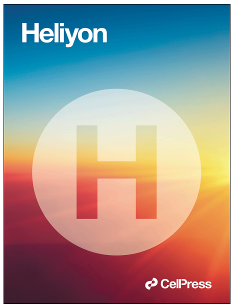

The unseen world beneath our feet: Heliyon Soil Science. Exploring the cutting-edge techniques and ambitious goals of modern soil science

Charlotte Poschenrieder, Riccardo Scalenghe

PII: S2405-8440(23)05986-8

DOI: https://doi.org/10.1016/j.heliyon.2023.e18778

Reference: HLY 18778

To appear in: *HELIYON*

Please cite this article as: The unseen world beneath our feet: Heliyon Soil Science. Exploring the cutting-edge techniques and ambitious goals of modern soil science, *HELIYON*, https://doi.org/10.1016/j.heliyon.2023.e18778.

Editorial

The unseen world beneath our feet: Heliyon Soil Science. Exploring the cutting-edge techniques and ambitious goals of modern soil science

Charlotte Poschenrieder[1], Riccardo Scalenghe[2]

[1]Universitat Autònoma de Barcelona, Spain [2]Università degli studi di Palermo, Italy

Abstract In the face of climate change, ecosystem destruction, desertification, and increasing food demand, soil conservation is crucial for ensuring the sustainability of life on Earth. The Soil Section of Heliyon aims to be a platform for basic and applied soil science research, emphasizing the central role of soils and their interactions with human activities. This editorial highlights recent research trends in soil science, including the evolving definition of soil, the multifunctionality of soils and their biodiversity, soil degradation and erosion, the role of soil microflora, advancements in soil mapping techniques, global change and the carbon cycle, soil health, the relationship between soil and buildings, and the importance of considering soil quality in land use planning and policies. The Heliyon Soil Science section seeks to publish scientifically accurate and valuable research that explores the diverse functions of soil and their significance in sustainable land-use systems.

In the present scenario of climate change, progressive destruction of natural ecosystems, desertification, increasing food demand, and social and economic uncertainties, soil conservation is a fundamental pillar for attaining the sustainability of our life on Earth. The Soil Section of Heliyon aims to be the mouthpiece of basic and applied soil science research visualizing this central role of soils and how it is impacted by human action.

The leitmotiv of Heliyon, and of its soil section, is to publish any paper reporting scientifically accurate and valuable research, which adheres to accepted ethical and scientific publishing standards. This editorial aims to highlight recent research trends that may guide and inspire our potential contributors.

Soil Science research has experimented spectacular change during the last decades and even the definition of soil and soil science is changing with the progress in experimental technologies and scientific knowledge (Hartemink, 2016). The view of soil as a mere physicochemical system serving as a substrate to sustain vegetation and crop production has been replaced by the recognition of the multifunctionality of soils and their biodiversity (Zheng et al., 2019; Zwetsloot et al., 2021). This is opening new perspectives into the research of the dynamic mechanisms putting soil into the centre of mitigation of climate change, carbon sequestration, sustainability of food production, nutrient cycling, water storage and purification, source of raw materials including construction materials, pharmaceuticals and genetic resources, and even the archaeological cultural heritage.

Among the captivating subjects that ignite the field of soil science, the degradation of soils, specifically erosion, stands out as a prominent topic (Borrelli et al., 2021). Undoubtedly, another crucial aspect to investigate is the living component of the soil, with a particular emphasis on the microflora (Angst et al., 2021; Coban et al., 2022; Wang et al., 2021).

The representation of soil on a map is inherently intertwined with the evolution of the discipline since its inception. This subject continues to captivate attention, particularly concerning the methods of gathering data (which are becoming increasingly from remote) and the systems employed for data processing (Liu et al., 2022; Poggio et al., 2021). An area of interest that is experiencing a rapid growth is the subject of global change (Yang et al., 2021), the ramifications related to the carbon cycle (Bai and Cutrufo, 2022; Villarino et al., 2021; Witzgall et al., 2021). The topic of soil health remains somewhat ambiguous, yet it is steadily gaining popularity.

The relationship between soil and buildings (Hjort et al., 2022) or soil as a building material (on other celestial bodies), however sporadic, are certainly themes of the future (Caluk and Azizinamini, 2023).

