg N ha^{-1}) in the no-till malt barley–pea rotation where every phase of the crop rotation occurred in each year. The narrow rates of NRMB from 40 to 80 kg N ha^{-1} were tailored to determine the exact rate of N fertilization that can sustain malt barley yield and quality. Treatments were arranged in a factorial design with three replications. The plot size was 6 m × 6 m.

Before malt barley and pea were planted, oat cover crop was planted in September of the previous year in cover crop–treated plots from 2013 to 2018 under the no-till system at 60 kg ha^{-1} using a no-till drill in the malt barley–pea rotation. Cover crop did not receive any fertilizers, herbicides, pesticides, or irrigation. In March of the following year, cover crop biomass yield was determined by harvesting biomass from two 0.4 m^2 areas from a plot, compositing, and oven drying at 65°C for 3 days. Because of limited growth due to lower precipitation during the cover crop growing season (from September of the previous year to March of the following year), cover crop biomass yield was not determined in 2018 and 2019. After biomass harvest, cover crop was terminated by applying glyphosate [*N*-(phosphonomethyl) glycine] at 1.8 kg a.i. ha^{-1}.

In late April of each year from 2014 to 2019, using a no-till drill, six-row malt barley (Certified Tradition, Busch Agricultural Resources) was planted at 45 kg ha^{-1} and pea (Majoret, Macintosh Seed) inoculated with proper *Rhizobium* sp. at 101 kg ha^{-1} to a depth of 3.8 cm under no-till condition in different plots. At planting, both malt barley and pea received band applications of P fertilizer as triple super phosphate at 11 kg P ha^{-1} and K fertilizer as muriate of potash at 27 kg K ha^{-1} at 5 cm to the side and 5 cm below seeds. A broadcast application of N fertilizer as urea at desired N fertilization rates was applied to malt barley, a week after planting. The desired N fertilization rates, considered as plant available N, included both fertilizer and soil residual NO_3-N content (Technicon Inc.), which was determined to a depth of 60 cm after crop harvest in the fall of each previous year. However, the 0 kg N ha^{-1} treatment included only soil NO_3-N content. Pea did not

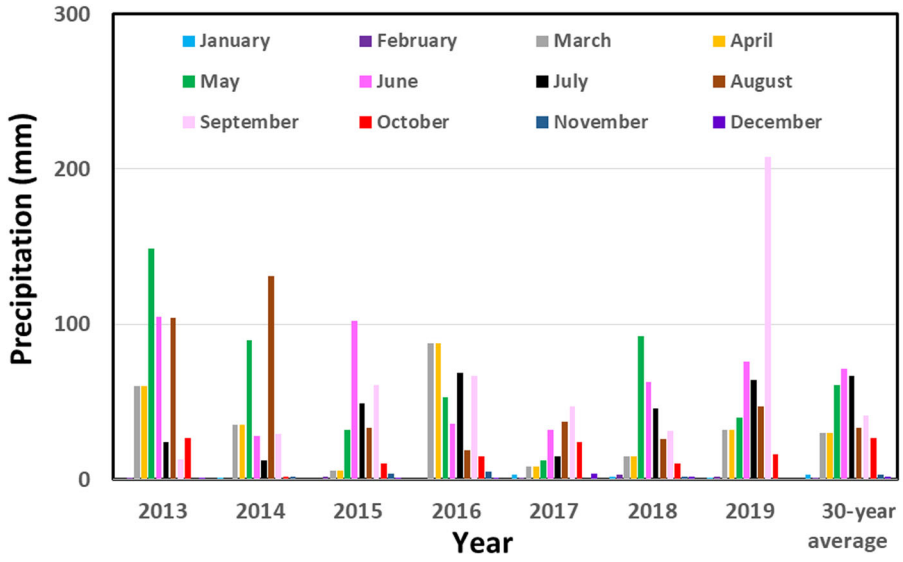


FIGURE 1 Average monthly precipitation during the experimental period from 2013 to 2019 at the research site. Data for 30-year average precipitation were also shown.

