Received: 21 November 2019 | Accepted: 8 February 2020

DOI: 10.1002/agg2.20033

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Agrosystems

Comparison of nutrient management recommendations and soil health indicators in southern Idaho

April B. Leytem [1] | Christopher W. Rogers [1] | David Tarkalson [1] | Robert S. Dungan [1] | Richard L. Haney [2] | Amber D. Moore [3]

[1]USDA Agricultural Research Service Northwest Irrigation and Soils Research Laboratory, 3793N 3600E, Kimberly, ID 83341, USA

[2]USDA Agricultural Research Service Grassland Soil and Water Research Laboratory, 808 E. Blackland Rd., Temple, TX 76502, USA

[3]Department of Crop and Soil Science, Oregon State University, 2750 SW Campus Way, Corvallis, OR 97331, USA

Correspondence
April B. Leytem, USDA Agricultural Research Service Northwest Irrigation and Soils Research Laboratory, 3793N 3600E, Kimberly, ID, USA.
Email: april.leytem@ars.usda.gov

Funding information
Idaho Barley Commission; Independent Dairymens Environmental Action League; Northwest Potato Research Consortium; Idaho Wheat Commission

Abstract

Advanced soil tests can improve the estimation of plant available nutrients to better match fertilizer additions with plant needs and, in some cases, provide a measure of soil health. In the present study, 334 samples from four separate studies were evaluated using the Soil Health Tool (SHT) vs. the standard regional (University of Idaho [UI] Guidelines) method for determining fertilizer application, assuming a crop of spring irrigated wheat. Recommended N applications using the SHT were ∼138 kg ha^{-1} greater than the UI recommendations. Nitrogen mineralization predicted using the SHT (47 kg ha^{-1}) was similar to the N mineralization value used in the regional methodology (50 kg ha^{-1}). The P fertilizer recommendations were similar between the t wo methodologies with the SHT recommending, on average 4.7 kg ha^{-1} less P than the regional method. The lower P recommendation are likely due to a lack of accounting for the effects of high calcium carbonate levels on the P availability from fertilizers in this region. The soil health score (SHS) was correlated with measures of soil C but was not positively correlated to crop yield. In some instances, increasing SHS were correlated with decreases in crop quality as the addition of manure increased soil C but also created issues such as high salt contents and release of late season N. With modification to more accurately represent irrigation conditions and including sampling to greater soil depths, the SHT may be tailored to better estimate soil nutr i ent status and provide better fertilizer recommendations for the region.

1 | INTRODUCTION

The practice of soil testing has been developed and improved upon over the last century, as a means to effectively predict crop nutrient need and crop growth response. Most soil tests consist of using chemical methods to estimate the quantity of plant available nutrients in the soil and have been developed based on regional soil properties. Soil tests provide an index of nutrient availability which must be correlated to specific crop response, typically yield, and subsequently calibrated against nutrient rate response via field and greenhouse experiments to accurately predict the nutrient needs of the crop (Havlin, Beaton, Tisdale, & Nelson, 1999). A fertilizer recommendation is then provided based on the soil test nutrient status and

Abbreviations: PAN, plant available nitrogen; PAP, plant available phosphorus; SHS, soil health score; SHT, Soil Health Tool; UI, University of Idaho.

the target crop yield. In some cases, fertilizer recommendations are based on limited data or are outdated due to changes in plant genetics and crop management over time. In addition, many guidelines were designed with the concept of building up a bank of nutrients in the soil to avoid deficiencies, particularly for P and K.

As new environmental and consumer pressures have led to a call for more "sustainable" cropping systems, improvements in soil testing and fertility recommendations are needed to improve plant nutrient requirement estimates and the amount of these nutrients that may be supplied by soils over the growing season. Improved soil tests that provide information as to what plant nutrients are available in the soil at the time of pre-plant as well as the amount of nutrients that will become available over the course of a crop production season would improve our ability to determine fertilizer recommendations that maintain crop productivity while protecting the environment.

In addition to predicting the nutrient-supplying capacity of soils, there has been pressure from environmental agencies (i.e., federal, state, and non-governmental organizations [NGO's]) to develop soil tests that can quantify the effects of management practices on soil health. As defined by the FAO (2008), healthy soils maintain a diverse community of soil organisms that control plant disease, insect and weed pests, recycle plant nutr i ents, improve soil structure, and improve crop production. The adoption of management strategies to improve the overall health of the soil can improve crop production by enhancing soil nutri ent cycling, nutrient retention, water retention, increasing porosity and drainage, and reducing erosion (Ontl & Schulte, 2012; Milne et al., 2015). Tracking the influence of management practices on soil health requires metrics that can be utilized to determine whether these practices are having positive or negative effects. Soil testing laboratories have been getting more requests from producers to offer soil testing methods that will provide an indication of soil health in addition to the traditional measurements of soil fertility status.

The Soil Health Tool (SHT) is comprised of several soil tests that were developed with the goal of accurately estimating plant available nutrients, making defensible fertilizer recommendations, and assessing the nutrient cycling of soils (Haney, Haney, Smith, Harmel, & White, 2018). The SHT includes measurements of water extractable organic carbon (WEOC); water extractable organic nitrogen (WEON); water extractable nitrate nitrogen (NO_3–N) and ammonium nitrogen (NH_4–N); Haney, Haney, Hossner, and Arnold (H3A) extractable P; and carbon dioxide carbon (CO_2–C) evolution after a 24-h incubation (Haney, Brinton, & Evans, 2008, 2010). These data are then used to support an algorithm that is designed to estimate plant available nitrogen (PAN) and phosphorus (PAP) and provide an indication of soil health as related to nutrient and C cycling (Haney et al., 2018). The sampling protocol calls for the collection of a 0- to 15-cm soil sample in the spring prior to planting.

Core Ideas

- The soil health tool recommended 138 kg ha^{-1} more N fertilizer than regional guidelines.
- The soil health tool recommended P fertilizer similar (–4.7 kg ha^{-1}) to regional guidelines.
- Soil health score was positively correlated to measures of soil C but not crop yield.

Both dairy and row crop producers in southern Idaho have shown interest in using the SHT as both an indicator of soil health and to provide fertilizer recommendations. Current nutrient recommendations provided by the University of Idaho call for soil sampling to a depth of 61 cm for N and 30 cm for P in the spring prior to planting to determine the amount of nutrients available in the soil (Brown, Hart, Horneck, & Moore, 2010; Brown, Stark, & Westermann, 2001; Robertson & Stark, 2003). This is common for the region, as both Oregon and Washington, also call for 0- to 30-cm sampling depths for P and 0- to 61-cm depths (and deeper) for N (Horneck et al., 2010; Moore, Wysocki, Chastain, Wilson, & DuVal, 2019). Dairy producers in southern Idaho are required by statute to soil sample to a minimum of 30 cm for P determination and it is suggested to sample to 61 cm for N determination (Idaho State Department of Agriculture [ISDA], 2020). Due to regulations and standard protocols in the region, producers may be likely to send samples for analysis via the SHT that are collected from the top 30 cm of soil as opposed to the recommended 15 cm. Due to these differences, along with variation in climate and soil type, many producers, crop consultants, and other technical service providers have questioned whether the fertilizer recommendations provided by the SHT are appropriate for crop growth in the region.

One of the novel aspects of the SHT is the inclusion of a rapid test for estimating N mineralization over the growing season. The estimation of N mineralization is one of the most difficult factors for determining accurate crop N recommendations. There are several tests that have been proposed for estimating N mineralization including 7-d anaerobic incubation, Illinois Soil N Test, direct steam distillation, amino sugar N, and various CO_2 flux measurements (Bushong et al., 2008; Christensen & Mellbye, 2006; Franzluebbers, Haney, Honeycutt, Schomberg, & Hons, 2000; Khan, Mulvaney, & Hoeft, 2001; Roberts, Norman, Fulford, & Slaton, 2013; Roberts, Norman, Slaton, & Wilson, 2016; Schomberg et al., 2009). The success of these tests has varied with both crop and regional conditions. Improvements in estimating N mineralization over the growing season would improve the accuracy of fertilizer N recommendations as well as reduce production costs and protect the environment.

The objectives of this study were to (a) evaluate the use of the SHT for making fertilizer recommendations vs. using the standard regional method, (b) compare the N mineralization potential determined with the SHT method to laboratory and field data, and (c) examine the relationship between the SHT soil health score and crop yields and quality.