Land use, intricately tied to planning and policies, undergoes continuous evolution, necessitating an increasing emphasis on the consideration of soil quality (Winkler et al., 2021; Zhou et al., 2021). A fertile land which can be likened to a metaphorical untouched wilderness, demanding utmost attention.

Illustrating the functions of soil: An in-depth perspective

In an era marked by growing concerns over environmental sustainability and food security, the Heliyon Soil Science section has the ambition to open some windows on the complicated dynamics of Earth's most vital resource: soil. Soil that since the dawn of humankind has developed various functions, in addition to the original one of supporting life on planet Earth. Functions that would satisfy the development and growth of this new and demanding species. In earlier times, when technology was limited, land use was restricted by the natural functions of the soil. Over time, however, advances in technology have led to a disconnection between soil functions and land use. When certain natural functions were inadequate for specific types of land use, humans employed technology to solve the problem: wet soils were drained, dry soils irrigated, poor soils fertilized. Recently, there has been a growing emphasis on sustainable development, which has highlighted the negative consequences of altering natural soil functions. Drainage, for instance, can cause peat oxidation, the creation of greenhouse gases, and acidification. Irrigation may result in salinization. Over-fertilization can result in water pollution. To achieve sustainable land-use systems that balance economic, environmental, and social criteria, it is important to consider natural soil functions to avoid disrupting natural processes, which can be difficult to correct. Soil performs various functions, and we can differentiate them based on their roles. Some commonly mentioned soil functions include: (1) producing crops, (2) carrying traffic and buildings, (3) filtering, buffering, and reacting to solutes passing through, (4) providing base materials for industry, (5) offering a habitat for plants, animals, and microbes and (6) reflecting past practices as a cultural and historical artefact (Bouma, 2006). The goal of HLY Soil Science is to host papers describing at least one of these soil functions.

Some extreme examples: soil reflecting past practices, soil filtering-buffering-reacting capacity, plant and soil interaction

>Between other functions, soil also plays an important role in the preservation of our archaeological records. In this case, some essential techniques that have gained significance. For instance, the possibility of studying isotopes has opened many windows on our past: carbon (Frumkin and Comay, 2021), or nitrogen (Szpak, 2014), or strontium (Sr) isotopes (Britton et al., 2020 The first nationwide Sr isotope baselines are starting to be available (Ladegaard-Pedersen et al., 2020; Snoeck et al., 2020). Cutting-edge techniques, such as analysing rare earth elements (REE) in both soils and artefacts, might provide crucial information about the history of the area and the origin of the materials used by ancient civilizations (Andreae et al., 2020; Scalenghe et al., 2015). In addition, for the exploration of the historical function of the soil some techniques have become important:

- Light Detection and Ranging (LiDAR) (Dorison, 2022)
- X-ray fluorescence spectroscopy (Kennedy and Kelloway, 2021)
- Uranium–thorium (U-Th) dating (Sear et al., 2020)
- Multi-sensorial remote sensing (Dalton et al., 2022)
- High-throughput sequencing (Teuber et al., 2017)
- Portable X-ray fluorescence (pXRF) (Williams et al., 2020)
- Unmanned aerial vehicles (Orengo and Garcia-Molsosa, 2019)
- 3D Printing (Needham et al., 2022).

>Soils act as both source and sink of greenhouse gases thus strongly influencing global climate. Both the organic (SOC) and inorganic (SIC) soil carbonools can contribute to the opposed processes of sequestration and release of atmospheric CO_2. An important step to understand these complex processes is the development of easy-to-hand technologies for the assessment of soil carbon stock worldwide. A cost-efficient methodology is further

required for the establishment of unified protocols of measurement, reporting and verification (MRV) that are used to credit carbon sequestration by farmers (Oldfield et al., 2022). Sampling, models, and remote sensing technologies are currently used alone or in combination (hybrid approaches) to assess soil carbon. The precise estimation implies expensive sampling and analytical tasks. The spatiotemporal variations of SOC in different agroecosystems and our gaps in understanding the processes that determine stabilization versus decomposition of SOC are major limitations (Harden et al., 2018). Recently, a simple indicator system suitable for multiple purposes has been developed (Wiesmeier et al., 2019). The system is based on soil texture and allows rough estimations of SOC over different scale ranges under temperate climates. The LandPKS mobile app helps for quick soil texture estimation (https://landpotential.org/mobile-app/). Unfortunately, this indicator system is not suitable for tropical climate and paddy soils and further developments for these more complex scenarios are urgently needed.

