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On-Farm Evaluations of Pre- and In-Season Variable Rate Nitrogen For Potato

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Abstract

Potato (Solanum tuberosum L.) and wheat (Triticum spp.) are important crops that require nitrogen (N), which is spatially and temporally variable. One option for N management is a variable rate pre- and in-season N (VRPIN) system, which includes applying a conservative variable rate N (VRN) at preemergence followed by in-season assessment and, if needed, additional VRN. The objective was to evaluate potato yield and quality for VRPIN. Two to four zones were identified within five potato fields near Grace, Idaho, USA in 2021. Zone delineations were based on farmer field knowledge, topography, bare soil imagery, yield map history, and historical in-season visible and normalized difference vegetation index (NDVI) imagery. The N rates for each zone were determined by yield goal levels and residual topsoil N, legume credits, manure credits, crop residue, and irrigation water N concentration. Uniform strips were placed through all zones as a positive control based on N management used by the grower. The crop canopy was monitored in-season at least twice weekly for visible and NDVI remote sensing to check for pattern changes, and tissue samples were taken in mid-rate N zones three times and in every zone once and analyzed for nitrate-N (NO_3-N). In general, total and U.S. No. 1 tuber yields and size increased and specific gravity decreased with pre-emergent VRN compared to the uniform N management. This study will be repeated in 2022 on another six potato and eight wheat fields.

Keywords
Potato, variable rate nitrogen (VRN), variable rate pre- and in-season nitrogen (VRPIN), normalized difference vegetation index (NDVI), tissue sample, yield potential, nitrogen, zone

INTRODUCTION

Globally, wheat (*Triticum* spp.) is first in acreage and third in value among all crops, with potato (*Solanum tuberosum* L.) first in acreage and value among annual vegetable and fruit crops (Hopkins and Hansen, 2019). Although relatively higher in value, potato is necessarily grown in rotation with other crops (Hopkins et al., 2007; 2020; Myers et al., 2008). In many regions, such as is common in the Pacific Northwest USA, wheat is included as the rotational crop with potato (Myers et al., 2008).

Plants require an optimal amount of N, with both deficiencies and excesses negatively impacting crop production (Geary et al., 2015; Pedersen et al., 2021). Excess N can also be harmful to the environment, with concerns of nitrate (NO_3-N) in drinking water, eutrophication of surface water, reactive N [ammonia (NH_3)] volatilization, and greenhouse gas [nitrous oxide (N_2O)] emission (Holland & Schepers, 2010; Hong et al., 2006; Hopkins, 2020; LeMonte et al., 2016, 2018; Stefaniak et al., 2021; Whitley & Davenport, 2003). With half of all global fertilizer production, N is the nutrient of greatest environmental concern and has the largest impact on crop production (Hopkins, 2020). Wheat and, especially, potato require careful N management as it is also an expensive component to the growth and production process (Hopkins et al., 2007, 2020; Schwalbert et al. 2019).

Crop N needs are spatially and temporally variable based on topography, soil properties, environment, and biotic/abiotic stress (Ruffo et al., 2006). Applying variable rate N (VRN) within a field could improve crop growth and N use efficiency (NUE) (Hong et al., 2006). Variable rate pre- and in-season N (VRPIN) is an optimal N management system that involves applying a conservative variable base rate at or shortly after planting followed by in-season assessment and, if needed, VRN—with the plant being the predictive integrator of this process. Improving N management through VRN has been expected to improve crop production, decrease input costs, and decrease environmental concerns (Bragagnolo et al. 2013; Hong et al., 2006; Hurley et al. 2004; Koch et al. 2004; Mamo et al. 2003; Scharf et al. 2005). Studies have used crop sensing, modeling, yield maps, topography and soil properties to create management zones, some collectively and some individually (Bourdin et al. 2017; Holland & Schepers, 2010; Pedersen et al. 2021; Schwalbert et al. 2019). While some studies have shown success in VRN zones, others have not (Long et al. 2015; Schwalbert et al. 2019). Hong et al. (2006) studied VRN in a soybean-wheat-maize-wheat crop rotation and found that utilizing site-specific remote sensing to drive N rates improved yields or N:harvest ratios in all three years of the study in corn and wheat, while also observing the increases of NO_3-N in groundwater from additional N used compared to a reduced presence of NO_3-N in groundwater when N inputs were traditional rates or reduced.

