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Technological Advances in Soil Monitoring & Sustainable Management

Soil, this thin layer on the Earth's surface composed of **inorganic and organic substances**, is the **primary natural resource** for the production of **food, fibers, and bioenergy**, while also playing a **crucial role in ecosystems** and **global climate regulation**. It consists of various **solid (mineral, organic), liquid, and gaseous components**, which interact with each other and the external environment.

Beyond supporting production, soil also provides **environmental services** such as **carbon storage, nutrient cycling, water infiltration and retention, and biodiversity**

shelter. Soils are **naturally heterogeneous** due to significant variations in factors like **parent material (rocks), landscape (topography), climate, weathering (the natural process of rock breakdown and alteration), and biological activity**.

These differences are reflected in the **physical, chemical, and biological properties** of the soil, which can vary due to the **complex interactions** of several factors, including **biological** (earthworms, microorganisms, ants), **edaphic** (texture, structure, organic matter, nutrients), **anthropogenic** (human activity), **topographic** (slope, lowlands, or elevations), and **climatic** (temperature, humidity, precipitation).

Soil characteristics can **vary spatially**, even **within the same field or paddock**, extending to a **regional scale**. These variations may arise from **soil formation factors** or from **management practices, fertilization, and crop rotation**.

> ***The Irish physicist William Thomson stated that "what cannot be measured, cannot be improved," emphasizing that soil property variations must be monitored and quantified to understand the effects of land use and management systems.***

Therefore, **soil characterization is essential** for **decision-making in sustainable soil and agricultural management**, ensuring **food security**—that is, production in the **necessary quantity and quality**.

Additionally, other **urgent challenges** include **monitoring the effects of climate change on soil, preventing land degradation, and preserving environmental services**

These applications have driven the **development of sensors** to **measure soil properties**, complementing or even **replacing conventional laboratory techniques** used for soil analysis.

New technologies serve as **valuable tools** to enhance knowledge in **soil science disciplines**:

- **Pedology**, which studies the **origin, evolution, and classification** of soil as a **natural component of the landscape**.
- **Edaphology**, which examines **soil's influence on living organisms**.

> Three main approaches can be highlighted for **soil monitoring**:

- The first, and most **traditional**, uses **conventional methods** based on sample collection and **laboratory measurements**.
- The second utilizes **remote sensing**, with images from **aerial vehicles** and **satellites**.
- The third involves **proximal sensing**, which provides detailed data from closer distances.

*Currently, the **traditional method** involves **soil sampling in the field** followed by **laboratory analysis** in various segmented work stages. The* *overall process of **soil sampling and analysis** follows these steps: **planning and sampling, sample preparation, soil analysis, data management, interpretation,** and **recommendation**.*

Generally, the methods used by traditional laboratories, which involve **chemicals**, are more **time-consuming**, have **environmental impact**, and can be **costly**.

Soil and surface characterization through **remote sensing** via **aerial vehicles** (either piloted on-site or remotely) or **satellites** has made significant advances. This is an **efficient, non-contact approach** that does not require **direct access to the field**. It has greatly improved in terms of **spatial** and **temporal resolution**. However, challenges still exist, such as **cloud interference** and **surface cover**, like vegetation, crops, and crop residues.

Remote sensing techniques offer several advantages over other methods of measuring soil properties, including:

- **Large-scale coverage**
- **Non-destructive nature**
- The ability for **temporal monitoring**
- The capture of **different light spectra**
- **Rapid data acquisition**

However, new techniques have been extensively studied, such as **proximal soil sensing** using **field sensors**. These sensors provide **quantitative results** and can be more **time- and cost-effective** than conventional laboratory analyses. They are becoming **smaller, faster, more accurate, more energy-efficient**, **wireless**, and **smarter**.

There are different types of **proximal sensors** for measuring **chemical, physical, and biological soil properties**, operating in

both **non-destructive** and **destructive** or **non-invasive** ways. These include **electromagnetic, optical, mechanical, acoustic, or electrochemical sensors**.
Soil analysis based on **images and sensors** offers several advantages over conventional laboratory methods, such as **lower cost**, **higher efficiency**, **faster results**, and the ability to **collect large datasets**.

