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Moving away from the geostatistical lamppost: Why, where, and how does the spatial heterogeneity of soils matter?

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ABSTRACT

Since the late 1970s, thousands of scholarly articles, books and reports have dealt with the application of the mathematical theory of geostatistics to characterize the spatial "variability" of soils, and to produce soil property maps. Insensibly, this application of geostatistics appears to have become an end in itself, and the reasons why one should be concerned about the spatial heterogeneity of soil properties are rarely if ever made clear any more. In this context, the purpose of the present critical review article is to return to some of the primal questions that motivated this interest in the topic several decades ago. After a brief review of the background behind the application of geostatistics to soils, a number of situations and modeling efforts are described where, even though soils undoubtedly vary spatially, nothing seems to be gained practically by explicitly accounting for their spatial heterogeneity in order to reach a number of management or research objectives. Contrastedly, whenever the spatial heterogeneity of soil properties in the field might be relevant, it is shown that very different perceptions about it emerge, depending on the type of measurement that is performed. This suggests that the approach one adopts to characterize spatially-varying soil properties should be dictated by whatever goal one pursues. For example, if the objective is to evaluate the "ecosystem services" of soils in a given region and to reach decisions about them, one should probably first consider the (typically large) spatial scale that is most relevant to the decision-making process, then proceed via a top-down approach to characterize the spatial heterogeneity of soil services, if and when appropriate. In other contexts, it is argued that measurements should be patterned after the behavior of plants or microbes present in soils, relative to which, unfortunately, the macroscopic measurements that are now routinely carried out appear largely irrelevant or misleading. The article concludes with a number of potential lessons learned from the analysis of the research on the spatial heterogeneity of soils, which bear relevance to the broader practice of soil science.

1. Introduction

In the late 70s, the publication by Journel and Huijbregts (1978) of their landmark textbook on geostatistics greatly contributed to popularize the work carried out earlier by Matern in Sweden, Gandin in the Soviet Union, Krige in South Africa, and Matheron in France, and described in detail by the latter (Matheron, 1962, 1965), on the statistical analysis of the spatially-varying properties of meterorological events, forests, and geological formations. Soon thereafter, geostatistical techniques were adopted enthusiastically by hordes of ecologists and soil scientists, eager to generate maps of soil properties of interest within agricultural fields, watersheds, ecoregions, or even entire countries. Research in the area took off like a brush fire, rapidly gathering tremendous momentum. According to Google Scholar, an astounding total of 33,700 articles, book chapters, and reports have been written so far on the use of geostatistics to quantify in some way what has come to be described as the spatial "variability" of soils but should probably be referred to more appropriately as their spatial variation or, like in the following, as the spatial heterogeneity of their properties. The Web of Knowledge (Thomson Reuters, Princeton, New Jersey) lists a less impressive, but still commendable, number of about 12,260 articles that use "soil*" and either "geostatistics", "kriging", or "kriged" as descriptive keywords. Judging from the rate at which articles on the topic are being published at present – more than 3000 in 2013 according to Google Scholar – the brush fire

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still appears to burn unabated, more than 35 years after the initial spark.

In view of how hugely fashionable the application of geostatistics has obviously been in the study of soils during the past three decades, one is unavoidably reminded of the very astute observations made by Vatn and Bromley (1994) in a context that is slightly different but nonetheless so remarkably relevant that part of their text is worth repeating here *in extenso*: "The history of science warns us that the mere popularity of a particular epistemological program is not sufficient evidence of its truth content. Nor is popularity a sufficient guarantee that those in a shared pursuit will not lose sight of the larger issues at hand. Indeed, it could very well be that the considerable popularity of a particular research program serves, in a perverse way, to reduce the probability that its ultimate purpose will be kept firmly in view. The very popularity of the research program then becomes self-reinforcing and serves both to envelope an ever larger share of those who might otherwise follow different research programs, and to stifle dissent out of fear of being thought out of the very broad and encompassing 'mainstream.' Meanwhile, the research becomes ever more involuted, and it becomes easier to lose sight of why one began the journey in the first instance. If we may be permitted a nautical metaphor, a long series of technically perfect tacking maneuvers may very well deposit the fastidious crew at a destination quite devoid of virtue."