2 | MATERIALS AND METHODS

2.1 | Sample collection and analysis

For this evaluation, 334 soil samples were collected from four different studies throughout southern Idaho. The majority of soils were classified as silt loams. Regional precipitation ranges from 180 to 305 mm and average annual temperatures range from 5 to 13 °C. A description of the studies is included below. The number of samples included in the analysis from each study are included in Table 1. Studies 1 and 2 followed the standard regional protocol for s oil sampling (0–61 cm), while Studies 3 and 4 followed the protocol specific to the SHT (0–15 cm) in addition to standard protocols.

The focus of Study 1 was to evaluate the effects of dairy manure application rate (18, 36, and 52 Mg ha^{-1} dry wt.) and timing (manure repeatedly applied either annually or biennially), or synthetic fertilizer applications on soil nutrient cycling, crop yield, and crop quality. The treatments also included a control that received no nutrient applications. The study was initiated in the fall of 2012 and consisted of two adjacent fields that were treated identically with the exception that the crop rotation was staggered between the two fields. The crop rotation consisted of barley (Hordeum vulgare L.)–sugarbeet (Beta vulgaris L.)–wheat (Triticum aestivum L.)–potato (Solanum tuberosum L.). Field 1 started the rotation with wheat in 2013 while Field 2 started the rotation with barley in 2013. Soil samples were collected in late March of 2013, 2014, and 2015 with 10 subsamples collected and composited by plot for the 0- to 30-cm depth, and five subsamples collected and composited for the 30- to 61-cm depth. Soils were thoroughly mixed and subsampled for analysis. Subsamples were stored in a cooler overnight and then shipped to the University of Idaho Analytical Sciences Laboratory (Moscow, ID) the following day for analysis of NO_3–N and NH_4–N, using a 2 M KCl extraction with analysis via flow injection (OI Flow Solution 3000 FIA, Xylem Inc.), and Olsen P (Olsen, Cole, Watanabe, & Dean, 1954). Additional subsamples were dried and stored (till April 2015) and sent to the ARS unit in Temple, TX, for analysis via the SHT (Haney et al., 2018).

Wheat and barley yield were determined with an Almaco plot harvester (1.5-m header, ~26 m^2 per plot). Tuber yield was determined for each plot using a single row potato digger (Grimme) with 33.5 m of row (1 m wide) within each plot harvested. Sugar beets were mechanically harvested for yield (21 m of row, 1.2 m wide) with a two-row beet harvester. Plant samples were analyzed for quality including protein (barley), specific gravity (potato), percentage sucrose (sugar beet), and brei NO_3 (sugar beet). Barley protein was determined by near-infrared (NIR) spectroscopy on a Foss NIR 6500 on a subsample of whole grain. Specific gravity in potato was determined on approximately 4.5 kg of tubers via the weight in air/weight in water method (Kleinkopf, Westermann, Wille, & Kleinschmidt, 1987). Sugarbeet samples (two samples of eight beets per plot) were submitted to the Snake River Sugar Company Tare Lab in Paul, ID. Percentage sucrose was determined using an Autopol 880 polarimeter (Rudolph Research Analytical) and a half-normal weight sample dilution and aluminum sulfate clarification method (ICUMSA Method GS6-3 1994) and NO_3 was measured using a multimeter model 250 (Denver Instruments) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc.).

The release of plant available N over the growing season from treatments in Field 2 was evaluated using a ∼100-d aerobic laboratory incubation to determine potentially mineralizable N, and an in situ (in field) aerobic incubation to determine N release patterns as influenced by the same temperatures that affected plant growth under field conditions. Soil samples t hat were collected at pre-plant, as described above, were used for the aerobic lab incubation. Soil samples from the 0- to 30-cm depth were incubated at 22 °C for 100–112 d (107 d for 2013, 112 d for 2014, 100 d for 2015) in 0.05-mm thickness polyethylene resealable bags (15 by 23 cm) at existing field moisture. Gravimetric soil moisture content of sampled soils ranged between 16 and 22%, depending on the year and the manure rate. Soil moisture levels were maintained by weighing soils on a weekly basis and adding distilled water to individual bags to bring them back up to the original moisture content.

In addition to a controlled laboratory incubation, in situ incubations were also conducted using the buried bag method as described by Westermann and Crothers (1980). Soil samples for the in-situ incubation were collected 1–2 wk after planting from Field 2, to avoid bag destruction during tillage and planting operations. Soil samples were collected from the 0- to 30-cm soil depth, with 10–13 subsamples composited from each plot. Soils were aerobically incubated under field conditions by placing the composited soil samples from each plot into polyethylene tubes with a thickness of 0.10 mm and a 5.7 cm diam., with the tube portion containing soil being 30 cm long after being knotted on both ends. The secured soil bags were placed back in the auger holes in each plot where the soil sample had been taken, down to a depth of 30 cm. Buried bags were installed on 12 Apr. 2013, 3 May 2014, and 13 Apr. 2015. Soils were incubated for 153 d in 2013, 159 d in 2014, and 182 d in 2015. The bags were sequentially removed

TABLE 1 Number of soils samples used to evaluate the Soil Health Tool listed by study and analysis component

	Number of samples from each study used in analysis					
Study	Available N	N mineral-ization	Available P	Fertilizer rec-ommendations	Yield	Quality
1	192	95	189	188	184	129
2	42	–	42	42	–	–
3	47	–	47	47	–	–
4	30	–	30	30	–	–
Total	311	95	308	307	184	129

and destructively sampled over the course of t he growing season. For both incubation studies, soils were analyzed for NO_3-N and NH_4-N content at Day 1 and final day (and at mid-July [18 July 2013, 17 July 2014, and 20 July 2015] prior to grain harvest for in-situ measurements) of incubation experiment, using KCl extractions and flow injection analysis, as described above. Net N mineralization was calculated by subtracting inorganic N (NO_3–N + NH_4–N) concentrations from the first day of the lab or in situ incubation from the inorganic N concentrations measured on the final day.

In Study 2, samples (42) were collected from producer fields across southern Idaho that had a histor y of synthetic fertilizer application. Four subsamples were collected at each site using a 7.6-cm bucket auger from a depth of 0–30 and 30–61 cm and composited. After collection, soil samples were dried at 40 °C in a forced-convection oven and were subsequently ground and homogenized to pass through a 2-mm sieve. Soil NO_3–N and NH_4–N were determined via 2 M KCL extraction and analyzed via flow injection analysis. Olsen P was determined using the method cited previously. Dried subsamples (0–30 cm) were sent to a commercial laboratory for analysis via the SHT test.

In Study 3, samples (47) were collected from 15 producer fields across the Fort Hall growing area in southeastern Idaho in the spring of 2015. The fields had a history of synthetic fertilizer application and/or manure. At each sample location 15 subsamples in a 7.3 m^2 area were collected using a 1.9-cm push probe from a depth of 0–15 cm and composited. At the same time and sites, one deep core (4.1 cm diam.) was collected using an AMS 9110-AG probe (AMS Inc.) to a depth of 61 cm. Cores were divided into two depths (0–30 and 30–61 cm) and composited.

In Study 4, samples (30) were collected from a past research study at the USDA-ARS Northwest Irrigation and Soils Laboratory near Kimberly, ID, in spring 2013 (Robbins, Mackey, & Freeborn, 1997). In spring 1991, the USDA-ARS research study consisted of applying manure (44 dry Mg ha^{-1}) and commercial fertilizer (245 kg N ha^{-1}, 135 kg P ha^{-1}) to both soils that were eroded and not eroded. Since 1991, the entire research area has uniformly received commercial fertilizer based on published soil test and crop nutrient recommendations. Soil sample collection was the same as in Study 3. For Studies 3 and 4, soil samples were dried at 40 °C in a forced-convection oven and were subsequently ground and homogenized to pass through a 2-mm sieve. Soil NO_3–N and NH_4–N and Olsen P were determined using the method cited previously. Dried subsamples (0–15 cm) were sent to a commercial laboratory for analysis via the SHT test.

2.2 | Soil test comparisons and fertility recommendations

The SHT was compared to the standard regional method for determining fertilizer recommendations in southern Idaho, assuming a crop of spring irrigated wheat, following the University of Idaho (UI) guidelines (Brown et al., 2001). The UI guidelines are based on multiple years of field data in the region and use projected yield along with a measure of soil test N and P as well as a credit for N mineralization to determine N and P application rates. For this comparison, the values for available N and the recommendations for N and P needed were taken directly from the SHT analysis provided by the laboratory assuming a crop of wheat with an expected yield of 7400 kg ha^{-1} (114 bu $acre^{-1}$). This provides a comparison of what recommendation a producer would receive based on the SHT vs. the regional recommendations.

