Article

Soil Health as a Dynamic, Plant-Specific Attribute: Redefining Its Role Beyond Traditional Soil Quality Indicators

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ABSTRACT

Soil health is vital to both food security and ecological stability and represents a key research frontier in soil science. However, the implications of soil health remain unclear and are often conflated with soil quality. In this study, plant growth performance was used as an indicator of soil health, assuming that better plant growth reflects healthier soil. We compared the growth rates of *Dodonaea viscosa* (L.) Jacq. in two different soil types—yellow-brown soil (Luvisols) with good soil quality (higher fertility), and dry red soil (Lixisols) with lower soil quality (lower fertility). Plants were grown in both untreated and treated soils, with treatments including nitrogen (N), phosphorus (P), combined nitrogen-phosphorus (NP) addition, and arbuscular mycorrhizal fungi (AMF) inoculation in pot experiments. Soil quality was evaluated using the soil quality index. Our results show that the addition of limiting nutrients (N or P) and AMF significantly enhanced plant growth in both soils. However, *D. viscosa* consistently showed poorer growth in the yellow-brown soil than in the dry-red soil. This suggests that the yellow-brown soil, despite its higher soil quality, had a lower overall health. These findings highlight the distinction between soil health and quality and indicate that higher fertility does not necessarily equate to better soil health. Moreover, soil health appears to be plant species-specific, because different plant species respond differently to various soil conditions. Thus, advancing soil health initiatives should prioritise the identification of plant species that are most compatible with the specific attributes of the soil.

KEYWORDS: soil health; soil health assessment; soil quality; soil fertility; soil microorganism

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INTRODUCTION

Healthy soil is vital for sustainable food production, biodiversity, and ecological security. However, reports indicate that at least 33% of the world's arable soil is degraded, and soil health is increasingly threatened [1]. It is projected that 90% of the world's soil will be degraded by 2050 [2]. Thus, conserving soil health is crucial for achieving Sustainable Development Goals (SDGs), and has become a research hotspot in soil science [3–5].

Soil health was put forward by British ecologist Balfour in his 1947 book "Soil for Life"; different scholars defined different connotations of soil health—The prevailing view among researchers is that soil health represents the soil's sustained capacity to support biological productivity, enhance air and water quality, and contribute to the health of plants, animals, and humans [6]. Researchers have varying perspectives on soil health. According to Mocek [7], "It refers to the soil's ability to function as a dynamic living system within the limits of its ecosystem and land use, supporting the productivity of plants and animals, preserving or improving the quality of water and air, and fostering the overall health of both plant and animal". Furthermore, the NRCS, USA (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/. Accessed on 21 Apr 2025) defines soil health—also known as soil quality (SQ)—as the ongoing ability of soil to operate as a vital, living ecosystem that supports the growth and sustainability of plants, animals, and humans. Most researchers believe that "soil quality" is synonymous with "soil health" [8].

When we assess SH, we refer to agricultural soil health, as it is associated with several ecosystem services, such as water and nutrient regulation, carbon cycling, and food production [9]. Soil health is typically assessed by formulating a holistic soil health index (SHI) composed of key soil attributes. SHI systems typically include physical, chemical, and biological performance indicators [10–13]. However, some scholars have suggested that soil health evaluation indicators should not only be limited to soil physical and chemical health indicators but that soil biological, environmental, ecosystem and human health indicators should also be considered [14]. However, researchers have used significantly different evaluation indicators [15]. Several scholars [16,17] believe that soil pollutants, including heavy metals and emerging contaminants, should be considered as indicators of soil health. Furthermore, Rinot [6] proposed an evaluation of soil health based on soil functional indicators, such as regulation, support, and supply. Hughes [18] argued that soil health evaluation, which is essential for soil health management, must account for the high spatial variability of soils. Thus, the threshold values for assessment indicators should be region-specific. Recent studies [4,14,19,20] have considered soil microorganisms as core soil health indicators.

Several studies have shown that different types and doses of fertilisation would lead to different health states in farmland soils. For example, organic, organic-inorganic, and microbial fertilisers generally improve soil health [15,21–24], and balanced fertilisation significantly improves soil health. However, the application of biological carbon alone does not appear to improve soil health [25]. Although significant progress has been achieved in soil health research, several challenges remain unresolved. For instance, soil scientists, agronomists, and ecologists have not reached an agreement on the concept of soil health. Consequently, different researchers have different definitions and emphases on soil health in different periods and fields. Although "soil health" and "soil quality" are often used interchangeably, differences between the two are not always well understood. We have often found that different plants grow differently in the same soil, suggesting that soil health varies from plant to plant.