receive any N fertilizer. Because crops were grown under dryland condition, no irrigation was applied. To control weeds and pests, malt barley received a mixture of bromoxynil (3, 5-dibromo-4-hydroxybenzonitrile) and fenoxaprop-P {(R)-2-[4(6-chloro-1, 3-benoxazol-2-yloxy) phenoxy] propionic acid} at 0.5 kg a.i. ha^{-1}. Pea received sonalan [*N* ethyl-*N*-2(2-methyl-2 propenyl)-2, 6 dinitro-4-trifluromethyl benzeneamine] at 1.0 L ha^{-1} in the fall followed by postemergence herbicide of a mixture of bentazon [3-isopropyl-1-*H*-2,1,3-benzothiadiazin-(3*H*)-one 2,2 –dioxide] and sethoxydim {2-[1-(ethoxyimino) butyl]-5-2-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexene-1-one}at 0.12 kg active ingredient per ha. In late July and August of every year, 2 days before grain harvest, aboveground biomass of malt barley and pea was harvested by cutting plants at 2.5 cm above the ground with a knife from two 0.4 m^2 areas within a plot, and composited. Grains were harvested from a swath of 11.0 m × 1.5 m using a combine harvester. After grain harvest, crop residues were returned to the soil.

2.2 | Data collection

At 2 week after planting, pea plant density was determined by counting the number of plants from two 0.4 m^2 areas randomly within a plot. Pea straw yield was determined by separating straw from grains in the aboveground biomass and oven drying at 65˚C for 3 days. The separated grains were used to determine harvest index by dividing grain yield by aboveground biomass (sum of grain and straw yields) after grains were oven dried at 65˚C for 7 days. Actual pea grain yield was determined by weighing grains harvested by the combine harvester after oven drying a sample at 65˚C for 7 days.

A C and N analyzer (LECO) was used to determine N concentrations in cover crop biomass and pea straw and grains after grinding the oven-dried samples to 1 mm. Nitrogen accumulation in cover crop biomass and N uptake by pea straw and grain were calculated by multiplying their yields by N concentrations. Pea N harvest index was calculated by dividing grain N uptake by aboveground biomass N uptake (sum of grain and straw N uptake). Pea grain protein concentration was determined by multiplying grain N concentration by 6.25 (Sainju & Pradhan, 2024). Pea grain test weight was determined by weighing grains filled in a 0.95 L container (Lenssen et al., 2018). Because of labor constraints, grain test weight was measured only in 2014, 2017, and 2019.

Soil samples were collected to a depth of 60 cm under malt barley after crop harvest in September of every year from 2014 to 2019. A truck driven hydraulic probe (3.5 cm inside diameter) was used to sample soil at five places within a plot, composited, air dried, and ground to 2 mm. NO_3-N concentration in the soil was determined by using an autoanalyzer after extracting a sample with 2 mol L^{-1} KCl for 1 h. Soil residual NO_3-N content was determined by multiplying NO_3-N concentration by the bulk density and thickness of the soil layer. Bulk density for soil cores collected in the field was determined by dividing the weight of oven dried soil at 105˚C for 24 h by the volume of the core.

2.3 | Analysis of data

Data for soil residual NO_3-N content, cover crop biomass yield, and N accumulation, as well as pea plant density, grain and biomass yields, harvest index, N concentration, N uptake, N harvest index, protein concentration, and grain test weight

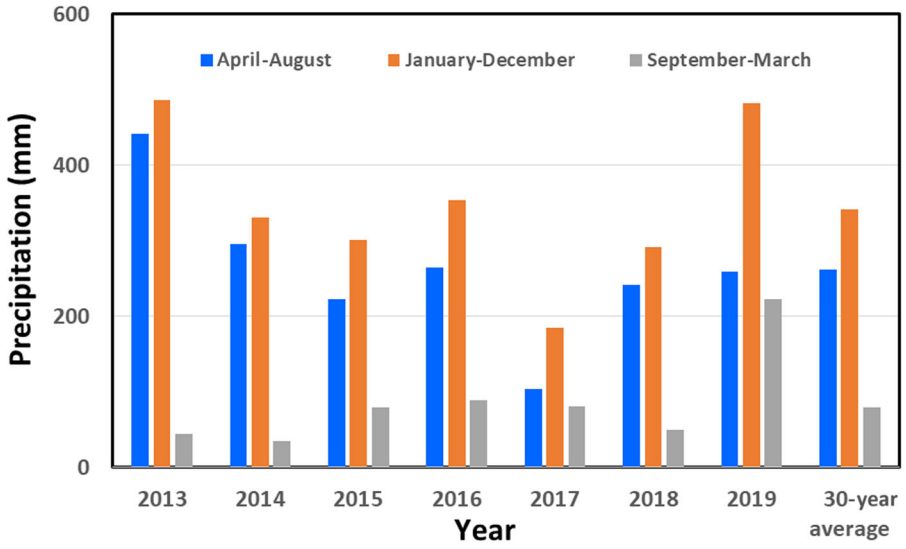


FIGURE 2 Pea growing season (April–August), cover crop growing season (September–March), and annual (January–December) precipitations from 2013 to 2019 at the study site. Data for 30-year average precipitation were also shown.