The SHT recommendations were based on measures of PAN including N mineralization and PAP including P mineralization in the top 15 cm of s oil. Brief descriptions of these calculations are included below, det ailed explanations can be found in Haney, Haney, Smith, and White (2017).

$$\text{PAN kg ha}^{-1} = [(\text{NH}_4 - \text{N}_w \times 2.24) + (\text{NO}_3 - \text{N}_w \times 1.6)] + \text{Nmin} \quad (1)$$

where NH_4–N_w is water extractable NH_4–N (mg kg^{-1}), 2.24 converts to kg ha^{-1}, NO_3–N_w is water extractable NO_3–N (mg kg^{-1}), 1.6 is the conversion factor from mg kg^{-1} soil to kg ha^{-1} assuming a 30% loss of NO_3–N to leaching and denitrification, Nmin (kg ha^{-1}) is the potential N mineralized over the growing season.

$$\text{Nmin (kg ha}^{-1}\text{)} = \text{MAC} \times \text{WEON} \times 2.24 \times n \quad (2)$$

where MAC is microbially active C measured as the amount of 1 d CO_2–C release (mg kg^{-1} soil) relative to active organic C (WEOC, mg kg^{-1} soil), WEON is water-extractable organic N (mg kg^{-1}), 2.24 converts to kg ha^{-1}, and n is the number of rainfall and irrigation events throughout the growing season, a value of 4 is typically used.

$$\text{PAP (P}_2\text{O}_5\text{, kg ha}^{-1}\text{)} = (\text{PO}_4 - \text{P (H3A)} \times 2.24 \times 2.3) + \text{Pmin} \quad (3)$$

where PO_4–P is the H3A extractable P (mg kg^{-1}), 2.24 converts to kg ha^{-1}, 2.3 converts P to P_2O_5, Pmin is the potential mineralizable P.

$$\text{Pmin (kg ha}^{-1}\text{)} = \text{MAC} \times \text{EOP} \times 2.24 \times 2.3 \times n \quad (4)$$

where EOP is H3A extractable organic P, 2.24 converts to kg ha^{-1}, 2.3 converts P to P_2O_5, n is t he number of rainfall and irrigation events throughout the growing season, a value of 4 is typically used.

The regional recommendations were calculated following the UI guidelines as follows:

$$\text{Plant Available N (PAN) kg ha}^{-1} = [(\text{NH}_4 - \text{N} + \text{NO}_3 - \text{N mg kg}^{-1} (0 - 30\text{ cm}) \times 4.48) + (\text{NH}_4 - \text{N} + \text{NO}_3 - \text{N mg kg}^{-1} (31 - 61\text{ cm}) \times 4.48)] + 50.4\text{ kg ha}^{-1}\text{ mineralized N} \quad (5)$$

where NH_4–N and NO_3–N were determined via KCl extraction (see above), the value of 4.48 converts mg kg^{-1} to kg ha^{-1} and a value of 50.4 kg ha^{-1} of mineralized N was suggested by the guidelines. The PAN was then subtracted from the N needed for wheat (230 kg ha^{-1}) as determined by the SHT to calculate the additional fertilizer N needed.

The P needed for wheat production was determined using the UI fertilizer guideline (Brown et al., 2001) and is based on soil Olsen P concentration and the calcium carbonate content of the soil.

The differences in N and P recommendations between the two methods were calculated as follows:

N or P needed (kg ha^{-1}) using the Soil Health Tool – N or P needed (kg ha^{-1}) using UI Guidelines.

We then made a comparison of available N and fertilizer P needed using adjusted calculations to better reflect the conditions in southern Idaho (Studies 1 and 2). The adjusted SHT calculations were as follows:

$$\text{PAN kg ha}^{-1} = [(\text{NH}_4 - \text{N}_w \times 4.48) + (\text{NO}_3 - \text{N}_w \times 3.2)] + \text{Nmin} \quad (6)$$

where NH_4–N_w is water extractable NH_4–N (mg kg^{-1}), 4.48 converts to kg ha^{-1} assuming a 0- to 30-cm soil depth, NO_3–N_w is water extractable NO_3–N (mg kg^{-1}), 3.2 is the conversion factor from mg kg^{-1} soil to kg ha^{-1} assuming a 30% loss of NO_3–N to leaching and denitrification and a 0- to 30-cm soil depth, Nmin (kg ha^{-1}) is the potential N mineralized over the growing season.

$$\text{Nmin (kg ha}^{-1}\text{)} = \text{MAC} \times \text{WEON} \times 4.48 \times n \quad (7)$$

where MAC is microbially active C, WEON is water extractable organic N (mg kg^{-1}), 4.48 converts to kg ha^{-1} assuming a 0- to 30-cm soil depth, and n is the number of rainfall and irrigation events throughout the growing season, a value of 9 was used for n as that is a typical number of irrigations for wheat.

$$\text{PAP (P}_2\text{O}_5\text{, kg ha}^{-1}\text{)} = (\text{PO}_4 - \text{P (H3A)} \times 4.48 \times 2.3) + \text{Pmin} \quad (8)$$

where PO_4–P is the H3A extractable P (mg kg^{-1}), 4.48 converts to kg ha^{-1} assuming a 0- to 30-cm soil depth, 2.3 converts P to P_2O_5, Pmin is the potential mineralizable P.

$$\text{Pmin (kg ha}^{-1}\text{)} = \text{MAC} \times \text{EOP} \times 4.48 \times 2.3 \times n \quad (9)$$

where EOP is H3A extractable organic P, 4.48 converts to kg ha^{-1} assuming a 0- to 30-cm soil depth, n is the number of rainfall and irrigation events throughout the growing season, a value of 9 was used for n as that is a typical number of irrigations for wheat.

These were compared to the PAN calculated using the UI standard methodology with the exception that we only used the N values for the 0- to 30-cm soil depth and P needs were determined as described above.

$$\text{PAN kg ha}^{-1} = (\text{NH}_4 - \text{N} + \text{NO}_3 - \text{N mg kg}^{-1} (0 - 30\text{ cm}) \times 4.48) + 50.4\text{ kg ha}^{-1}\text{ mineralized N} \quad (10)$$

where NH_4–N and NO_3–N were determined via KCl extraction (see above), the value of 4.48 converts mg kg^{-1} to kg ha^{-1} and a value of 50.4 kg ha^{-1} of mineralized N is suggested by the guidelines.

2.3 | Soil health score relationships

The soil health score (SHS) generated using the SHT was compared to crop parameters (Study 1 only) that would be of interest to producers. The SHS is calculated as follows:

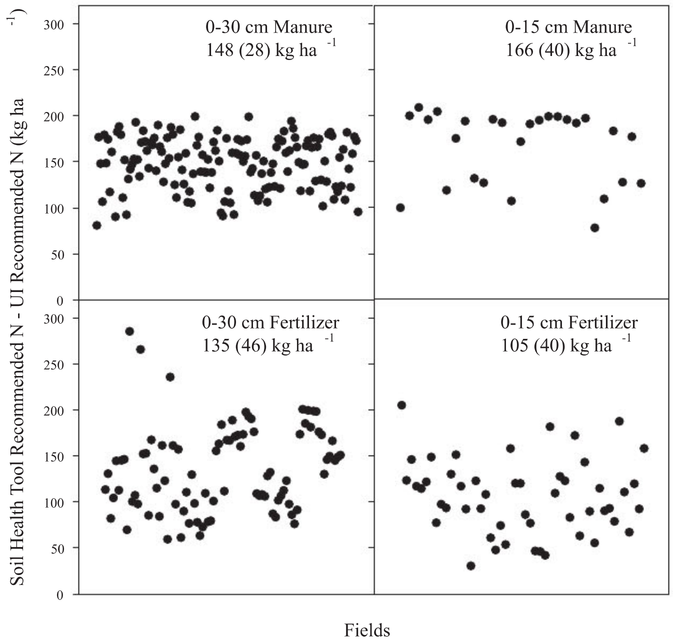

FIGURE 1 Difference in fertilizer N recommendations using the Soil Health Tool vs. UI (Soil Health Tool N recommendation–University of Idaho [IU] N recommendation) by depth and field history. Data from all studies included

