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Putting the soil health principles to the test in Iowa

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Abstract

One of the most popular soil conservation campaigns is based on the USDA Natural Resource Conservation Service's Soil Health Principles (NRCS-SHPs). The NRCS-SHP program identifies four principles—maximize presence of living roots, minimize disturbance, maximize soil cover, and maximize biodiversity—with the underlying assumption that the more principles one follows, the greater improvements in soil health. Despite the popularity of the NRCS-SHPs, this underlying assumption has not been rigorously tested. To do so, we used nine long-term experiments all located in central Iowa, but with varying degree of NRCS-SHP adoption, to determine if greater adoption increases three slow-changing (maximum water holding capacity, bulk density [BD], and soil organic carbon) and three dynamic (microbial biomass carbon [MBC], potentially mineralizable carbon [PMC], and permanganate oxidizable carbon [POXC]) soil health indicators. We regressed these indicators with a soil health principle score that can scale soil management based on adoption of the NRCS-SHPs. Of the slow-changing soil properties, increased adoption of NRCS-SHPs only decreased soil BD ($R^2 = 0.22$, $p = 0.024$). On the other hand, increased adoption of NRCS-SHPs strongly predicted increases in both MBC and PMC and across two sampling dates ($R^2 > 0.23$, $p < 0.015$); POXC, however, did not increase with greater adoption. The consistent increases in MBC and PMC with greater adoption of NRCS-SHPs supports their usefulness as sensitive indicators of positive soil health change. Our study provides scientific evidence to support the NRCS-SHPs concept, improving its usefulness as an extension campaign, and stands as a step toward evidence-based soil conservation.

1 | INTRODUCTION

Scientists and non-scientists alike are boldly exploring new frontiers of soil health. Soil health has emerged from previous concepts like "soil tilth" and "soil quality" that preceded it (Karlen et al., 2021). While soil health can be defined and measured in many ways, the current zeitgeist is centering around a definition of maximizing all soil ecosystem services (Adhikari & Hartemink, 2016), and not just provisioning food, fiber, and fuel (i.e., agriculture's *Prime Directive*). These lesser-known and undervalued soil ecosystem services include water storage and delivery, carbon storage, climate change mitigation, efficient nutrient cycling, water purification, and habitat for organisms. Carbon storage, in particular,

Abbreviations: BD, bulk density; MBC, microbial biomass carbon; NRCS-SHP, Natural Resource Conservation Service's Soil Health Principles; PMC, potentially mineralizable carbon; POXC, permanganate oxidizable carbon.

is garnering a lot of attention with the rapid growth of voluntary carbon market programs in agriculture (Keenor et al., 2021).

Evidence suggests that centuries of cultivation have led to many unintentional negative environmental consequences, including declines in soil health (Fenton et al., 2005; Kibblewhite et al., 2008; Montgomery, 2007). For instance, in the United States Midwest, current soils have much less soil organic matter (SOM) compared to pre-cultivated soils (Aref & Wander, 1997; De et al., 2020; Sanderman et al., 2017). This loss in SOM is concomitant with diminished healthy soil functioning (Hudson, 1994; King et al., 2020). Yet with fertilizer and other costly external inputs, we are still able to increase crop productivity and even efficiency (Cassman & Dobermann, 2022; Oldfield et al., 2019), that is, if environmental externalities are not included (Paudel & Crago, 2021; Tegtmeier & Duffy, 2004).

A significant body of research has documented the individual practices that can restore soil health. But despite the evidence and soil health campaigns, some of these practices have poor adoption rates in the US Midwest (e.g., cover crops; Arbuckle & Roesch-McNally, 2015; Zhou et al., 2022). However, there are early adopter farmers that adopt soil health restoration practices even before soil scientists can offer clear evidence, and their decisions are often based on local knowledge and anecdotal evidence (Gruver & Weil, 2007; O'Neill et al., 2021).

Perhaps one of the most widely known campaigns for increasing SOM and restoring soil health is the USDA Natural Resource Conservation Service's "Soil Health Principles" (Fuhrer, 2020; USDA-NRCS, n.d.; Figure 1), hereafter referred to as NRCS-SHPs. The NRCS-SHPs were derived from decades of prior research on individual practices and concepts converging in the 1990s as soil health concept was popularized (Doran et al., 1996; Karlen et al., 2021). The collective NRCS-SHPs first included five principles circa 2010 (Figure 1a; personal communications with NRCS employees, 2023; Zogbaum, n.d.): minimize disturbance, maximize soil cover, maximize living roots, maximize crop diversity, and integrating livestock. Later, the NRCS-SHPs were reduced to four principles (circa 2018), with the largest change being the crop (or plant) diversity and livestock integration were combined into the one principle of "maximizing diversity" (Figure 1b; USDA-NRCS, n.d.). More recently, non-governmental/non-profit organizations, universities, and industry have added a fifth (or sixth) principle of "context" (Figure 1c; The Nature Conservancy, 2024).

Adding context to the NRCS-SHPs is a key for two important reasons. First, context covers inherent soil properties that are well understood to govern overall ecosystem service capacity for a given soil. For example, a sandy soil is never going to have the same ability to store water as a silt loam, regardless of how many or how long a farmer has implemented practices covering the NRCS-SHPs. Second, individual farmers have different motivating factors and operate within different economic markets. They also have unique ancillary management practices and thus will have different pathway for adoption of NRCS-SHPs (Arbuckle & Roesch-McNally, 2015; Roesch-McNally et al., 2018). The NRCS-SHPs have moved beyond the confines of the conservation agency and are mentioned in the soil science literature (Guo, 2021; Stewart et al., 2018; Stott & Moebius-Clune, 2017) and used as part of university soil health extension recommendations (Moebius-Clune et al., 2016).

