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Fertilizer nitrogen recovery of irrigated spring malt barley

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Abstract

Well-defined nitrogen (N) management in irrigated two-row malting barley (*Hordeum vulgare* L.) is critical for yield and quality and to minimize environmental impacts. Data on fertilizer N recovery efficiency (FNRE) and the fate of fertilizer-N in the soil are lacking. The study objective was to determine uptake and partitioning of ^{15}N-labeled urea in the plant and soil. Urea was either surface applied or incorporated at a total N rate (inorganic-N + applied N) of 214 kg N ha^{-1} at planting. Three malt cultivars were grown, and samples were collected four times during the growing season (Feekes growth stages 4/5, 10.0, 11.2, and 11.4). Barley plants at Feekes 11.2 and 11.4 were separated into vegetative tissue and spikes. Plant N accumulation was lowest at Feekes 4/5 and reached a maximum at Feekes 11.2, whereas FNRE was greatest at Feekes 10.0. Nitrogen was redistributed from vegetative tissue to the spike from Feekes 11.2 to 11.4. Plant FNRE averaged 43% at Feekes 11.4. Total plant–soil FNRE for the surface application was 66%, which was less than the incorporated FNRE of 77%. Results provide evidence of the increased plant–soil system FNRE of incorporated applications in high-input barley production systems compared with surface applications despite no yield difference. Similar FNRE as compared to previous work with lower yields was measured, and modern cultivars out-yielded an older cultivar with no reduction in FNRE. Results of the study indicate that a relatively high plant–soil system FNRE of irrigated malting barley was achieved under high-input, irrigated conditions common in southern Idaho.

1 | INTRODUCTION

In the United States, barley (*Hordeum vulgare* L.) production is largely concentrated in higher-latitude and/or higher-elevation areas with shorter growing seasons (USDA-NASS, 2017). Leading producers include Idaho, Montana, and North Dakota; Idaho represents 30% of total grain production on 200,000 ha annually or 20% of the total hectarage (USDA-NASS, 2017). Average yield in Idaho (~5,000 kg ha^{-1}) is nearly 30% greater than the U.S. average due to the majority of production being for malting barley under irrigated conditions (IBC, 2017). Strict quality specifications must be met for malting barley (e.g., protein concentrations, plump kernels) (IBC, 2017). Application of N to barley considers both yield and quality goals. Increased N rates tend to increase yield and protein content but decrease the percentage of plump kernels (Robertson & Stark, 2003). If N is applied in excess, protein and plump kernels may reach a level that is unacceptable for maltsters. Excess N applications may also cause plant lodging, which leads to increased disease pressure, and the crop may be rejected or compensation reduced based upon contract specifications.

Abbreviations: ADM, aboveground dry matter; FNRE, fertilizer nitrogen recovery efficiency; TDM, total aboveground dry matter; TN, total nitrogen

Malting barley fertilizer management practices were developed with both yield and quality goals in mind (Robertson & Stark, 2003). Lower fertilizer-N rates are prescribed for malting barley as compared to feed barley or other small grains, such as wheat (*Triticum aestivum* L.) (Brown, Stark, & Westermann, 2001; Robertson & Stark, 2003). Specific fertilizer recommendations for malting barley have been developed, including the recommendation to avoid fertilization after tillering to minimize the chance of excessive grain protein. Fertilizer-N placement (i.e., surface vs. incorporation) can affect N losses via ammonia volatilization where fertilizer is commonly applied by surface broadcasting, which is most susceptible to ammonia volatilization (Rogers, Dari, & Walsh, 2018). Fertilizer is also applied by incorporation via tillage or banded beside the seed row where ammonia volatilization losses of N can be reduced as compared to surface applications (Dari, Rogers, & Walsh, 2018; Rogers et al., 2018). Judicious N use is an important factor in ensuring optimal economic yields while minimizing negative environmental impacts. Thus, an understanding of N accumulation patterns and redistribution during the growing season within the barley plant would provide key information in terms of nutrient cycling, which is important for improving fertilizer-N management (Bashir, Norman, Bacon, & Wells, 1997).

