From Dust Bowl to Dust Bowl: Soils Still a Frontier of Science

by Philippe C. Baveye, David Rangel, Astrid R. Jacobson, Magdeline Laba, Christophe Darnault, Wilfred Otten, Ricardo Radulovich, and Flavio A.O. Camargo

Editor's note: The following is an abbreviated version of an article that was originally published in the November–December 2011 issue of the Soil Science Society of America Journal *(75:2037–2048). Due to space constraints, the reference section is omitted here but can be viewed online in the original paper at www.soils.org/publications/sssaj/tocs/75/6.*

When the Soil Science Society of America (SSSA) was created 75 years ago, the U.S. was suffering from major dust storms, causing the loss of enormous amounts of topsoil as well as human lives. These catastrophic events reminded public officials that soils are essential to society's well-being. The Soil Conservation Service was founded, and farmers were encouraged to implement erosion mitigation practices at a time when many questions about soil processes were still poorly understood. In this article, we argue that the current status of soils worldwide parallels that in the U.S. three quarters of a century ago. We show with several concrete examples that, in spite of remarkable progress in our understanding of soil processes in the last few decades, many aspects of soils still remain extremely elusive and poorly understood. We feel that pointing out these many persistent "islands of ignorance" would be extremely helpful in terms of alerting public opinion about the significance of soils, attracting more students to the study of soils, and affecting policy-making related to soil degradation and conservation.

Soils Affect Society

Dust Bowls and Skinning of the Earth: Those Who Cannot Remember the Past…

Dust bowls have reappeared in the last decade, reminiscent of the 1930s. One of these dust bowls is located in China. Even though they were already suffering from overplowing and overgrazing, the northwestern provinces of Inner Mongolia, Gansu, Qinghai, Ningxia, and Xinjiang, plowed ever more marginal lands after 1994, when a decision was made by the Chinese government to require that all cropland used for construction be offset by land reclaimed elsewhere (Yang and Li, 2000). Inner Mongolia led the way with a 22% cropland expansion. In addition, following economic reforms in 1978, livestock populations in the region have grown rapidly, often far beyond the land's carrying capacity. A direct result of these two trends is that soils have deteriorated, wind erosion has

intensified, and the once infrequent, seasonal dust storms have become a far more common occurrence. In April 2001, one of the worst dust storms in memory hit Beijing and then drifted eastward, eventually blanketing areas from Canada to Arizona with a layer of dust. Similar dust storms have continued since. On 20 Mar. 2010, the first day of spring, another massive sandstorm went from the arid terrain of Inner Mongolia to China. The yellow dust reduced visibility and air quality to potentially hazardous levels in the nation's capital, delaying flights at Beijing's airport and prompting a dust warning in Seoul, before it travelled as far away as Taiwan (Fig. 1) and Japan.

Fig. 1. Picture of Lonjing Township (Taichung County, Taiwan) on 21 Mar. 2010, after a dust storm originating from north mainland China blew over the region. *Photo courtesy of* 阿爾特斯 */ Wikipedia.*

These dust storms, in China and elsewhere (e.g., Australia and the U.S.), and the frequent brown plumes at estuaries, where sediment-laden river waters enter oceans, are unmistakable manifestations of soil erosion at a grand scale. Yet, as Montgomery (2007) argues, soil erosion is far more widespread than that. He estimates that we are now losing about 1% of our topsoil every year to erosion, most of this loss caused by agriculture, and that, in more ways than one, we are "running out of dirt." The evidence is everywhere that we are skinning the earth: "We see it in brown streams bleeding off construction sites and in sediment-choked rivers downstream from clear-cut forests. We see it where farmers' tractors detour around gullies, where mountain bikes jump deep ruts carved into dirt roads, and where new suburbs and strip malls pave fertile valleys. This problem is no secret." (Montgomery, 2007). And if it gets worse than it is at the moment, it could periodically bring air transportation to a halt, cause major health hazards, or make our rivers unnavigable.