Soil microorganisms are main drivers of soil processes including cycling of carbon, nitrogen, and other nutrients. Microbe activity thus largely determines the role of soils in both climate change mitigation (Naylor et al., 2020) and food production. The fast development and cheapening of omic tools allow now to characterize the biodiversity of soil microorganisms thus opening wide possibilities for studying soil microbe functions in sequestration and release of greenhouse gases, in nutrient cycling, and in the sustainable production of healthy food. “Omic” approaches in soil science are using genomics, metagenomics, transcriptomics, proteomics, metabolomics, and ionomics to assess the dynamic interactions among soil microbes, and among soil microbes, plants, and the physical and chemical soil components. These complex interactions largely determine the multifunctionality of soil and their ability to provide agroecosystem services for sustainability. Both the biomass and the biodiversity of the soil microbiome is enormous and despite quick progress in genomic studies most soil microbes are still unidentified. How agronomic practices such as fertilization, organic amendments, pH corrections, tilling, irrigation, and crop species and genotypes affect soil microbiome diversity and, in consequence, soil multifunctionality is a further research area of global interest.

Another problem that needs the development of new experimental approaches is the difficulty of the functional characterization of soil microbes that are not culturable but may play an important role in soil properties. Especially under stressful conditions certain bacteria enter in a viable, but not culturable state. Combination of metagenomics, metatranscriptomics and proteomics can provide useful information on the identity and functionality of such microorganisms. The development of artificial intelligence (AI) and machine learning (ML) tools is essential for handling the huge amount of data and for the establishment of both useful models and Artificially Intelligent Soil Quality Index (AISQI) (Gomes Zuppa de Andrade et al., 2021). Fruitful approaches thus require a close cooperation among soil scientists, microbiologists, and bioinformatics.

>Soil fertility is a main factor determining both crop yield and food quality (Fischer et al., 2020). Plant-based food is becoming increasingly popular especially for reducing the environmental footprint of our diet (Alcorta et al., 2021). A plant's capacity to supply essential minerals to consumers depends on three main factors: availability in the soil (Barrow and Hartemink, 2023), the plant's efficiency to take up and transport the mineral to edible parts (Huang et al., 2022), and the bioavailability of the mineral nutrient to the consumer (Huey et al., 2022). On a global scale, about 25% of the soils are alkaline. Low availability of essential micronutrients like Fe and Zn are characteristic for these high pH soils. In fact, crop yields are affected by Zn and/or Fe deficiency in many of the areas with alkaline soils. Low levels of these micronutrients, especially in grain crops like rice and wheat, can consequently lead to malnutrition, mainly hitting the low-income population (Bailey et al., 2015). Biofortification of cereal crops, especially with Zn and Fe, but also Se

and iodine is a major objective of current research (Cakmak and Kutman, 2018; Dwidevi et al., 2023; Izydorczyk et al., 2021). Ongoing biofortification studies consider agronomic biofortification, genetic biofortification, and microbial biofortification. Agronomic biofortification is an efficient tool to enhance the availability of target micronutrients and their uptake by plants on deficient soils. Current research in this field mainly focuses on more efficient fertilizers and amendments through the development of new formulations including nanoparticles with different coatings or microfluidic encapsulation (Le et al., 2021), foliar applications (Husted et al., 2023), and organic amendments (Celestina et al., 2019). Recent life-cycle assessment studies showed advantages of nanofertilizers of different micronutrients over conventional fertilizers (Escribà-Gelonch et al., 2023). Bottlenecks for a global application of fertilizers based on nanotechnology are improvement of efficiency (Su et al., 2022) and uncertainties about their transformation processes in the soil and the derived environmental impact (dos Santos et al., 2022).