Quantification of applied fertilizer-N recovery is critical for determining the N use efficiency of barley production systems. Recent assessments of global and U.S. cereal N use efficiency are 35 and 41%, respectively (Omara, Aula, Oyebiyi, & Raun, 2019). Previous research, focused in rainfed systems, on fertilizer-N recovery of barley has indicated variation in the amount of recovery within the plant as well as in the plant–soil system. Research on a pH 6.9 loamy soil in Canada indicated 23–53% recovery of labeled fertilizer in the plant where maximum fertilized yield was 5,108 kg ha^{-1}, and 82–95% of the fertilizer N was accounted for in the plant–soil system at the culmination of the study (Tomar & Soper, 1981). Research in Australia on a sandy loam with clay subsoil reported greater fertilizer N recovery under rainfed (20–31%) than irrigated conditions (11–27%), with maximum fertilized yields of 4,100 kg ha^{-1} (Smith & Gyles, 1988). Fertilizer N recovery in the plant–soil system from Smith and Gyles (1988) at maturity ranged from 75 to 85%, with no treatment differences between irrigated and nonirrigated malting barley. Further research in Australia on a clay-loam soil with clay subsoil reported much lower recovery (20%) in the plant where the plant–soil system recovery was 60–67% (Smith & Gyles, 1989). Research from Switzerland on a noncalcareous loamy pH 7.4 soil reported that 31% of added N was recovered in the barley plant and 87% was recovered in the plant–soil system, where the majority of the labeled N recovered in the soil was in the top 0–30 cm (Vos, Duquest, Vedy, & Neyroud, 1993). Research in Alaska on a silt-loam soil with a pH of 5.3 in the surface soil reported 41% recovery in the plant and 85% recovery in the plant–soil system where mean fertilized yields were 3,284 kg ha^{-1} (Knight & Sparrow, 1993).

Core Ideas

- Maximum FNRE of barley plants was 53% and occurred at Feekes 10.0.
- System FNREat Feekes 11.4 was greater (77%) for incorporated than surface (66%).
- FNRE (in the plant–soil system) within the current study was similar to previous work.
- Yields were greater and FNRE of the two modern cultivars did not differe from an older cultivar.

Despite the amount of information available concerning barley response to fertilizer-N application, we are unaware of any work that has directly assessed fertilizer N recovery efficiency (FNRE) in high-input, high-yielding irrigated spring malting barley in the western United States. Thus, the objectives of this study were to determine (a) the total and fertilizer-N accumulation of several malt barley cultivars when fertilizer was surface applied versus incorporated, (b) accumulation and redistribution of fertilizer-N recovered within the barley plant, and (c) the amount and distribution of fertilizer-N recovered within the soil profile at Feekes 11.4.

2 | MATERIALS AND METHODS

2.1 | Plot management and experimental design

The field experiment was conducted during the 2016 and 2017 growing seasons at the University of Idaho Aberdeen Research and Extension Center in Aberdeen, ID (42˚58′29″ N, 112˚48′55″ W) on a Declo loam soil (coarse-loamy, mixed, superactive mesic Xeric Haplocalcids) (USDA-NRCS, 2012). Initial soil fertility parameters collected from prior to planting and fertilizer applications in each growing season were determined (Table 1). In short, samples were oven-dried at 40 ˚C and crushed and sieved to pass a 2-mm screen. Soil pH was determined potentiometrically using a 1:1 soil/deionized water ratio, ammonium and nitrate were determined by 2 M KCL extraction and spectrophotometric analysis, and soil-P was determined by $NaHCO_3$ extraction and spectrophotometric methods (Miller, Gavlak, & Horneck, 2013).

Three malting barley cultivars commonly grown in irrigated production in southern Idaho were selected: Anheuser Busch Voyager (Voyager), Coors Moravian 69 (Moravian 69), and Harrington. In recent surveys, Voyager and Moravian 69

TABLE 1 Initial soil fertility status of field sites for studies conducted during the 2016 and 2017 growing seasons at the Aberdeen Research and Extension Center, Aberdeen, ID

Year	Depth	pH	NH_4–N	NO_3–N	Olsen-P
	cm		mg kg^{-1}		
2016	0–30	8.3	4.1	2.9	17
	30–60	8.2	4.0	8.0	
2017	0–30	8.2	4.3	3.0	19
	30–60	8.2	4.0	9.2	

represented nearly 35% of the malt barley acreage in Idaho (AMBA, 2020). Voyager was released in 2011 by Busch Agricultural Resources and had average yields of 7,330 kg ha^{-1}, protein of 112 g kg^{-1}, and an average plant height of 97 cm in irrigated performance trials in southern Idaho (Marshall et al., 2018). Moravian 69 is a short-statured cultivar that was released by Coors Brewing Co. in 2000 and had average yields of 7,903 kg ha^{-1}, protein of 113 g kg^{-1}, and an average plant height of 86 cm in the same performance trials. Harrington was released by the University of Saskatchewan in 1981, is considered a standard for malt quality, and had an average yield of 6,397 kg ha^{-1}, protein of 116 g kg^{-1}, and an average plant height of 91 cm.