Depending on one's perspective on the merits, or lack thereof, of trends and fashions in scientific research, one can look at this incisive assessment by Vatn and Bromley (1994) as either cynical or insightful when it comes to the research involving geostatistics in soil science. Regardless of which description applies, it is of interest to inquire whether the reasons why "one began the journey in the first instance" are still clearly in sight in this field. Evidence suggests that they are not, and that the situation is reminiscent of the popular joke (apparently inspired by the Scottish poet Andrew Lang) about a drunkard looking for his car keys not where he is certain he lost them, but under a lamppost because, as he says, "there is more light here and I can hang on to the lamppost". Indeed, from the multitude of articles devoted in recent years to what has become termed by some, symptomatically, "soil geostatistics" (e.g., Lark, 2012), a strong impression emerges that the use of geostatistics has in most cases become an end in itself, relegating to the very distant – and obscure – background some of the original questions about soil spatial heterogeneity that may have motivated the authors' interest in geostatistics in the first place.

In this context, the key objective of the present critical review article is to return to some of these primal questions about the significance of the spatial heterogeneity of soil properties, and about whether it is imperative to be able to describe it quantitatively, using any one of an array of available theoretical frameworks. A useful first step in this analysis is to outline the historical background of the work on the application of geostatistics to soils, in order to better understand what contributed to its being framed the way it has from the outset. Then, we propose a quick overview of a number of situations where spatial variation, even though it is undoubtedly present, is not necessarily relevant to our attempts to describe soil-related processes, or at least does not have to be taken into account explicitly in the manner it has been accounted for in the last few decades. The next step in the analysis deals with situations where local measurements of a spatially-varying soil parameter are obtained and interpolated to address specific purposes, and where it is shown that the volume of soil over which local measurements are made influences significantly the perception one gets of the spatial variation of soils. In that context, the key question, which does not appear to have been asked very much at all in the soil geostatistics literature, is that of determining which measurements are appropriate, at what spatial scale. This question is addressed in the subsequent section in terms respectively of the topical assessment of the services soils provide to human societies, and then of the response of plants and microbes to spatially-varying soil properties. The article concludes with a quick overview and discussion of some of the lessons that the past three decades of research on soil spatial heterogeneity have taught us. These lessons should guide us in the future, as we finally address some aspects of the topic that have been neglected so far, and they may be applicable as well to other areas of the study of soils.

2. Historical background

Accounts of when exactly humans began to grapple with the spatial variation of soils are lost in the night of times. It is likely that already centuries if not millennia ago, peasants walking alongside their oxen or horses as they worked their fields, or when weeding them by hand, developed a very good feel for the differences among the properties of soils at different locations. In some cases, like Belgium and the Netherlands, this peasant knowledge apparently extended to fatal livestock diseases, e.g., scrapies or "sway-back" (Charlet et al., 2012), associated with individual parcels of land, on which farmers systematically avoided to establish pastures (Voisin, 1959; Joseph Baveye, personal communication, 2002). One likely, but hardly researched, outcome of such daily soil observation over many generations is that it determined the actual size and configuration of agricultural fields to maximize their uniformity, which in turn facilitated their cultivation (Oliver, 2010). Another outcome, much better documented, is that most advanced societies, even those that never developed an alphabet or script, came up with some form of indigenous system of soil classification (e.g., Sandor and Furbee, 1996; Barrera-Bassols and Zinck, 2003; Sampietro Vattuone et al., 2008), and tried early on to understand what made some soils behave very differently than others (Baveye, 2013). Eventually, starting in Russia in the 19th century, this preoccupation led to the launching of extensive soil survey programs around the globe, which have perdured to this day.

Agricultural mechanization, especially the adoption of tractors and harvesters with internal combustion engines, and the progressively increasing reliance on fertilizers in the late 19th and early 20th century, changed completely the agricultural landscape and the perception of the spatial variation of soils. Farmers were encouraged and occasionally coerced to consolidate small fields into larger units, which it was considered economical and time-efficient to treat as uniform units. Somewhere along the lines of this evolution, the spatial variation of soils at the field scale became entirely ignored, to the point that many farmers, when they were attempting to get samples analyzed to determine what amendments were needed, often took only one sample per field, regardless of its extent. Some researchers tried early on to argue that this practice was not defendable. For example, Kelley (1922), in Riverside (California), conducted a study where he laid out transects, along which samples were drawn at consistent intervals and were then analyzed for various chemical components. He concluded that "the analysis of a single soil sample drawn from one place within the area studied, has very little value. [...] one or more samples from each of several of the experimental plots contained practically no alkali salts; other samples contained high concentrations of one or more salts; and still others had a composition intermediate between these extremes. If similar variation characterizes the distribution of salts in alkali soils generally, it may be safely concluded that the analysis of samples such as are commonly submitted by practical farmers is a waste of time. In fact, the conclusions that are likely to be drawn from the analysis of such samples may be so erroneous as to lead to the recommendation of practices the very opposite of those that should be employed."

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