Wheat yields can vary greatly throughout a single field and economic benefits could be achieved when utilizing VRN (Robertson et al., 2008). Historical yield maps determining different yield potential areas, and other resources such as crop canopy sensors could be used to improve variable rate pre- and in-season N (VRPIN) in wheat production (Roberson et al., 2008; Stamatiadis et al., 2018; Thomason et al., 2011). Although crop canopy sensors prove useful in improving NUE, these are generally very costly, and may not be a cost-effective management tool for managing VRN for many producers.

The VRPIN approach used in wheat mentioned above could also be utilized in potato to assess effectiveness in N management and production. Proper N management can optimize tuber size, production, grade specific gravity and other quality features in potato (Hopkins et al., 2020; Stefaniak et al., 2021). Source, rate and timing of N fertilizer in potato crops can significantly affect the production and quality of potato yields (Hopkins et al., 2020, Westermann, 2005). In a study testing multiple N rates on different cultivars of potato, Fontes et al. (2010) found that potato yields significantly increased with increased N rates. Many studies have been performed to determine which indices may best predict the required VRN rate in-season for potato (Giletto & Echeverria, 2016). A two-year study on VRN in potato found that utilizing VRN with remote sensing decreased N and resulted in increased NUE while maintaining tuber yield (Bohman et al., 2019; Bohman et al., 2020). While VRN research has been performed on potato, most of the work has focused on in-season VRN without the pre-emergence VRN (Bohman et al., 2019; Bohman et al., 2020). These studies referenced above were performed on small plot scales. Kempenaar et al. (2017) noted that pre-emergence VRN data or systems have not been addressed in potato. With the lack of studies on pre-emergence VRN and the lack of full field scale experiments of this subject on potato, this concept must be explored further. There is also the need to perform additional VRN research in different regions, and on different potato varieties to gain greater understanding on the best process of managing VRPIN to get the best results (Westermann, 2005; Whitley & Davenport, 2003; Zebarth & Rosen, 2007).

A simple approach to VRN management that utilizes field history and grower knowledge is needed to advance precision N management in a cost-effective way for growers. Many studies on VRN have been performed using models, crop canopy sensors, and remote sensing, but experiments with readily available resources and straightforward practices are not as well-studied. Practicing such simple VRPIN approaches has the potential to increase production while reducing fertilizer, costs, and negative environmental impacts. Precision N management has been studied extensively in other regions of the country, but few replicated field-level trials exist in Idaho or Utah. Local studies are needed to validate whether a simple VRPIN approach is feasible and economic for potato producers in this region. The objectives of this study were (i) to determine how VRPIN based on historical yield data, grower knowledge, topography, normalized difference vegetation index (NDVI), and in-season sampling impacted potato yield and quality.

MATERIALS AND METHODS

Site Description

In 2021, five potato fields ranging in size of 50, 35, 18, 35, and 23 ha for fields A, B, C, D, and E, respectively, with wheat-wheat-potato rotations, located near Grace, Idaho, USA (elevation 1687 m above sea level) were established as field sites. This area has a semi-arid climate typified by relatively hot days and cool nights during the growing season. The average annual precipitation is 390 mm with the majority occurring during winter as snow.

Zone Delineation

Two to four zones were visually identified within each field (Fig. 1) based on utilizing layers of information, including: grower field knowledge, topography, bare soil imagery, yield map histories of potato and rotational crops, historical in-season visible and NDVI imagery. These layers were used to find overlapping patterns of some or all the following zone types:

- consistently average yields,
- consistently high yields with no inherent limitations,
- consistently low yielding areas with limitations that are not reasonably possible to correct (e.g. shallow soil, persistent hard pans, soil textural problems, steep slopes, north facing slopes, and certain soil borne pest/pathogen infestations),
- consistently low yielding areas with limitations that are possible to correct (e.g. low soil fertility of nutrients other than N, low organic matter, simple compaction, and correctable soil borne pest/pathogen infestations),
- sporadically yielding areas with limitations that are often not readily apparent.

