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Rethinking discovery in soil science with artificial intelligence

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KEYWORDS

decision support systems, hypothesis generation, machine learning, multi-agent artificial intelligence, soil science

An Editorial on the Frontiers in Science Lead Article

Enhancing soil science research with multi-agent artificial intelligence systems

Key points

- Multi-agent artificial intelligence (AI) systems extend beyond prediction to support hypothesis generation, experimental design, and scientific reasoning, representing a shift in how research can be conducted in soil science.
- By integrating diverse data sources and emulating collaborative workflows, multi-agent AI offers a new approach to addressing complex, interdisciplinary soil challenges that are difficult to resolve with conventional tools.
- Despite their potential, the effectiveness of AI systems in soil science is constrained by data limitations, transparency, and interpretability, making human expertise essential for validation and responsible application.

Soil science has always dealt with complexity. Soil is a dynamic, living system influenced by interactions between minerals, organisms, water, and climate, operating across spatial and temporal scales. Over the past two decades, the discipline has increasingly adopted digital tools—from remote sensing to machine learning (ML)—to better describe and predict this complexity. Yet, as Minasny and colleagues argue in their recent Frontiers in Science lead article (1), prediction alone is no longer sufficient.

Recent advances in artificial intelligence (AI), particularly large language models and autonomous multi-agent systems, are beginning to shift the role of AI from prediction toward reasoning and discovery. These systems are capable not only of analyzing data but also of generating hypotheses, designing experiments, and structuring lines of inquiry. For a field such as soil science, where complexity, fragmentation of data, and interdisciplinary challenges often constrain progress, this represents a potentially transformative shift. The proposal by Minasny et al. (1) to use multi-agent AI systems suggests a shift in how scientific research can be conducted. Instead of treating AI as a tool for data analysis, they position it as a collaborator in the research process. In this framework, multiple specialized agents can work together to review literature, analyze data, generate and refine hypotheses, design

experiments, and simulate elements of peer review. This extends well beyond current applications of ML, which are largely focused on pattern recognition and prediction.

Conventional ML approaches have delivered significant advances (2). They enable the mapping of soil properties, interpretation of spectral data, and prediction of outcomes from large datasets. However, they rarely address a central component of scientific progress: understanding mechanisms and formulating new hypotheses. In many cases, models are trained and applied without fully engaging with the underlying processes that drive observed patterns. From a real-world perspective, this limitation is particularly evident in long-term field experiments and cropping systems. Decades of work in such systems have shown that soil processes are highly dependent on context, with strong variability across sites, seasons, and management histories (3, 4). Models may capture general trends, but they often have difficulty explaining site-specific inconsistency driven by interactions among climate, management, and biological processes (5). The challenge has never been prediction alone, but understanding within the context of real-world complexity.

Multi-agent AI systems can help address this gap (6). By coordinating multiple interacting agents with defined roles, such as literature analysis, data interpretation, hypothesis generation, and critique, these systems can emulate aspects of collaborative scientific reasoning. In effect, they resemble a research team that integrates different types of expertise, iteratively refining ideas and exploring alternative explanations. This is particularly attractive for soil science, where progress often depends on integrating physical, chemical, and biological perspectives. A case study presented by Minasny et al. (1), focused on mineral-associated organic carbon saturation, demonstrates how such a system could work. The multi-agent system generated a diverse set of hypotheses, evaluated them through structured review processes, and ranked them according to criteria such as plausibility and scalability. The outcome is not a single, definite answer, but a structured exploration of competing explanations—reflecting the iterative nature of collaborative scientific research.

This ability to systematically explore and organize hypotheses may prove most valuable in early-stage discovery, where progress is often hampered by the limits of individual expertise and the time required to synthesize diverse sources of knowledge. By accelerating this process, multi-agent AI systems could help identify promising new research directions more efficiently. Beyond hypothesis generation, these systems may underpin the development of integrated soil monitoring and decision-support frameworks. For example, they could combine sensor networks, remote sensing data, and process-based models to create dynamic representations of soil systems. In practical terms, this could enable real-time decision support, where AI systems interpret sensor data, detect anomalies, and propose management strategies. Compared to existing tools, the added value lies in their ability to integrate multiple state streams and provide structured reasoning across them.

Such capabilities may also advance research on soil microbiomes by linking genomic data with environmental conditions, helping to unravel complex biological interactions. In the context of climate change, multi-agent systems may be used to test how soils respond to different management strategies or

environmental scenarios, supporting efforts to enhance resilience and carbon sequestration. These developments highlight the growing importance of soil science in addressing global challenges. Soils have multiple critical functions essential to food production, carbon storage, water regulation, and biodiversity, yet they are under increasing pressure from land degradation and climate change (4). Tools that improve our ability to understand and manage soils therefore have implications that extend well beyond the scientific domain.

At the same time, it should be emphasized that the adoption of multi-agent AI raises important challenges. For example, a key issue is the quality and representativeness of the data that feed these systems. Soil data are often unevenly distributed, with strong biases toward certain regions or land uses, and the AI systems could reinforce these biases rather than correct them. Another concern is transparency. As AI systems become more complex, it becomes harder to trace how conclusions are reached. This could be particularly important in soil science, where decisions can have long-term impacts on ecosystems and livelihoods. Ensuring that AI systems can explain their reasoning in ways that are meaningful to researchers and experts will therefore be essential. These challenges are significant. Data gaps, particularly in underrepresented regions, may distort conclusions, while limited interpretability may reduce trust in AI-driven insights. Addressing this will require better data infrastructure, greater transparency, and continued expert oversight. There is also a risk that hypotheses and recommendations generated by AI systems may be accepted without sufficient scrutiny. As highlighted by the Minasny et al., AI should be viewed as augmentative rather than autonomous. Human expertise remains vital, not only to validate results but also to frame the right questions and interpret findings within real-world contexts.

Multi-agent AI should not replace conventional scientific approaches but rather serve as a valuable complement. These systems have the potential to scale and accelerate research processes, particularly in soil science, where complexity is overwhelming. At the same time, we, the scientific community, face the challenge of integrating these tools thoughtfully. This will require not only technical development but also changes in how research is conducted, evaluated, and taught. Training the next generation of soil scientists and agronomists to work effectively with AI, while maintaining a strong foundation in fundamental principles, will be critical.

Ultimately, progress will depend on linking field-based knowledge with AI-assisted reasoning. By combining empirical understanding with computational tools, there is an opportunity to move from fragmented observations toward a more integrated understanding of soil systems. The goal should be to support discovery and innovation grounded in both data and experience.

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Author contributions

JKL: Conceptualization, Resources, Methodology, Writing – review & editing, Writing – original draft, Investigation.

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The author declared that generative AI was not used in the creation of this manuscript.

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