Due to the nature of destructive sampling for ^{15}N analysis and similar to Walker, Martin, and Gerard (2006) and Rogers et al. (2016), plot areas for both ^{15}N sampling and yield determination were planted. Individual plot areas were 3.0 m long with seven rows at an 18-cm row spacing with a 2.5-m border between plots on all sides. Yield and ^{15}N plots were handled identically except nonlabeled urea was applied in the yield plots to allow yield measurements and for sampling of barley tissue to determine native atom percentage (atom%) ^{15}N for the site. Barley was seeded following oat (*Avena sativa*, L.) with a small-plot drill on 20 Apr. 2016 and 23 Apr. 2017 at a rate of 323,748 seeds ha^{-1} following the recommendations for irrigated spring barley in Idaho (Marshall et al., 2018; Robertson & Stark, 2003). The source of labeled fertilizer-N was ^{15}N-labeled urea (3.34180 atom% ^{15}N) (Sigma-Aldrich) processed into 2.4 by 3.0 mm prills (International Fertilizer Development Center). Nitrogen was applied based on University of Idaho Extension guidelines at N rates of 129 and 122 kg N ha^{-1} (2016 and 2017, respectively) prior to planting to achieve a total N rate (i.e., soil inorganic-N + applied N) of 214 kg N ha^{-1} and was either broadcast applied or incorporated prior to planting (Robertson & Stark, 2003). Fields were prepared in the spring with shallow tillage using a disc and roller harrow. Broadcast and incorporated N was applied by hand on the same day as planting at a rate of 129 and 122 kg N ha^{-1} in 2016 and 2017, respectively. Incorporated N applications were applied by hand and then incorporated to a depth of approximately 5 cm using a plot-size spring-tooth harrow in individual plots on the same day. Plots were irrigated using a hand-line irrigation system sourced from a groundwater well where a mean of 40 cm of water as precipitation and irrigation occurred annually (Figure 1) (Neibling, Rogers, & Quereshi, 2017; Robertson & Stark, 2003). Plots were managed to be weed and insect free according to current University of Idaho recommendations (Robertson & Stark, 2003). The experiments were arranged as a randomized complete block with cultivar (i.e., Harrington, Moravian 69, and Voyager) by fertilizer placement (i.e., surface and incorporated) and four replications where 0 N check plots of each cultivar were included in each block to verify yield responsiveness of the study sites.

2.2 | Collections and processing of tissue and soil samples

A 1-m row sample was collected at growth stages of Feekes 4/5, 10.0, 11.2, and 11.4 (Miller, 1999). A single sample was collected at each growth stage from even-numbered rows of each plot at the soil surface 30 cm from the top and bottom edge of the plots. Sampling from even-numbered rows and avoiding the outer borders was done to avoid any potential edge effects associated with the plots. Whole plant analysis was conducted for the Feekes 4/5 and Feekes 10.0 sampling. The remaining samples (i.e., Feekes 11.2 and 11.4) were separated into culms plus leaves (vegetative tissue) and spikes to allow for determination of N partitioning.

Tissue samples were dried at 65 ˚C until a constant weight was achieved. Whole plant samples were weighed for the Feekes 4/5 and Feekes 10.0 sampling. Later samplings were separated, and vegetative tissue and spike portions were weighed for dry matter. The sum of dry matter of vegetative tissue plus spikes was defined as total dry matter (TDM) and was converted to an area basis (kg ha^{-1}). Tissue weights were recorded, and the samples were ground to pass a 1-mm sieve using a Wiley Mill (Thomas Scientific) for determination of total N and atom% ^{15}N. Four soil cores (2.5 cm diameter) were collected from each plot and composited as one representative sample from 0 to 30, 30 to 60, and 60 to 90 cm following barley harvest on 14 Aug. 2016 and 10 Aug. 2017. Individual samples were ground and homogenized using a mortar and pestle to pass a 1-mm sieve and analyzed for atom% ^{15}N.

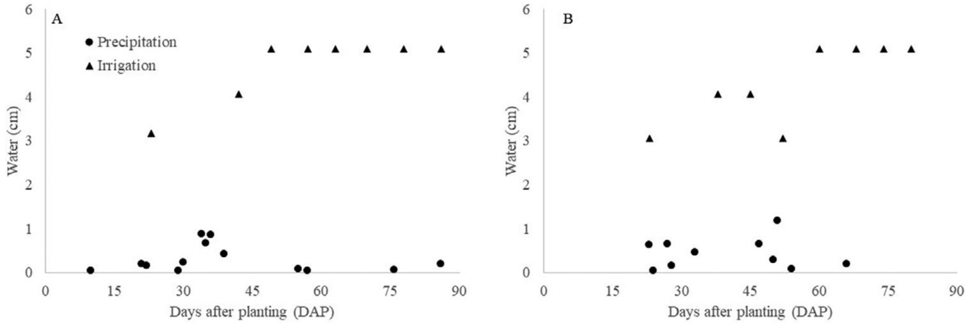

FIGURE 1 Precipitation and irrigation events during the 2016 (A) and 2017 (B) growing season for malting barley grown in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID

In the nonlabeled plots, barley grain was harvested using a small-plot combine equipped with a weigh system (Juniper Systems) on 14 Aug. 2016 and 10 Aug. 2017. Grain yield was corrected to a moisture content of 120 g kg^{-1}. A 1,000-g grain subsample was collected from individual plots and was de-awned and cleaned (Pfeuffer Sample Cleaner, Model SLN). Samples were analyzed for test weights and plump kernels based on USDA Federal Grain Inspection Service standards (USDA, 1997, 2013). Plant height was determined at Feekes 11.4 as the height from the soil surface to the spike apex where awns were not included.