Therefore, the hypotheses of this study were as follows: (1) soil health and quality are distinct, (2) soil health varies across plant species, and (3) nutrient addition and microbial inoculation are unlikely to alter the difference of soil health degree between various soils for a specific plant.

To test these hypotheses, we used plant growth (biomass and other indicators) to evaluate soil health [18,26], and our previous study's related results [27].

MATERIALS AND METHODS

Study Site

The study was carried out at the Yuanmou Research Station administered by the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu. This field site is geographically positioned in Yuanmou County (101°35'–102°05'E, 25°25'–26°07'N), situated within the southwestern territory of China. The region represents a characteristic dry-hot valley in the lower Jinsha River basin, marked by elevated temperatures (mean annual temperature: 20 °C) and low humidity (mean annual precipitation: 650 mm).

The soil types were Lixisols and Luvisols, based on the Food and Agriculture Organization of the United Nations (FAO) soil taxonomy, and dry red soil and yellow-brown soil, respectively, according to the Chinese soil taxonomy. The tested plant is *D. viscosa* that grow primarily in Lixisols, but not in Luvisols. The detailed information were described in our previous study [27].

Experimental Design

Test was carried out by pots. All pots (dimensions: upper diameter 26 cm × lower diameter 16 cm × height 24 cm) were randomly arranged within the greenhouse facility. Following an initial saturation irrigation protocol (administered until drainage occurred from the base), each container received 15–20 *Dodonaea viscosa* seeds that had undergone physical scarification to overcome dormancy prior to sowing. *D. viscosa* is one kind of typical species in dry-hot valleys in southwest China, characterized by high capacity of drought and barren tolerance, and widely used for vegetation restoration in this area. The detailed information were described in our previous study [27].

Nutrient Addition Test

After two seedlings were growing well in each pot, we started adding different nutrients (nitrogen/N and phosphorus/P). There were four types of nutrient treatments: (1) Control (CK, no nutrients added); (2) Only nitrogen (N) added; (3) Only phosphorus (P) added; (4) Both nitrogen and phosphorus (NP) added together.

Incubation AMF Test

The experimental design comprised two distinct soil types—high-altitude yellow brown soil and low-altitude dry red soil—combined with three AMF inoculation treatments. Each treatment combination (soil × AMF) was replicated six times to ensure statistical robustness. The three AMF treatments were: no inoculation of AMF (control), inoculation of Non-native AMF (purchased strains), and inoculation of native AMF (Collected from the rhizosphere soil of *D. viscosa*).

The detailed information above were described in our previous study [27].

Measurements

Plant height was determined using a standardized measuring tape, while stem diameter was recorded with a vernier caliper. Following plant maturation, twelve mature leaves of uniform size were randomly selected per container and subjected to digital scanning. Leaf area quantification was performed using ImageJ software. At harvest, plant tissues were manually separated into roots, stems, and leaves. All samples were subsequently oven-dried at 80 °C until achieving constant mass, with dry biomass recorded.

Statistical Analysis

The data collected in this study were statistically analyzed using SPSS software (version 19.0), IBM Corporation, Armonk, New York, USA. A three-way analysis of variance (ANOVA) was employed to assess the main effects and interactions of soil type, nutrient treatment, and AMF inoculation on plant growth characteristics, biomass distribution, and leaf nutrient concentrations. Prior to conducting the ANOVA, the Shapiro–Wilk test was performed to confirm the normality of the data. Additionally, the least significant difference (LSD) test was applied to compare variations between soil types and among the four nutrient treatments within each soil type.

RESULTS

Effects of Nutrient Addition on the Growth of *D. viscosa* on Two Soil Types

Results showed that except for plant height, the soil type had a significant effect on the growth and physiological characteristics of *D. viscosa* (Table 1) [27]. Plant height, leaf area, root and leaf biomasses were significantly higher ($p < 0.05$) in dry red soil than in yellow-brown soil, indicating that health of red soil is better than that of yellow-brown soil.

Table 1. Statistical results of the two-way ANOVA presented as F values and level of significance (*p*) on *D. viscosa* growth.

Indicators	Soil Type		Nutrient Treatment		Soil × Nutrient	
	F	*p*	F	*p*	F	*p*
Height	1.28	0.287	0.97	0.415	2.51	0.034
Leaf area	5.86	0.005	2.25	0.094	3.84	0.003
Root biomass	61.42	<0.001	2.89	0.045	2.32	0.048
Leaf biomass	75.08	<0.001	9.00	<0.001	4.45	0.001

Effects of AMF Inoculation on the Growth of *D. viscosa* in Two Soils

Results showed that soil type, AMF treatment, and the interaction between soil and AMF significantly affected the growth, and biomass accumulation of *D. viscosa* (Table 2) [27]. At the end of the experiment, the plant height, leaf area and biomasses of *D. viscosa* in dry red soil was significantly ($p < 0.05$) higher than that in yellow-brown soil, indicating that microbial inoculation do not alter status of soil health.