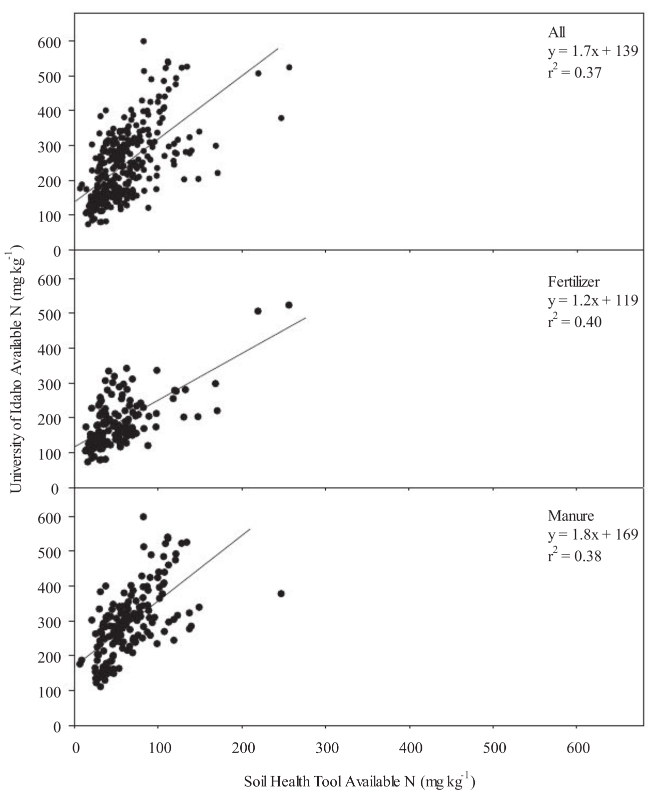

FIGURE 2 Soil Health Tool available N (Equation 1, 0–15 cm) vs. available N calculated following the University of Idaho guidelines (Equation 5, 0–61 cm) for (top panel) wheat using all data, (middle panel) data from fields with fertilizer only, and (bottom panel) data from fields with a history of manure. Demonstrates impact of sampling depth on available N. Data from all studies included

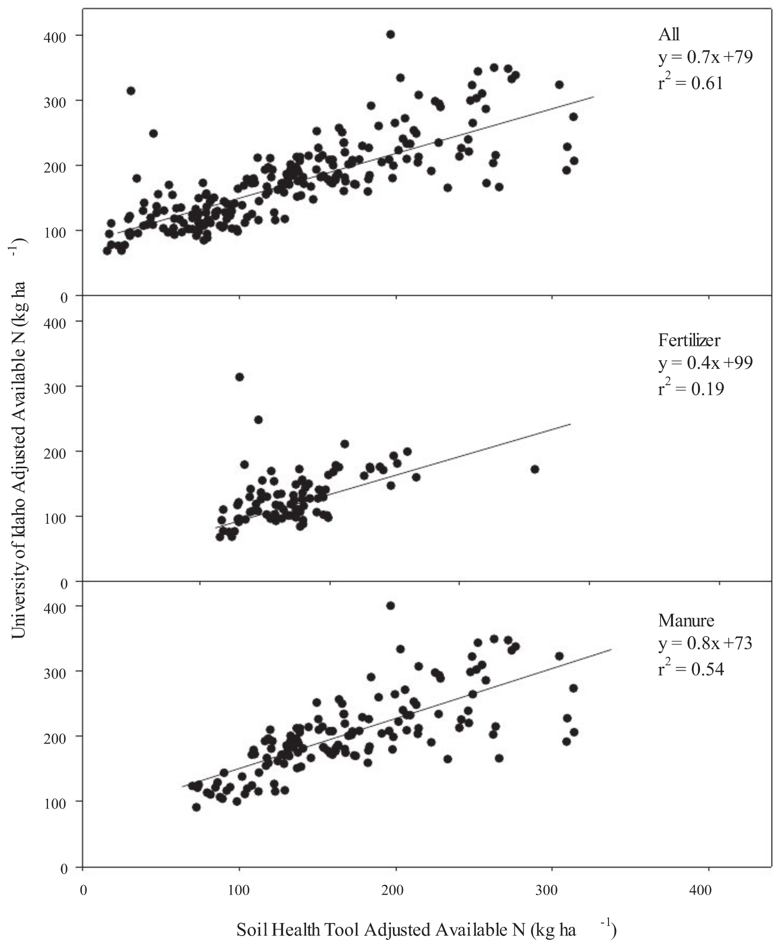

FIGURE 3 Soil Health Tool adjusted available N (Equation 6 (0–30 cm) vs. available N calculated following the University of Idaho guidelines (Equation 10 (0–30 cm) for (top panel) wheat using all data, (middle panel) data from fields with manure only, and (bottom panel) data from fields with a history of fertilizer. Data from Studies 1 and 2

$$SHS = 1\ d\ CO_2 - C/10 \times WEOC/100 \times WEON/10 \quad (11)$$

where 1-d CO_2–C is the C released by soil microbes 24 h after re-wetting the soil, WEOC and WEON are water extractable organic C and N, respectively.

The SHS was evaluated against crop yield to determine if an increasing SHS resulted in greater yield. The SHS was also evaluated against several crop quality parameters that would be of interest to producers. In barley, the SHS was compared to the grain protein content, as the majority of barley grown in the region is for malt and high protein contents (>12%) can have negative impacts on malt quality. In potato, the SHS was compared to specific gravity where higher specific gravity is desirable. In sugar beet, the SHS was compared to percentage sucrose which is the main use of the crop in the region as well as brei nitrate which is a contaminant found in sucrose extracts.

2.4 | Statistical analysis

All statistical analysis was performed using SAS (SAS Institute Inc.). Statistical analyses of the data (all studies combined) were performed with a factorial ANOVA using the PROC GLM (general linear models) procedure with sampling depth and field history (manure or fertilizer) and their interactions as main effects in the model. Linear regression analysis was used to determine the relationship between available N

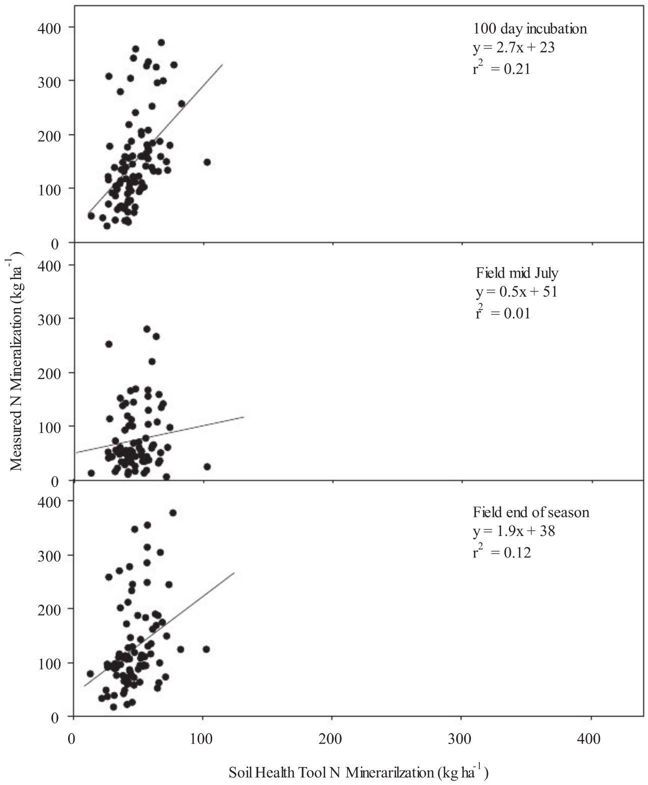

FIGURE 4 Nitrogen mineralization (0–30 cm) estimated using the Soil Health Tool (Equation 7) vs. measured (top panel) in either a laboratory incubation study, (middle panel) in the field in mid-July (middle panel), or (bottom panel) in the field at the end of season. Data from Study 1

determined via the SHT and UI recommendations (data from all studies) and adjusted SHT N and UI N (data from Studies 1 and 2). Linear regression analysis was used to determine the relationship between Nmin determined in the laboratory and field vs. determined using the SHT (Study 1). Linear regression analysis was used to determine the relationship between SHS and organic C (data from all studies) and yield and crop quality parameters (data from Study 1). Pearson correlations were performed to deter mine relationships between N mineralization and soil parameters (data from Study 1). Statements of statistical significance were based on a P value < .05.

3 | RESULTS AND DISCUSSION

3.1 | Nitrogen recommendations

One of the main questions asked by producers and technical service providers in the region is, how do the fertilizer recommendations derived from the SHT compare to those recommended following t he UI fertilizer guidelines? This was evaluated by comparing recommendations estimated using the SHT method (values obtained directly from the laboratories providing the analysis) vs. UI methods for the region. The effects of sampling depth (15 vs. 30 cm) and field history (manure vs. fertilizer) on the difference in N recommendations between the two methods (SHT recommendation and UI recommendation) was evaluated. There was no main effect of sampling depth ($P = .27$), however there was a significant effect of field history ($P < .0001$) and their interaction ($P < .0001$). Fields having a history of manure, on average, had a higher N recommendation than fields with a history of fertilizer irrespective of sampling depth (Figure 1). Sampling to 15 cm resulted in higher N recommendations for fields with a manure history and lower N recommendations for fields with a history of fertilizer compared to fields sampled at 30 cm. The lack of an effect of sampling depth was not unexpected as the soils in this region are typically conventionally tilled and also include crops such as pot ato and sugar beet which result in mixing of the top 30 cm of soil with harvest, therefore there tends to be little stratification of soil within the top 30 cm.