Despite the popularity of NRCS-SHP campaign and its adoption by other entities (Figure 1), the concept's underlying assumption has not been put to the test. Individually, each NRCS-SHP is supported by some rigorous research testing the ability of a particular principle to enhance a particular soil ecosystem service. For example, multiple meta-analyses, compiling over 100 studies each, show no-tillage tends to increase soil organic carbon (SOC) compared to conventional tillage over a typical experiment duration of 5–10 years (Nicoloso & Rice, 2021; West & Post, 2002). Likewise, a handful of meta-analyses demonstrate that most cropping systems that include a cover crop—a crop not harvested but used for erosion mitigation, reduce nutrient loss, or improve soil health—-also find a net increase in SOC (McClelland et al., 2021; Poeplau & Don, 2015). No-tillage, cover crops, and other practices like diversifying rotations or adding perennial crops like *Miscanthus* × *giganteus* have had stronger, more consistent positive effects on soil biota than disturbed, annual, and low-diversity agroecosystems (Kim et al., 2020; McDaniel et al., 2014; Tiemann & Stuart Grandy, 2014;

Core Ideas

- The NRCS Soil Health Principles (NRCS-SHPs) combined effects stand untested.
- We used a novel metric and six soil health indicators across nine long-term experiments in Iowa to test it.
- Soil organic carbon, permanganate oxidizable carbon, and water holding capacity did not relate to NRCS-SHPs.
- Bulk density decreased with greater adoption of NRCS-SHPs.
- Microbial biomass and potentially mineralizable carbon increased with NRCS-SHPs adoption.

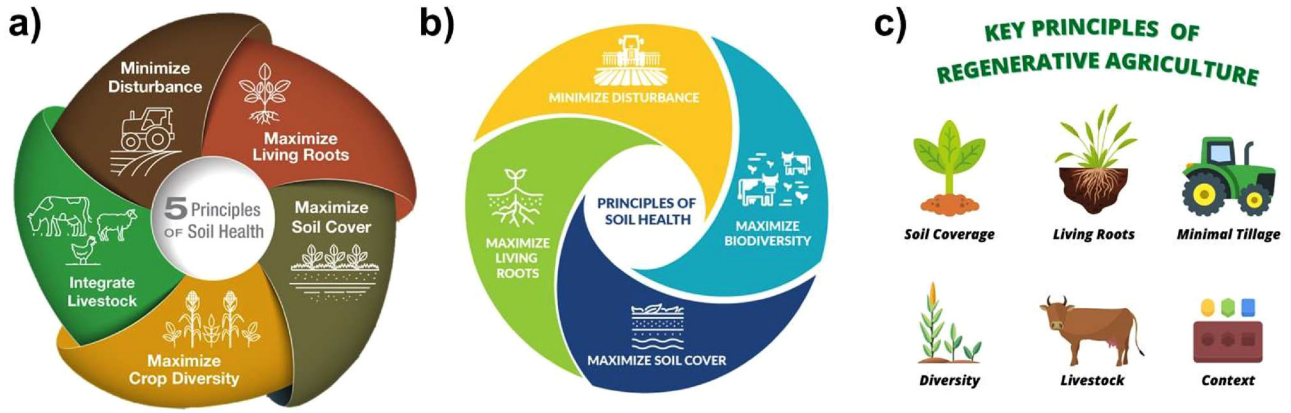

FIGURE 1 Infographics showing the five (a), four (b), or six (c) principles of soil health (sometimes also referred to as "Regenerative Agriculture"). (a) Five principles of soil health from State of Wisconsin Department of Agriculture (2023). (b) Four principles of soil health from United States Department of Agriculture Natural Resource Conservation Service (Fuhrer, 2020; USDA-NRCS, n.d.). (c) The Nature Conservancy's adoption of the soil health, or as they call it "Regenerative Agriculture," principles (The Nature Conservancy, 2024). The Nature Conservancy is a nongovernmental, non-profit that seeks to improve conservation worldwide. All accessed on June 10, 2022.

Zuber & Villamil, 2016). Specific practices like these are not mutually exclusive to one NRCS-SHP and can often apply to two or more NRCS-SHPs. For example, the practice of using cover crops can fulfill the soil cover, maximize living roots, and increase plant diversity.

A natural assumption, or hypothesis, emerging from the NRCS-SHPs is that *the more you follow, the greater your soil health*. Yet this hypothesis has not been rigorously evaluated. There is a paucity of knowledge exchange, or information feedback, between conservation organizations and research institutions that hinders evidence-based conservation (Briske et al., 2017; Ferraro & Pattanayak, 2006; Gibbons et al., 2011; Roux et al., 2006). The NRCS-SHPs are a good example of this, where these recommendations could be enhanced with more rigorous testing.

We sought to answer the question: Does soil health increase with greater adoption of practices that fulfill the NRCS-SHPs? In order to answer this question and quantitatively test the NRCS-SHPs, we created a novel index called the Soil Health Principle (SHP) score to regress with several well-known metrics of soil health: maximum water holding capacity (MWHC), bulk density (BD), SOC, microbial biomass carbon (MBC), potentially mineralizable carbon (PMC), and permanganate oxidizable carbon (POXC). We calculated the SHP score across 109 individual plots from nine long-term experiments ranging in many practices covering an adoption gradient of the NRCS-SHPs. Our overarching hypothesis is that adopting management practices that cover more of the NRCS-SHPs, whether via greater fulfillment of individual principles or adding additional principles (or both), will positively increase a soil health indicator (except BD, which should decrease).

2 | MATERIALS AND METHODS

2.1 | Site characteristics and experimental design

We collected soil samples in 2018 from nine long-term experiments in central Iowa (Figure 2; Table 1). Seven out of nine long-term experiments were located in the southwest corner of Boone County, IA (Figure 2).

All of the long-term experiments were either randomized complete block design or split-plot design experiments with a minimum of three to a maximum of six randomized, blocked replications (Table 1). At the time of soil sampling, the treatments across experiments had been in place for an average of 12 years. These long-term experiments were established as early as 1998 (e.g., OCNK; Delate et al., 2004) and as late as 2015 (e.g., LAMPS; Tejera et al., 2019), so ranging from 3 to 20 years of treatments being in place. Some of the plots were individually tile-drained in order to collect water leached from the plots (e.g., ADWQ-RDS and COBS). The planting/harvesting dates, fertilizer rates, fertilizer source, and other management factors varied and depended on the individual research questions.

