A simple cultivar suitability index for low-pH agricultural soils

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Funding information  
Western SARE; Montana Fertilizer Advisory Committee

1 INTRODUCTION  
Lime applications are effective for remediating low-pH surface soils but can be cost-prohibitive for farmers, especially in dryland wheat (Triticum aestivum L.) systems with low economic margins. Thus, planting wheat cultivars that carry the Al resistance gene TaAlmt1 is more common than liming. However, there is a knowledge gap regarding the relative importance of TaAlmt1 expression and adaptedness for preserving grain yield in acidic soils (Gillespie, Marburger, Carver & Zhang, 2020; Scott, Fisher, & Cullis, 2001). Here, we define adaptedness as the ability of a cultivar to achieve high grain yield across multiple locations with disparate weather and soil conditions.

A field study was conducted to determine if adapted spring wheat cultivars carrying TaAlmt1 outyielded adapted noncarriers in lime-amended and unamended low-pH soils. Interestingly, a high degree of within-replicate and within-plot variability in plant vigor was detected. A literature search failed to corroborate this observation, although spatial heterogeneity of soil pH is well documented (Burrough, 1983; Campbell, 1978; McBratney & Webster, 1981; Wong, Asseng, Robertson, & Oliver, 2008).

We tested the hypotheses (a) that adaptedness is important for preserving grain yield in low pH soils and (b) that soil

Abbreviations:  
AlKCl, KCl-extractable aluminum; Al sat, aluminum saturation; CVs, coefficients of variation; Y AVG, grain yield averaged across lime-amended and unamended low-pH soils; Y L, grain yield in lime-amended soils; Y U, grain yield in unamended, low-pH soils.
pH-driven spatial heterogeneity confounds grain yield results in low-pH field trials. Our goal was to develop a simple, generalizable cultivar suitability index robust to complications arising from field-scale heterogeneity in the edaphic environment.

2 | MATERIALS AND METHODS

2.1 Site description and study design

Field trials were established at two dryland farms in Chouteau County, MT, near the towns of Highwood and Geraldine in 2018 and 2019. The dominant soil series were Bearpaw clay loam (fine, smectitic, frigid Vertic Argoisults) mixed with Vida clay loam (fine-loamy, mixed, superactive, frigid Typic Argoisults) at Highwood and Scobey clay loam (fine, smectitic, frigid Aridic Argiustolls) mixed with Kevin clay loam (fine-loamy, superactive, frigid Aridic Argiustolls) at Geraldine (Soil Survey Staff, 2020). Trials were planted in a complete factorial design consisting of two lime rates (0 and 11 Mg ha⁻¹) and nine cultivars with four replicates. Each plot (1.5 m by 6 m) was harvested with a small-plot combine to determine grain yield.

2.2 Lime amendments and soil analyses

Ag lime (Montana Limestone Company) with 99% passing through a 0.149-mm sieve was applied on 12 Oct. 2017 at Geraldine and 31 Oct. 2017 at Highwood. The lime was incorporated with tillage to 12 cm at Geraldine and 15 cm at Highwood. One (in 2018) and four (in 2019) soil cores (0–10 cm) per lime treatment per replicate per site were collected prior to seeding for a total of 80 samples. Soil pH, base cations, and KCl-extractable Al (AlKCl) were determined for each sample. Aluminum saturation (Alsat) was calculated as AlKCl (cmolₑ⁻kg⁻¹) expressed as a percentage of the effective cation exchange capacity (Kariuki et al., 2007; Sumner & Miller, 1996).

2.3 Cultivar classification

Nine spring wheat cultivars were grouped into adapted and nonadapted classes based on yield results from Montana State University spring wheat adaptation trials established in 13 dryland environments in 2019 (MSU, 2019b). One exception was made: ‘Dagmar’ (PI 690450) showed promise in limited testing but was not present in all statewide trials and was excluded from the MSU (2019b) summary. ‘Dagmar’ was classified as adapted in the current study. For the remaining eight spring wheat lines, the median yield of the dataset, 3.6 Mg ha⁻¹, was used to differentiate between nonadapted cultivars (‘WB Gunnison’ [PI 665064], ‘Brennan’ [PI 658041], and ‘SY Soren’ [PI 662048]; mean yield = 3.4 Mg ha⁻¹) and adapted cultivars (‘Vida’ [PI 642366], ‘Duclair’ [PI 660981], ‘Lanning’ [PI 676978], ‘Alum’ [PI 676289], and ‘MT 1673’; mean yield = 3.8 Mg ha⁻¹). Of the nine cultivars and experimental lines investigated, only Alum, Lanning, and Duclair carry TaAlmt1, setting up three resistance-adaptedness classes for yield comparisons: adapted carriers, adapted noncarriers, and nonadapted noncarriers.