Utilizing the SHT, N recommendations were 30–285 kg ha^{-1} greater than recommendations using the UI methodology. On average, the SHT recommended 138 kg ha^{-1} of additional N fertilizer beyond what the UI recommendations would suggest. Based on the price of urea in May 2018 (US$305.6 tonne^{-1}, indexmundi.com), this would equate to a cost of approximately \$42 ha^{-1}. Sites with a history of manure had recommendations that were an average of 124 kg ha^{-1} greater N using the SHT compared to UI methods. Sites with a history of fertilizer had an average of 151 kg ha^{-1} greater N recommendations. The higher N recommendations using the SHT would be expected as the UI recommendations include soil NO_3 and NH_4 down to 61 cm compared to the shallower sampling depth of the SHT. Roper, Osmond, Heitman, Wagger, and Reberg-Horton (2017) also found that in the Piedmont and mountain region of North Carolina that, in some instances, the SHT N fertilizer recommendations were greater (7–21%) than using the standard method for the state. These findings are in contrast to a previous study in Texas where use of the SHT to determine fertilizer rates compared to what producers were applying to their fields would result in reduced fertilizer application rates by 30–50%, although the farmer determined fertilization practices may not have used a standard method (Harmel & Haney, 2013). Therefore, the differences in N fertilizer recommendations between the SHT and traditional methods are heavily dependent on the regional fertilizer guidelines.

Figure 2 illustrates the relationship between available N determined with the SHT as provided by the laboratories and that calculated following the UI guidelines. While the two measurements are linearly related, the inclusion of the N at deeper depths by the UI guidelines results in more calculated available N using that method. Overall, there was a positive relationship between the two measures of PAN (r^2 = .37), with a slight improvement in this relationship when the data was broken out between fields receiving manure (r^2 = .40) vs. fertilizer (r^2 = .38). The UI method calculated approximately 3.5 times more available N than was calculated using the SHT due largely to the issue of sampling depth. This increased to nearly four times when evaluated using the manure data alone. To remove the effect of including the lower soil depths and to account for the effect of irrigation on potential N mineralization, an adjusted available N was calculated for the SHT and compared to available N for the first 30 cm that would be derived with the UI method. The typical number of irrigations for wheat in southern Idaho is approximately nine which is close to twice the value that is typically used by laboratories providing SHT calculations. When the adjusted SHT PAN was compared with the PAN calculated using the UI method (0- to 30-cm soil depth only), the relationship was improved (r^2 = .61 for all soils, Figure 3). The adjusted SHT PAN was only 1.2 times less than that calculated using the UI method. When evaluated for sites with fertilizer only or manure only the relationship was not as good with r^2 of .19 and .54, respectively. This suggests that N fertilizer recommendations utilizing the SHT could be improved by adjusting either the soil depth or the number of irrigations typical for the region. However, unless data from the 15- to 61-cm depth is included in the SHT calculations, the fertility recommendations utilizing this tool will likely always be greater than the standard regional method in southern Idaho.

3.2 | Nitrogen mineralization

One of the potential benefits of utilizing the SHT is that the tool is designed to determine the PAN over the growing season as opposed to determining only inorganic N at the start of the growing season. The soil organic N pool contains potentially mineralizable N which provides readily available N to plants over the growing season (Haney et al., 2008; Haney et al., 2012) and should be accounted for when determining total PAN. By doing so, the idea is that fertilizer recommendations can better account for total PAN over the season and therefore adjust the amount of N fertilizer needed for crop production. The current UI recommendations include a fixed value of 50.4 kg ha^{-1} of mineralizable N over the growing season, while the SHT calculates N mineralization.

The SHT uses a combination of a measure of microbial activity, determined from release of CO_2–C following a 24 h incubation period and the active organic N fraction in the soil (determined with a water extraction) along with the number of wetting and drying periods throughout the season to estimate mineralizable N. The measurement of CO_2–C release has been found to vary greatly depending on the procedure used (Franzluebbers, 2016, Haney et al., 2008, Rogers, Schroeder, Rashed, & Roberts, 2018, Wade et al., 2018), which can result in large variations of estimated N mineralization. To evaluate this rapid test, we compared the N mineralization estimated using the SHT (Equation 7) with that measured in either the laboratory or in the field (Study 1, Figure 4). There was a poor relationship between the SHT estimated mineralized N and that measured in the lab (r^2 = .22) or field (r^2 = –.04). Nitrogen mineralization estimated with the SHT was less than 100 kg ha^{-1}, while actual measured net N mineralization in the laboratory or field approached 400 kg ha^{-1} for some treatments. However, the average N mineralization calculated with the SHT was 47 kg ha^{-1} which is similar to the value used in the UI recommendations (50.4 kg ha^{-1}). Compared to net N mineralization measured in laboratory incubations, the SHT method estimated an average of 3.1 times less N mineralization. Field net N mineralization data collected in either July or end of season (October) were poorly correlated with the SHT estimates with an average of 1.5 and 2.6 times more N mineralized in the field compared to the SHT estimated mineralizable N, respectively. For comparison, the laboratory incubation N mineralization data were similar to the end of season field data (0.83 times) with an r^2 = .54.

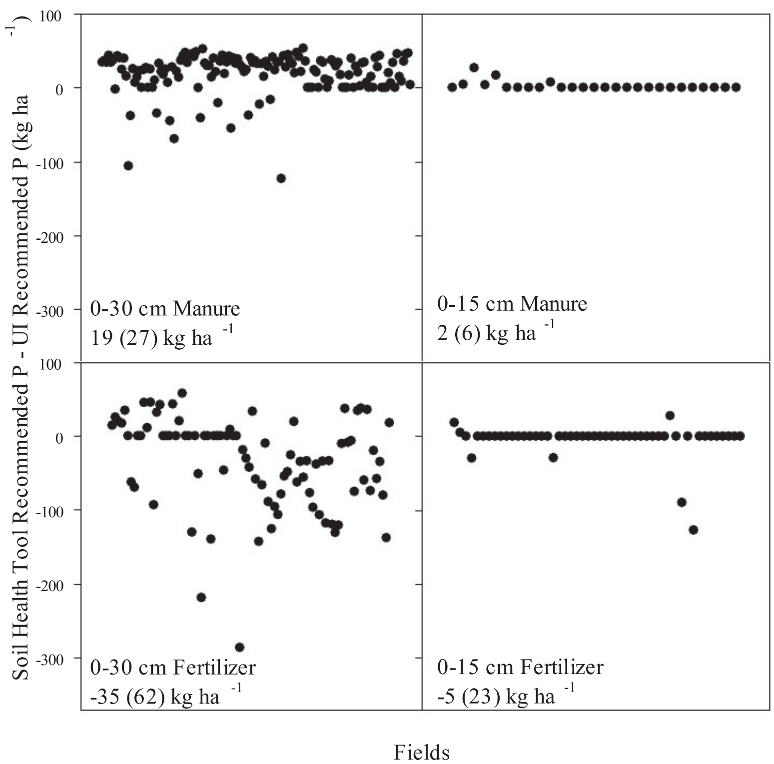

FIGURE 5 Difference in fertilizer P recommendations using the Soil Health Tool vs. University of Idaho (UI) (Soil Health Tool P recommendation–UI P recommendation) by soil depth and field history (manure vs. fertilizer). Data from all studies included

Studies evaluating soil parameters useful for estimating soil N mineralization have found that a combination of total N and CO_2 flush after 3 d of incubation were good predictors of potentially mineralizable N (Gilmour & Mauromoustakos, 2011; Schomberg et al., 2009). Wade, Horwath, & Burger (2016) reported that total soil N had the greatest predictive ability for estimating N mineralization on soils in California's agricultural region, which like soils in southern Idaho, are predominantly arid, loamy, and have low total C contents (<17 g kg^{-1}). They found little correlation between different measures of respiration and N mineralization for soils without cover crops. Rogers et al. (2018) reported poor correlation between N mineralization and the flush of CO_2 compared to a 7-d anaerobic incubation in alkaline soils from Idaho when the top down wetting and gel paddle method was used, but reported a strong correlation when capillary wetting and infrared gas analysis were used. In Study 1, net N mineralization estimated via 100 d incubation was highly correlated with several pre-plant soil measures including total N (r = .84), organic N (r = .83), and soil organic matter (r = .84, data not shown). In the case of these arid soils with low organic matter contents, a measure of total N may be more appropriate to more accurately capture the pool of N available for mineralization. In addition, perhaps longer incubation periods to better capture potential microbial activity may be necessary due to the low organic matter content of these soils.