The soils at eight of the nine sites were developed in Wisconsinan glacial till parent material. The climate is similar at all the sites, with narrow ranges of mean annual precipitation (876–974 mm) and mean annual temperature (8.6–9.7°C) (Iowa State University, 2020). Eight out of nine experiments had soils in the Clarion, Nicollet, Webster, and Canisteo soil series (Table S1; Soil Survey Staff, 2024). The ninth site near Greenfield, IA, was of the Macksburg silty clay loam and Nira silty clay loam soil series, which developed under older glacial

TABLE 1 Description of long-term agricultural experiments in Iowa (109 individual plots).

Long-term experiment name	Experimental design	Main treatments, plot numbers (*n*)	Other pertinent details	Reference(s) for more experimental information	Grand or total no. of plots (*N*)	Years since Est.
Residue removal	Randomized complete block	• Residue removal (0%), 8 • Residue (100%), 8	All plots are continuous maize and chisel plowed. Both residue treatments are included with and without biochar.	Rogovska et al. (2016)	16	11
Comparison of biofuel systems (COBS)	Randomized complete block	• Continuous maize, 4 • Continuous maize + cereal rye cover crop, 4 • Prairie, 4	All plots are no-till. Maize crops receive fertilizer. There are two treatments of prairie—with and without N fertilizer.	Jarchow et al. (2015)	12	17
Agricultural drainage water quality-research and demonstration site (ADWQ-RDS)	Stratified random block design (based on drainage)	• Tillage winter fallow, 4 • Tillage + cover crop, 4 • No-tillage winter fallow, 4 • No-tillage + cover crop, 4	All plots are maize-soybean rotation.	Qi et al. (2011)	16	8
Perennial ground cover	Randomized complete block	• Continuous maize, 3 • Continuous maize + kentucky bluegrass intercropped (living mulch), 3	All plots are strip-tilled.	Chen et al. (2022)	6	3
Long-term cover crop	Randomized complete block	• Continuous maize, 5 • Maize-soybean, 5 • Maize-soybean + cereal rye cover, 5	All plots are no-till.	Moore et al. (2014)	15	15
Long-term assessment of miscanthus productivity and sustainability (LAMPS)	Staggered start split-plot randomized complete block	• Continuous maize, 8 • *Miscanthus* × *giganteus*, 8	All plots are no-till. Both treatments include two N fertilizer rates (0 and 224 kg N ha^{-1}).	Tejera et al. (2019)	16	3
Marsden agricultural diversification experiment (MADE)	Randomized complete block	• Maize-soybean (synthetic fertilizer), 4 • Maize-soy-oat/alfalfa-alfalfa + manure fertilizer, 4	Synthetic N added as UAN (or 32%). Animal manure was added as composted cattle manure.	Liebman et al. (2008)	8	16
Organic conventional neely-kinyon	Randomized complete block	• Maize-soybean (synthetic fertilizer), 4 • Maize-soy-oat/alfalfa-alfalfa + manure fertilizer, 4	Synthetic N added as UAN (or 32%). Animal manure chicken manure.	Delate and Cambardella (2004)	8	20
Long-term tillage trials	Randomized complete block	• Moldboard plow, 4 • Chisel plow, 4 • No-tillage, 4	Maize-soy and maize-maize-soy rotations. One site with and without rye cover crop. Two sites: One near Boone, IA and one near Gilmore City, IA.	Al-Kaisi and Archontoulis (2015)	12	16

FIGURE 2 Maps showing the location of nine long-term experiments where this study was conducted. Seven of nine experiments were located in southeast corner of Boone County, Iowa.

till with a cap of loess (Table S1). The soil clay content ranged from 17% to 36%, and soil pH ranged from 4.7 to 8.3 (w/w in 0.01 M $CaCl_2$) at 0- to 15-cm depth. Higher soil pH values are due to calcareous soils in the Des Moines Lobe region (Khan & Fenton, 1994; Prior, 1991). More detailed information on the soils can be found in Tables S1 and S2 (Middleton et al., 2021).

2.2 | Soil sampling

A total of 109 composite soil samples were collected once for slow-to-change soil health indicators (autumn), and at two time points (late-spring/early-summer and autumn) for dynamic indicators. Soil samples for late-spring/early-summer were collected between June 12 and July 2, 2018 and autumn between October 18 and November 20, 2018. For this study, we examined both slower-to-change and more dynamic soil health indicators at two time periods. The three slower-to-change soil health indicators were measured during autumn sampling: MWHC, BD, and total SOC (Table 2). The three more dynamic soil health indicators are biochemical in nature and are often reported to be "early indicators" of management impacts in individual agroecosystem experiments (Bagnall et al., 2023; Culman et al., 2012; McDaniel & Grandy, 2016). These soil properties are defined as dynamic because they may also vary within the growing season (Culman et al., 2012; McDaniel & Grandy, 2016), so we sampled and analyzed soils in both spring and autumn. Dynamic soil health indicators included MBC, PMC measured in a 14-day incubation, and POXC. All soil health indicators except BD (see details below) were measured on a composite sample of 10 soil cores (2.86-cm diameter, 0- to 15-cm depth). These composite samples were fresh-sieved to <2 mm and subsampled for gravimetric water content and microbial biomass (details below); the remainder was air-dried at room temperature until reaching a stable mass (~1 month).

TABLE 2 Soil health indicators measured in this study.