2.3 | Analyses

Total N (TN) and atom% ^{15}N for both plant and soil samples were determined by the University of California Davis Stable Isotope Facility (Davis, CA) via an elemental analyzer interfaced to a continuous flow isotope ratio mass spectrometer (Europa, Sercon, Ltd.). Fertilizer N recovery efficiency (FNRE) was calculated as outlined by Greub, Roberts, Slaton, and Kelley (2017).

$$\text{FNRE} = \left[\text{TN}\,(x - y/z - y)\,/R\right] \times 100$$

where TN is the total N uptake (kg N ha^{-1}) of the sampled plant or soil material, x is the atom% ^{15}N measured in the plant or soil material, y is the average native atom% ^{15}N measured from barley check plot plant or soil material, z is the atom% ^{15}N of the enriched urea fertilizer applied, and R is the ^{15}N application rate (kg N ha^{-1}).

2.4 | Statistical analyses

The experiment was a factorial arranged in a randomized complete block design of cultivar (i.e., Harrington, Moravian 69, and Voyager) by fertilizer placement (i.e., surface and incorporated) with four replications of each treatment and 0-N check plots of each cultivar in each block. Total N uptake, total plant fertilizer recovery and partitioning (i.e., vegetative tissue and spikes), as well as yield and quality parameters were analyzed by ANOVA. Where applicable and similar to Rogers, Dari, Hu, and Mikkelsen (2019), stage of sampling was treated as a repeated measures, and plant part (i.e., vegetative tissue and spike) was treated as a split-plot factor. Because 0-N plots cannot have either surface or incorporated treatments imposed, site responsiveness was determined by analyzing yield based on designated treatment combinations of check, incorporated, and surface by the three cultivars for a total of nine treatment combinations. For all analyses, year and block were treated as random factors (Carmer, Nyquist, & Walker, 1989; Moore & Dixon 2015). Statistical analyses were performed in JMP 15.0 (SAS Institute). All mean separations were performed using Fisher's protected LSD as a post hoc multiple comparison analysis at the $P < .05$ level as appropriate.

3 | RESULTS AND DISCUSSION

Total aboveground dry matter (TDM) and total accumulated N differed based on the growth stage and cultivar × fertilizer management interaction where FNRE differed based on the main effects of fertilizer management and growth stage (Table 2).

3.1 | TDM, N accumulation, and FNRE

Total aboveground dry matter (i.e., vegetative tissue plus spike) increased from Feekes 4/5 (790 kg ha^{-1}) until Feekes 11.4 (17,050 kg ha^{-1}), which is consistent with previous research in barley and wheat (Table 3) (Bashir et al., 1997; Lasztity, Biczok, & Ruda, 1984; Rogers et al., 2019). The magnitude of TDM at Feekes 11.4 was similar to that measured previously in the same production system in Idaho by Rogers et al. (2019) as well as studies in Spain and the Czech Republic (Cossani, Slater, & Savin, 2009; Kren, Klem,

TABLE 2 *P* values from ANOVA of cultivar (C), fertilizer management (FM), and growth stage (GS) for total dry matter (TDM), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) of whole barley plants (vegetative tissue + spikes) at the Aberdeen Research and Extension Center, Aberdeen, ID

Effect source	TDM	TN	FNRE
C	.36	.06	.58
FM	<.01	.08	.04
C × FM	.03	.02	.41
GS	<.001	<.001	<.001
C × GS	.72	.49	.75
FM × GS	.06	.35	.41
C × FM × GS	.55	.64	.98

TABLE 3 Effect of growth stage averaged across fertilizer management and cultivar on total dry matter (TDM), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) at the Aberdeen Research and Extension Center, Aberdeen, ID

Growth stage	TDM	TN	FNRE
	kg ha^{-1}	kg N ha^{-1}	%
Feekes 4/5	790d[a]	37.3c	16.6c
Feekes 10.0	5,481c	140.7b	53.0a
Feekes 11.2	14,198b	160.6a	43.2b
Feekes 11.4	17,050a	154.2ab	43.2b

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$.