2.4 Statistical analysis

Linear mixed modeling was performed using R v. 4.0.0 (R Core Team, 2020) with the lmer function of the lme4 package v. 1.1-23 (Bates et al., 2015). Model parameters were estimated by restricted maximum likelihood. In the full model, site-year, cultivar, lime, and a lime × cultivar interaction term were designated as fixed effects, with lime included as a random effects term nested in replicate and site-year. Effects of site-year were nonsignificant (p = .511) and a lime × cultivar interaction was not detected (p = .204), supporting an assessment of cultivar yield differences across site-years and lime treatments. In the models for grain yield in lime-amended soils (Yl) and in unamended, low-pH soils (Yu), cultivar was designated as a fixed effect term and replicate as a random effects term nested in site-year, whereas lime treatment was designated as an additional random effects term nested in replicate and site-year in the model for grain yield averaged across amended and unamended soils (YAVG). Assumptions of normality and homogeneity of variance were satisfied according to the shapiro.test function in base R and the leveneTest function in the R package car v. 3.0-8 (Fox & Weisberg, 2019), as well as visually. Within-cultivar grain yields adjusted for random effects terms (i.e., estimated marginal means) and Tukey pairwise comparisons among cultivars were calculated using the emmeans function from the R package emmeans v. 1.4.7 (Lenth, 2020). Contrasts of adapted carriers, adapted noncarriers, and nonadapted noncarriers
TABLE 1  Lime-amended (YL) and unamended (YU) grain yields and YAVG average yield of spring wheat TaAlmt1 carriers (+) and noncarriers (−), ± SD. Results are summarized across four site-years. Pairwise comparisons revealed no statistical differences among cultivars.

| Cultivar   | TaAlmt1 | YL   | YU   | YAVG |
|------------|---------|------|------|------|
| Alum       | +       | 2.70 ± 0.65 | 2.49 ± 0.68 | 2.60 ± 0.66 |
| Brennan    | −       | 2.69 ± 0.69 | 2.06 ± 0.81 | 2.39 ± 0.80 |
| Dagmar     | −       | 2.79 ± 0.60 | 2.40 ± 0.59 | 2.58 ± 0.62 |
| Duclair    | +       | 2.78 ± 0.91 | 2.31 ± 0.50 | 2.56 ± 0.77 |
| Lanning    | +       | 2.57 ± 0.84 | 2.55 ± 0.82 | 2.56 ± 0.81 |
| MT 1673    | −       | 2.65 ± 0.65 | 2.50 ± 0.67 | 2.57 ± 0.65 |
| SY Soren   | −       | 2.53 ± 0.70 | 2.20 ± 0.60 | 2.35 ± 0.65 |
| Vida       | −       | 2.65 ± 0.55 | 2.43 ± 0.55 | 2.53 ± 0.55 |
| WB Gunnison| −       | 2.65 ± 0.70 | 2.18 ± 0.56 | 2.43 ± 0.67 |

were performed using Scheffe adjustment for multiple comparisons in the contrast function of the emmeans package (Lenth, 2020).

3  | RESULTS AND DISCUSSION

3.1  | Suitability index

Pairwise comparisons failed to detect cultivar differences in YL, YU, and YAVG due to large within-cultivar standard deviations across site-years (Table 1). However, YAVG for adapted TaAlmt1 carriers was greater than for nonadapted, noncarriers (p = .024). Similarly, YAVG of adapted noncarriers was greater than nonadapted noncarriers (p = .008). There was no difference in YAVG between adapted TaAlmt1 carriers and adapted noncarriers (p = .939). Results suggest that YAVG is an appropriate index for cultivar suitability, defined here based on distribution characteristics of resistance-adaptedness clusters in YL–YU data space (Figure 1).