Slow-to-change or dynamic soil health indicator	Soil health indicator (abbreviation)	Units	Method	Measure of soil ecosystem services
Slow-to-change	Maximum water holding capacity (MWHC)	%	Filter paper and drainage method (Nelson et al., 2023)	• Water storage • Habitat • Soil carbon sequestration
	Bulk density (BD)	g cm^{-3}	Core method (Grossman & Reinsch, 2002)	• Provisioning food/fiber/fuel • Habitat • Water storage
	Total soil organic carbon (SOC)	%	Elemental analyzer (Nelson & Sommers, 1996)	• Soil carbon sequestration • Habitat
Dynamic	Microbial biomass carbon (MBC)	mg C kg^{-1}	Chloroform fumigation-extraction (or CFE, Vance et al., 1987)	• Carbon/nutrient cycling • Habitat • Soil carbon sequestration
	Potentially mineralizable carbon (PMC)	mg C kg^{-1}	14-day, aerobic incubation (McDaniel & Grandy, 2016)	• Carbon/nutrient cycling • Habitat
	Permanganate oxidizable carbon (POXC)	mg C kg^{-1}	Weil et al. (2003) method	• Carbon/nutrient cycling • Habitat

2.3 | Slow-to-change soil health indicator analyses

MWHC was measured using the funnel, filter paper, and drainage method outlined in Nelson et al. (2023), and it is the gravimetric water held by soil at a water potential near −2.45 kPa. Briefly, this method uses 10 g of soil dried for 24 h at 105°C, then placed in a funnel with a folded Whatman #1 filter paper. The soil and filter paper are wetted and weighed 6 h after excess water is drained. By subtracting moisture lost from evaporative loss using a saturated control filter paper with no soil, the mass of water retained in the soil plus filter paper is calculated as g H_2O kg^{-1} dry soil.

BD samples were collected by using 10-cm diameter × 7.5 cm deep stainless-steel rings. Samples were collected from 0- to 7.5-cm and 7.5- to 15-cm depths, separately, by hammering in the steel rings at three locations per plot (Grossman & Reinsch, 2002). These sub-plot replicates were spaced equidistant from each other and from edges of the plot. Rings containing samples were excavated, sieved for coarse fragments, and oven dried at 105°C for 24 h. BD (g cm^{-3}) was calculated by dividing the oven-dried mass (without coarse fragments) by the sample volume for each depth, and then averaging both depths.

SOC was measured using dry combustion with an elemental analyzer (Nelson & Sommers, 1996). Air-dried, <2 mm soil samples were oven-dried at 105°C and then pulverized with an 8000 M Mixer/Mill ball mill grinder (SPEX SamplePrep). Samples were acid fumigated with 12 M HCl if pH > 7 to remove inorganic carbon (Harris et al., 2001). All samples were rolled in tin and analyzed on a Vario Max elemental analyzer (Elementar Americas Inc.).

2.4 | Dynamic soil health indicator analyses

Microbial biomass C was measured using a chloroform fumigation-extraction (CFE) method (Vance et al., 1987). Two fresh 5 g sub-samples of each soil sample were split into a plastic 50-mL conical test tube (non-fumigated) and 50-mL glass beakers meant for 24 h chloroform fumigation in a desiccator jar (fumigated). After 24 h, both non-fumigated and fumigated soils were extracted with 25 mL of 0.5 M K_2SO_4 solution. Samples were shaken for 1 h at 200 rpm, centrifuged at 72 *g* for 3 min, filtered through Whatman #1, and extracts were stored frozen at −20°C until analysis. Extracts were analyzed for non-purgeable organic C via combustion on a Shimadzu TOC-L analyzer (Shimadzu Corp). MBC was calculated as the difference between fumigated and non-fumigated samples and adjusted by using a common extraction efficiency factor of 0.45 (Joergensen, 1996).

PMC was measured using 14-day aerobic incubation (modified from McDaniel & Grandy, 2016). Briefly, 5 g of air-dried soil sample was brought to 50% MWHC in 50-mL conical centrifuge test tubes. During the incubation, CO_2 concentration was measured in the tube headspace by using a LI-830 CO_2 gas analyzer (LI-COR). CO_2 production was calculated as the difference between a T_0 measurement, immediately after flushing with ambient air, and a T_1 measurement after closed incubation. Soil CO_2 production was measured on 1, 3, 5, 7, 10, and 14 days after initial wetting to more accurately capture initial pulse of CO_2.

POXC was measured using the Weil et al. (2003) method. Briefly, POXC was measured using 2.5 g air-dried soil that was shaken with 18 mL of distilled and deionized water and 2 mL 0.2 M $KMnO_4$ for 2 min on a reciprocal shaker at 120 rpm. After allowing particles to settle for 10 min,

5 mL of supernatant were diluted with 49.5 mL of deionized water before placing 200 µL in a well of a clear microplate, which was analyzed on a Biotek Synergy HTX multi-mode microplate reader (BioTek Instruments) to determine absorbance at 550 nm. POXC was then calculated by relating absorbance to the amount of reagent remaining in liquid phase.

2.5 | Calculating SHP score and statistical analyses

In this study, we developed a novel index that quantitatively ranks incorporation of the five NRCS-SHPs across the 109 plots in what we call a (SHP score, Table 3). Each NRCS-SHPs is unweighted. It is possible that each NRCS-SHP may have different leverage on improving soil health. In fact, that is most likely the case. However, currently there is insufficient information for weighting the NRCS-SHPs, so an unweighted metric is most appropriate. Furthermore, this is a first attempt at a score like this, and it is better to provide a proof-of-concept rather than a weighted approach. In the future, further research may refine a score like this to provide weights to NRCS-SHPs that may be more important for improving soil health.

Our overall SHP score calculated from five separate functions, each with a unique equation based upon fulfillment of a particular NRCS-SHP (Table 3). The SHP score equation is as follows:

$$\text{SHP score} = = \sum_{n=1}^{109} f\,(a) + f\,(b) + f\,(c) + f\,(d) + f\,(e) \quad (1)$$

where each individual NRCS-SHP has a unique function $f(n)$ with scoring methods that are outlined in Table 3. Here, $f\,(a)$ is the soil armor, $f\,(b)$ is the minimize disturbance, $f\,(c)$ is the maximize plant diversity, $f\,(d)$ is the maximize living roots, and $f\,(e)$ is the animal integration. Each function has a value that ranges from 0 to 1 on ranked on how each practice from Table 1 fulfills an NRCS-SHP (Figure 1). With 0 being unfulfilled and 1 being fully fulfilled. Some of the functions' scoring methods are categorical [e.g., $f(a)$, $f(b)$, and $f(e)$], whereas others are continuous and based on cropping-system-specific metrics and equations meant to differentiate that particular NRCS-SHP on a gradient [e.g., $f(c)$ and $f(d)$]. So, with each function having a maximum value of 1 (Table 3), then the maximum overall SHP score is 5. We did not have any management practices fully fulfilled all five NRCS-SHPs. The lowest overall SHP score is 0.16 for disc-tilled, continuous corn, and our highest SHP score was 4 for a perennial, prairie biomass cropping system.