TABLE 1 Interaction between N fertilization rate to malt barley (NRMB) and year on soil residual NO_3-N content to a depth of 60 cm under malt barley, averaged across cover crops, in the malt barley–pea rotation.

NRMB (kg N ha^{-1})	2014	2015	2016	2017	2018	2019	Average
	Soil residual NO_3-N content (kg N ha^{-1})						
0	3.22	3.15	5.64bc	6.34c	5.17	2.26b	4.21d
40	3.12	4.45	4.37c	6.10c	4.92	2.77b	4.49cd
50	3.34	4.36	5.14bc	6.78bc	5.65	2.57b	4.55bcd
60	3.14	4.14	7.76a	7.13bc	4.58	3.29b	4.82abc
70	2.84	4.35	7.54a	8.33ab	5.93	5.02a	5.38a
80	2.31	4.32	6.23ab	9.78a	5.73	3.52ab	5.07abc

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test.

were analyzed using the SAS-MIXED model (Littell et al., 2006). In the data analysis, cover crop, NRMB, and their interaction were considered as fixed effects, year as the repeated measure variable, and replication as the random effect. The least square means test (Littell et al., 2006) was used to separate means and interactions when significant at a threshold p value of ≤0.05, unless mentioned otherwise.

3 | RESULTS

3.1 | Soil residual NO_3-N

Soil residual NO_3-N content was significantly affected by NRMB and year, with a significant NRMB × year interaction. Averaged across cover crops, soil residual NO_3-N content was 34%–78% greater for 60 and 70 than 0, 40, and 50 kg N ha^{-1} of NRMB in 2016 (Table 1). In 2017, soil residual NO_3-N content was 37%–60% greater for 80 than 0, 40, 50, and 60 N ha^{-1} of NRMB. In 2019, soil residual NO_3-N content was 34%–122% greater for 70 than 0, 40, 50, and 60 kg N ha^{-1} of NRMB. Averaged across cover crops and years, soil residual NO_3-N content generally increased with increasing NRMB. Averaged across cover crops and NRMBs, soil residual NO_3-N content was greater in 2017 than other years.

3.2 | Cover crop biomass yield and nitrogen accumulation

Cover crop biomass yield was affected by NRMB and year, with a significant NRMB × year interaction (Table 2). Cover crop biomass yield was 100%–111% greater for 70 than 40, 60, and 80 kg N ha^{-1} of NRMBs in 2015 and 51%–392% greater for 40, 50, and 80 than 0, 60, and 70 kg N ha^{-1} of NRMBs in 2016 (Table 3). There was no significant difference in cover crop biomass yield among NRMBs in

TABLE 2 Effect of year on cover crop biomass yield and N accumulation, averaged across N fertilization rates to malt barley (NRMBs), in the malt barley–pea rotation. Sources of variation in the analysis of variance included NRMB and year (Y).

Year	Cover crop biomass yield (Mg ha^{-1})	Cover crop biomass N accumulation (kg N ha^{-1})
2014	0.40b	5.79c
2015	0.50b	11.36ab
2016	0.91a	15.65a
2017	0.40b	9.63bc
Significance	*p* values	
NRMB	**0.011**	0.256
Y	**<0.001**	**0.010**
NRMB × Y	**<0.001**	0.172

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test. Bold numbers denote significant *p* values.

TABLE 3 Interaction between N fertilization rate to malt barley (NRMB) and year on cover crop biomass yield in the malt barley–pea rotation.

NRMB (kg N ha^{-1})	Cover crop biomass yield (Mg ha^{-1})			
	2014	2015	2016	2017
0	0.35	0.57ab	0.27c	0.32
40	0.45	0.38b	1.33a	0.46
50	0.45	0.54ab	1.12a	0.41
60	0.35	0.38b	0.74b	0.42
70	0.37	0.76a	0.62bc	0.29
80	0.43	0.36b	1.32a	0.49

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test.