But what is the **best technology for soil monitoring**? The most efficient approach will depend on the **objective**, but a **combination of remote and proximal sensors**, along with **laboratory methods**, can be advantageous. Therefore, the choice of method depends on the **specific measurement** being sought.

> ***A single sensor often does not provide enough information to reliably predict various soil properties. Therefore, data fusion from different sensors, measuring different properties, can increase prediction accuracy.***

The future trend in soil monitoring points to the use of **high-resolution images and sensors**, combined with **more localized and specific laboratory determinations**.

The **real-time analysis and processing** of information can enhance the **accuracy, precision**, and **speed** of diagnostics. To achieve this, **new digital technologies** will be essential.

We have seen that **emerging technologies**, many of which result from research, large companies, and **AgTechs** (startups in agriculture), are promoting **data-driven innovation** that improves **strategic decision-making**. The growing need for **soil monitoring** is driving innovations in **methods, sensors**, and **equipment**.

Digital technologies such as the **Internet of Things (IoT)**, combining **sensors, robots, and UAVs (Unmanned Aerial Vehicles)** with **artificial intelligence (AI)** software, **blockchain**, **virtual reality**, and **augmented reality**, are driving the rapid advancement of **management information systems** in agriculture. These technologies have significant potential for use in **soil monitoring and management.**

There are **IoT-enabled sensors** that collect, analyze, and transmit real-time data on parameters such as **temperature, humidity, electrical conductivity**, and **nutrient concentration**. **Robotics** is also expected to impact soil monitoring by enabling **more precise and efficient sampling and analysis**, while reducing effort and increasing work capacity.

Data analysis, including **signal processing**, **sampling**, and **calibration**, is advancing with **artificial intelligence**, encompassing **machine learning**, **modeling**, and **data fusion** from multiple sensors.

Techniques for digital soil mapping, applying **artificial intelligence**, have also progressed, relating **geographically referenced data** from field and laboratory measurements, along with **environmental data**. These maps provide insights into the **spatial variability** of soil properties in a given area, identifying potential degradation risks such as **erosion, nutrient depletion**, and **compaction**.

> *There are also **immersive technologies**, such as **virtual reality (VR)** and **augmented reality (AR)**, which can contribute to improving the **efficiency** and **accuracy** of soil data collection and analysis.*

With **VR**, it will be possible to create **realistic simulations** of different production environments, allowing technicians and farmers to **test and evaluate management practices**.

AR will enable the overlay of information about **soil conditions**, **crop growth**, and other **landscape and climate data**. This presents an opportunity for technicians and farmers to easily identify areas that may need attention, such as **critical pest infestation points** or **nutrient deficiencies**.

Finally, **blockchain** can bring **security** and **transparency** to the data collected by soil sensors, as well as enable the **tracking of various equipment and inputs** in the supply chain. The data collected is stored in a **decentralized, tamper-proof** manner, ensuring **data security** and improving **transparency** and **traceability** for farmers and landowners.

The **Food and Agriculture Organization (FAO)** has designated **December 5th** as **World Soil Day**. This date serves as a reminder of the importance of this natural resource in our lives. This year's theme highlights the importance of **data and information** to **understand soil** and support **better decisions** for **sustainable management**, **food security**, and **environmental services**.

Moreover, **well-managed soil** is key to achieving several **Sustainable Development Goals (SDGs)**, such as those related to **hunger reduction (SDG 2)**, **extreme poverty (SDGs 1, 3)**, and the **improvement of environmental protection (SDGs 6, 11, 12, 14, 15)** and **global climate (SDG 13)**.

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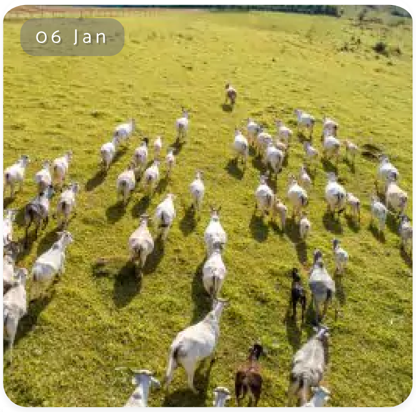

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