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Soil fertility evaluation and mapping

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Abstract
The determination of the appropriate application rate of plant nutrients is achieved by considering both the crop's nutrient requirements and the soil's capacity to supply nutrients. As a result, assessing soil fertility plays a critical role in agricultural practices and has become a fundamental step in managing soil and ensuring successful crop production. A systematic approach to evaluating soil fertility is pivotal for achieving well-balanced and sufficient fertilization in crop cultivation. Various methods are commonly employed to gauge soil fertility, including observing nutrient deficiency symptoms in plants, analyzing plant tissues, cultivating plants and microorganisms, and conducting chemical analysis of soil samples. Notably, substantial advancements have been made in the realm of digital soil mapping in recent times. This sophisticated technology provides the most precise insights into soil and crop conditions. Its applications encompass diverse areas such as land assessment, territorial management, agricultural extension, safeguarding the environment and other initiatives. Detailed maps of soil nutrients are important to identify the areas of fertility constraints and assist farmers on agricultural management measures for better crop productivity. The connection between soil fertility evaluation and mapping is profound, as soil fertility data is systematically translated into map attributes for widespread utilization by farmers and other stakeholders.

Keywords: Soil fertility, evaluation, mapping, nutrient management

1. Introduction

Soil, often regarded as the Earth's living skin, is considered one of our planet's most vital resources. Its pivotal role in supporting terrestrial life, especially in the context of agricultural systems, underscores the significance of understanding and managing soil fertility. Soil fertility, the inherent capacity of soil to supply essential nutrients to plants, has served as the foundation of global food production. In parallel, the discipline of soil mapping, facilitated by advancements in digital and spatial technologies, has emerged as a critical tool for characterizing the spatial distribution of soil attributes. The interplay between soil fertility and mapping, and their broader implications for sustainable agriculture and environmental management, is the core focus of this comprehensive review paper (Troeh and Thompson, 2005; Iticha and Takele, 2019) [25, 10].

In this review, a journey is embarked upon to explore the intricate interrelationship between soil fertility and mapping, shedding light on their synergistic contributions to modern agriculture and environmental science. The journey begins with an in-depth examination of soil fertility, delving into the underlying principles, factors influencing it, and its significance in crop production. Then, a pivot is made towards the realm of soil mapping, exploring its evolution from traditional approaches to cutting-edge digital methodologies. Through a thorough analysis of current literature, the ways in which soil fertility and mapping converge and complement each other are dissected, illustrating their indispensable roles in sustainable land management, precision agriculture, and environmental protection (Dharumarajan *et al*., 2022) [6].

As this intricate terrain is navigated, the pivotal role played by Geographic Information Systems (GIS), remote sensing, and machine learning in advancing our understanding of soil fertility and facilitating its efficient mapping is uncovered. Moreover, the practical applications of this interrelationship, including precision nutrient management, land-use planning, and mitigating environmental challenges such as soil degradation and climate change, are emphasized (Maguire, 1991; Shayakhmetov *et al*., 2019) [15, 22].

In this age of unprecedented global challenges, the synthesis of soil fertility and mapping knowledge becomes a potent tool for optimizing agricultural practices, conserving natural resources, and ensuring food security for a burgeoning world population. This review paper aims to provide a comprehensive and up-to-date synthesis of the current state of knowledge in this dynamic field, offering valuable insights for scientists, policymakers, and practitioners working towards a sustainable and resilient future (Gan-lin *et al*., 2017) [30].

2. Soil Fertility

The term 'fertile' signifies the ability to yield bountifully, and a fertile soil is characterized as one that can produce abundant crops under suitable environmental conditions. Soil fertility primarily revolves around the inherent capability of soil to furnish nutrients in sufficient quantities and in the right proportions to support the growth of specific plants. This provision of nutrients becomes possible when other factors conducive to growth, such as light, water, temperature, and the physical state of the soil, are favorable. In essence, soil fertility represents a distinct attribute of the soil, albeit a concealed one. This characteristic cannot be replaced or supplemented by additional attributes without altering the very essence of the term (Fig 1). The perception of soil fertility is influenced by subjective judgments of value, and the specific attributes associated with it may vary among different soil resources (Westerman and Tucker, 1978; Furey and Tilman, 2021) [27, 8].