Svobodova, Misa, & Neudert, 2014) but greater than that measured by Malhi, Johnston, Schoenau, Wang, and Vera (2006) in Canada. Differences in the magnitude of TDM accumulated during the growing season are largely regulated by moisture, cultivar selection, and management. Dryland production can be particularly unpredictable in terms of TDM due to precipitation, whereas irrigated production, as studied in this experiment with consistent irrigation and fertilizer management practices, is more stable.

Total N accumulation between growth stages increased to a maximum at Feekes 11.2 stage and did not differ at Feekes 11.4 (Table 3). The magnitude of uptake at Feekes 11.2 and Feekes 11.4 was similar to Malhi et al. (2006) but less than Rogers et al. (2019). Variation from previous work in Idaho by Rogers et al. (2019) on irrigated production may be a result of the differences in uptake and increased variability associated with the two forms of fertilizer management, differences in cultivars used, and environmental variation among growing seasons. Although not a significant change, after Feekes 11.2 and similar to Rogers et al. (2019), N was lost from the plant likely due to plant senescence, volatilization of N from the plant leaves, and leaching from the leaves from irrigation water applied following Feekes 11.2. Thus, previous research and these results indicate that physiological maturity measurements of N may not represent maximum N accumulation.

Fertilizer-N recovery increased from a low of 16.6% at Feekes 4/5 to a maximum of 53% at Feekes 10.0 (Table 3). Percentage FNRE decreased following Feekes 10.0 and remained the same at both Feekes 11.2 and 11.4 samplings (43.2%). Similar trends in uptake, with varied reductions in FNRE during the latter portion of the cropping season for barley and wheat, have been previously reported (Bashir et al., 1997; Vos et al., 1993). The interaction of cultivar × fertilizer management indicated that TDM was greatest from the cultivar Voyager, whereas the other cultivars did not differ (Table 4). The TN uptake was generally greater from incorporated treatments; despite this, no differences in FNRE were measured. Incorporation of fertilizer increased TDM and FNRE averaged across growth stages and cultivars compared with surface-applied fertilizer (Table 5). This variation results from increased loss mechanisms (i.e., ammonia volatilization, denitrification, leaching, etc.) occurring in the surface-applied fertilizer that reduced fertilizer recovery within the plant.

3.2 | N partitioning and redistribution

Aboveground dry matter (ADM) (i.e., vegetative tissue and spike dry matter individually), accumulated N, and FNRE for the vegetative tissue and spike portions of the barley crop at Feekes 11.2 and 11.4 differed between growth stages among plant parts as well as between fertilizer management practices (Table 6). Additionally, ADM differed based on the interaction of cultivar, growth stage, and plant part as well as

TABLE 4 Effect of cultivar and fertilizer management on total dry matter (TDM), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) averaged across growth stage (Feekes 4/5, 10.0, 11.2, and 11.4) for whole barley plants at the Aberdeen Research and Extension Center, Aberdeen, ID

Cultivar	FM	TDM	TN	FNRE
		kg ha^{-1}	kg N ha^{-1}	%
Harrington	incorporated	9,503b[a]	127.5abc	40.7 ns
Moravian 69	incorporated	9,376b	117.4bcd	40.7 ns
Voyager	incorporated	10,391a	137.8a	40.7 ns
Harrington	surface	9,424b	133.5ab	39.3 ns
Moravian 69	surface	8,875b	113.3 cd	37.9 ns
Voyager	surface	8,713b	109.7d	34.3 ns

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$. ns, not significant.

TABLE 5 Effect of fertilizer management on total dry matter (TDM), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) averaged across cultivar and growth stage (Feekes 4/5, 10.0, 11.2, and 11.4) for whole barley plants at the Aberdeen Research and Extension Center, Aberdeen, ID

Fertilizer management	TDM	TN	FNRE
	kg ha^{-1}	kg N ha^{-1}	%
Incorporated	9,757a[a]	127.6 ns	40.8a
Surface-applied	9,004b	118.9 ns	37.2b

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$. ns, not significant.

cultivar × fertilizer management. Moravian 69 spike weights were the greatest where Voyager and Harrington did not differ (Figure 2). Aboveground dry matter and TN were partitioned from the vegetative tissue to the spike between Feekes 11.2 and 11.4 (Figure 3). Recovered fertilizer-N was also partitioned from the vegetative tissue to the spike between Feekes 11.2 and 11.4. Maximum FNRE was measured in the spike at Feekes 11.4 (33.7%), and 9.5% was recovered in the vegetative tissue. These results are similar to Bashir et al. (1997), where 9.0 and 37.7% of applied ^{15}N were

TABLE 6 *P* values from ANOVA of cultivar (C), fertilizer management (FM), growth stage (GS), and plant part (PP) for total dry matter (TDM), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) at the Aberdeen Research and Extension Center, Aberdeen, ID