3.3 | Phosphor us recommendations

There was no effect of sampling depth (P = .19) on the difference in P recommendations between the SHT and UI method. As with N recommendations, there was a significant effect of field history (manure vs. fertilizer P < .0001) and a significant interaction (P < .001). Recommended P on fields with manure history sampled at 0–15 cm were less than those sampled at 0–30 cm while the opposite was true for the fields with fertilizer (Figure 5). Overall, the average difference in P fertilizer recommendations was –4.7 kg ha^{-1}. As seen in Figure 5 there were a lot of instances where the difference between methods was "zero" due to the large numbers of soils that had high levels of P. To evaluate these relationships without the

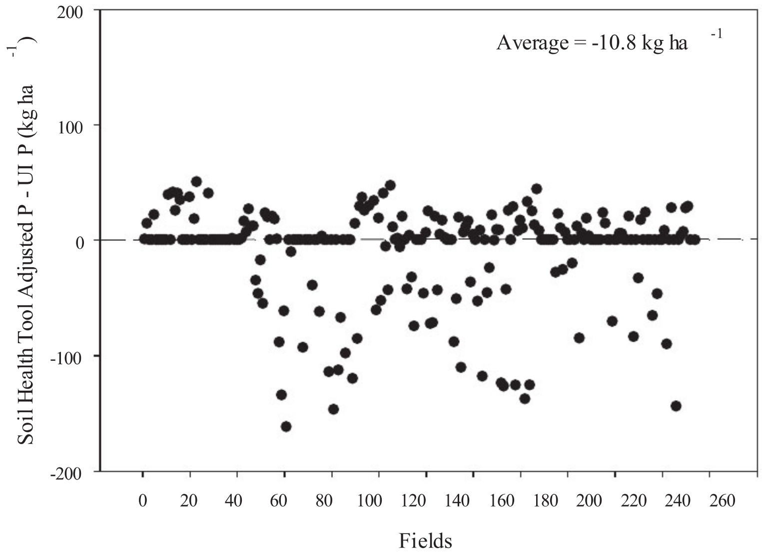

FIGURE 6 Difference in fertilizer P recommendations using the adjusted Soil Health Tool vs. University of Idaho (UI) for each field (Adjusted Soil Health Tool P recommendation–UI P recommendation) for Studies 1 and 2

influence of these high P soils, we removed instances where both methods recommended no P application and evaluated the data again. This resulted in no significant effects of sampling depth ($P = .94$) or interaction ($P = .42$), but field history was still significant ($P < .0001$).

Sites with a history of synt hetic fertilizer only had an average P fertilizer recommendation of 30 kg ha^{-1} less using the SHT vs. the UI methods and ranged from 0 to 45 kg ha^{-1}. The P fertilizer recommendations for sites with a history of manure application were, on average, 17 kg ha^{-1} greater using the SHT compared to UI methods, with recommendations ranging from 0 to 53 kg ha^{-1}. Roper et al. (2017) found little differences between fertilizer P recommendations utilizing the SHT vs. standard methods for North Carolina with only one site being significantly different, where the SHT recommended greater P application than the standard state method. In the present study, one concern is that 41% of sites that had a history of synthetic fertilizer applications that would have received P application utilizing the UI method would not have received fertilizer P using the using the SHT recommendations, which may result in a loss of yield. The discrepancies in P fertilizer needs determined using the SHT are likely related to the decreased efficacy of the H3A extractant under soil conditions with higher pH and inorganic C contents (Dari, Rogers, Leytem, & Schroeder, 2019). In addition, regional recommendations account for the amount of calcium carbonate in the soils which will precipitate P making the P in fertilizer less plant available.

As with N, the SHT recommendations were adjusted to reflect a 30-cm sampling depth and include nine irrigation events. The adjusted P fertilizer recommendations decreased the overall P fertilizer recommended utilizing the SHT vs. the UI method (Figure 6). The average recommendation decreased from –4.7 to –10.8 kg ha^{-1} less P needed with the SHT, with recommendations ranging from 50 to 162 kg ha^{-1} less fertilizer P. However, as mentioned earlier, there is concern that the recommendations that are much less t han the standard regional recommendations may result in a loss of crop yield.

3.4 | Soil health score, yield, and crop quality

The SHT provides a SHS with the goal of enabling producers to track whether management practices are improving or decreasing soil health. The SHS was positively correlated to both soil organic matter ($r^2 = .36$) and soluble organic C ($r^2 = .44$; Figure 7). Research has shown that increasing the organic matter content of soils has many positive benefits including increased retention of water and nutrients, enhanced nutrient cycling, and improved soil structure which improves soil permeability, aeration, and drainage and reduces erosion, leading to improved water quality in groundwater and surface waters (Ontl & Schulte, 2012; Milne et al., 2015). In a study in t he inland Pacific Northwest, Morrow, Huggins, Carpenter-Boggs, and Reganold (2016)

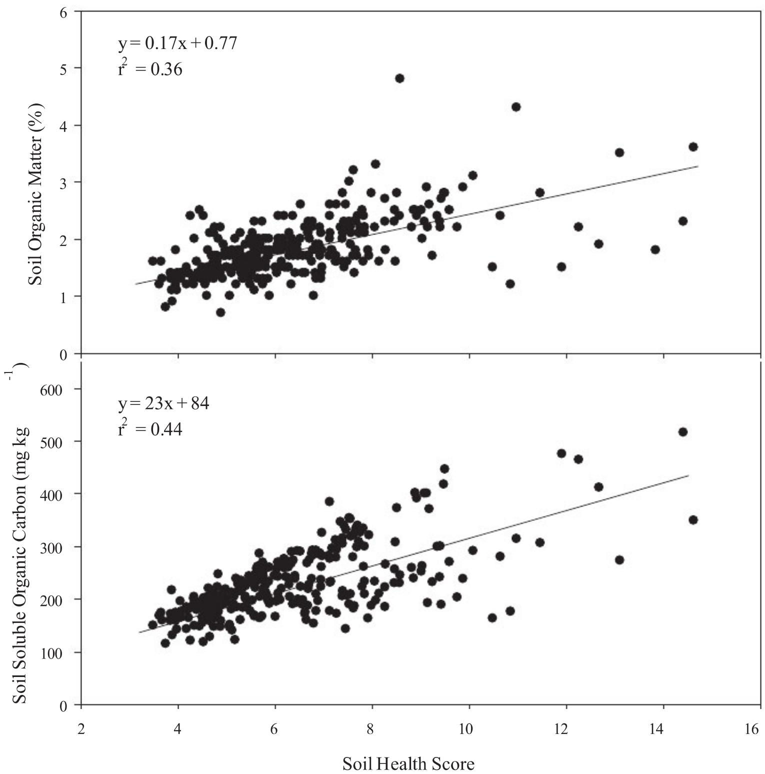

FIGURE 7 Relationship between soil health score and soil organic matter and soil soluble organic C (0- to 30-cm depth). Data from all studies included

also found that the SHS for a variety of soils was correlated with both soil organic C (r = .54) and soluble organic C (r = .46).

While the SHS was not designed to predict yield or crop quality, many producers have questioned whether an increase in SHS is related to these metrics. In the present study, there was not a positive relationship between the SHS and yield of wheat, potato, or barley in Study 1 (Figure 8). There was a positive relationship between sugar beet dry matter yield and the SHS (r^2 = .27), although the effect of SHS on yield appeared to diminish at a SHS > 5. As the SHS is a relative indication of the biological activity of the soil, it provides a baseline indicator of soil health. The addition of fertilizers and manure can compensate for poorer soil health and result in good yields even though overall quality of the soil may be poor which is why there may not necessarily be a positive relationship with yield.

