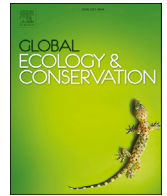




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## Short Communication

## Soil Health Gap: A concept to establish a benchmark for soil health management

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## ABSTRACT

Growing calls and the need for sustainable agriculture have brought deserved attention to soil and to efforts towards improving or maintaining soil health. Numerous research and field experiments report soil health in terms of physicochemical and biological indicators, and identify different management practices that can improve it. However, the question remains how much of cultivated land has degraded since the dawn of agriculture? What is the maximum or realistically attainable soil health goal? Determination of a benchmark that defines the true magnitude of degradation and simultaneously sets potential soil health goals will optimize efforts in improving soil health using different practices. In this paper, we discuss a new term “Soil Health Gap” that is defined as the difference between soil health in an undisturbed native soil and current soil health in a cropland in a given agroecosystem. Soil Health Gap can be determined based on a general or specific soil property such as soil carbon. Soil organic carbon were measured at native grassland, no-till, conventionally tilled, and subsoil exposed farmlands. Soil Health Gap based on soil organic carbon was in order of no-till < conventional till < subsoil exposed farmland and subsequently, maximum attainable soil health goal with introduction of conservation practices would vary by an existing management practice or condition. Soil Health Gap establishes a benchmark for soil health management decisions and goals and can be scaled up from site-specific to regional to global scale.

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## 1. Introduction

The core concepts of “soil health” date back over 100 years and have evolved ever since (Brevik, 2018). Doran et al. (1996) defined soil health as “the capacity of soil to function as a vital living system, within an ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health”. In brief, soil health, sometimes referred to as soil quality, is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (NRCS, 2017).

Soil is a finite, dynamic, and fragile living resource with differential physical, chemical, and biological properties in time and space (Lal, 2009). Soil degradation, together with climate change and population growth pose a grave risk to global food security and environmental quality (Allen et al., 2011; Oliver and Gregory, 2015). Soil degradation is generally attributed to

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poor soil and nutrient management, overgrazing, excessive crop residue removal, and large-scale non-agricultural activities (Karlen and Rice, 2015). Fundamental to the soil health concept is the idea that soil is a living ecosystem, and well-being of soil is essential for achieving ecosystem services, including high quality air and water, promoting a diverse biotic and microbial community structure, supporting a high level of crop productivity, and promoting human health.

In recent years, soil health has garnered increasing attention; however, the effort to quantify it has been challenging and evolving. In general, a healthy soil has sufficient mineral nutrients, adequate rooting depth, growth-promoting microorganisms, lower pest and weed pressure, and resistance and resilience to land degradation (Magdoff, 2001). Consequently, healthy soil suppresses pests and diseases, increases yield, and improves crop quality (Van Bruggen and Semenov, 2000). Climate change and population expansion add to the global urgency to optimize soil resource management and restore degraded land to maintain or enhance soil health and ecosystem services, and to ensure food security for a growing population expected to reach 9.2 billion people by 2050.

Lack of relevant site-specific and/or property-specific soil health benchmarks has limited research efforts to measuring effects of different management practices on certain or several soil health indicators (Silveira and Kohmann, 2019). A benchmark can be a reference soil health in uncultivated/undisturbed native soil in an agroecosystem and that will allow determination of a gap in soil health in a managed cropland. In most cases, native soils will have higher scores for soil health indicators than cultivated cropland in a given agroecosystem. Such score- or soil property-based benchmark will be a location specific because of the climate and its effects on soils. At places where it is difficult to find native virgin land, soil from nearby farmstead or close to farm fences that are not cultivated or minimally disturbed can be used to determine the soil health benchmark. However, a farm fence would be a poor reference area in the Great Plains, since the fence-line soil has probably been disturbed in the past and has received dust from repeated wind erosion events that result in a poor representation of native soil.