2014 and 2017. Cover crop biomass N accumulation was affected by year, but not by NRMB and its interaction with year (Table 2). Averaged across NRMBs, cover crop biomass yield was 82%–128% greater and biomass N accumulation was 64%–170% greater in 2016 than 2014 and 2017.

3.3 | Pea plant density, straw yield, nitrogen concentration, and nitrogen uptake

Pea plant density was affected by year, but not by cover crop, NRMB, and their interaction (Table 4). Averaged across cover crops and NRMBs, plant density was 21%–69% greater in 2019 than other years (Table 5). Pea straw yield was affected by NRMB and year (Table 4). Averaged across cover crops and NRMBs, straw yield was 24%–46% greater in 2016 and 2019 than other years (Table 5). Averaged across cover crops and years, straw yield was 15%–20%

TABLE 4 Analysis of variance for pea parameters with sources of variations as cover crop (CC), N fertilization rate to malt barley (NRMB), and year (Y) in the malt barley–pea rotation. Parameters are plant density, straw yield, grain yield, harvest index, straw N concentration, grain protein concentration, straw N uptake, grain N uptake, N harvest index, and grain test weight.

Source	Plant density	Straw yield	Grain yield	Harvest index	Straw N concentration	Grain protein concentration	Straw N uptake	Grain N uptake	N harvest index	Grain test weight
	p values									
CC	0.161	0.252	0.867	0.446	**0.005**	0.672	0.114	0.946	0.207	0.722
NRMB	0.916	**0.017**	0.797	**0.004**	**0.003**	**<0.001**	**<0.001**	0.970	**0.029**	**<0.001**
CC × NRMB	0.614	0.968	0.862	0.930	0.889	0.840	0.968	0.880	0.747	0.594
Y	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
CC × Y	0.432	0.439	0.824	0.983	0.577	0.897	0.862	0.967	0.979	0.951
NRMB × Y	0.971	0.140	**0.011**	**0.007**	0.579	0.957	0.248	**0.015**	**0.034**	**<0.001**
CC × NRMB × Y	0.965	0.982	1.000	0.996	0.998	1.000	0.999	1.000	0.999	0.790

Note: Bold values denote significant *p* values.

TABLE 5 Effect of year on pea plant density, straw yield, straw N concentration, straw N uptake, and grain protein concentration, averaged across cover crops and N fertilization rates to malt barley, in the malt barley–pea rotation.

Year	Plant density (million ha^{-1})	Straw yield (Mg ha^{-1})	Straw N concentration (g N kg^{-1})	Straw N uptake (kg N ha^{-1})	Grain protein concentration (g kg^{-1})
2014	0.95c	2.57b	12.6d	32.3d	229bc
2015	0.83d	2.71b	22.3b	60.8b	239ab
2016	0.87d	3.36a	23.1a	78.1a	242a
2017	1.16b	2.41b	16.2c	39.0c	206d
2018	1.17b	2.42b	23.1a	56.2b	221c
2019	1.41a	3.53a	10.0e	35.4cd	196d

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test.

TABLE 6 Effect of N fertilization rate to malt barley (NRMB) on pea straw yield, straw N concentration, straw N uptake, and grain protein concentration, averaged across cover crops and years, in the malt barley–pea rotation.

NRMB (kg N ha^{-1})	Straw yield (Mg ha^{-1})	Straw N concentration (g N kg^{-1})	Straw N uptake (kg N ha^{-1})	Grain protein concentration (g kg^{-1})
0	2.45b	17.3b	40.9c	205b
40	2.90a	18.9a	54.7a	226a
50	2.94a	18.9a	54.5a	226a
60	2.81a	18.8a	52.1ab	225a
70	2.65ab	18.8a	49.6b	226a
80	2.86a	18.4a	54.0a	227a

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test.

greater for 40, 50, 60, and 80 than 0 kg N ha^{-1} of NRMBs (Table 6).