Table 2. F-value and *p*-value of two-factor ANOVA for the effects of AMF and soil type on *D. viscosa* growth.

Indicators	Soil Type		AMF		Soil Type × AMF	
	F	*p*	F	*p*	F	*p*
Height	34.53	<0.001	2.10	0.141	7.77	0.002
Leaf area	3.48	0.072	6.47	0.005	3.80	0.034
Above biomass	136.84	<0.001	122.71	<0.001	49.62	<0.001
Root biomass	23.34	<0.001	19.41	<0.001	13.47	<0.001

DISCUSSION

Soil Health Is not Equal to Soil Quality, and It Is Different for Different Plant

Currently, most researchers believe that soil health is synonymous with soil quality [8]. As observed in the present study, the growth rate of *D. viscosa* was lower in yellow-brown soil (higher quality) than in dry red soil (lower quality), suggesting that higher soil quality does not necessarily equate to healthier soil for a specific plant species. This discrepancy emphasises that soil health is not determined solely by physical and chemical properties, such as fertility; it is a dynamic, plant-dependent characteristic. Therefore, soil health must be understood in terms of the specific plants it supports, as different plant species exhibit distinct responses to varying soil conditions. These findings are also supported by Lal [28], who stated that the terms soil quality and soil health, while similar, should not be used interchangeably. Furthermore, it also aligns with the idea that soil health is not an absolute measure, but one that depends on biological interactions between soil and plant species [29].

Recent studies have confirmed this distinction. For instance, Molefe [30] highlighted that soil health is shaped by interactions between plant roots, microbial communities, and organic matter, which vary significantly across plant species. Similarly, Niu [31] suggested that different plant species with varying root architectures and metabolic activities can either promote or hinder soil health, further illustrating that soil health is highly context-specific and plant-dependent [32].

Therefore, we define soil health as: it refers to the ability of a soil to continuously provide the necessary physical, chemical and biological properties for the healthy life process of a certain type of plant on it. In this way, soil health involves specific plants and is an attribute indicator within the soil-plant system, it doesn't matter about soil health without concerning a plant. On the other hand, soil quality refers to the integrated performance of the physical, chemical and biological properties of the soil, and does not involve plants. The difference between them can be illustrated by the following conceptual model (Figure 1).

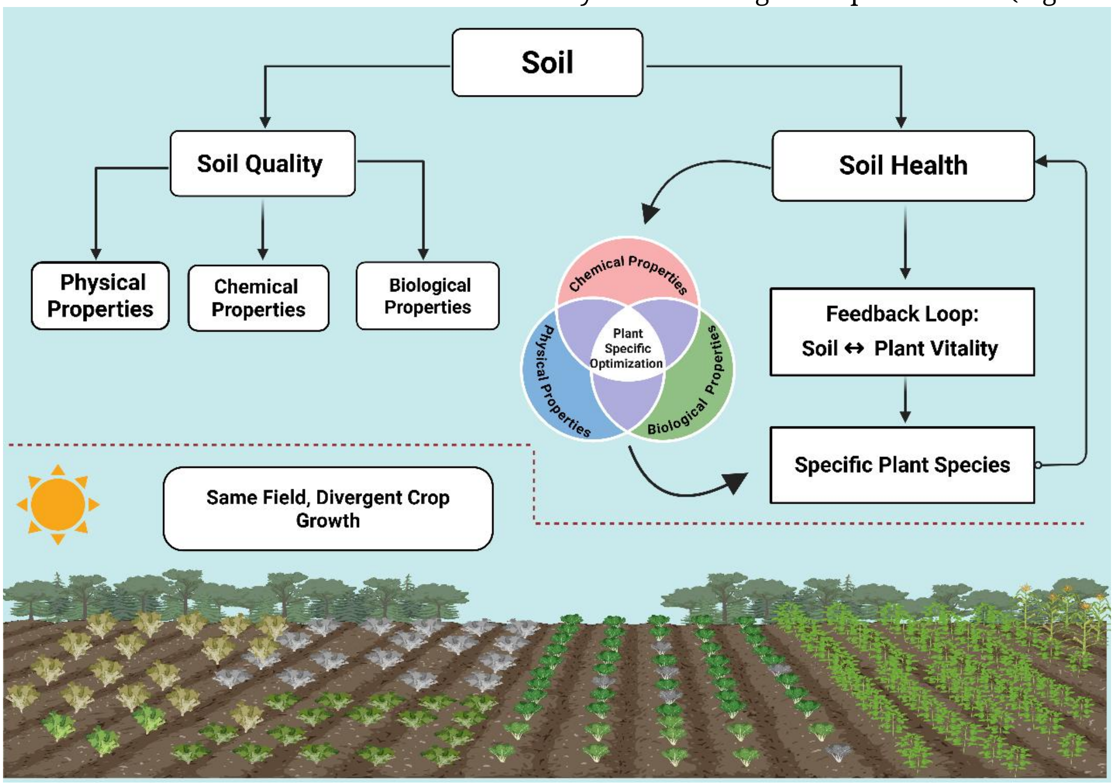

Figure 1. Conceptual model contrasting soil health and soil quality based on plant species.