Once a benchmark for an area is identified, soil health can be determined based on a general or specific soil property such as soil carbon (C) or soil aggregation. Soil C is a foundation for many soil health initiatives as it corresponds to soil ecosystem services. Soil C losses due to cultivation and land use have increased soil erosion and reduced nutrient provision for soil across the globe. Determining a soil health benchmark based on a general or specific soil property in undisturbed soil will give a measure of soil degradation, and simultaneously set potential soil health goals. Such understanding of a gap in soil health in a cropland will inform soil health management decisions and thereby, optimize efforts in improving soil health.

The objective of this paper is to define the “Soil Health Gap” and use a specific example to illustrate the concept. The example compares a currently managed farm field and similar soil that has native perennial vegetation and has not been disturbed. Once defined, the Soil Health Gap (SHG) concept can be scaled up from site-specific cases to a regional and then to a global scale. The specific and quantified SHG is expected to vary by location, management, and agroecosystem and consequently, the appropriate soil health management tool will vary. Understanding of SHG in local, regional, and global level can help identify and prioritize potential areas for improving soil health.

## 2. Definition of Soil Health Gap

Soil Health Gap is defined as the “*difference between soil health in an undisturbed native virgin soil and current soil health in a cropland in a given agroecosystem*” (Fig. 1).

$$SHG_x = (SH)_n - (SH)_m \quad (1)$$

Where,  $SHG_x$  = Soil Health Gap with the subscript indicating a general or specific property,  $(SH)_n$  and  $(SH)_m$  refer to soil health in n; native soil and m; managed cropland soil.

Soil properties such as infiltration, macropores, aggregate size and stability, soil organic matter (SOM), aeration, surface and groundwater quality along with soil biotic communities such as microorganisms, invertebrates would collectively define the soil health (Doran and Parkin, 1994; Parr et al., 1992). There are several efforts to identify and establish critical limiting indicators characterizing soil health in different agricultural systems (Sánchez-Navarro et al., 2015). For a system as complex as soil, the soil health index will be a function of several indicators and may have to be developed for a given soil or agroecosystem.

There are several benchmarks that would be important to inform soil health management. Soil health threshold values will suggest the limit beyond which management practices will affect soil health. Soil health critical values will determine the limit at which soil health will deteriorate if soil health management practices are not introduced. These limits are dynamic and change with climate and soil properties (Arshad and Martin, 2002). The SHG would be based on the soil health benchmark property from the native undisturbed soil, represent the extent of soil degradation, and set a maximum potential soil health goal.

A native undisturbed soil offers a baseline reference to what soil would be has it been left uncultivated and undisturbed all along. Losses of topsoil and C primarily due to cultivation and land use have deteriorated soil and soil ecosystem services across the globe. Soil health of a native virgin soil based on a specific or general property might be a benchmark that suggests the highest target for soil health management. As management practices are identified to address a general or specific issue in farmland, such quantitative benchmark will provide a maximum goal to attempt for and attain for a long-term sustainability.