Pea straw N concentration was affected by cover crop, NRMB, and year (Table 4). Averaged across NRMBs and years, straw N concentration was 10% greater for no cover crop than cover crop. Averaged across cover crops and NRMBs, straw N concentration was 4%–131% greater in 2016 and 2018 than other years (Table 5). Averaged across cover crops and years, straw N concentration was 6%–9% greater with than without NRMB (Table 6). Pea straw N uptake was affected by NRMB and year (Table 4). Averaged across cover crops and NRMBs, straw N uptake was 28%–142% greater in 2016 than other years (Table 5). Averaged across cover crops and years, straw N uptake was 9%–34% greater for 40, 50, and 80 than 0 and 70 kg N ha^{-1} of NRMB (Table 6).

3.4 | Pea grain yield, protein concentration, and nitrogen uptake

Pea grain yield was affected by year, with a significant NRMB × year interaction (Table 4). Averaged across cover crops, grain yield was 40% greater for 40 than 60 kg N ha^{-1} of NRMB in 2015 (Table 7). In 2018, grain yield was 45%–167% greater for 60 and 80 than 0, 40, and 70 kg N ha^{-1} of NRMB. There was no significance difference in grain yield among NRMBs in 2014, 2016, 2017, and 2019. Averaged across cover crops and NRMBs, grain yield was greater in 2019 than other years.

Pea grain protein concentration was affected by NRMB and year (Table 4). Averaged across cover crops and NRMBs, grain protein concentration was 6%–17% greater in 2016 than other years, except in 2015 (Table 5). Averaged across cover crops and years, grain protein concentration was 10%–11% greater with than without NRMB (Table 6).

Pea grain N uptake was significantly affected by year, with a significant interaction for NRMB × year (Table 4). Averaged across cover crops, grain N uptake was 40% greater for 40 than 60 kg N ha^{-1} of NRMB in 2015 (Table 7). In 2018, grain N uptake was 45%–224% greater for 80 than 0, 40, and 70 kg N ha^{-1} of NRMB. There was no significant difference in grain N uptake among NRMBs in 2014, 2016, 2017, and 2019. Averaged across cover crops and NRMBs, grain N uptake was greater in 2016 than other years.

3.5 | Pea harvest index and nitrogen harvest index

Pea harvest index was significantly affected by NRMB and year, with a significant interaction for NRMB × year (Table 4). Averaged across cover crops, harvest index was

TABLE 7 Interaction between N fertilization rate to malt barley (NRMB) and year on pea grain yield, grain N uptake, grain test weight, harvest index, and N harvest index, averaged across cover crops, in the malt barley–pea rotation.

NRMB (kg N ha^{-1})	2014	2015	2016	2017	2018	2019
	Grain yield (Mg ha^{-1})					
0	3.03	2.70ab	3.94	1.32	1.26d	4.53
40	2.82	3.02a	3.58	1.02	2.32bc	3.96
50	2.89	2.80ab	3.57	1.09	2.77ab	4.00
60	2.67	2.16b	3.30	1.06	3.29a	4.05
70	2.83	2.85ab	3.55	1.01	1.75cd	4.28
80	2.57	2.57ab	3.62	0.86	3.37a	3.96
	Grain N uptake (kg N ha^{-1})					
0	110	99ab	143	33	38d	122
40	103	115a	142	36	85bc	129
50	109	105ab	139	37	102ab	130
60	98	82b	130	36	120ab	131
70	104	109ab	141	35	63cd	137
80	95	114ab	141	30	123a	127
	Grain test weight (kg hL^{-1})					
0	74.5c	–	–	84.6	–	82.4b
40	80.9b	–	–	84.5	–	83.3a
50	80.9b	–	–	84.7	–	83.4a
60	81.7a	–	–	84.4	–	83.1a
70	81.1ab	–	–	84.7	–	83.3a
80	81.1ab	–	–	84.6	–	83.2a
	Harvest index					
0	0.54ab	0.53	0.52	0.36a	0.45	0.59a
40	0.51b	0.51	0.50	0.29ab	0.45	0.54ab
50	0.54ab	0.50	0.51	0.31ab	0.50	0.50b
60	0.51b	0.47	0.54	0.29ab	0.52	0.53ab
70	0.62a	0.52	0.54	0.29ab	0.46	0.54ab
80	0.48b	0.49	0.51	0.27b	0.50	0.57ab
	N harvest index					
0	0.78	0.64a	0.66	0.49	0.55	0.83a
40	0.75	0.64a	0.62	0.46	0.55	0.78ab
50	0.78	0.63ab	0.63	0.49	0.60	0.75b
60	0.75	0.56b	0.63	0.47	0.62	0.78ab
70	0.80	0.65ab	0.66	0.46	0.56	0.78ab
80	0.74	0.62ab	0.66	0.44	0.60	0.80ab

Note: Numbers followed by different letters in a column are significantly different at $p \leq 0.05$ by the least square means test. "–": not measured.