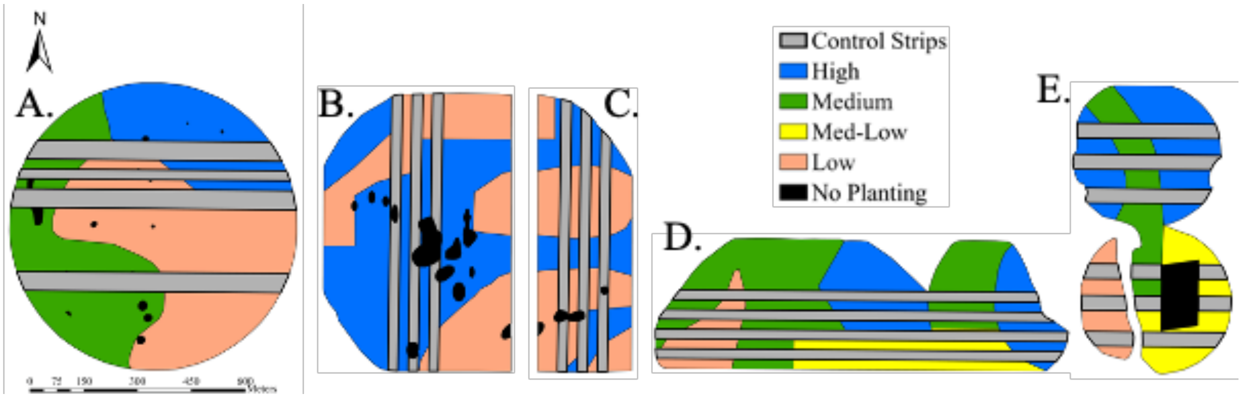

Figure 1. Nitrogen zones for five potato fields (A - E).

Pre-Emergence Nitrogen Rates

Banded fertilizer was applied at 8.1 kg N ha^{-1} uniformly to all fields prior to planting.

Potato were planted between 11 and 15 May in 0.86 m wide rows with varieties including: Russet Burbank, Frito Lay 2137, Actrice, Waneta, and Frito Lay 2137 varieties for fields A, B, C, D, and E, respectively (Fig. 1). Soil samples (12-15 cores per sample) were collected randomly throughout each zone to 30 cm deep between 18-19 May. These samples were air dried, ground (< 2 mm) and analyzed for NO_3-N (Table 1) by the Utah State University Analytical Lab (Logan, Utah, USA). The base N rates for each zone were determined as a function of variety and yield goal, with reductions for residual topsoil N, crop residue, irrigation water NO_3-N concentration, and legume and/or manure credits (if any) (Hopkins et al., 2020). The N predicted to be needed for the season was applied via broadcast with a Miller Condor fertilizer spreader (St. Nazianz, Wisconsin, USA) shortly after planting between 27 May and June 3 using a polymer coated urea (PCU; Nutrien, Saskatoon, Canada) (Table 2). Control N strips were placed through all zones as a positive control based on N management used by the grower. The N was incorporated into the soil during hilling, which occurred shortly after fertilization.

Table 1. Nitrate (NO^3-N) levels at beginning of 2021 growing season

Field	Zone	NO_3-N
		mg kg^{-1}
A	High	17
	Medium	12
	Low	10
B	High	7
	Low	11
C	High	8
	Low	9
D	High	9
	Medium	9
	Med-Low	10
	Low	8
E	High-East	24

Medium	23
Med-Low	22
Low	21
High-West	19

Table 2. Pre-emergence nitrogen (N) rates for each zone in five potato fields. Zones were based on yield potential, with some fields not having all zones (not applicable = N/A).