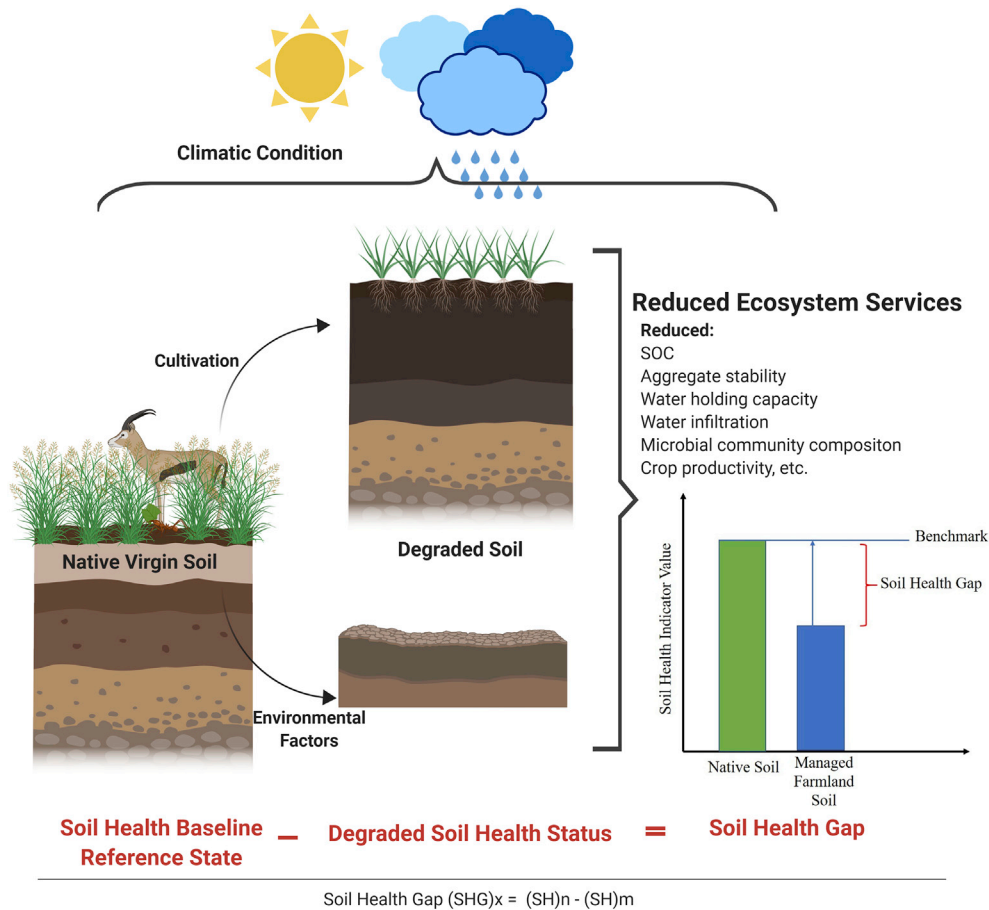


Fig. 1. Graphical abstract of **Soil Health Gap** concept.

A site-specific benchmark should be established from maximum possible number of sampling at different timestamps throughout a year to avoid confounding effects of sampling error and seasonal effects. Soil Health Gap will help in identifying soil health issues with realistically maximum attainable goal for a long-term sustainability and beyond qualitative improvement of soil health. Correlation of SHG with crop production, and ecosystem services including nutrient leaching in soil profile, greenhouse gas emissions, diversity in biotic community over time and space will provide better understanding of different soil health indicators and their quantitative effects on soil health. This gap concept allows to address a specific indicator of soil health as necessary and relevant to objectives considering farmer, environmentalist, engineers, or economist's perspectives. As efforts for developing soil health index are underway, we will elaborate the concept of SHG with respect to a specific soil health indicator. Here, soil organic C is chosen to determine SHG and the choice of soil health indicator(s) will depend on knowledge and experiences with soil health measurements in a region and on the availability of supporting data.

### 2.1. Soil Health Gap from soil carbon perspective

Soil C is an important soil health indicator and will be a crucial factor in developing any soil health index as it affects both the physicochemical and biological properties of soil (Lal, 2016). The soil C pool contains both organic C (SOC) and inorganic C forms. Soil organic C (SOC) pool is dynamic and affects water infiltration, nutrient retention, aggregate stability, and provides resilience against climate extremes. It also helps in maintaining diverse and dynamic soil biotic communities and controls the biogeochemistry of nutrient cycling. Management influences soil C storage at different levels. Concepts of "potential," "attainable," and "actual" C levels in soil as affected by various factors and agronomic practices were well presented in Ingram and Fernandes (2001). They concluded that improving crop and soil management on soils worldwide would result in increased soil C and subsequent improvements to overall soil health. Determining the benchmark for soil C levels will result in setting realistic goals.