Data were first checked for normality and heterogeneity of variances with histograms and normal *Q–Q* plots with *resid* and *qqnorm* packages in R v4.3.1 (R Core Team, 2023). All data were deemed acceptable, and no transformations were needed, but two outliers were removed from SOC dataset. For all regression analyses and visualization, we used SigmaPlot v15 (Inpixon). We used standard linear regressions ($y = mx + b$) between the SHP score as the independent variable on the x-axis (Range: 0.16–4) and the soil health indicator as the dependent variable on the y-axis (Table 1). The equation, adjusted R^2, and p-value are reported for all linear regressions as goodness-of-fit or strength of correlation metrics. When the linear regression model was significant, $\alpha < 0.05$, the linear regression model and 95% confidence bands were plotted. Because the experiments are so close, and many occur in the same fields (two or three in some instances), not to mention the soil series are all similar (Tables S1 and S2), it is debatable whether there is a "site effect" that needs to be accounted for. However, to check for co-dependence of the experiment, we also ran linear mixed models with the experiment as the random variable using *lmerTest* package in R v4.3.1 (R Core Team, 2023).

3 | RESULTS AND DISCUSSION

3.1 | Slow-to-change variables in response to the NRCS's soil health principles

Of the three slower-changing variables we chose to evaluate, only BD varied with the SHP score ($R^2 = 0.22$, $p = 0.024$; Table S3). BD decreased with greater adoption of the NRCS-SHP, partially confirming our overarching hypothesis. Even though only one of the long-term experiments had only been in place for 3 years (Table 2), when soil BD was regressed with the SHP score it showed a moderate decrease from ~1.3 to 1.2 g cm^{-3} (Figure 3). BD could arguably have been considered a dynamic soil property, and our analysis supports this.

Decreasing soil BD by following more NRCS-SHPs aligns with other studies that show a rapid decrease in BD with management change (Baldwin-Kordick et al., 2022; Blanco-Canqui et al., 2006; Celik et al., 2010; Daly et al., 2023; Ibrahim et al., 2018; Shawver et al., 2021). However, other studies that have tested practices falling under one or more NRCS-SHPs show no effect of tillage on soil BD, even after many years (Blanco-Canqui & Ruis, 2020; De et al., 2020; Poffenbarger et al., 2020). No-tillage can actually increase BD by 3.7% compared to conventional tillage, on average, but that effect lessens through time according to a global meta-analysis (Li et al., 2020).

TABLE 3 Soil health principles and scoring methods.

Soil health principle	Description	Scoring method	Maximum and minimum possible points (with examples)
Maximize cover (i.e., soil armor)	The amount of residue or plant biomass coverage.	Residue removed = 0 Moldboard plow = 0 Chisel plow = 0.25 No-tillage = 0.5 Perennial crop/plant = 1	0—Continuous maize residue removal 1—Biomass crop *Miscanthus* × *giganteus*
Minimize disturbance	The frequency and intensity of tillage.	Moldboard plow = $1-\frac{1 \times \text{No. of plants tillage events}}{4\ \text{years}^a}$ Chisel plow = $1-\frac{0.5 \times \text{No. of plants tillage events}}{4\ \text{years}^a}$ Strip till = $1-\frac{0.25 \times \text{No. of plants tillage events}}{4\ \text{years}^a}$ No-tillage = 1	0—Yearly moldboard plow 1—No-tilled maize-soybean rotation
Maximize plant diversity	Plant (or crop) diversity based on diversity in time (rotated in a year)[a] and space (mixed species for a given year)[b].	Total plant diversity score = Time + space, with… Time = $0.5 \times \frac{\text{No. of plants crops in 4 years}}{4\ \text{(maximum rotation length)}^a}$ Space = $0.5 \times \frac{\text{No. of plants per hectare}}{12}$ [1 for monoculture, 12 is maximum[b]]	0.16—Continuous corn 1—Restored native, prairie
Maximize living roots (i.e., perenniality)	The duration, or proportion of year, that there is living plant on the soil.	Annual crops = 0 Cover crops = 0.5 Perennial crop/plant = 1	0—Annual crops (maize or soybean) 1—Restored native, prairie
Animal integration	*Indirect* animal integration by addition of animal manure. There were no direct, integrated livestock studies in this experiment.	Synthetic fertilizer = 0 animal manure = 1	0—Synthetic fertilizer for maize-soy 1—Composted cattle manure added in 4-year rotation (maize-soy-oat/alfalfa-alfalfa)

[a]Four years is the maximum length of a crop rotation (e.g., maize-soybean-oat/alfalfa-alfalfa from Marsden agricultural diversification experiment [MADE], Table 1).

[b]The maximize plant diversity (MPD) score is based on the addition of diversity in time and space. Jarchow and Liebman (2013) measured prairie plant species from 2009 to 2011. The number of 12 species was the minimum counted in 1 year and used as the maximum here.