Microbial biofortification uses microorganisms to enhance availability and uptake of nutrients by plants. Unfortunately, most of the studies using plant growth promoting microorganisms are being performed under controlled lab or greenhouse conditions in microcosm or mesocosm approaches. Although, recently, promising results from field experiments have been reported (Ahmad et al., 2023), the development of commercial synthetic microbial communities (SynComs) is complex and multidisciplinary approaches are necessary to develop more efficient SynComs (Delgado -Baquerizo, 2022). Moreover, long-term field trials analyzing microbe survival rates and efficiency, as well as cost-benefit analyses are clearly required.

Genetic biofortification uses breeding, and gene editing approaches for achieving both higher nutrient efficiency (enhanced uptake and translocation to grain) and improvement of bioavailability to humans of grain micronutrients. However, excessive boosting of micronutrient availability in the soil and/or overexpression of genes to enhance uptake can cause yield penalties due to phytotoxicity. Improved knowledge on the ion homeostasis mechanisms in plants, especially concerning the regulatory mechanisms that govern the balance between uptake, binding, transport and storage in different compartments and organs is required to solve this bottleneck.

For the successful development and management of biofortified crops it is evident that agronomic, genetic, and microbial biofortification, are not alternative strategies but must be approached together to achieve an optimal bioavailability of nutrients in human diets and animal feed. For this purpose, both basic and applied research is required to achieve a better knowledge on soil-plant genotype-microbe feedbacks which is crucial for the development of efficient rhizosphere engineering (Zhang et al., 2023) and biofortification strategies.

Pollution of soils with inorganic and organic contaminants is of ever-growing concern. In addition to old burdens, mainly heavy metals and metalloids from mining activities and metal processing industries and classical organic pollutants like PCBs and PAHs, new, still poorly explored danger is coming, among others, from e-waste, pharmaceuticals, nanoparticles, microplastics and microfibers (Moekel et al., 2020; Xu et al., 2021; Shah et al., 2022; Chai et al.,2020; Kwak and An, 2021). How soil multifunctionality is affected by these new threats is a further hot topic that deserved research efforts, especially considering real field situations.

Conclusions and perspectives

Ambitious goals of modern soil science which would be intriguing to be discussed in this journal:

- When soil is unsealed, pedogenesis begins anew. Which direction this process takes and the key factors necessary for the soil to perform all its original functions are important considerations
- Utilizing extraterrestrial soil for the construction of habitats on celestial bodies

- Collection, mapping, and standardizing soil data for informed predictions based on preexisting knowledge
- Indicator systems for soil carbon under tropical climate and for paddies
- Integration of different soil “omic” aproaches, soil indicators, IA, and ML for creating soil quality and health indexes
- Fate of new soil pollutants
- Basic and applied research into soil – plant-genotype - microbe feedbacks for the development of efficient rhizosphere engineering and biofortification strategies.

Essential components for a successful submission to HLY soil science, addressing the reader's expectations

When preparing a paper to submit to HLY Soil Science, it is crucial not to overlook certain key aspects that emphasize the importance of open data availability, replicability of experiments, precise geographic information, and accurate taxonomic classifications. By addressing these elements, you can enhance the reader's experience and fulfil their expectations. Here are the essential considerations to include in your paper:

Open Data: Emphasize the availability of your research data in an open and accessible format. Provide a clear description of where the data can be obtained, whether it is through a public repository, a dedicated website, or any other means. This transparency fosters scientific collaboration and allows others to replicate or build upon your findings.

Replicability: Provide detailed descriptions of your experimental procedures and methodologies to ensure replicability, enabling other researchers to reproduce your experiments and validate your results.

Precise geographic information: Clearly specify the precise geographic location of your study site using coordinates (latitude and longitude). This information enables accurate spatial referencing and allows for better comparison and integration with other studies. It also aids in establishing the context of your research within a specific geographical region.

Precise and updated soil taxonomy: Utilize a precise and updated soil taxonomy system to classify the soils studied in your research. Adhere to internationally recognized classification systems, such as the World Reference Base for Soil Resources (WRB), ensuring consistency and facilitating cross-referencing with other studies. When possible, please, include detailed soil profile descriptions, physical and chemical properties, and any relevant soil classification updates.