22% greater for 70 than 40, 60, and 80 kg N ha^{-1} of NRMBs in 2014 (Table 7). In 2017, harvest index was 33% greater for 0 than 80 kg N ha^{-1} of NRMB. In 2019, harvest index was 18% greater for 0 than 50 kg N ha^{-1} of NRMB. Averaged across cover crops and NRMBs, harvest index was greater in 2019 than other years.

Pea N harvest index was also significantly affected by NRMB and year, with a significant interaction for NRMB × year (Table 4). Averaged across cover crops, N harvest index was 14% greater for 0 and 40 than 60 kg N ha^{-1} of NRMBs in 2015. In 2019, N harvest index was 11% greater for 0 than 50 kg N ha^{-1} of NRMB. Averaged across cover crops and NRMBs, N harvest index was also greater in 2019 than other years.

3.6 | Pea grain test weight

Pea grain test weight was significantly affected by NRMB and year, with a significant interaction for NRMB × year (Table 4). Averaged across cover crops, grain test weight was

9%–10% greater for 60 than 0, 40, and 50 kg N ha^{-1} of NRMB in 2014 (Table 7). In 2018, grain test weight was 2%–3% greater with than without NRMBs. Grain test weight did not vary among NRMBs in 2017. Averaged across cover crops and NRMBs, grain test weight was greater in 2017 than other years.

4 | DISCUSSION

4.1 | Soil residual NO_3-N content

Soil residual NO_3-N content was <10 kg N ha^{-1} in all treatments and years (Table 1), suggesting that both malt barley and cover crop may have taken most of the applied fertilizer N. As a result, the risk of N losses to the environment though surface runoff, leaching, volatilization, denitrification, and gaseous emissions is low (Eickhout et al., 2006; Ross et al., 2008). Increasing NRMB increased soil residual NO_3-N content in 2016, 2017, and 2019, an indication of increased N availability that both malt barley and cover crop were unable to extract from the soil as NRMB increased. However, some of the soil residual NO_3-N content may be a result of soil organic matter mineralization, as was observed for the 0 kg N ha^{-1} of NRMB where no N fertilizer was applied. This suggests that NO_3-N contribution from the mineralization of soil organic matter can be substantial that can affect pea yield and quality. The greater soil residual NO_3-N content in 2017 than other years was probably due to lower N uptake stemming from lower malt barley yield (Table 7) due to lower growing season precipitation in that year (Figure 1).

4.2 | Cover crop biomass yield and nitrogen accumulation

Cover crop biomass <1.5 Mg ha^{-1} in all treatments and years (Table 3) was due to reduced growing season precipitation (September–March) and air temperature. Cover crop biomass usually depends on cover crop growing season precipitation and air temperature in the northern Great Plains (Antosh et al., 2022). The cover crop growing season precipitation ranged from 35 mm in 2014 to 89 mm in 2016, with 30-year average of 79 mm (Figure 1). Although we did not collect air temperature, it can be as low as −30°C in January and February (Sainju et al., 2024). The cold weather can reduce cover crop growth and biomass production (Antosh et al., 2022). Our result of winter cover crop biomass yield <1.5 Mg ha^{-1} was similar to <2 Mg ha^{-1} observed by Antosh et al. (2022) in North Dakota, which receives slightly greater precipitation (410 mm) than our site. Higher cover crop growing season precipitation and increased N availability due to greater soil residual NO_3-N content and soil organic N mineralization may have increased cover crop biomass yield for 40, 50, and 80 kg N ha^{-1} of NRMB in 2016 (Tables 1 and 3). Although soil residual N was greater in 2016 and 2017 than other years (Table 1), cover crop growing season precipitation was greater in 2016 (89 mm) than 2017 (45 mm), which may have resulted in greater soil organic N mineralization that increased N availability and cover crop biomass in 2016. Because of the limited growth, cover crop biomass yield was not reported for 2018 and 2019. Increased cover crop biomass yield also resulted in greater cover crop N accumulation in 2016 than other years (Table 2).