An increasing SHS was associated with poorer crop quality in some instances (Figure 9). In barley, as the SHS increased, grain protein increased, due to increased PAN from organic sources (r^2 = .13). An increase in grain protein is a concern for growers producing malt barley as malt quality decreases at higher protein levels. In barley and wheat, increasing SHS was also associated with greater lodging which can negatively affect yields and quality (data not shown). In potato, as SHS increased, specific gravity decreased (r^2 = .55) possibly due to consequential increases in soluble salts from the manure applications. There is a high correlation between the specific gravity of the tuber and the starch content as well as the percentage of dry matter or total solids. These are important to the potato processor because they affect the quality and yield of the processed product. They also affect processing costs because the oil absorption rates during frying are related to dry matter levels. Higher specific gravity contributes to higher recovery rate and better quality of the processed product. In sugar beet, as SHS increased the percentage sucrose of the beets decreased (r^2 = .27) and impurities (measured as brei NO_3) increased (r^2 = .32), likely due to release of PAN later in the season combined with higher concentrations of various salt compounds from manure applications. This decrease in

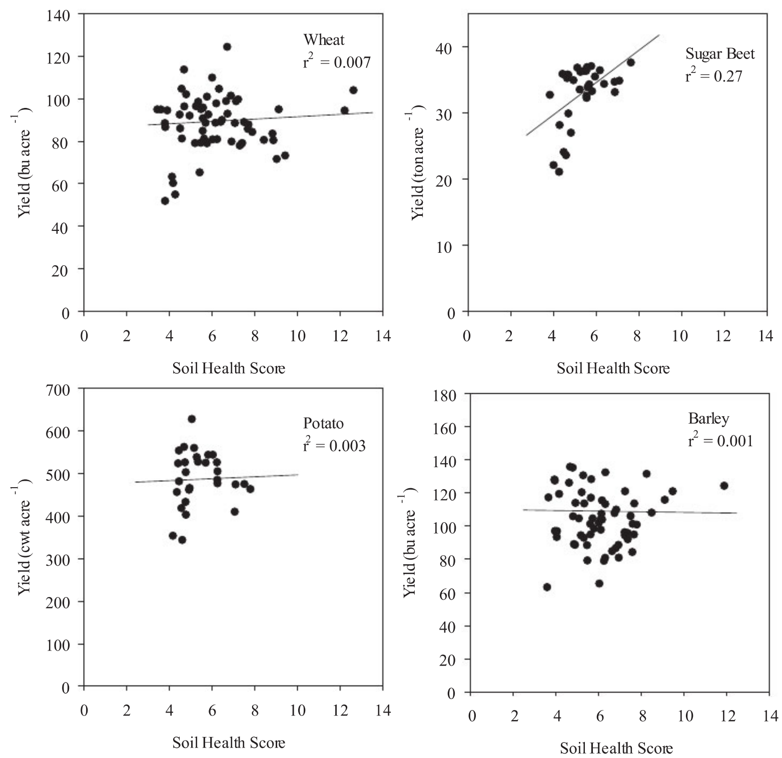

FIGURE 8 The Soil Health Tool soil health score and yield of wheat, sugar beet, potato, and barley. Data from Study 1

sucrose content along with an increase in impurities can lead to less recoverable sugar from the beets.

A lack of trend between SHS and yield as well as negative impacts on crop quality, in some cases, demonstrates that soil health indicators that are highly driven by changes in soil organic matter must be carefully evaluated with other factors. This is not an indication of faultiness of these types of tests. In this instance, as the increase in soil organic matter was driven by manure application, the greater the amount of manure applied the greater the SHS. However, there can be negative impacts on soil properties at higher manure application rates. As SHS increased, both the electrical conductivity and Na adsorption ratio in soils increased (Study 1, data not shown) which can affect overall yields in salt sensitive crops. From an environmental aspect, as SHS increased, Olsen P increased (data not shown) due to t he overapplication of P with heavy manure application rates. This buildup of soil test P is a potential risk for off-site P losses due to erosion and leaching with negative impacts on receiving water bodies. High application rates of manure may also overapply N which can lead to potentially negative environmental impacts as ammonia and nitrous oxide gas may be lost as well NO_3 leaching that can impact groundwater quality. In addition, the extra N in manure can negatively impact the quality of crops, such as sugar beet, by releasing N late in t he season and in this instance driving sugar content down. This demonstrates that when using soil health indicators that are linked to changes in soil organic matter, it is important to understand potential unintended consequences. If soil C is increasing due to high manure application rates, then these changes need to be interpreted cautiously as there may be potential negative aspects to these changes in soil C stores.

Development of advanced soil tests that can better predict the availability of nutrients over the growing season have the potential to decrease N and P applications which not only saves producers money but will reduce the environmental impact of agricultural production. The SHT could be part of a suite of tools for use in the semi-arid Pacific Northwest region with some modification. Because regional guidelines call for deeper soil sampling to determine N fertilizer applications, use of the tool in its present form would recommend greater N application (~138 kg ha^{-1}) than the current regional methodology. However, it does appear that making some adjustments to the calculations in the SHT can provide

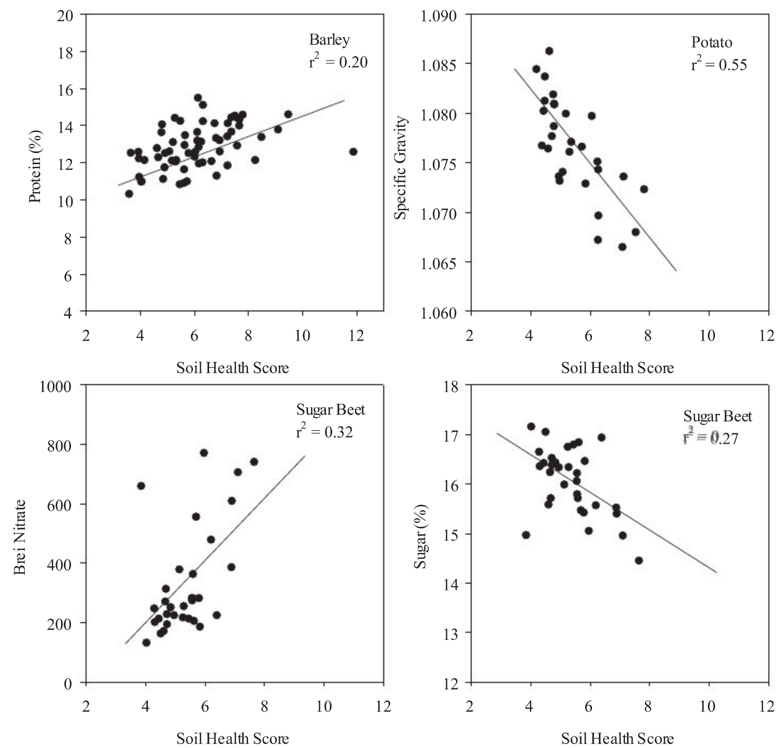

FIGURE 9 Soil Health Tool soil health score and barley protein, potato specific gravity, sugar beet sugar (%) and brei nitrate (mg kg $^{-1}$). Data from Study 1

similar available N estimates for the top 30 cm of soil. While N mineralization was not well predicted utilizing the method included in the SHT, the average estimated available N for these soils (47 kg ha^{-1}) was similar to the N mineralization value used in the current regional methodology (50 kg ha^{-1}). The P fertilizer recommendations were more similar between the two methodologies with the SHT recommending, on average 4.7 kg ha^{-1} less P than the regional method. This lower P recommendation is likely due to a lack of accounting for the effects of high calcium carbonate levels on the P availability from fertilizers in this region. Modification of the SHT to better account for irrigation practices and inclusion of soil testing to deeper depths would improve the ability of the test to assess the fertility status of these soils and improve fertilizer recommendations. The SHS provided by the test was not positively related to crop yield and was negatively related to crop quality for some crops. As the SHS is highly correlated to the amount of C in the soil, this is not surprising as manure additions will increase soil C but may have other negative impacts such as high P, increased late season available N, and higher salts. Therefore, care must be taken when interpreting the SHS (and other soil health indicators that are closely related to soil C) and evaluate it against other soil/plant parameters. As the SHT was designed solely for 0- to 15-cm depth samples, collecting soil samples to a depth of 30 or 60 cm and sending them to labs that utilize the SHT is not recommended as it will result in overestimating the amount of N and P fertilizer needed as well as greatly dilute the SHS. Producers wishing to use the SHT could collect samples from the 0- to15 and 15- to 30-cm depth and add the PAN and PAP from these depths together, which would be a better representation for sampling down to 30 cm.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

April B. Leytem https://orcid.org/0000-0001-5976-402X
Christopher W. Rogers https://orcid.org/0000-0002-1989-1582
Robert S. Dungan https://orcid.org/0000-0002-7560-5560

REFERENCES

Brown, B., Hart, J., Horneck, D., & Moore, A. (2010). Nutrient management for field corn silage and grain in the inland pacific northwest. PNW 615. Moscow, ID: Pacific Northwest Extension, University of Idaho.