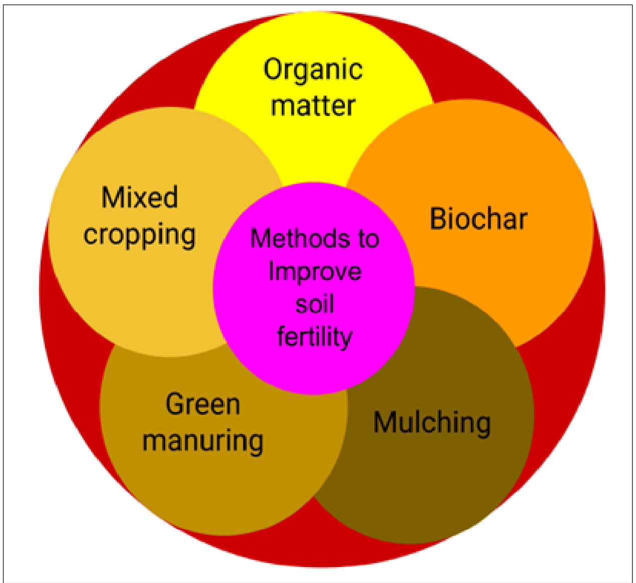

Fig 1: Methods to improve soil fertility

3. Soil Fertility Evaluation

Nutrient management practices formulated to achieve economically optimum plant performance as well as minimal leakage of plant nutrients from the soil plant system can only be optimised after soil fertility evaluation. Thus, soil fertility evaluation is a central feature of modern soil fertility management. The fundamental purpose of soil fertility evaluation is to quantify the ability of soils to supply nutrients for plant growth.

Soil fertility evaluation can be carried out using a range of field and laboratory diagnostic techniques and a series of increasingly sophisticated empirical and theoretical models that quantitatively relate indicators of soil fertility to plants response. The diagnostic techniques include chemical and biological soil test, visual symptoms of plant growth for nutrient deficiency or toxicity symptoms and chemical analysis of plant tissue. New approaches include passive or active optical sensing technologies and geographical information systems that facilitate landscape scale site-specific assessment of soil fertility and can better describe and address the spatial variability of soil fertility. In view of the need to balance productivity and environmental protection for a wider and more diverse range of land uses, soil fertility evaluation is more complex today as illustrated conceptually (Black, 2013) [4].

4. Some adaptable techniques for determining soil fertility evaluation

4.1 Nutrient deficiency symptoms

The visual appearance of a plant has long served as an indicator of its nutritional status. When the soil fails to provide an adequate supply of one or more essential plant nutrients, plants begin to display signs of nutrient deficiency, which are essentially early warning signals of nutritional deprivation. These deficiency symptoms are specific to the lacking nutrient and manifest differently in various plant species. For instance, a shortage of phosphorus (P) often results in stunted growth, while nitrogen (N) deficiency leads to overall yellowing of leaves along with reduced growth. Iron (Fe) deficiency, characterized by interveinal chlorosis, is linked to soil pH levels. Potassium (K) deficiency manifests as marginal spotting that eventually progresses to the complete necrosis of leaf margins. Evaluating soil fertility based on the availability of nitrogen (N), phosphorus (P), and sulfur (S) requires careful, experienced observation but can be limited by the concept of "Hidden hunger," where yield loss occurs without visible deficiency symptoms due to factors such as multi-nutrient deficiencies, pest infestations, disease, and nutrient toxicity (Jeyalakshmi and Radha, 2017) [11].

In many instances, nutrient deficiencies are not easily distinguishable, and the symptoms may overlap with other causes or be masked by the presence of other nutrients. Some typical examples include:

- Nitrogen (N) deficiency being mistaken for sulfur (S) deficiency.
- Calcium (Ca) deficiency being confused with boron (B) deficiency.
- Iron (Fe) deficiency being similar to manganese (Mn) deficiency.
- Leaf stripe disease in oats resembling manganese (Mn) deficiency.
- Effects of viruses, stunted growth (little leaves), etc., resembling zinc (Zn) deficiency.
- Brown streak disease in rice being similar to zinc (Zn) deficiency.
- It's important to note that deficiency symptoms always indicate a severe lack of nutrients, meaning the crop may have already experienced reduced yields before these symptoms become visible (McCauley *et al*., 2009; Abbas *et al*., 2021) [18, 1].

4.2 Plant analysis

The analysis of plant composition concerning essential growth elements can be interpreted using two commonly employed methods:

4.2.1 Critical Nutrient Concentration (CNC): This method identifies the nutrient concentration in plants that is minimally required for achieving optimal growth. It signifies the threshold below which the crop's response to fertilizer application becomes noticeable (Dow and Roberts, 1982; Hauer-Jakli and Trankner, 2019) [7, 9].