Soils and Climate Change

Another avenue by which soils could very significantly affect society in years to come is related to global climate change. Soils are major players in the carbon cycle. Globally, world soils contain more than 1,550 Pg of carbon in the surface meter alone (Baveye, 2007). This is more than twice the amount of carbon in the atmosphere. To put it differently, soils contain the equivalent of about 300 times the amount of carbon now released annually through the burning of fossil fuels. In addition, in many soils, carbon stocks contain large amounts of nitrogen, whose metabolism by microorganisms can also contribute significantly to greenhouse gas emissions. Therefore, even small changes (less than 1%) in the amount of carbon contained in soils may lead to sources or sinks of greenhouse gases that could be significant relative to those released by fossil fuel combustion (Rustad et al., 2000). Increased release of carbon by world soils could drastically exacerbate atmospheric CO_2 levels, leading to accelerated global warming and eventually to a positive feedback mechanism that might cause climate change to get completely out of hand (Baveye, 2007).

However, attempts to sequester carbon in soils by a variety of means, if they were successful, could have exactly the opposite effect. At this juncture, it is uncertain whether soils in temperate and tropical regions are likely to be net sources or sinks of greenhouse gases. Only in the high-latitude permafrosts, particularly in Siberia, is the situation more clear cut in favor of a positive feedback to climate warming. Siberia has extensive areas (10^6 km^2, or roughly 1.5 times the size of Texas) of deep (up to 90 m) deposits of organic-rich frozen loess that accumulated during the Pleistocene. Their large organic carbon pool (roughly 450 Pg, more than half the amount of carbon in the atmosphere) has not been considered generally in most global carbon inventories (Zimov et al., 2006). Similar deposits occur less extensively in Alaska, where recent evidence suggests that permafrost is thawing at a much faster rate than previously anticipated. The organic carbon in these soils decomposes quickly upon thawing and is released to the atmosphere. Simultaneously, methane gas entrapped as large bubbles in the permafrost is released so fast that it prevents the surface from freezing, even in the midst of winter (Walter et al., 2006). Since methane is between 18 and 25 times more potent as a greenhouse gas than CO_2, its release by permafrost is significant, at least in the short term (until methane is transformed into CO_2).

Urban Soils

In recent years, the world population has become increasingly urbanized. There are large differences among countries, but on average, more than 50% of people live in urban or suburban areas, and this number is increasing constantly. In many cases, a consequence of this trend is that cities are expanding into what used to be their industrialized outskirts, where researchers have found that soils are routinely contaminated with a variety of organic and inorganic compounds. Even in the traditional city centers, contaminant levels in soils are often significantly elevated with historic pollutants such as lead from paint and gasoline or polyaromatic hydrocarbons from vehicular exhaust or coal-fired power plant emissions (Belluck et al., 2003; Morillo et al., 2007). In recent years, the public at large has become more aware of potential problems associated with contaminant levels in urban soils, in part because contaminants are likely to affect children more directly, given the tendency of toddlers and infants to ingest significant amounts of soils through hand-to-mouth transfer when playing, for example, in public parks. In a number of cities in the U.S. and Europe, parent associations have voiced serious concern about the financially motivated construction of day-care facilities and schools on former brownfields. Even though soils at these sites may have been considered "clean" (i.e., with contaminant concentrations less than regulatory limits) at the time the buildings were erected, reports of noticeable emanations of volatile organic chemicals are causing parental concern over their children's exposure to chemicals that could affect their well-being and cognitive development (Weber, 2011).

Soils and Food Security

Perhaps surprisingly, food security comes last in this rapid overview of areas in which soils matter to society.

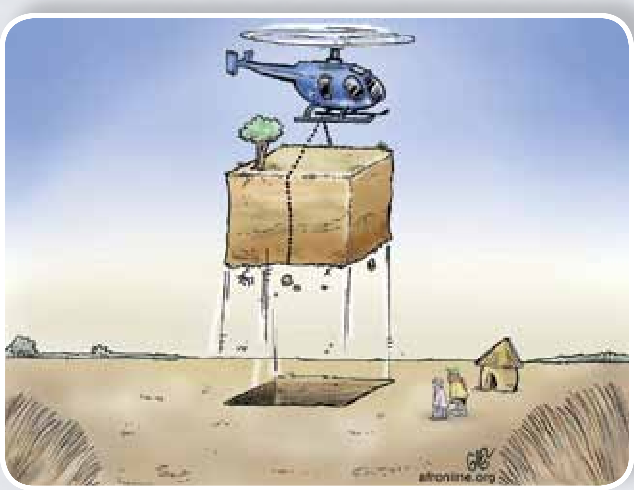


Fig. 2. Populations in developing countries, particularly in Africa, are increasingly concerned about the "land grab" process, by which foreign countries are leasing large tracts of land to produce food for export. *Cartoon by Damien Glez for Afronline.org and reproduced with author's permission.*

Most authors would probably have broached this connection first, as by far the most important for soils. Countless articles in recent years (e.g., Pimentel et al., 2010) have commented on the causal relationship between decreases in per capita cropland and shortages of basic foods, especially as biofuel production begins to compete for available land.