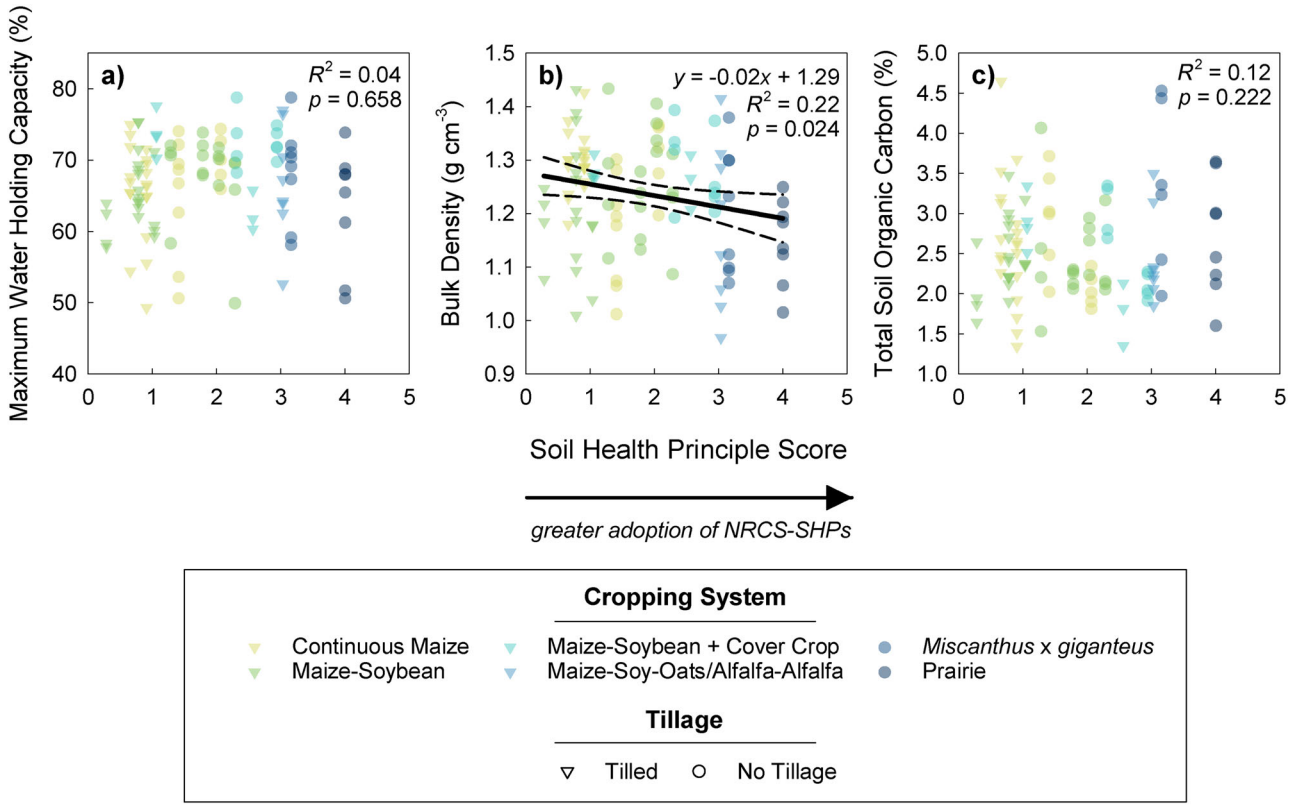

FIGURE 3 Slower-to-change soil properties in relation to the Soil Health Principle score (see Equation 1, Table 3). Slow-to-change soil properties include (a) maximum water holding capacity, (b) bulk density, and (c) soil organic carbon. NRCS-SHPs, Natural Resources Conservation Service's Soil Health Principles. Plot-level soil health indicator values, $n = 109$, from nine long-term experiments (Table 1). Linear regression and 95% confidence bands are shown if the F-test comparison is statistically significant ($p < 0.05$).

A few local experiments in Iowa have also shown mixed effects of conservation management on soil BD and time-since implementation appears important. One study showed no effect of no-tillage on soil BD at 0–15 or 15–30 cm compared to chisel plowing after 3–7 years of implementation (Al-Kaisi et al., 2005), but a 31-year study showed that no-tillage decreased BD by ~10% compared to chisel plowing (Karlen et al., 2013). Even a management practice like perennial grassland restoration after annual row cropping, which covers multiple NCRS-SHPs, can take decades before a lower soil BD was observed (De et al., 2020). Comparing soil BD under no-tillage and other tillage practices can be tricky for many reasons, including (but not limited to): timing of soil sampling after the last tillage event, inherent differences in soil texture, and management legacy.

MWHC is regulated by soil texture, structure, and organic matter (Nelson et al., 2023). While it does not reflect macrostructural differences among conservation practices because of sieving, there are instances where management alters <2 mm soil structural properties (Malobane et al., 2021; Schlüter et al., 2018). For example, some evidence showed that at least one of the experimental treatments in our nine studies, a perennial biomass crop *Miscanthus* × *giganteus*, significantly increased MWHC by 15% compared to monocropped maize for stover removal (Studt, 2019; Studt et al., 2021). Furthermore, by using a nearby chronosequence experiment in northern Iowa and southern Minnesota, researchers found that soil MWHC under native grasslands was ~20% greater than under maize-soybean cropping (De et al., 2020). However, despite these selected studies, when we applied the SHP score to soil MWHC, we found no significant relationship (Figure 3).

Bagnall et al. (2022) recommend using intact cores to best measure soil water holding capacity and that this method best discriminates among agricultural conservation practices like decreased tillage, organic fertilizer application, and residue retention within a large survey of long-term experiments in North America (Norris et al., 2020). However, the intact core method is not scalable to most on-farm situations because of labor and costs. This highlights the challenge in tradeoffs between more scientifically rigorous or acceptable methods with more inexpensive and accessible methods for soil hydraulic properties (Govindasamy et al., 2023; Nelson et al., 2023).

It is no surprise, again given the short duration of some of the long-term experiments (Table 2), that SOC did not

correlate with SHP score. SOC is slow to change even after 20 years in some relevant studies in the US Midwest (De et al., 2020; Poffenbarger et al., 2020; Rui et al., 2022). Other, independent researchers have also documented no treatment effect on SOC in the very same experiments that we sampled here but with soils that were sampled deeper. For example, Poffenbarger sampled the Marsden Agricultural Diversification Experiment 13 years after establishment to 90 cm and found no effects of diversified cropping on SOC concentrations or stocks (Table 1; Poffenbarger et al., 2020). Other researchers have found more significant effects of tillage on SOC stocks over a 12-year timeline sampling soils to 60-cm depths (Al-Kaisi & Kwaw-Mensah, 2020). If we were to sample all these plots again in 20–25 years, we may find a better linear relationship between SHP score and SOC. While the interest in soil C markets is driving demand to monitor SOC changes (Smith et al., 2020), our study, in addition to these other studies showing lack of rapid change in SOC, highlights the need to look at other more quick-to-change soil properties.