4.2.2 Diagnosis and Recommendations Integrated System (DRIS): DRIS is an innovative approach to interpreting plant or leaf analysis. It represents a comprehensive system that assesses all the nutritional factors that may limit crop production. By doing so, it enhances the likelihood of achieving high crop yields through more precise fertilizer recommendations. In summary, CNC establishes the minimal nutrient concentration needed for maximum growth, while DRIS offers a holistic approach to plant analysis, addressing all nutritional factors that might restrict crop production and ultimately improving fertilizer recommendations (Bhaduri *et al*., 2013) [2].

4.3 Growing of plants and microorganisms

Plants

(a) Mitscherlich's pot culture method
(b) Neubauer seedling method

Microorganisms

(a) Azotobacter plague method
(b) Aspergillus niger method
(c) Cunninghamella-plague method for P

4.3.1 Plants

(a) Mitcherlich's pot culture method

The plants are grown in a small volume of soil in pots or other containers under controlled conditions and analyzed for P_2O_5 and K_2O content.

(b) Neubauer seedling method

This approach relies on the concept of maximizing the absorption of nutrient elements by cultivating a substantial number of seedlings in a limited amount of soil. Consequently, the soil becomes depleted of nutrients, and the entire plant is subsequently analyzed to assess nutrient uptake. For instance, a significant number of seedlings, such as rye, are cultivated in a restricted soil volume. The total uptake of P_2O_5 and K_2O is quantified, and a reference value is subtracted to determine the soluble root content of P_2O_5 and K_2O, expressed as milligrams per 100 grams of air-dry soil, commonly referred to as "Neubauer numbers" (Siddiqua, 2018) [23].

4.3.2 Microorganisms

(a) Azotobacter plague method (Sackett and stewart technique)

A small soil sample, mixed with either corn starch or sucrose, is inoculated with *Azotobacter* bacteria and then allowed to incubate. The strength and vitality of the resulting bacterial colonies are assessed to classify the soil's deficiency level, ranging from severe deficiency to no deficiency, in the specific elements being evaluated (Thompson, 1998; Kolesnikov *et al*., 2011) [24, 12].

(b) Mehlich's Aspergillus niger method: This method entails the incubation of soil with *Aspergillus niger*, a fungus. After cultivating a dense mycelium layer on a suitable medium's surface, the process involves assessing the mycelium's weight and its capacity to absorb K_2O from the soil. This assessment is used to ascertain the critical threshold value for available K in the soil (Mangale and Sumner, 1983; Cavalcanti *et al*., 2015) [16, 5].

(c) Mehlich's cunninghamella-plague method

It involves incubating soil using *Cunninghamella* (a phosphorus sensitive organism).To measure the colony diameter(mm) to explain the soil available P status (Bhattacharya and Sengupta, 2020) [3].

4.4 Soil chemical analysis

Soil chemical analysis is an important and rapid tool for evaluating and correcting the plant nutrient deficiencies. Different reagents are used to extract plant available NPK, secondary and micronutrients (Rayment and Lyons, 2011) [21].

1. Available nutrient (in soil)

a) **N:** Alkaline permanganate method (Subbhia Asija)
b) **P:** Acidic soil - Bray's method - Alkaline soil - Olson method.
c) **K:** Ammonium acetate / Flame photometer.
d) **S:** Calcium dihydrogen - Phosphate / Turbidity method.
e) **Ca, Mg, Na, K:** Ammonium acetate (Hanway and Heidan Method)

2. Available nutrient (in plant)

a) Fe - 4.5 ppm, Mn - 2.0 ppm, Zn - 0.6 ppm, Cu - 0.2 ppm.
b) B - Hot water soluble dictionary < 0.1 ppm Low, 1 to 2 Normal, >2 High.
c) MoO_4 - Grigg and Tamm method buttered at pH 3.0, 470 nm, 0.04 to 0.20 ppm (Rayment and Lyons, 2011) [21].

3. Total element analysis

a) Total nitrogen analysis by Kjeldhal method
b) Total P, Ca, Mg, Zn, Cu, Fe, Na_2CO_3- Fusion method / H.F. digestion.

5. Soil mapping

Soil mapping involves creating graphical representations to convey information about the spatial distribution of soil characteristics. This process includes pinpointing and characterizing various types of soils, gathering data on their location, nature, properties, and potential uses, and documenting this information on maps and supporting documents to illustrate the spatial distribution of each soil type. These soil maps are primarily intended to delineate regions with consistent soil attributes that are valuable for determining suitable land utilization, rather than for soil classification (McBratney, 2003; Lamichhane, 2019) [17, 14].