We propose that cultivar suitability be quantified as the length of AB, the normal distance from a line, L, to a point, B, calculated as follows:

\[
AB = \frac{1}{\sqrt{m^2 + 1}} (Y_U + mY_L) \tag{1}
\]

where \(m\) is the slope of the line normal to L. Because slopes of the lines of best fit for both resistance-adaptedness clusters (Figure 1, open and closed symbols) are approximately –1, justification is provided for setting \(m\) (i.e., the slope of the line normal to L) equal to 1. Thus, Equation 1 simplifies to

\[
AB = \frac{(Y_U + Y_L)}{\sqrt{2}} \tag{2}
\]

which is directly related to the arithmetic mean of \(Y_U\) and \(Y_L\), providing conceptual justification for the use of YAVG as a cultivar suitability index. A similar framework has been used in other disciplines, including remote sensing applications (Zhan, Qin, Ghulan, & Wang, 2007).
3.2 | Grain yield variability

Comparisons of wheat yield coefficients of variation (CVs) were made in a low-pH (<5.0) adaptation trial and three unlimed, neutral- or near neutral-pH (~6.5–7.5) adaptation trials near the current study over the same period (2018–2019; data not presented). Trialwide grain yield CVs in neutral-pH environments (MSU, 2019a) averaged 9.4 ± 3.5% compared with 18.5 ± 5.6% in the low-pH environment. Similarly, when averaged across site-years, grain yield CVs of neutral-pH spring wheat adaptation trials (MSU, 2019a) were 38 and 51% of the current study’s unamended and lime-amended yield CVs, respectively. This pattern extends beyond spring wheat to different crop species assessed in nearby trials. For example, yield CVs of neutral-pH adaptation trials with field pea (Pisum sativum L.) (MSU, 2018b; MSU, 2019c), canola (Brassica napus L.) (MSU, 2018a; MSU, 2019a), and barley (Hordeum vulgare L.) (MSU, 2019a) were 28, 29, and 43% of unamended low-pH yield CVs and 28, 37, and 65% of lime-amended yield CVs, respectively. The relatively large CVs calculated for $Y_U$ and particularly $Y_L$ highlight the logistical challenges of low-pH cultivar comparisons and provide indirect evidence for spatial variability of the edaphic environment as a confounding factor.

3.3 | Soil variability

Large standard deviations in $AI_{KCl}$ and Al sat within individual site-years and lime treatments were observed in the current study (Table 2), despite considerable effort to locate spatially homogeneous acid soils for trial establishment. Limed soils exhibited more variability in $AI_{KCl}$ and Al sat in 2019 than in 2018, suggesting sample size affected variability or variability increased with time from application. The high degree of variability in $AI_{KCl}$ and Al sat in limed and unlimed soils is especially interesting in light of the comparatively low variability in soil pH. When assessed at the field scale, where pH can range by up to 3 pH units (R. Engel, personal communication, 2020), cultivars with strong yield potential in both low-pH and neutral-pH soils will likely outperform those with strong yield potential in low-pH soils only. Basing cultivar recommendations on $Y_{AVG}$ could minimize impacts of potentially confounding factors (e.g., edaphic spatial heterogeneity) and increase the likelihood that crop consultants and other agricultural professionals will endorse the best-adapted cultivar for a given environment, farm, or field. Unavailability of $Y_{U}$ data may warrant approximation of $Y_{AVG}$ as mean grain yield in low- and nearby neutral-pH trials, although additional research is needed.

4 | CONCLUSION

Visualizations in $Y_L$–$Y_U$ data space as well as contrasts of $Y_{AVG}$ among well-adapted $TAAlmt1$ carriers, adapted noncarriers, and nonadapted noncarriers suggest (a) adaptedness is important for achieving high grain yield under low-pH field conditions and (b) $Y_{AVG}$ is an appropriate index for cultivar suitability. This study provides evidence supporting the hypothesis that low-pH adaptation trials may be confounded by pH-driven spatial heterogeneity in the edaphic environment. We argue that the spatial complexity of pH, $AI_{KCl}$, and Al sat within agricultural fields, along with the high yield CVs observed in this and other low-pH adaptation trials, provides ample justification for cultivar recommendations based on $Y_U$ and $Y_L$ averages. Because $Y_L$ data are often unavailable, future work should investigate the integrity of cultivar recommendations based on grain yield averages across low- and nearby neutral-pH field trials. In future low-pH field trials, alternative experimental designs and/or spatially explicit yield corrections are advised.

ACKNOWLEDGMENTS

The authors are grateful to USDA’s Western Sustainable Research and Education program and the Montana Fertilizer Advisory Committee for funding this research. Special thanks to Dr. Rick Engel, whose contributions significantly improved early versions of this manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.
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