Zone	Field				
	A	B	C	D	E
	------------------------------kg N ha^{-1}------------------------------				
Control	179	146	146	157	135
High	213	179	179	191	168
Medium	179	N/A	N/A	157	135
Med-Low	N/A	N/A	N/A	135	118
Low	146	112	112	123	101

Post-Emergence Nitrogen Rates

The crop canopies were monitored in-season at least twice weekly for visible and NDVI pattern changes, especially row closure differences utilizing Sentinel 2 and Landsat 8 satellite imagery (FarmShots, Durham, North Carolina, USA). Composite petiole samples (Hopkins et al., 2020) were taken in the control N zones three times (2 July, 23 July, 31 July for field B, 6 Aug for remaining fields) to evaluate overall nutrition and NO_3-N trends and then, based on the control petiole NO_3-N concentration and canopy imagery, composite petiole samples were taken in every zone once (31 July for field B, 06 Aug for remaining fields) and analyzed for NO_3-N by the ServiTech, Inc. laboratory (Dodge City, Kansas, USA). If NO_3-N levels were low based on Hopkins et al. (2020), additional fertilization plots were created within the applicable zone to apply VRN to small portions of each zone.

Harvest Measurements

Tuber samples were collected at harvest (17-27 Sep), approximately 21 d after vines were chopped and then sprayed with sulfuric acid, to determine yield and quality at 4-6 locations within each zone in a paired sampling structure. Each pair consisted of a sampling from the uniform and the VRN strips. Samples were hand collected from 3.0 m (10 m^2) dug using a four-row windrower (crossover). Tubers were separated by grade (U.S. No. 1, U.S. No. 2 and malformed; USDA, 2011) and then counted and weighed for each grade. Average tuber size was calculated by dividing the weight of all tubers within a specified grade by the respective count. A random sub-sample of 16 U.S. No. 1 tubers were collected from within each sampling area for determining solids percentage (specific gravity) (Kleinkopf et al., 1987) and internal and external quality (brown center, hollow heart, and disease, insect, or nematode infestations).

All replicated data were analyzed by ANOVA (SAS Studio 3.8, SAS, Cary, North Carolina, USA) with mean separation performed by Least Significant Difference (LSD).

RESULTS AND DISCUSSION

The residual soil NO_3-N concentrations at the beginning of the growing season commonly had low residual concentrations for the fields with wheat as the previous crop (Table 1). Field E had four years of alfalfa as the previous crop and had residual NO_3-N approximately twice as high as the other fields. These values were factored into the base N fertilizer rate for each field (Fig. 1). Zones with higher rates had higher yield potential than those with lower rates.

Surprisingly, in-season visible and NDVI imagery revealed minimal spatial variability in crop growth. The petiole tissue NO_3-N concentrations are known to drop steadily through the growing season (Hopkins et al., 2020; Zebarth & Rosen, 2007), which is what was observed in these fields (Table 3). However, the concentrations dropped somewhat more dramatically than was expected. Field B had low N towards the end of the season. However, due to the timing of harvest and a scheduled early harvest, additional N was not needed. The fields generally had ample N through July, but were likely slightly N deficient towards the end of the season in Aug. We were prepared to variably apply N in-season, but it was decided to not do so for any of the fields based on the lack of variability across zones (all zones were classified as low; Hopkins et al., 2020). Other studies showed the need to apply in-season VRN, while this study did not. One reasoning for this could be due to the higher rates of N applied at pre-emergence compared to other studies. The higher rates of VRN applied at pre-emergence did reduce the risk of deficiency throughout the season but could have been applied in excess in certain zones. If rates in this study were initially lower, differences in NDVI and petiole NO_3-N concentrations may have become present within and across zones, thus requiring in-season VRN applications. Although fields were being observed with NDVI from satellite imagery, subtle changes within small areas of the fields may not have been detected due to the lower resolution from the satellite imagery compared to remote sensing data that was gathered by handheld sensors or other high-resolution sensors in other studies (Bohman et al., 2019; Bohman et al., 2020; Giletto & Echeverria, 2016; Morier et al., 2015,). Bohman et al. (2019) also found that using a N sufficiency index predicted crop N status that compared well to petiole samples. The visuals from in-season NDVI imagery for these fields did follow the trend of the petiole sample results, but more research needs to be performed to know if NDVI from satellite imagery reflects the details of N status throughout each zone within a field, as there are still many variables within a field-scale study that can affect NDVI values other than N deficiencies.