3.2 | Dynamic, or fast-changing, variables in response to the NRCS's soil health principles

We showed that soil MBC was the variable most strongly related to the SHP score regardless of the sampling time ($R^2 > 0.41$, $p < 0.001$; Figure 3; Table S3). For each NRCS-SHP adopted, there was an increase in soil MBC of 35.7 and 47.8 mg C kg^{-1} for spring and autumn, respectively. A plethora of studies have shown microbial biomass to be very responsive to management practices, and they almost universally show that microbial biomass increases with practices that fall under the NRCS-SHPs (Kallenbach & Grandy, 2011; Li et al., 2018; Lori et al., 2017; McDaniel et al., 2014; Muhammad et al., 2021; Zuber & Villamil, 2016). According to the slopes of our linear regressions and reasonable assumptions (Table S4), you could expect a microbial biomass increase in the range of 1300 to 7380 kg ha^{-1} for adoption of each NRCS-SHP (in the top 0–15 cm of soil). Another way to frame it is, you could expect an equivalent biomass increase of one large American bison (*Bison bison*) up to one moderately sized African bush elephant (*Loxodonta africana*) per hectare for the adoption of each NRCS-SHP!

Microbial biomass is the "eye of the needle" that all plant and animal residues pass through before becoming persistent SOC and plant-available nutrients (Tate, 2017). Indeed, Geyer et al. (2020) showed that initial microbial biomass was one of the best predictors of stabilization of labile C in laboratory incubations. Based on the mounting evidence, including this study (Figure 4), we advocate for the use of microbial biomass to monitor change in soil health because of its sensitivity to conservation management, ability to act as an early indicator of positive change (Powlson et al., 1987), and critical role in long-term, persistent C stabilization and nutrient cycling (Geyer et al., 2020; Horwath, 2017; Li et al., 2019; Paul & Voroney, 1980; Tate, 2017). While few commercial laboratories will run the CFE method, some will provide an index of microbial biomass from phospholipid fatty acid extracts. However, the cost remains prohibitive to most farmers and agronomists (Bagnall et al., 2023; Stewart et al., 2018).

Similar to the MBC findings, PMC was also related with the SHP score across both sampling times ($R^2 > 0.23$, $p < 0.015$; Figure 3; Table S3). For adoption of each NRCS-SHP, PMC increased by 5.9 and 7.6 mg C kg^{-1} soil for spring and autumn sampling. PMC, like MWHC, is a composite measure that incorporates soil properties like microbial-available C, microbial biomass, and N-supplying power of a soil (Franzluebbers et al., 2018; Hurisso et al., 2016; McDaniel et al., 2020; Paul et al., 1999). In addition to being a sensitive soil health indicator, this measurement shows some promise as a predictor of maize nitrogen needs (Bean et al., 2020; Franzluebbers, 2018; Yost et al., 2018), and thus may one day be used to inform fertilizer recommendations. However, the lack of a standardized protocol for PMC is a source of variability and likely hindering progress on this goal (Laffely et al., 2020; Leeford et al., 2023; Wade et al., 2018).

Unlike MBC and PMC, POXC did not correlate with the SHP score (Figure 3; Table S3), although POXC has been shown to be sensitive to management practices in the United States (Culman et al., 2012, 2013; Hurisso et al., 2016; Wade et al., 2020). Here, however, we did not observe a consistent trend with greater implementation of the NRCS-SHPs. It is unclear what POXC is actually measuring, whether it is labile or more processed SOM (Culman et al., 2012; Tirol-Padre & Ladha, 2004), but it is an easy and relatively inexpensive soil measurement and does in some cases measure change in soil health. According to our evidence here and elsewhere, we agree with the recent Soil Health Institute assessment that it is not a priority measurement for monitoring changes in soil health (Bagnall et al., 2023).

3.3 | Implications for evidence-based conservation

The USDA-NRCS mission is to provide technical and financial assistance to producers interested in adopting conservation practices (USDA-NRCS, n.d.). While efforts have undoubtedly increased soil conservation practices, especially in the last decade, farmer adoption of the practices that fall under NRCS-SHPs remain low. For example, only 5%–10% of farmers in the US Midwest have adopted winter cover crops (Zhou et al., 2022). While there are many reasons for this low adoption of winter cover crops, among other practices that fulfill one or more of the NRCS-SHPs, part of the resistance is likely due to lack of confidence in the beneficial outcomes.