Detailed soil nutrient maps are particularly valuable for identifying areas with fertility limitations and assisting farmers and agricultural management in optimizing crop yields. They are especially useful for tasks such as assessing soil suitability for specific crops and evaluating the drainage capabilities of a particular area. The rise of Digital Soil Mapping as an alternative approach to meet the growing global demand for spatial soil data depends on its capacity to (i) enhance spatial resolution and expand coverage and

(ii) provide pertinent information. Utilizing digital techniques allows for rapid analysis of the foundational map data and the application of quantitative assessments that ensure consistency throughout the mapped area (Lagacherie, 2008; Wadoux *et al*., 2020) [13, 26].

6. Different scales of soil mapping

Every cartographical map is characterized by a scale, and this scale plays a crucial role in determining the level of detail that can be represented on the map.

For instance, soil maps created at various scales (e.g., 1:5000, 1:100000, 1:500000) were integrated into a Geographic Information System (GIS) and compared based on the number of soil classes and discrete soil units within these classes. Notably, there were significant discrepancies in the quantity of soil classes between the highly detailed (1:5000) survey and the other two scales. The moderately detailed (1:100000) and reconnaissance-level (1:500000) maps exhibited similar numbers of soil classes, but there were some variations in soil classifications that directly influenced their suitability for land use planning (Zeraatpisheh *et al*., 2020) [28].

7. Usage of soil mapping: Soil maps find their most frequent applications in activities related to land assessment, spatial planning, agricultural extension services, environmental preservation, and similar undertakings (Fig 2). Initially, Digital Soil Mapping primarily concentrated on modeling soil landscapes, aiming to quantify the connections between soil properties and environmental factors. Over time, the focus of soil mapping gradually evolved, moving beyond soil variability and predictive techniques tailored for diverse applications. These applications primarily revolved around soil functions to varying degrees. Soil functions encompass a range of roles, including supporting biomass production, serving as reservoirs for storing, filtering, and transforming nutrients and water, hosting biodiversity, providing platforms for human activities, offering sources of raw materials, and safeguarding geological and archaeological heritage. These functions, whether directly or indirectly, contribute to the well-being of humanity (Gan-lin *et al*., 2017) [30].

Global soil maps are becoming enriched with interpretations and functional insights. They have the potential to enhance decision-making in addressing various global challenges, such as increasing food production and alleviating hunger, mitigating climate change, and combating environmental degradation. This collaborative effort is spearheaded by the Food and Agriculture Organization (FAO) in coordination with numerous universities and institutes, which have integrated regional soil maps into a comprehensive Harmonized World Soil Database (HWSD) that is widely utilized (Minasny and McBratney, 2010) [19].

Fig 2: Usage of Soil Mapping

8. Interrelationship between Soil fertility evaluation and soil mapping

There is a significant relationship for determining soil fertility through mapping. For major applications such as soil sampling, soil analysis, preparation of fertility maps, etc. the use of digital soil mapping is prerequisite. It acts as spatial indicators of limitations and potentials of soils. It helps formulating, establishing and maintaining site specific soil fertility programmes. It is a tool in farmer education and awareness campaigns and a device for predicting the behavioral patterns of soils. Geographic Information System (GIS) is one of the computer based systems used in digital soil mapping for creating databases of secondary and micronutrients, analysing various decision supporting tools like segregation, isolation, selection, buffering, etc (Maguire, 1991; Shayakhmetov *et al*., 2019) [15, 22].

9. Conclusion

In conclusion, the intricate interrelationships among soil fertility, mapping, and their broader implications are essential components in our efforts to sustainably manage the Earth's resources. Soil fertility, as a fundamental determinant of agricultural productivity, plays a pivotal role in ensuring food security for a growing global population. Mapping, especially through digital and spatial technologies, empowers us to understand the spatial distribution of soil attributes, enabling precise land-use planning, environmental protection, and agricultural management. The synergy between soil fertility and mapping extends beyond mere data collection; it guides us in making informed decisions about nutrient management, crop suitability, and land-use practices. Moreover, it allows us to address pressing global challenges like food production, environmental conservation, and climate change mitigation. As we move forward, the integration of innovative tools such as Geographic Information Systems (GIS) and digital soil mapping will continue to enhance our understanding of soil fertility's intricacies. These tools empower us to create comprehensive databases, optimize nutrient management strategies, and predict soil behavior, thus contributing to sustainable agriculture, environmental protection, and improved quality of life for people around the world. In this pursuit, collaboration between agricultural experts, scientists, policymakers, and stakeholders remains crucial to harness the full potential of soil fertility mapping for a resilient and sustainable future.

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