Effect source	ADM	TN	FNRE
C	.83	.05	.24
FM	<.001	.02	<.01
C × FM	<.001	.10	.54
GS	<.001	.38	.96
C × GS	.77	.65	.41
FM × GS	.97	.62	.27
C × FM × GS	.56	.45	.59
PP	<.001	<.01	<.01
C × PP	.02	.68	.92
FM × PP	.61	.12	.06
C × FM × PP	.95	.74	.85
GS × PP	<.001	<.01	<.01
C × GS × PP	.03	.45	.99
FM × GS × PP	.46	.46	.16
C × FM × GS × PP	.72	.65	.89

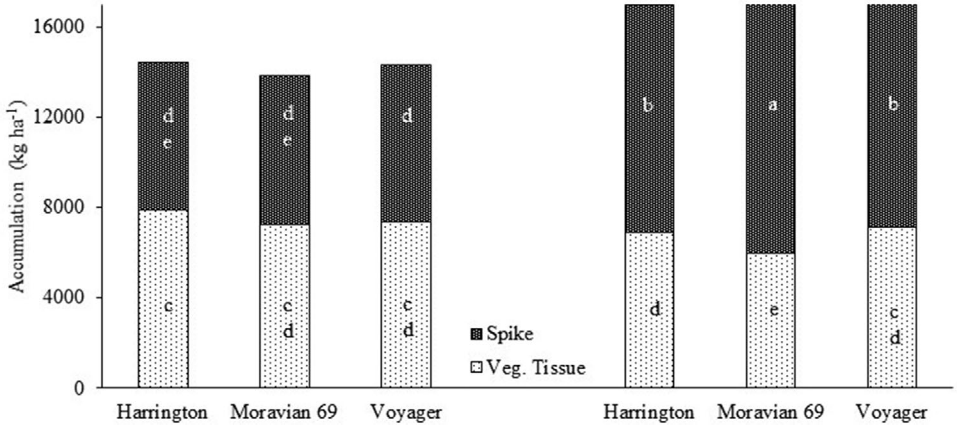

FIGURE 2 Effect of cultivar, plant part (vegetative tissue and spike), and growth stage averaged across fertilizer management on above ground dry matter in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID. Different letters indicate significant differences as compared using Fisher's protected LSD at $P < .05$

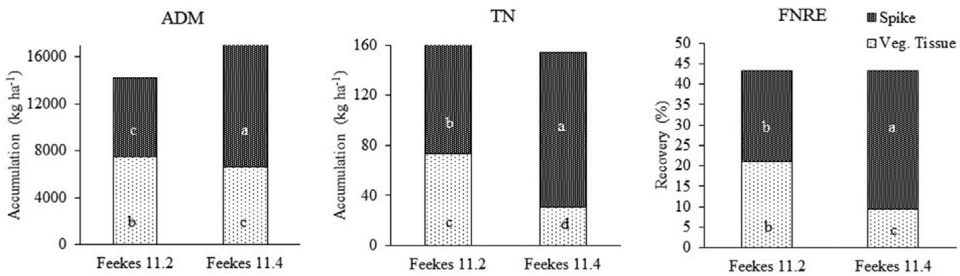

FIGURE 3 Effect of plant part (vegetative tissue and spike) and plant growth stage averaged across cultivar and fertilizer management on aboveground dry matter (ADM), total N uptake (TN), and fertilizer-N recovery efficiency (FNRE) in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID. Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$

recovered in the vegetative tissue and spike at Feekes 11.4 in wheat, respectively. Incorporation of fertilizer-N resulted in greater ADM, TN, and FNRE as compared to surface-applied fertilizer averaged across cultivar, growth stage, and plant part (Table 7). Averaged across growth stage and plant part, ADM was greatest from incorporated fertilizer for Voyager compared with either Harrington or M69, which did not differ where all incorporated treatments were greater than surface applications (Figure 4). These results indicate increased plant growth and N uptake when fertilizer was incorporated as compared to surface applied.

3.3 | Fertilizer-N recovery in the soil

Only the depth of sampling (0–30, 30–60, and 60–90 cm) had a significant effect (Table 8) on FNRE in the soil, where cultivar and fertilizer management did not affect soil-N recovery. The majority of the recovered N (22.1%) was measured in the top 0-to-30-cm depth, whereas only 4.0 and 1.8% were measured in the 30-to-60-cm and the 60-to-90-cm depths, respectively (Table 9). Total N recovery in the 0-to-90-cm depth was 28% in the loam-textured soil selected for this study, which was more than double the TN recovery reported by Bashir et al. (1997) in a sandy-loam soil cropped to wheat. In contrast, Knight and Sparrow (1993) recovered 44% of the applied N on a silt-loam soil and Vos et al. (1993) recovered 56% in a loam soil cropped to barley in Alaska and Switzerland, respectively. Soil texture and moisture regimes are likely a major factor because finer-textured soils have a greater ability to retain N and greater amounts of water can increase leaching.