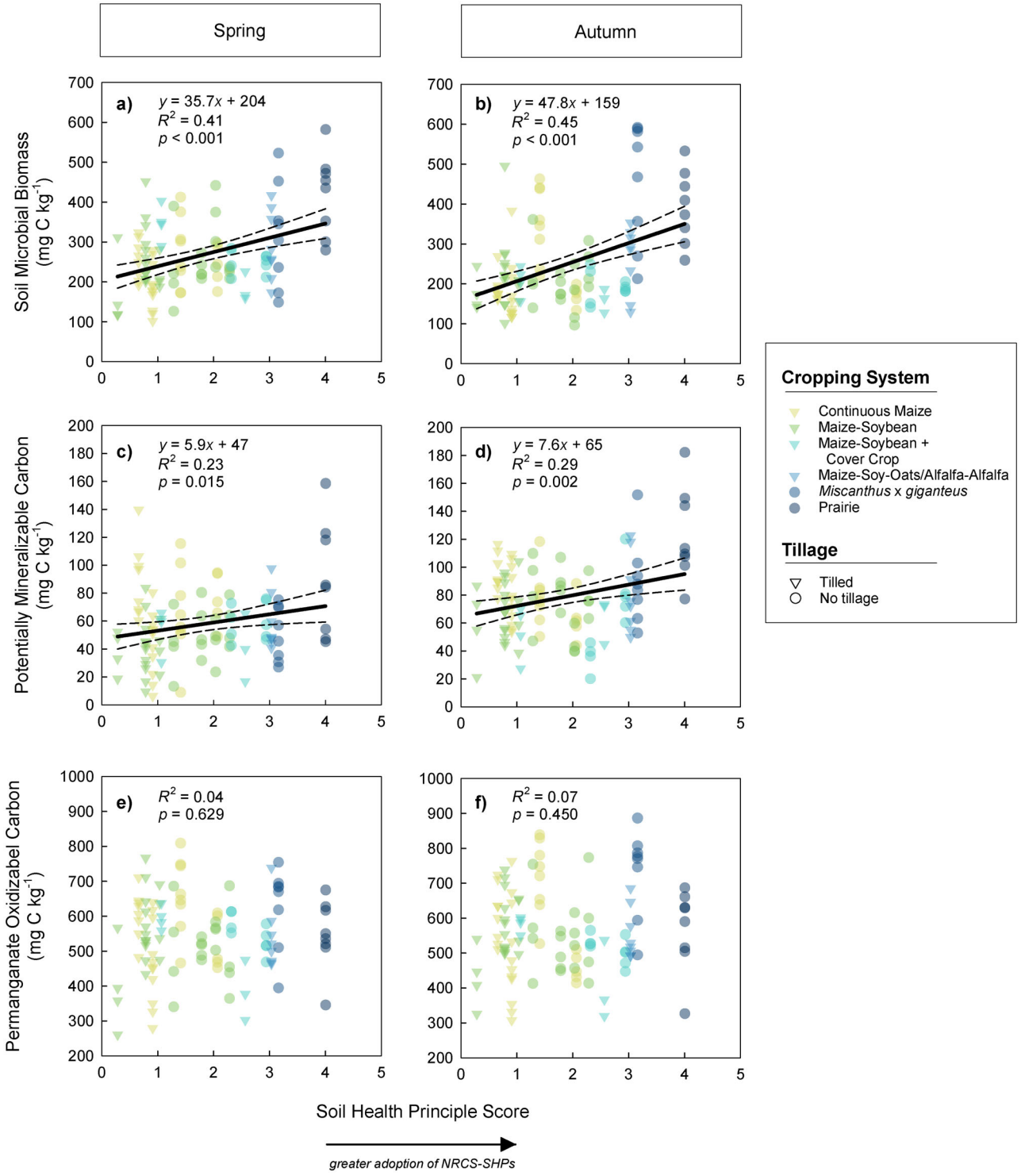

FIGURE 4 Dynamic soil properties in relation to the Soil Health Principle score measured in spring (*left panels*) and autumn (*right panels*) (see Equation 1, Table 3). Dynamic soil properties include (a), (b) microbial biomass carbon, (c), (d) potentially mineralizable carbon in 14-day incubation, (e), and (f) permanganate oxidizable carbon. NRCS-SHPs, Natural Resources Conservation Service's Soil Health Principles. Plot-level soil health indicator values, $n = 109$, from nine long-term experiments (Table 1). Linear regression and 95% confidence bands are shown if the F-test comparison is statistically significant ($p < 0.05$).

Ideally, better collaboration and communication, including incorporation of evidence-based conservation, could bolster this lack of farmer confidence in current recommendations. However, due to barriers in knowledge exchange between management agencies like USDA-NRCS and research institutions, farmers lack a pathway to evidence-based conservation (Briske et al., 2017; Ferraro & Pattanayak, 2006). There are many cultural and economic reasons underlying this barrier in knowledge exchange. For example, lack of funding can limit the extent of cross-institution collaboration and hinder evidence-based knowledge exchange on soil conservation practices. However, better funding and cross-institution communication are not panaceas. Some farmers remain skeptical of research evidence because the findings may not align with the evidence they have observed from their experience (NRCS employee personal communication, 2023). There may be good reasons for this discrepancy, including but not limited to: the small scale of plot-based research that most research institutions use, differences in goals/priorities, lack of standardized soil health measurement protocols, and farming equipment differences between research and commercial farms.

One way to break down this barrier to knowledge exchange and provide an "information feedback loop" is to form collaborative efforts between management agencies and research institutions (Roux et al., 2006). Our study provides one example of this type of collaboration. We have taken a concept derived from the USDA-NRCS and applied an evidence-based framework to test the hypothesis: *greater adoption of NRCS-SHPs results in healthier soil*. Improving knowledge exchange between "experts" and "users" (Roux et al., 2006), thereby enhancing this information feedback loop, can better serve farmers deciding whether to implement soil conservation practices. And in turn, have potential benefits to the rest of society based on positive environmental outcomes.

4 | CONCLUSION

Our study tested the USDA-NRCS concept of soil health principles (Figure 1)—maximize soil cover, minimize disturbance, maximize plant diversity, maximize living roots, and integrate animals—and our guiding hypothesis was that greater adoption of practices fulfilling the NRCS-SHPs would increase soil health. We tested this by using a novel, quantitative index and nine long-term experiments in Iowa to show that greater adoption of NRCS-SHP does result in healthier soils based on a three out of six soil health indicators (e.g., soil BD, microbial biomass, and PMC). We hope that future studies can test this hypothesis in other regions of the world to expand upon our findings.

This study is one example of a collaboration between a management agency and research institution meant to increase evidence-based conservation. These collaborations form an information feedback loop benefiting both parties by grounding conservation in science and guiding research in applied, conservation problem-solving (rather than reductionist research not relevant to producers). More studies like this are needed to ultimately benefit producers with scientifically rigorous conservation assistance.

AUTHOR CONTRIBUTIONS

M. D. McDaniel: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; visualization; writing—original draft; writing—review and editing. **T. A. Middleton**: Conceptualization; data curation; formal analysis; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be made available at the Iowa State University Digital Repository (https://www.lib.iastate.edu/collections/digital-repository-iowa-state-university) and upon email request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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