Table 3. Composite (non-replicated) in-season petiole nitrate (NO_3-N) concentrations within the control strips for three sample dates and for all zones at the last sampling date.

Field	Zone	July 2	July 23	July 31/Aug 6[1]
		----------------------------	mg kg^{-1}	----------------------------
A	Control	24,100	12,600	2,940
	Low			1,650
	High			5,200
B	Control	19,100	5,300	830
	Low			110
	High			150

C	Control	23,400	8,700	300
	Low			390
	High			800
D	Control	22,600	11,500	1,600
	High			310
	Med-Low			1,780
	Low			150
E	Control	24,600	9,200	2,750
	High-East			5,000
	High-West			3,300
	Med-Low			1,840
	Low			3,420

[1]Field B was sampled July 31. The rest of the fields were sampled Aug 6.

Average field yields, as measured by the potato harvester's yield monitor, were good for this high elevation seed potato region at: 38, 26, 43, 37, and 44 Mg ha^{-1} for fields A, B, C, D, and E, respectively. Small plot measurements showed that there was significant treatment (VRN) × zone interactions in three and two fields for total and U.S. No. 1 tuber size, respectively. There was also a significant VRN × zone interaction for yield in one field, but no interactions for specific gravity (Table 4). When combined across zones, there were significant treatment effects for VRN in one and two additional fields for total and U.S. No. 1 tuber size and two additional fields for yield. Two fields showed significant differences for specific gravity, although the effect was negative for VRN in both (Tables 4 and 5).

Table 4. P values from ANOVA with statistically significant values shown in bold-face type (*P* = 0.10).

Field	VRN	Zone	VRN*Zone	VRN	Zone	VRN*Zone
	---------- Total Yield ----------			------ U.S. No. 1 Yield -----		
A	**0.008**	0.471	0.322	**0.010**	0.512	0.494
B	0.409	0.687	**0.039**	0.339	0.671	**0.059**
C	0.150	0.608	0.245	0.168	0.682	0.220
D	0.797	**0.011**	0.147	0.823	**0.011**	0.148
E	**0.028**	0.190	0.325	**0.026**	0.200	0.278

	---------- Total Size ----------			------ U.S. No. 1 Size ------		
A	**0.056**	0.124	**0.099**	**0.034**	**0.099**	0.165
B	**0.092**	**0.006**	**0.010**	**0.059**	**0.005**	**0.010**
C	0.929	0.508	0.550	0.990	0.645	0.634
D	**0.003**	0.205	**0.057**	**0.004**	0.213	**0.058**
E	**0.034**	0.418	0.253	**0.037**	0.446	0.254
	------- Specific Gravity -------					
A	**0.050**	0.937	0.882			
B	0.543	**0.079**	0.253			
C	0.865	0.145	0.447			
D	**0.023**	**<0.001**	0.912			
E	0.825	**<0.001**	0.575			

Table 5. Average potato tuber yield, size, and solids (specific gravity). Fields with significant difference for a measured parameter for the interaction between treatment (variable rate nitrogen) and zone are shown in bold-face type. Within field and dependent variable, values sharing the same letter are not significantly different from one another (*P* = 0.10).

		-- Yield, Mg ha^{-1} --		-- Size, g tuber^{-1} --		Specific Gravity
Field	Zone	Total	U.S. No. 1	Total	U.S. No. 1	
A	Control	40 a	38 a	**156 b**	150 a	1.081 a
	High	46 a	44 a	**162 a**	156 a	1.079 a
	Low	43 a	41 a	**162 a**	159 a	1.079 a
	High	**36 a**	**35 a**	**147 a**	**145 a**	1.092 a
B	Control	**36 a**	**35 a**	**142 b**	**139 b**	1.096 a
	Low	**32 b**	**31 b**	**113 c**	**111 c**	1.097 a
C	High	56 a	54 a	159 a	156 a	1.056 a
	Control	51 a	50 a	156 a	156 a	1.058 a
	Low	58 a	57 a	156 a	153 a	1.059 a
D	High	42 a	42 a	**164 a**	**164 a**	1.071 a
	Control	36 a	36 a	**133 c**	**133 c**	1.078 a
	Med-Low	39 a	39 a	**153 b**	**153 b**	1.074 a
	Low	29 a	29 a	**136 c**	**136 c**	1.079 a