Brown, B., Stark, J., & Westermann, D. T. (2001). Southern Idaho fertilizer guide: Irrigated spring wheat. CIS 828. Moscow, ID: University of Idaho.

Bushong, J. T., Roberts, T. L., Ross, W. J., Norman, R. J., Slaton, N. A., & Wilson, C. E., Jr. (2008). Evaluation of distillation and diffusion techniques for estimating hydrolysable amino sugar-nitrogen as a means of predicting nitrogen mineralization. Soil Science Society America Journal, 72, 992–999. https://doi.org/10.2136/sssaj2006.0401

Christensen, N. W., & Mellbye, M. E. (2006). Validation and recalibration of soil test for mineralizable nitrogen. Communications in Soil Science and Plant Analysis, 37, 2199–2211. https://doi.org/10.1080/00103620600817416

Dari, B., Rogers, C., Leytem, A., & Schroeder, K. (2019). Evaluation of soil test phosphorus extractants in Idaho soils. Soil Science Society America Journal, 83, 817–824. https://doi.org/10.2136/sssaj2018.08.0314

FAO. (2008). An international technical workshop. Investing in sustainable crop intensification. The case for improving soil health. Integrated Crop Management, 6, 69–114. Rome: FAO.

Franzluebbers, A. J. (2016). Should soil testing services measure soil biological activity? Agricultural & Environmental Letters, 1, article 150009. https://doi.org/10.2134/ael2015.11.0009

Franzluebbers, A. J., Haney, R. L., Honeycutt, C. W., Schomberg, H. H., & Hons, F. M. (2000). Flush of carbon dioxide following rewetting of dried soil related to active organic pools. Soil Science Society America Journal, 64, 613–623. https://doi.org/10.2136/sssaj2000.642613x

Gilmour, J. T., & Mouromoustakos, A. (2011). Nitrogen mineralization from soil organic matter: A sequential model. Soil Science Society America Journal, 75, 317–323. https://doi.org/10.2136/sssaj2010.0123

Haney, R. L., Brinton, W., & Evans, E. (2008). Soil CO2 respiration: Comparison of chemical titration, CO2 IRGA analysis and the Solvita gel system. Renewable Agriculture and Food Systems, 23, 171–176. https://doi.org/10.1017/S174217050800224X

Haney, R. L., Franzluebbers, A. J., Jin, V. L., J ohnson, M. V., Haney, E. B., White, M. J., & Harmel, R. D. (2012). Soil organic C:N vs. water-extractable organic C:N. Open Journal Soil Science, 2, 269–274. https://doi.org/10.4236/ojss.2012.2303210.4236/ojss.2012.23032

Haney, R. L., Haney, E. B., Hossner, L. R., & Arnold, J. G. (2010). Modifications to the new soil extractant H3A-1: A multi-nutr i ent extractant. Communication Soil Science Plant Analysis, 41(12), 1513–1523. https://doi.org/10.1080/00103624.2010.482173

Haney, R. L., Haney, E. B., Smith, D. R., Harmel, R. D., & White, M. J. (2018). The soil health tool–Theory and initial broad-scale application. Applied Soil Ecology, 125, 162–168. https://doi.org/10.1016/j.apsoil.2017.07.035

Haney, R. L., Haney, E. B., Smith, D. R., & White, M. J. (2017). Removal of lithium citrate from H3A for determination of plant available P. Open Journal Soil Science, 7, 301–304. https://doi.org/10.4236/ojss.2017.711022

Harmel, R. D., & Haney, R. L. (2013). Deter mining nitrogen fertilizer rates with a recently-developed soil test methodology. Open Journal Soil Science, 3, 91–99. https://doi.org/10.4236/ojss.2013.32010

Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (1999). Soil fertility and fertilizers: An introduction to nutrient management (6th ed.). Upper Saddle River, NJ: Prentice Hall.

Horneck, D. A., Hart, J. M., Flowers, M. D., Lutcher, L. K., Wysocki, D. J., Corp, M. K., & Bohle, M. (2010). Nutrient management guide: Irrigated soft white wheat. EM 9015-E. Corvallis, OR: Oregon State University Extension Service.

Idaho State Department of Agri culture. (2020). Idaho nutrient management handbook. Boise, ID: Idaho State Department of Agriculture. (In review.)

Khan, S. A., Mulvaney, R. L., & Hoeft, R. G. (2001). A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Science Society America Journal, 65, 1751–1760. https://doi.org/10.2136/sssaj2001.1751

Kleinkopf, G. E., Westermann, D. T., Wille, M. J., & Kleinschmidt, G. D. (1987). Specific gravity of Russet Burbank potatoes. American Potato Journal, 64, 581–587. https://doi.org/10.1007/BF02853760

Milne, E., Banwart, S. A., Noellemeyer, E., Abson, D. J., Ballabio, C., Bampa, F., … Zheng, J. (2015). Soil carbon, multiple benefits. Environmental Development, 13, 33–38. https://doi.org/10.1016/j.envdev.2014.11.005

Moore, A., Wysocki, D., Chastain, T., Wilson, T., & DuVal, A. (2019). Camelina nutrient management guide for the pacific northwest. PNW 718. Moscow, ID: Pacific Northwest Extension, University of Idaho.

Morrow, J. G., Huggins, D. R., Carpenter-Boggs, L. A., & Reganold, J. P. (2016). Evaluating measures to assess soil health in long-term agroecosystem trials. Soil Science Society America Journal, 80, 450–462. https://doi.org/10.2136/sssaj2015.08.0308

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular 939. Washington, DC: U.S. Department of Agriculture.

Ontl, T. A., & Schulte, L. A. (2012). Soil carbon storage. Nature Education Knowledge, 3, 35.

Robbins, C. W., Mackey, B. E., & Freeborn, L. L. (1997). Improving exposed subsoils and fertilizers and crop rotations. Soil Science Society America Jour nal, 61, 1221–1225. https://doi.org/10.2136/sssaj1997.03615995006100040030x

Roberts, T. L., Norman, R. J., Fulford, A. M., & Slaton, N. A. (2013). Field validation of N-STaR for rice produced on silt loam soils in Arkansas. Soil Science Society America Journal, 77, 539–545. https://doi.org/10.2136/sssaj2012.0252

Roberts, T. L., Norman, R. J., Slaton, N. A., & Wilson, C. E. Jr (2016). System and process for quantifying potentially mineralizable nitrogen for agricultural crop product. U.S. Patent 9354235 B2.t.

Robertson, L. D., & Stark, J. C. (2003). Idaho spring barley production guide. Bulletin 742. Moscow, ID: University of Idaho.

Rogers, C. W., Schroeder, K., Rashed, A., & Roberts, T. L. (2018). Evaluation of soil test for measuring potentially mineralizable soil N in southern Idaho Soils. Soil Science Society America Journal, 82, 1279–1289. https://doi.org/10.2136/sssaj2018.01.0054

Roper, W. R., Osmond, D. L., Heitman, J. L., Wagger, M. G., & Reberg-Horton, S. C. (2017). Soil health indicators do not differentiate among agronomic management systems in North Carolina soils. Soil Science Society America Journal, 81, 828–843. https://doi.org/10.2136/sssaj2016.12.0400

Schomberg, H. H., Wietholter, S., Griffin, T. S., Reeves, D. W., Cabrera, M. L., Fisher, D. S., … Tyler, D. D. (2009). Assessing indices for predicting potential nitrogen mineralization in soils under different management systems. Soil Science Society America Journal, 73, 1575–1586. https://doi.org/10.2136/sssaj2008.0303

Wade, J., Culman, S. W., Hurisso, T. T., Miller, R. O., Baker, L., & Horwath, W. R. (2018). Sources of variability that compromise mineralizable carbon as a soil health indicator. Soil Science Society America Journal, 82, 243–252. https://doi.org/10.2136/sssaj2017.03.0105

Wade, J., Horwath, W. R., & Burger, M. B. (2016). Integrating soil biological and chemical indices to predict net nitrogen mineralization across California agricultural systems. Soil Science Society of America Journal, 80, 1675–1687. https://doi.org/10.2136/sssaj2016.07.0228

Westermann, D. T., & Crothers, S. E. (1980). Measuring soil nitrogen mineralization under field conditions. Agronomy Journal, 72, 1009–1012. https://doi.org/10.2134/agronj1980.00021962007200060034x

How to cite this article: Leytem AB, Rogers CR, Tarkalson DT, Dungan RS, Haney RL, Moore AD. Comparison of nutrient management recommendations and soil health indicators in southern Idaho. Agrosyst Geosci Environ. 2020;3:e20033. https://doi.org/10.1002/agg2.20033