Signs that, in the minds of most people, soils and food production are irrevocably connected are all around us. For example, a number of countries, particularly in Asia and the Middle East, faced with food supply problems in the coming decade, have in the last 10 years initiated major programs to purchase vast expanses of land in Africa and Latin America. The global-scale "land grab" (Fig. 2) of unprecedented proportions that has unfolded has been studied very little in the academic literature to date (Robertson and Pinstrup-Andersen, 2010). Nevertheless, it seems clear that several relatively "land-rich" developing nations are sanctioning the sale or transfer of user rights of large tracts (sometimes millions of hectares) of farmland for foreign investment. Poor, smallholder farmers without formal land titles currently occupy much of the land leased or sold in these transactions, threatening the internal food security of the seller states. A further concern is that this land grab, particularly if it is associated with intensive agricultural practices in regions of the world like Sudan, Algeria, Madagascar, or Egypt, where water availability may be a significant issue at times, will lead to the same type of soil degradation that has afflicted northwestern China in the past decade and that we will see many more dust bowls in the future, complete with local starvation, population migration, and compromised national and international security.

Fig. 3. The production of different types of seaweed like these, in significantly larger quantities, could ease the pressure we have traditionally imposed on land for food production. The potential of seafarming to feed the world is virtually untapped. Perhaps the next green revolution should be blue... *Photo by Dr. David Rangel.*

Is this direct link between soils and food security as tight as tradition leads one to believe? Although answering this question forces us to break away with millennia of soil-based farming, one could easily argue that the answer is negative and that, if one dares think "outside the box," a very different outlook is possible. From a resource allocation perspective, fully recognizing that water is as important, if not more important, to crop production than a soil material in which crops can propagate their roots and that water will be scarce in many parts of the world in years to come, one would conclude that it would make sense to try to produce food where the water is. With the rare exception of countries, like Brazil, that are blessed with abundant water supplies, in general the requirement to go where the water is would force us naturally to turn to the oceans, which cover 71% of the earth's surface and contain 97% of the planet's water. Roughly two-thirds of the world population already live in coastal areas around the world, so that deriving food and energy from the oceans would not pose insurmountable logistic problems. In addition, Japan has shown, for centuries, that it is possible to derive sizeable quantities of food from oceans. Different types of seaweed, sea vegetables, and countless fish products, often not consumed in other countries, find their way in the daily diet of the Japanese population (Fig. 3).

Nothing would prevent other countries from jumping on the bandwagon and producing in the oceans; if not human food, at least animal feeds or sea crops that could be eventually converted into biofuels. If this trend toward a more widespread seafarming (Radulovich, 2011) or mariculture materialized, soils would be less solicited for food production and could be reforested to a far greater extent than at present, especially in erodible areas, or could be allowed more generally to be re-colonized by their natural vegetation. The significantly decreased soil degradation that would ensue would alleviate some of the problems mentioned earlier, including to a large extent (except in permafrost areas) the possible positive feedback of soils to climate change. To put things in more concrete terms, removal of the disproportionate food-security-related pressure currently exerted on soils, through a switch to seafarming, may prevent in the future some of the current environmental problems associated with mismanagement of soils, like dust bowls.

So Many Things We Do Not Know, Still…

While soils significantly affect human societies, there are still very many aspects of soils that we do not understand or that we grasp only superficially.