E	High-East	41 a	41 a	147 a	147 a	1.091 a
	Control	42 a	41 a	142 a	139 a	1.088 a
	Med-Low	43 a	43 a	142 a	139 a	1.089 a
	Low	46 a	45 a	150 a	147 a	1.084 a
	High-West	48 a	48 a	150 a	150 a	1.087 a

There were significant differences between VRN and their respective control strips in some fields for total and U.S. No. 1 yield (Fig. 2, Tables 4 and 5). The VRN treatment yielded numerically higher than the control strips for all fields except B, but the increases were only significant for fields A and E. For field B, there was a decrease in yield with VRN (Fig. 2), but this was only significant in the low yield potential zone (Tables 4 and 5). The overall and U.S. No. 1 yields for this field were much lower than expected. It is reasonably assumed that the reduction in N in the VRN low zone caused further reduction due to some factor that limited N availability. The reasons for this could be related to N loss mechanisms, such as leaching, denitrification, or volatilization. Further observation and measurement could help identify if one or more of these are the reason why this zone is constantly producing relatively lower yields than the rest of the field. The variety 'Actrice' grown in field C is known to require a relatively low N rate, which may explain the lack of response to N rates in any zones, suggesting that it may be more buffered against N differences than most other potato varieties. Some varieties, such as Russet Burbank, are known to be relatively more sensitive to N deficiencies and excesses (Hopkins et al., 2020).

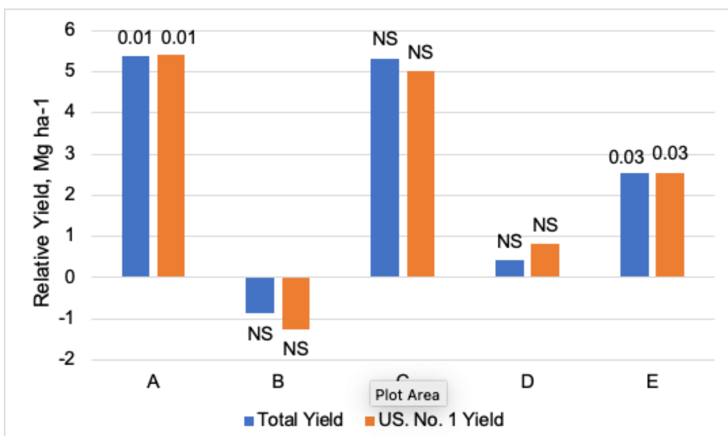

Figure 2. Relative yield differences averaged across zones between VRN treatments and control strips (VRN minus the control) for total and U.S. No. 1 with *P* values showing significance above bars (NS = not significant at *P* = 0.05.

Bohman et al. (2019) did not see significant differences in tuber yields between VRN and uniform rate treatments even though VRN treatments were lower than uniform treatments in their two-year study. Their N rate differences were similar to the rate differences between controls and VRN zones utilized in this study. Morier et al. (2015) also did not find significant differences in tuber yields among different N rates, but it should be noted the design for their study did not include creating zones based on yield potential and was set up as a small plot design. Bowen et al. (2022) had similar findings to this study with VRN in potato with mostly positive increases in yield, especially U.S. No. 1 yields, although they did not show any significant negative responses.

Tuber size, an important quality factor in determining crop selling price, was impacted relatively more consistently than yield (Tables 4 and 5; Fig. 3). Tuber size was numerically higher in all fields for the high yield potential zones (Table 5), although this was only significant in field D for both total and U.S. No. 1 tubers and for total tuber size in field A. Additionally, there was an overall increase in tuber size in field E (interaction was not significant, but the treatment effect was significant (Table 4, Fig. 3)). As with yield, field C showed no treatment effects and there was a significant interaction for field B with the low yield potential zone having a decrease in tuber size. In contrast, one of the low yield potential zones in field A had significantly greater tuber size than the control (Tables 4 and 5).