3.4 | Total plant and soil FNRE

Total plant and soil FNRE at Feekes 11.4 only differed based on fertilizer application method where cultivar differences and its interactions were not significant (Table 10). The incorporated fertilizer resulted in 77% FNRE, as compared to 66%

TABLE 7 Effects of fertilizer management on aboveground dry matter (ADM; vegetative and spike individually), total accumulated N (TN), and fertilizer-N recovery efficiency (FNRE) averaged across growth stages (Feekes 11.2 and 11.4) and plant parts (vegetative tissue and spikes) at the Aberdeen Research and Extension Center, Aberdeen, ID

Fertilizer management	ADM	TN	FNRE
	kg ha^{-1}	kg N ha^{-1}	%
Incorporated	8,177a[a]	83a	23a
Surface-applied	7,447b	74b	20b

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$.

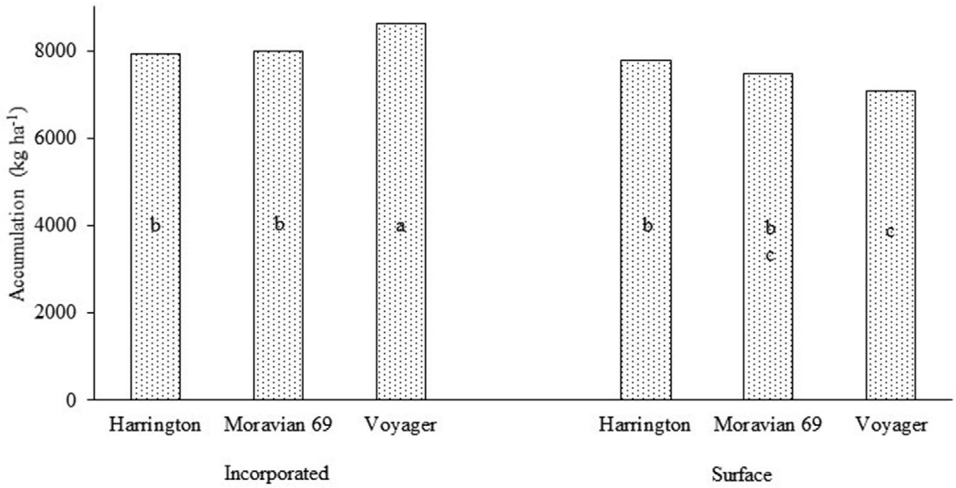

FIGURE 4 Effect of cultivar and fertilizer management averaged across plant part (vegetative tissue and spike) and growth stage (Feekes 11.2 and 11.4) on aboveground dry matter in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID. Different letters significant differences as compared using Fisher's protected LSD at $P < .05$

for the surface applied urea (Table 11). The highest uptake of 77% from the incorporated N treatments is within the range of previous FNRE values in barley. The maximum recovery reported was reported to be 85% in barley by Knight and Sparrow (1993), 86% in wheat by Bashir et al. (1997), 60–67% in barley by Smith and Gyles (1989), and 87% in barley by Vos et al. (1993). Although no direct measurements of loss were determined in this study, loss mechanisms would include ammonia volatilization following fertilizer applications, soil denitrification, nitrate leaching, and direct losses from the plant tissue. Irrigation is not commonly applied to barley in the region until plant growth is well underway and soil moisture is reduced, which was mimicked in this study, as noted by the first irrigations occurring over 20 d after planting (Figure 1). Previous work in southern Idaho soils has reported that incorporated applications lost nearly 10% of N, whereas surface urea applications lost upward of 30% of N that was applied over a 20-d period when no irrigation

TABLE 8 *P* values from ANOVA of cultivar (C), fertilizer management (FM), and soil depth (D) for fertilizer-N recovery efficiency (FNRE) for soil collected at the Aberdeen Research and Extension Center, Aberdeen, ID

Effect source	FNRE
C	.95
FM	.56
C × FM	.94
D	<.001
FM × D	.39
C × D	.92
C × FM × D	.59

TABLE 9 Effect of soil depth on fertilizer N recovery efficiency (FNRE) averaged across cultivar and fertilizer management in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID

Soil depth	FNRE
cm	%
0–30	22.1a[a]
30–60	4.0b
60–90	1.8b

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$.