4.3 | Pea plant density, straw yield, nitrogen concentration, and nitrogen uptake

The nonsignificant effect of cover crop and NRMB on pea plant density suggests that pea plant density was not altered by cover crop or soil residual NO_3-N content. However, greater plant density in 2019 than other years was probably due to increased soil water availability from higher precipitation in that year (Table 5, Figure 1). Total annual precipitation was greater in 2019 than other years and the 30-year average (Figure 1). Increased soil water availability can enhance pea plant density (Huang et al., 2017; Tao et al., 2017).

Increased soil N availability due to greater soil residual NO_3-N content from increasing NRMB likely increased pea straw yield for 40, 50, 60, and 80 compared with 0 kg N ha^{-1} of NRMB (Table 6). Soil residual NO_3-N content usually increased with increasing NRMB (Table 2). However, the nonsignificant difference in straw yield among NRMBs, except for 0 kg N ha^{-1}, suggests that slight increase in soil residual NO_3-N content resulting from increasing NRMB may not affect straw yield. Sainju and Pradhan (2024) reported that pea straw yield did not increase when N fertilization rate to previous crop exceeded 50 kg N ha^{-1} in the small grains–pea rotation. The greater straw yield in 2019 than other years was probably due to increased plant density (Table 5). Pea growth and straw yield are affected more by climatic condition than soil nutrient levels (Huang et al., 2017; Tao et al., 2017). Martin et al. (1994) showed that higher pea plant density increased its straw yield, but not grain yield.

The greater pea straw N concentration without than with cover crop (Figure 2) was probably due to increased N taken up by cover crop that reduced N availability for pea uptake. In contrast, greater straw N concentration with than without NRMB (Table 6) was probably due to increased soil N availability from increasing NRMB that increased soil residual NO_3-N content (Table 1). Because of small differences in soil residual NO_3-N content and biological N fixation, straw N concentration was not different among 40, 50, 60, 70, and 80 kg N ha^{-1} of NRMBs. Improved biological N fixation during years with normal growing season precipitation may

have increased straw N concentration in 2016 and 2018 (Tables 1 and 5). Greater straw yield increased pea straw N uptake for 40, 50, and 80 kg N ha^{-1} compared with other NRMBs (Table 6). Similarly, greater straw yield and N concentration increased straw N uptake in 2016 than other years (Table 5).

4.4 | Pea grain yield, protein concentration, nitrogen uptake, and test weight

Increased N availability due to greater NRMB may have reduced pea grain yield for 60 than 40 kg N ha^{-1} of NRMB in 2015 when the pea growing season precipitation was below the 30-year average (Tables 1 and 7). Some researchers (Bollman & Vessey, 2006; Ghaley et al., 2005; Huang et al., 2017) have demonstrated that increased N fertilization rate to pea can reduce its yield due to decreased nodulation and N fixing capacity. It may be possible that greater NRMB may have resulted in toxic effect for pea production during the dry year. When the pea growing season precipitation was near the normal, such as in 2018, increased N availability due to increasing NRMB, however, may have increased pea yield for 60 and 80 kg ha^{-1} compared with other NRMBs. Pea grain yield responds favorably to N fertilization rate when soil residual NO_3-N is <44 kg N ha^{-1} in years with normal growing season precipitation (Lafond et al., 2011; McKenzie et al., 2001; Raja et al., 2022). Sainju and Pradhan (2024) also observed that N fertilization to previous crop increased pea grain yield in the small grains–pea rotation during years with normal growing season precipitation. Lower grain yield in 2017 than other years was due to below-average growing season precipitation (Figure 1).

The nonsignificant difference in pea grain yield for 0 kg N ha^{1} compared with other NRMBs in all years, except in 2018 (Table 7) was probably due to greater soil residual NO_3-N content that enhanced grain yield. Soil residual NO_3-N content was not significantly among 0 kg N ha^{-1} and other NRMBs in most years (Table 1). It may be possible that greater mineralization of soil organic matter mineralization during years with near or above-average annual precipitation may have increased soil residual NO_3-N content in all years, except in 2017 when residual NO_3-N content was lower due to below-average precipitation (Table 1; Figure 1). Although residual NO_3-N content was not significantly different among NRMBs in 2018, drier condition due to below-average precipitation in 2017 may have reduced pea grain yield in the 0 kg N ha^{-1} of NRMB in 2018.