Underestimating Soil Biota

Perhaps the best illustration of how ignorant we still are, or to be precise, still were 18 years ago about many soil processes, is the doom of the Biosphere II experiment in Arizona, initially conceived as an attempt to create a balanced and self-sustaining replica of earth's ecosystems. By 26 Sept. 1993, when it became apparent after 18 months of operation that the experiment had flopped, the $200 million project had failed to meet many of its objectives. In particular, of the 25 small vertebrates with which the project began, only six did not die out by the mission's end. Almost all of the insect species were extinct, including those that had been included for the purpose of pollinating plants. But what really led to the demise of the project was the fact that oxygen concentration in the air could not be maintained at an appropriate level. There were several reasons for that, but one of the key ones, undoubtedly, was the fact that O_2 consumption by soil microorganisms had been grossly underestimated by the experts involved. Especially in the rainforest and savanna areas of Biosphere II, soils were rich in organic matter. Microbes metabolized this material at an unexpectedly high rate, in the process using up a lot of O_2 and producing significant amounts of CO_2. Not quite 18 months into the experiment, when oxygen levels dropped to the point where the crew could barely function, oxygen had to be pumped into the system so that crew members could complete the full two-year mission as planned.

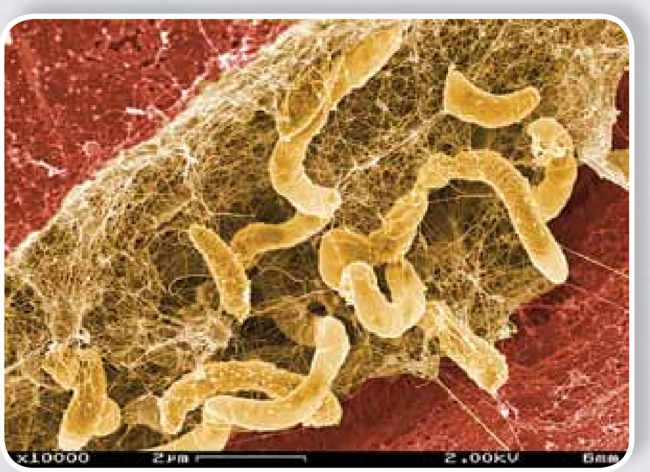


Image by Helen Kreuzer-Martin of the Pacific Northwest National Laboratory.

Soil Biodiversity

Far beyond the failure of Biosphere II, of course, microorganisms constitute a formidable challenge to anyone trying to understand soil processes, many of which in one way or another are mediated by, or at the very least involve, microorganisms. The identity of most of these microorganisms, however, remains largely a mystery. At this point, it is estimated that 99.5% of organisms in soils have not been cultivated (e.g., Gest, 2008; Zengler, 2009; Alain and Querellou, 2009). For a time, it seemed that metagenomics could dramatically change this picture and provide a wealth of information about soil biota while bypassing the need to cultivate the myriad of yet uncharacterized soil organisms. As some authors put it, "the blind survey of the streams of microbial sequences will undoubtedly facilitate the understanding of the mechanisms ruling the subterranean communities and bring exciting, unexpected discoveries" (Martin and Martin, 2010). Yet, the results to date are falling short of expectations. For instance, it remains unclear what percentage of the DNA present in soils is extracted by current techniques and how representative this fraction is (Thakuria et al., 2008; Hjort et al., 2010; Trevors, 2010). Even if one could somehow resolve these DNA extraction problems, as well as the enormous computational "metagenome analysis gridlock" that has apparently taken microbiologists by surprise (Martin and Martin, 2010), it is still unclear whether metagenomics, without a suite of other "omics," like metabolomics or proteomics, can really shed light on soil biodiversity (Baveye, 2009; Singh et al., 2009). Indeed, some of the experts in the field recently admitted that it will be necessary in the near future to "develop and apply new approaches to cultivate the previously uncultivated and rare members of the soil community to assign functions to the vast number of unknown or hypothetical genes that will undoubtedly be found" (Vogel et al., 2009). So, in many ways, we are back to square one. The soil biodiversity challenge not only remains intact, but in some ways has grown.

Carbon Sequestration in Soils

Another issue about which considerable uncertainty persists concerns the practical conditions under which active carbon sequestration in soils could be feasible. Terrestrial carbon sequestration is often presented as a "win-win" situation to offset a substantial portion of anthropic CO_2 emissions. Lal (2010), for example, has suggested that the technical potential of carbon sequestration in soils is as easily reachable as a "low-hanging fruit." Many disagree with this perspective (e.g., Baveye 2007; Goovaerts et al., 2009; Sanderman and Baldock, 2010). For example, in a detailed analysis of the Upper Midwest region, often heralded as a prime candidate for large-scale carbon sequestration, Fissore et al. (2010) reach the conclusion that, in that region at least, "there is limited capacity for terrestrial C sequestration." These major differences of opinion among