TABLE 10 *P* values from two ANOVAs of cultivar (C) and fertilizer management (FM), for fertilizer-N recovery efficiency (FNRE) of the plant–soil system and for harvest grain yield, protein, plump kernels, and tests weigh at the Aberdeen Research and Extension Center, Aberdeen, ID

Effect source	FNRE	Yield	Protein	Plump kernels	Test weight
C	.89	.04	<.01	<.01	<.01
FM	.04	.74	.90	.94	.62
C × FM	.94	.45	.75	.71	.95

TABLE 11 Effect of fertilizer management on fertilizer-N recovery efficiency (FNRE) within the plant–soil system at Feekes 11.4 averaged across cultivar in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID

Fertilizer management	Total plant–soil FNRE
	%
Incorporated	77a[a]
Surface	66b

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected LSD at $P < .05$.

was applied (Rogers et al., 2019). Losses via denitrification were likely minimal; Dungan, Leytem, Tarkalson, Ippolito, and Bjorneberg (2017) reported that less than 1 kg N ha^{-1} was lost through this pathway in southern Idaho soils cropped to barley. Decreased FNRE in the soil (Table 11) with depth indicates that leaching losses were also negligible. As noted above and in previous work by Rogers et al. (2019), reductions in TN occur in the barley plant during the latter portion of the season, indicating that gaseous losses from the plant may also be a contributing factor to N losses from the plant–soil system.

3.5 | Crop yield and quality

Malting barley is unique among grains because of the number of criteria that are required for it to meet malting specifications and to be acceptable to the buyer. Analysis of site responsiveness to fertilizer-N applications indicated that treatment combination was significant ($P < .05$) and that the fertilized plots did not vary among themselves with a yield of 8,458 kg ha^{-1}, which was greater than 0-N check plots that also did not vary among themselves with an average yield of 5,263 kg ha^{-1}. Despite increased TDM and FNRE from the incorporated fertilizer management (Table 5), crop yield and quality only differed based on cultivar, whereas fertilizer management and its interactions were not significant (Table 10). Yield and quality measurements in the current study are within the range of those typically measured in irrigated University of Idaho cereal variety extension trials (Marshall et al., 2018). Grain yield from Voyager and Moravian 69 did not differ and were greater than the older cultivar Harrington (Table 12). Total dry matter and yields in the current study were much greater than in previous studies on ^{15}N in barley largely due to the use of more modern cultivars and the high-input irrigated production system that is common in southern Idaho. Due to the destructive nature of sampling, yields are often not reported in ^{15}N tracer studies; however, yields from previous studies (Knight & Sparrow, 1993; Smith & Gyles, 1988; Tomar & Soper, 1981) rarely approached even those of our 0-N check plots, and our fertilized yields were more than 40% greater, indicating the need for this study. Protein values were within the range for malting barley specifications but were approximately 10 g kg^{-1} less than those reported by Rogers et al. (2019) with similar cultivars. This reduced protein content may be a factor that reduced total N uptake as compared to Rogers et al. (2019) in the plant because grain protein is largely comprised of N. Plumps and test weights were well above average and would have met malting barley specifications.

TABLE 12 Effect of cultivar averaged across fertilizer management on yield, protein, plump kernels, test weight, and height from barley grown in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID

Cultivar	Yield	Protein	Plump kernels	Test weight	Height
	kg ha^{-1}	g kg^{-1}		g L^{-1}	cm
Harrington	8,070b[a]	113a	970b	707a	80.2a
Moravian 69	8,628a	101b	980a	695b	68.3b
Voyager	8,677a	109a	980a	707a	79.8a

[a]Different letters for each parameter indicate significant differences as compared using Fisher's protected least LSD at $P < .05$.

4 | CONCLUSIONS

The current study provides the first FNRE data for modern cultivars under high-input irrigated production of malting barley in the western United States. Patterns of TDM, TN, and FNRE across the growing season and within the vegetative tissue and spike at the end of the season were similar as compared to previous research in barley and wheat. Total dry matter and TN accumulation in the current study were generally greater than in previous ^{15}N studies on barley but similar to studies of nutrient accumulation in Idaho and other higher-yielding areas. Partitioning and redistribution followed similar patterns as previous studies, with the current study having increased values due to increased plant growth under the irrigated study conditions. Despite having increased TDM and yield as compared to previous work, FNRE in the plant and soil was relatively similar to previous studies in lower-yielding systems, indicating that recovery in this system remained similar even with greater inputs and yields. Additionally, although fertilizer management affected TDM, TN, and FNRE, this did not result in significant differences in yield. Thus, variation or lack thereof in yield may not be a good indicator of FNRE or potentially negative impacts associated with fertilizer-N loss in barley systems because soil supplied N may be sufficient to compensate for losses that occur. These results indicate that FNRE from incorporated fertilizer is more efficient than surface applications, that modern cultivars (Moravian 69 and Voyager) out yielded the older cultivar Harrington with no reduction in FNRE, and that increased plant growth and yield under irrigated conditions in southern Idaho did not decrease the efficiency of the system at recovering applied fertilizer-N as compared to previous studies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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