The greater N availability due to increased NRMB also likely increased pea grain protein concentration with than without NRMB (Table 6), as soil residual NO_3-N content was higher with than without NRMB (Table 1). Although most of the N concentration in pea is contributed by biological N fixation, 35% of N is still taken up from the soil (Herridge et al., 2008; Huang et al., 2017). Our pea grain protein concentration of 205–227 g kg^{-1} is within the range of 130–380 g kg^{-1} reported by several researchers (Deba & Morris, 2022; Sainju & Pradhan, 2024). Enhanced N availability due to increased organic matter mineralization and improved biological N fixation may have increased grain protein concentration in 2016 (Table 5) when the growing season precipitation was above the average (Figure 1).

Enhanced grain yield and N concentration may have increased pea grain N uptake for 40 compared with 60 kg N ha^{-1} of NRMB in 2015 and for 80 compared with 0, 40, and 70 kg N ha^{-1} in 2018 (Table 7). As grain yields were greater with these NRMBs, grain protein concentration was also higher with than without NRMB (Table 6). While several researchers (Deibert & Utter, 2007; Kumar et al., 2015) observed increased pea grain N uptake with increasing N fertilization rate, others (Clayton et al., 2004; Izaurralde et al., 1990) showed that N fertilization had no effect on pea grain N uptake.

The greater pea grain test weight with than without NRMB in 2014 and 2019 (Table 7) was also likely due to increased N availability due to NRMB, as soil residual NO_3-N content was greater with than without NRMB (Table 1). This was in contrast with those shown by numerous researchers (Herridge et al., 2008; Huang et al., 2017; Lenssen et al., 2018; Sainju et al., 2019; Sainju & Pradhan, 2024) who reported that increasing N fertilization rate decreased pea grain test weight. Excluding 0 kg N ha^{-1}, grain test weight was, however, variable among NRMBs in 2015, but was not significantly different in 2019. This indicates that increasing NRMB can affect grain test variably in various years. Lower grain test weight in 2014 than 2017 and 2019 was probably due to decreased N availability, as soil residual NO_3-N content was lower in 2014 (Table 1).

4.5 | Harvest index and N harvest index

Increased grain yield relative to the sum of grain and straw yields increased pea harvest index for 70 compared with 40 and 60 kg N ha^{-1} of NRMB in 2014, 0 compared with 80 kg N ha^{-1} in 2017, and 0 compared with 50 kg N ha^{-1} in 2019 (Table 7). Although not significant, grain yield was somewhat greater for 70 kg N ha^{-1} of NRMB in 2014 and for 0 kg N ha^{-1} in 2017 and 2019 than other NRMBs (Table 7), but straw yield was not different between 0 and 70 kg N ha^{-1} of NRMB (Table 6). This shows that variation in grain yields largely resulted in differences in harvest index among NRMBs in various years. Lower grain yield compared to the sum of grain and straw yields due to decreased growing precipitation likely reduced harvest index in 2017 compared with other years.

Greater grain N uptake relative to the sum of grain and straw N uptake may have increased pea N harvest index for 0 and 40 compared with 60 kg N ha^{-1} of NRMB in 2015 and for 0 compared with 50 kg N ha^{-1} of NRMB in 2019 (Table 7). Grain N uptake was greater for 40 than 60 kg N ha^{-1} of NRMB in 2015 (Table 7), but straw N uptake was lower with than without NRMB (Table 6). This may have resulted in greater N harvest index for 0 and 40 kg N ha^{-1} of NRMB in 2015 and 2019. As with harvest index, lower grain N uptake relative to the sum of grain and straw N uptake due to reduced growing season precipitation probably decreased N harvest index in 2017 compared with other years.

5 | CONCLUSIONS

The NRMB had greater influence on dryland pea yield and quality than cover cropping in the semiarid region of the US northern Great Plains. Soil residual NO_3-N content following malt barley and cover crop biomass yield and N accumulation were modest, but soil residual NO_3-N content had greater effect on pea performance. The NRMB increased pea straw and grain yields, straw and grain N uptake, and grain protein concentration and test weight compared with no NRMB, but different NRMB had variable effect on these parameters due to variations on soil N availability. Nitrogen fertilization to malt barley enhanced pea yield and quality, regardless of cover cropping, in the malt barley–pea rotation in the northern Great Plains.

AUTHOR CONTRIBUTIONS

Upendra M. Sainju: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

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