In the context of soil C, SHG will be “the difference or depletion of soil C from native land to managed cropland in a given agroecosystem”.

$$SHG_C = (\text{Soil C})_n - (\text{Soil C})_m \quad (\text{II})$$

Where,  $SHG_C$  = Soil Health Gap with respect to soil C,  $(\text{Soil C})_n$  and  $(\text{Soil C})_m$  refer to soil C in n; native soil and m; managed cropland soil.

Davidson and Ackerman (1993) showed how cultivation of previously undisturbed soil contributes towards 20% SOC loss within initial 5 years and an additional 5% SOC within next 15 years. Wei et al. (2014) showed greater loss ( $43.1 \pm 1.1\%$ ) of SOC stocks during long-term cultivation. The earth has lost 133 Pg C (=8% of total global soil C) from the top 2 m of soils since the dawn of agriculture (Sanderman et al., 2017). The “4 per mille initiative” launched at 2015 United Nations Climate Change Conference COP 21 has fueled the demand to increase global soil C stocks by 0.4% every year to curb unprecedented increase in anthropogenic greenhouse gases, improve soil health, and increase climatic change adaptability (Minasny et al., 2017).

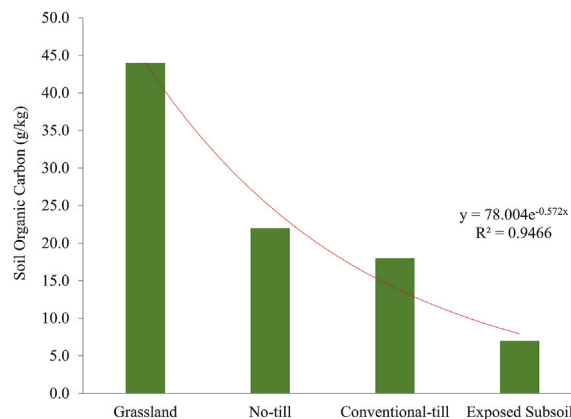
Reduced tillage, particularly no-till systems, adding diversity to crop rotations, adding cover crops into or following crops, and the addition of organic amendments are a few of the measures which can improve SOC. Spatio-temporal estimates of C distribution and technical potentials for soil C sequestration is highly uncertain and will vary with measurement and modeling techniques, soil-climate variables, and agronomic practices among others (Bai et al., 2019). Understanding and estimating SHG with respect to soil C might provide a measure of present soil degradation to help guide future soil health management decisions and provide a maximum value as an attainable goal.

## 2.2. Soil Health Gap: an example

The objective of this preliminary study was to determine SHG with respect to SOC in managed croplands in semi-arid U.S. High Plains. The hypothesis was that different systems of tillage would create different degree of SHG. Several 0–20 cm soil samples were collected and composited from undisturbed native prairie, no-till and conventionally tilled farmlands, and a farmland with exposed subsoil in Scottsbluff County in western Nebraska in the spring of 2020. The sites were characterized as Tripp very fine sandy loam (Coarse-silty, mixed, superactive, mesic Aridic Haplustolls). The native prairie land has been undisturbed and has no record of any management. The no-till farm has been under no-till since 2005. The cropping system initially included winter wheat (*Triticum aestivum*), maize (*Zea mays*), and dry beans (*Phaseolus vulgaris*). In 2006, spring canola (*Brassica napus*) was added following wheat. This provided a cropping system with two grass crops and two broadleaf crops. The conventionally tilled farm has been under maize-sugar beet (*Beta vulgaris*)-maize- dry bean rotation and received moldboard plowing at 30-cm depth every spring. A farm with exposed subsoil had a rolling hill levelled off for ease of management in 2003. That field is under strip tillage and planted to maize-sugar beet-dry bean rotation. Loss on ignition method was used to measure SOC in soil samples collected from all these sites (Hoogsteen et al., 2015).