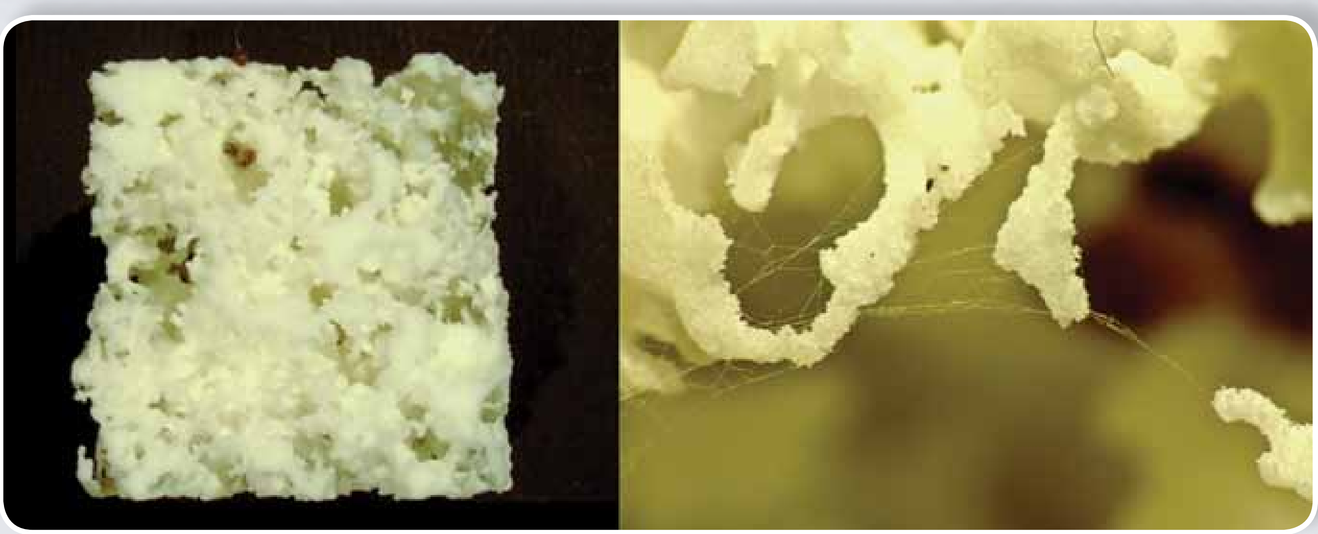


Fig. 4. Novel three-dimensional (3D) printing technologies afford innovative approaches to study interactions between pore geometry and microorganisms. A 3D replicate of soil structure derived from X-ray computed tomography data and printed in 3D Nylon 12 (**left**, sample size approximately 4 × 4 × 4 cm) enables a detailed analysis of the biophysical interactions influencing the colonization of the structure by the fungus *Rhizoctonia solani* (**right**). *Photos courtesy of the SIMBIOS Centre, Abertay University, and Loughborough University, UK.*

researchers about the feasibility of carbon sequestration appear caused in part by the extreme sensitivity of carbon accumulation toward the type of organic matter added to soils, as well as persistent questions about appropriate methodologies to sample soils (e.g., Senthilkumar et al., 2009; Syswerda et al., 2011).

Over the last decade, priming studies have demonstrated, time and again, that the simple addition of easily biodegradable carbon sources, or even some plant litter to soils as a way to stimulate sequestration, could seriously backfire and actually lead to decreases in soil carbon (Fontaine et al., 2004). Fontaine et al. (2007), for example, have shown that the addition of glucose to soils containing various types of organic matter, including some estimated to be around 2,500 years old, resulted in the biodegradation of some of this ancestral organic matter in addition to the added glucose. Similar results obtained by other researchers suggest that it may be tricky in practice to add organic matter in a way that does not cause more harm than good.

For a time, the adoption of no-tillage agricultural practices in agro-ecosystems was thought to be a realistic avenue for the sequestration of C in soils and is still frequently touted as such (e.g., Lal, 2010). However, results obtained by, e.g., VandenBygaart and Angers (2006), Baker et al. (2007), Yang et al. (2008), and Blanco-Canqui and Lal (2008) suggest that conclusions reached about the effectiveness of no-till depend strongly on how deep one is willing to dig to monitor soil organic matter changes. When one samples deeper in the soil profile than the traditional 30 or 40 cm, the alleged advantage of no-till over conventional tillage in terms of C sequestration disappears entirely or is even reversed in some cases.