Nutrient Addition and Microbial Inoculation Do not Alter the Difference of Soil Health Degree between Various Soils for a Specific Plant

Soil nutrient incompatibility or the lack of certain microorganisms hinders plant growth [27]. In this study, we found that while the addition of nitrogen and phosphorus, as well as the inoculation of AMF, positively affected the growth of *D. viscosa*, these interventions did not alter the overall health of the soil in which the plant grew. Despite improvements in growth performance, especially in the yellow-brown soil, the soil health of *D. viscosa* remained inferior to that of the dry red soil (Figure 2). These results suggest that nutrient and microbial adjustments can enhance soil quality by improving the availability of essential nutrients or by fostering beneficial microbial activities. However, these adjustments do not fundamentally alter the soil health of a given plant species, particularly when the intrinsic biological properties of the soil are not conducive to optimal plant growth.

Figure 2. Growth performance of *D. viscosa* after nitrogen and phosphorus nutrient addition and inoculation with AMF.

This finding is consistent with those of other recent studies emphasising that soil health is largely driven by biological factors such as microbial diversity and activity, which can be difficult to modify through external interventions such as nutrients. For example, some researchers [30,33,34] have argued that nutrient addition can enhance plant growth; however, the inherent biological conditions of the soil, such as microbial populations, play a more significant role in determining long-term soil health. Furthermore, the work by Wahab [35] on mycorrhizal fungi highlights that microbial inoculation can enhance plant growth and nutrient uptake but may not necessarily improve soil health if the fundamental soil structure or microbial community is not aligned with plant needs [36,37].

Plant-Soil Interactions and the Dynamic Nature of Soil Health

As we known, plant and soil always interacted, thus, there is need for plant-specific indicators of soil health [38]. The role of crop roots and their associated microbial communities in soil health is crucial and cannot be underestimated. Plants have a major impact on soil ecosystems through their root systems, which not only provide a physical structure but also affect microbial communities in the soil. Studies [30,39] have shown that plants with extensive root systems can improve soil health by promoting microbial diversity, nutrient cycling, and organic matter degradation. In addition, trees and deeply rooted crops contribute to improved soil porosity and organic material content, thereby promoting a more stable and healthy soil environment [40,41]. Furthermore, other researchers have reported that soil health is strongly related to soil biological diversity, including microbial populations that are directly affected by plant root exudates and other biological interactions [42,43]. Therefore, soil health cannot be effectively managed by exclusively focusing on its physical and chemical properties [28]. Instead, an integrated approach that considers plant diversity, microbial health, and ecosystem management is required [44].

The differences between soil health and quality are primarily applicable to sustainable soil management. Although soil quality provides a measure of the soil's potential to support plant growth, soil health offers a more holistic understanding of soil function and sustainability [45]. Sustainable farming practices, such as crop rotation, forestry, and the use of biological changes, can promote soil health by promoting microbial diversity and improving the nutrient cycle [46]. Moreover, the findings of our study emphasise that soil health is not a unique concept but depends on specific plant species and their interactions with the soil environment.

CONCLUSIONS

Our findings highlight that soil health is a dynamic and plant-specific attribute that extends beyond traditional measures of soil quality. Although nutrient addition and microbial inoculation can promote plant growth, they may not necessarily alter the fundamental health of the soil for a given plant. Soil health is influenced by a range of complex biological interactions between plants, microorganisms, and soil properties and plays an vital role in long-term agricultural sustainability. Future research should focus on balancing land management practices to enhance both soil quality and health through the careful selection and management of plant species.

AUTHOR CONTRIBUTIONS

GL: Conceptualization, Validation, Formal analysis, Writing—Original Draft, Project administration, Funding acquisition. XS: Methodology, Investigation, Writing. ZH: Writing-Review and Editing, Methodology, Investigation. XW: Writing-Review and Editing, Validation.

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DATA STATEMENT

Data will be made availability on request.

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CONFLICTS OF INTEREST

We hereby declare that there are no financial or personal relationships with individuals or organizations that could inappropriately influence the integrity or objectivity of our work, there is no professional or other personal interest of any nature or kind in any product, service and or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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