### 2.2.1. Results and discussion

The SOC measured between farms with different tillage histories had an exponential decline from grassland (4.4%) to no-till (2.2%) to conventionally managed (1.8%) farmland to subsoil exposed field (0.7%) (Fig. 2). The differences in SOC among these farms illustrate the increasing SHG between these farms. There are many confounding factors such as crop removal, depth of topsoil, soil loss, crop rotation, irrigation, and other management practices that could affect SOC. Irrespective of



**Fig. 2.** Soil organic C under native grassland, no-tilled and conventionally tilled farmlands on Tripp very fine sandy loams in Scottsbluffs, Nebraska. Red line with regression equation depicts regression fit of SOC across four locations.

factors responsible for the current soil health status, SHG presents a measure of extent of soil degradation compared to native undisturbed soil and presents maximum attainable soil health goal with introduction of conservation practices.

From equation (II),  $SHG_C = 44 - 22 = 22 \text{ g C kg}^{-1}$  for no-till

$SHG_C = 44 - 18 = 26 \text{ g C kg}^{-1}$  for conventionally tilled farmland

$SHG_C = 44 - 7 = 37 \text{ g C kg}^{-1}$  for subsoil exposed farmland

As management practices are introduced to enhance SOC in these fields, SHG provides a maximum attainable goal. In absence of SHG measurement, one may under- or over-estimate the soil health goals due to a lack of a measure of the possible highest target. Measured SHG in terms of SOC would suggest maximum attainable goal in terms of soil health improvement in a given agroecosystem. Greater the SHG, greater is an opportunity for soil health enhancement.

For a given set of climatic condition, SOC level has a steady state which will be higher in native undisturbed land than in farmland (Wortmann et al., 2017). Increasing SOC is agronomically and environmentally desirable but not always feasible for given climate, soil, and management conditions, as SOC moves towards a steady-state level unless there is a significant shift in practices. The best opportunity for improving soil health in cropland is when SOC is below that of undisturbed land. Conversion of croplands to grassland, crop residue management and no-till cropping have shown to increase C (Minasny et al., 2017). In a meta-analysis, Poeplau and Don (2015) estimated that cover crops could increase SOC by  $0.32 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  in the top 22 cm of agricultural soils. Biochar amendment, cover cropping, and conservation tillage could potentially increase C sequestration in croplands by 39%, 6% and 5%, respectively (Bai et al., 2019). As benefits of different management practices are documented, understanding SHG in terms of SOC would provide a benchmark for maximum potential goals and thereby, inform soil health management decisions and goals.

### 3. Soil Health Gap: challenges and opportunities

Scientific advancement in identifying primary soil health indicators and developing soil health index based on them is key to a reliable and quantitative measure of soil health. Current research efforts are directed towards determining the effects of different management practices on specific or several soil health indicators. Soil Health Gap will provide a much-needed universal system of determining benchmark for soil health management, irrespective of the fact if soil health is measured as a function of several indicators or based on a specific soil health indicator.

Analysis of SHG will provide the foundation for identifying significant soil health indicators which are limiting for current farm productivity and will help in devising agronomic practice plans to close the gap. It will help in prioritizing site-specific or farmland specific research, development, and intervention for a specific soil health indicator.

Soil Health Gap map can be developed as is done with Yield Gap using a bottom-up approach, scaling site-specific data to regional and global levels to assess soil health management potentials on regional, national, and global scales (Ittersum et al., 2013). Such information on SHG, on a local or broader scale, can help identify areas with the greatest potential to enhance soil health, prioritize efforts, and invest resources effectively. We therefore strongly emphasize on developing publicly available website with SHG assessment following a global protocol and making all the resources available to users. This will increase reproducibility and efficiency of different management practices to improve soil health. Availability of SHG from different agroecosystem around the globe will reduce the uncertainties in soil health improvement results as seen in cases of different amendments and agronomic practices considering the lack of true quantitative goal. A geospatial assessment of exploitable SHG will present opportunities to improve soil health and subsequently optimize agronomic production worldwide and better predict the future food security with changing land use pattern.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gecco.2020.e01116>.

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