Micro-heterogeneity of Soils

In the last few years, researchers have begun to recognize that the physical and chemical microenvironments in which microorganisms proliferate and are metabolically active in soils are extremely heterogeneous at all spatial scales, particularly at the micrometric scale typical of many microorganisms (Fig. 4). Significant technological advances in recent years have provided soil researchers with routine access to X-ray computed tomography systems, which once a number of roadblocks get resolved (e.g., Baveye et al., 2010), will enable the geometry of pores and solids in soils to be visualized at resolutions as small as 0.5 μm. Concomitant progress in synchrotron-based microfluorescence spectroscopy and near-edge X-ray spectromicroscopy (NEXAFS) of thin sections of soils has led to observations of sharp differences in accumulation of trace metals (Jacobson et al., 2007) and chemical composition of the organic matter (Schumacher et al., 2005) in soils over minute distances of the order of nanometers to micrometers, respectively.

Simultaneously, comparisons between explicit pore-scale simulations and macroscopic continuum approximations have shown that inhomogeneous solute distribution within soil pores can significantly affect macroscopic estimates of elemental turnover rates and that the error associated with large-scale rate estimates depends on the type of reaction, pore geometry, reaction kinetics, and macroscopic concentration gradient (Meile and Tuncay,

Spotlight on Soils: SSSA Celebrates 75th Anniversary

The Soil Science Society of America (SSSA), the international scientific Society that is the professional home to more than 6,000 soil scientists, celebrated its 75th anniversary in 2011 along with the 75th anniversary of its flagship journal, the *Soil Science Society of America Journal*.

In October, the organization held several anniversary activities during its 2011 Annual Meeting in San Antonio, TX, including a special awards ceremony outdoors in the Arneson River Theatre followed by a 75th anniversary reception in Maverick Plaza.

A national outreach plan that was launched in 2011 will continue to promote awareness of the importance of soils and the soil science profession in coming years. For more on the campaign, see www.iheartsoil.org.

Founded in 1936, SSSA supports peer-reviewed publications, an Annual Meeting, science policy activities, and the Certified Professional Soil Scientist Program. Today, SSSA continues to help its members advance the field of soil science through outreach to teachers, undergraduate and graduate students, and members around the world.

"During our 75-year history, the Soil Science Society of America has had many accomplishments," notes SSSA President Charles W. Rice, Kansas State University. "From our peer-reviewed journals, Annual Meeting, and educational outreach, we have much to celebrate. We look forward to the next 75 years in SSSA history, as the importance of the soil ecosystem moves to the forefront of discussions about climate change, food security, water quantity and quality, contamination, and human health.

As part of its efforts to promote awareness of soils as a critical ecosystem resource, SSSA recently completed its assessment of the Grand Challenges facing the soil science discipline. SSSA identified the most critical future research needs in soil science, pointing to: climate change, food and energy security, waste treatment and water quality, and human and ecosystem health. For more information the Soil Grand Challenges, including the full list of short-, medium-, and long-term research goals, visit: www.soils.org/about-society/grand-challenges.

Left: A mariachi band plays during the SSSA 75th anniversary reception in San Antonio. **Right:** SSSA members with more than 50 years of membership gather for a photo.

Right: SSSA held a special awards ceremony outdoors in the Arneson River Theatre during its Annual Meeting in San Antonio.

2006; Li et al., 2006). These experimental and modelling results raise a number of intriguing questions about the adequacy of the bulk-averaged measurements of soil (bio) chemical properties that, at the moment, are routinely carried out in wet-chemistry or microbiology laboratories around the world (Jacobson et al., 2007; Baveye, 2009) and on which current models of C and N dynamics in soils are based (Gras et al., 2010, 2011). Other questions that remain largely unanswered at this stage relate to the type of measurement that should be performed, beside macroscopic averages, and to the proper way to reflect the macroscopic emergence of microscale heterogeneities in models of soil dynamics (Baveye, 2010).