Again, these results are similar to Bowen et al. (2022) who frequently found increases in tuber size with VRN. Bohman et al. (2019) and Zebarth & Rosen (2007) found an increase in tuber size when VRN was greater than the control, and decreased tuber size when VRN was less than the control.

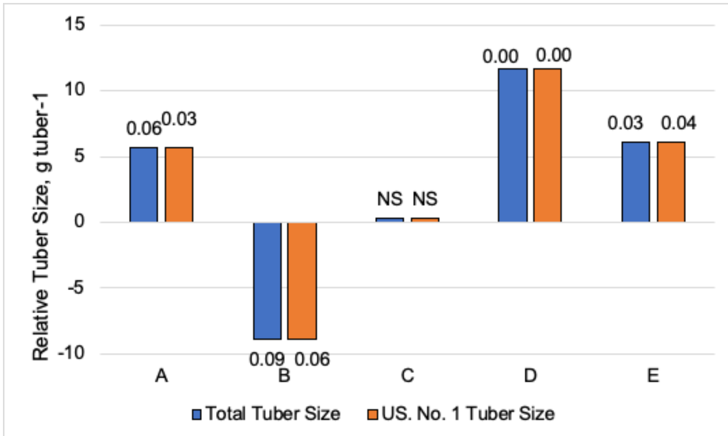

Figure 3. Relative tuber size differences averaged across zones between VRN treatments and control strips (VRN minus control) for total and U.S. No. 1 with P values showing significance above bars (NS = not significant at P = 0.10).

The VRN treatments resulted in numerically lower specific gravity in all fields, although only significant in two (Tables 4 and 5; Fig. 4). Relatively high N nutrition is known to result in decreased specific gravity, which seems to have negatively impacted the tubers overall despite there not being a significant interaction. Although these values decreased with VRN in two fields, the values did not become so low that they would impact the value of the crop for most contracts (values above 1.080 are generally acceptable). Bohman et al. (2019) found similar results showing significant differences in specific gravity between VRN and control treatments, and that higher rates of N reduced the specific gravity.

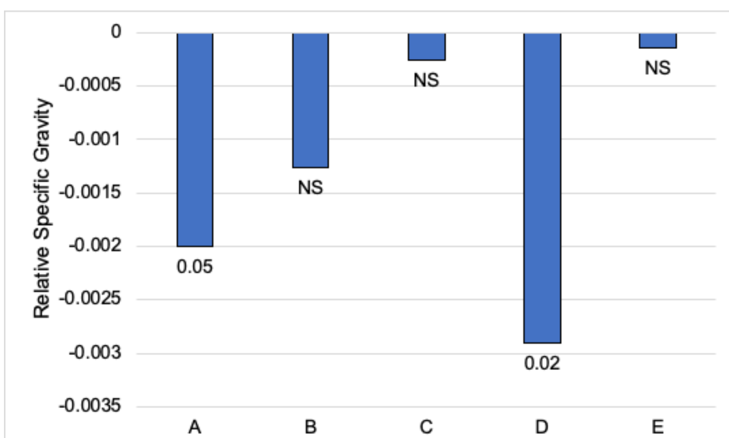

Figure 4. Relative tuber solids (specific gravity) differences between VRN treatments and control strips (VRN minus control) with *P* values showing significance below bars (NS = not significant at *P* = 0.05).

CONCLUSION

In general, utilizing the VRN procedure used in this potato study benefited total and U.S. No. 1 yields, as well as tuber size. However, specific gravity was negatively impacted. Overall, the increase in yield and crop quality would be expected to counter any negative impacts from the slight decreases in specific gravity. These results represent five site years of data, but all are from the 2021 season and additional years of data need to be collected for further evaluation. Further research to advance VRN should include (i) an improved and standardized process of determining potential yields within zones for optimal N rate and (ii) improved in-season monitoring via NDVI and petiole sampling for potential in-season N application.

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