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EDITORIAL

Advances and applications of multivariate statistics and soil-crop sensing to improve nutrient use efficiency and monitor carbon cycling

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Food insecurity poses an urgent and complex challenge on a global scale, resulting from the convergence of various interconnected factors. Among these contributing elements are the escalating global population, which places mounting pressure on food resources, and extreme weather events that disrupt traditional farming practices. Additionally, limited access to irrigation facilities further hinders consistent crop growth, while the alarming shrinking of arable land due to deforestation and rapid urbanization imposes additional constraints on agricultural productivity. Consequently, food insecurity looms as a significant threat, necessitating immediate attention and innovative solutions.

While synthetic fertilizers have played a critical role in improving yields and have greatly contributed to food security since the green revolution, their indiscriminate usage has caused regional boundaries for nitrogen and phosphorus to be exceeded (Steffen et al. 2015), resulting in environmental consequences. For example, more than 50% of the applied nitrogen fertilizer is not utilized by plants and is released into the environment, resulting in the leaching of nitrates into groundwater and the emission of nitrous oxide (N_2O) into the air, causing pollution (Rosa and Gabrielli 2023; Scheer and Rütting 2023). In cereal cropping systems, the efficiency of phosphorus fertilizers was estimated to be even lower, < 14% of applied phosphorus (Yu et al., 2021). When fertilizers are applied in excess to crop requirement (especially in livestock areas; Reid et al. 2019), positive phosphorus balances occur and, while most of residual phosphorus is retained in soil and contributes to building a soil phosphorus stock, the risk of environmental pollution increases (Panagos et al. 2022). Clearly, this calls for innovative and sustainable solutions to ensure high-quality food production without compromising the environment.

Precision technology for assessing the geospatial and temporal variations of nutrient stocks and flows and their impact on crop growth, influenced by soil properties, climate, crop, and soil management, may be one such solution, providing essential tools for farmers. These technologies include geographic information systems (GIS), global positioning systems (GPS), sensors, machine learning algorithms, internet of things (IoT), among others, all intended to contribute to intelligent management-based decisions. These technologies empower farmers to optimize crop growth, minimize waste, and enhance sustainability.

With the aim of promoting a more efficient nutrient use, initiatives like the 4R Nutrient Stewardship

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have been launched, advocating for the right source of fertilizers at the right rate, right time, and right place (Johnston and Bruulsema 2014). Indeed, precision N management allowed increasing fertiliser N recovery efficiency in spring maize from 21 to 39% when topdressing fertiliser application was based on crop demand as determined by optical sensors rather than soil test data (Sing et al. 2020). Juang et al. (2002) optimized phosphorus fertilizer application by conducting limited soil sampling, followed by interpolation using geostatistical methods. The resulting maps were subsequently employed for variable-rate phosphorus fertilizer application.

The adoption of precision agriculture requires a deep understanding of the spatial and temporal variability of soil properties, and of climatic conditions affecting nutrient cycles and crop growth. Despite advances in agriculture, traditional statistical approaches often assume that agricultural fields are uniform. However, in reality, spatial variability may exist within a single field, significantly impacting crop yields and nutrient flows. Grid-based intensive sampling is useful for understanding nutrient dynamics in the field, but it is expensive and time-intensive to cover large areas. Spatial modelling combined with sensing technologies could offer potential solutions to minimize sample collection and improve the understanding of soil property variability, thus enabling effective decisions on resource usage.

Geostatistical methods have played an important role in predicting soil variables in locations where soil sampling was not conducted based on augmented knowledge and interpolation techniques for producing continuous maps (Heuvelink and Webster 2022). Kriging, a widely used interpolation technique in soil science (Cattle et al. 2002; Guo et al. 2015), can provide valuable insights. Technological advances in proximal sensors and satellite remote sensing have ushered in a new era of data-driven agriculture. These technologies provide an unprecedented wealth of spatial information, capturing crucial details about soil properties, crop health, and environmental conditions over vast areas and extended periods. Characterizing soil properties over space and time with the help of sensors combined with statistical tools has increased tremendously in recent decades (McBratney et al. 2003), enabling accurate maps of soil properties to be used for efficient farm resource management.

A significant proportion of agricultural research systems possesses a complex and interconnected multivariate nature, meaning that they involve multiple variables and factors that influence the outcomes. In response to this complexity, the field of agricultural research has turned to the utilization of multivariate statistics. These sophisticated statistical techniques have garnered widespread adoption due to their effectiveness in handling diverse and interrelated data sets. Multivariate statistics play a pivotal role in facilitating a comprehensive understanding of the data collected from various aspects of agriculture. It enables researchers to extract novel insights from the data that might not be apparent through conventional univariate analyses. These insights can lead to the discovery of innovative strategies for improving overall agricultural productivity. Recognizing the importance of multivariate statistics and soil-crop sensing to improve nutrient use efficiency and monitor carbon cycling, this special issue collected four papers focusing on the spatial prediction of soil nutrients and site-specific nutrient management.

The variability of soil nutrients is influenced by a variety of environmental factors. To understand the spatial behaviour of total available phosphorus, Zhang et al. (2023) conducted a study in Northeast China during freeze–thaw cycles. They used Moran's I index to incorporate spatial patterns into the mapping process. The impact of environmental factors, such as topography and nutrients, on soil phosphorus was analysed using a structural equation model. From the spatial analysis, they found that the soil steepness, pH and soil carbon are the key factors that influence the available phosphorus at all soil depths.

Several attempts were made to increase the number of spatial covariates incorporated in the modelling process and to use a flexible, non-linear model structure, aiming for an accurate prediction model. A study by Zhao et al. (2023) generated a digital soil map for soil organic carbon in a sugarcane field, using multiple sensors (electromagnetic induction, Gamma-ray, and Vis–NIR) for accurate mapping. These maps enabled a reduction in fertilizer costs to 36% while achieving baseline yield potential. This study also highlighted research gaps in including remote sensing data in the modelling process to improve the prediction capability of soil carbon content.

Designing appropriate sets of digital covariates to model soil properties is key to producing accurate maps of soil nutrients and enabling efficient land management. In a study conducted in northeastern Iran, Keshavarzi et al. (2023) used machine learning algorithms to predict the spatial distribution of soil micronutrients (iron, zinc, copper, and manganese). They tested different sets of digital covariates (including satellite and climate data) and found that accurate maps could be obtained when expert opinions were integrated into the modelling process, effectively identifying micronutrient deficiencies and excess hotspots in the study area.

Finally, Corti et al. (2023) developed a new decision support system to apply cattle manure and urea to maize based on the spatial variability of soil and crop properties, testing its performance in a two-year field trial in northern Italy. Inputs to the decision support system were derived from geophysical methods, near-infrared spectroscopy, and multispectral images of maize and yield maps. Compared to a fixed nitrogen rate, site-specific nitrogen management showed no reduction in yield and nitrogen uptake and demonstrated potential environmental benefits in the less yielding zones of the field.

This special issue thus provides examples showing how embracing technological advances and developing sustainable nutrient management practices can help us maintain soil resources with minimized impact on the environment.

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