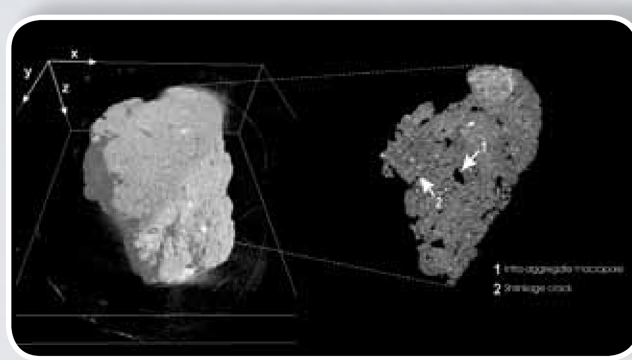
Soils Are a Crucial Frontier of Science: Why Does It Matter?

The various examples described and discussed in the preceding sections demonstrate that soil issues continue to be critical to the survival of mankind, let alone because even if floating cities ever develop, as some architects envision, most humans will still be in close contact with soils on a daily basis. Paradoxically, soils also remain, for the most part, very poorly understood, and research to improve that state of affairs will be challenging in the foreseeable future. In many respects, as Montgomery (2007) puts it, soils are our "most underappreciated, least valued, and yet essential natural resource."

A second reason for arguing the case that soils are a critical frontier of science is that doing so will require researchers to publicize the fact that there are still many aspects of soils that we are only dimly aware of or that remain extremely controversial. The soil science community in the past has not been keen to advertise its ignorance or to stimulate debates on contentious issues (Baveye, 2006; Baveye et al., 2006). This is understandable in the context of trying to convince skeptical audiences, for example groups of farmers in extension programs, that we know what we are talking about. However, a risk with such a portrayal is to make soil science appear boring and lackluster to prospective students, as if there were nothing left to discover about soils. This may in part explain the significant drops in enrollments in soil science in the last few years in most countries (Baveye, 2006; Baveye et al., 2006), with few exceptions (Baveye et al., 2010; Camargo et al., 2010). In other disciplines, areas of uncertainties are debated much more openly. They appear to stimulate great enthusiasm and attract the best minds among the younger generations. Perhaps a campaign to promote soils as a frontier of science could have a similar effect.

Take-Home Message

Over the last 75 years, much progress has been made in our understanding of a wide range of soil processes.



Reconstructed 3D view of an imaged soil aggregate and cross-sectional view of an image slice showing intra-aggregate macropores and shrinkage cracks. The aggregate has a diameter of approximately 5 mm, and the achieved voxel resolution was approximately 5 μm. *Image originally submitted with the* Soil Science Society of America Journal *article "Three-Dimensional Quantification of Intra-Aggregate Pore-Space Features using Synchrotron-Radiation-Based Microtomography" by Peth et al. (72:897–907).*

Yet, this knowledge does not always seem to be taken into account by decision makers, as is clearly the case in the various regions of the world that currently suffer from the same type of severe wind erosion as that of the 1930s in the U.S. In addition, in spite of all the progress made, there are still many aspects of soils about which little is known. In that sense, soils remain very much a frontier of science, as they were seven decades ago. Active emphasis of this "frontier" state of our discipline seems to be particularly appropriate at this time of shrinking financial support for scientific research across the board and of dwindling enrollments in soil science programs in most countries.

P.C. Baveye, *Laboratory of Soil and Water Engineering, Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY and SIMBIOS Centre, Abertay University, Dundee, Scotland, UK;* **D. Rangel**, *Laboratory of Soil and Water Engineering, Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, NY;* **A.R. Jacobson**, *Plants, Soils, and Climate Department, Utah State University, Logan, UT;* **M. Laba**, *Institute for Resource Information Sciences, Cornell University, Ithaca, NY;* **C. Darnault**, *Hydromechanics and Water Resources Engineering Laboratory, Department of Civil and Materials Engineering, University of Illinois at Chicago, Chicago, IL;* **W. Otten**, *SIMBIOS Centre, Abertay University, Dundee, Scotland, UK;* **R. Radulovich**, *Department of Agricultural Engineering, University of Costa Rica, San Jose, Costa Rica; and* **F.A.O. Camargo**, *Laboratory of Soil Microbiology, Department of Soils, Federal University of Rio Grande do Sul, Bento Goncalves, Porto Alegre, RS, Brazil*