Plant and animal taxonomies: Include accurate and up-to-date taxonomic classifications for the plant and animal species mentioned in your study. Provide complete scientific names, including genus, species, and, if necessary, subspecies or varieties. This precision ensures clarity and facilitates further research or comparisons with other studies.

By incorporating these essential elements into your paper, you demonstrate a commitment to open science principles, enhance the reproducibility of your research, provide valuable geographic context, and ensure accurate taxonomic classifications. These considerations not only align with the expectations of readers and reviewers in the field of soil science but also contribute to the broader scientific community by facilitating collaboration, knowledge exchange, and the advancement of research in related disciplines.

Acknowledgments

The Food and Agriculture Organization (FAO) has crafted an infographic elucidating the functions of soil, and we extend our gratitude for granting us the permission to utilize it.

References

Ahmad, M., Hussain, A., Dar, A., Luqman, M., Ditta, A., Iqbal, Z., Ahmad, H.T., Soufan, F.N., Almutairi, K., El Sabagh, A. 2023. Combating iron and zinc malnutrition through mineral biofortification in maize through plant growth promoting Bacillus and Paenibacillus species. Frontiers in Plant Science, 15, 1094551, doi: 10.3389/fpls.2022.1094551

Alcorta, A., Porta, A., Tárrega, A., Alvarez, M.D., Vaquero, M.P. 2021. Foods for plant-based diets: challenges and innovations. Foods, 10, 293, doi: 10.3390/foods10020293

Andreae, M.O., Al-Amri, A., Andreae, T.W., Garfinkel, A., Haug, G., Jochum, K.P., Stoll, B., Weis, U. 2020. Geochemical studies on rock varnish and petroglyphs in the Owens and Rose Valleys, California. PLoS ONE e0235421, doi: 10.1371/journal.pone.0235421

Angst, G., Mueller, K.E., Nierop, K.G.J., Simpson, M.J. 2021. Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. Soil Biology & Biochemistry 156, 108189, doi: 10.1016/j.soilbio.2021.108189

Bai, Y.F., Cotrufo, M.F. 2022. Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science 377, 603–608, doi: 10.1126/science.abo2380

Bailey, R.L., West Jr, K.P., Black, R.E. 2015. The epidemiology of global micronutrient deficiencies. Annals of Nutrition and Metabolism, 66(2), 22–33, doi: 10.1159/000371618

Barrow, N.J., Hartemink, A.E. 2023. The effects of pH on nutrient availability depend on both soils and plants. Plant and Soil doi: 10.1007/s11104-023-05960-5

Borrelli et al., 2021. Soil erosion modelling: A global review and statistical analysis. Science of the Total Environment 780, 146494, doi: 10.1016/j.scitotenv.2021.146494

Bouma, J. 2006. Soil functions and land use. In: Certini G., Scalenghe R. (eds.) Soils: Basic Concepts and Future Challenges, 9780521851732, pp. 211–222, doi: 10.1017/CBO9780511535802.016

Britton, K., Le Corre, M., Willmes, M., Moffat, I., Grün, R., Mannino, M.A., Woodward, S., Jaouen, K. 2020. Sampling plants and malacofauna in 87Sr/86Sr bioavailability studies: implications for isoscape mapping and reconstructing of past mobility patterns. Frontiers in Ecology and Evolution 8, 579473, doi: 10.3389/fevo.2020.579473

Cakmak, I., Kutman, U.B. 2018. Agronomic biofortification of cereals with zinc: a review. European Journal of Soil Science, 69, 172–180, doi: 10.1111/ejss.12437

Caluk, N., Azizinamini, A. 2023. Introduction to the concept of modular blocks for lunar infrastructure. Acta Astronautica 207, 153–166, doi: 10.1016/j.actaastro.2023.03.004

Celestina, C., Hunt, J.R., Sale, P.W.G., Franks, A.E. 2019. Attribution of crop yield responses to application of organic amendments: A critical review. Soil and Tillage Research, 186, 135–145, doi: 10.1016/j.still.2018.10.002

Chai, B., Li, X., Liu, H., Lu, G., Dang, Z., Yin, H. 2020. Bacterial communities on soil microplastics at Guiyu, an e-waste dismantling zone of China. Ecotoxicology and Environmental Safety, 195, 110521, doi: 10.1016/j.ecoenv.2020.110521

Coban, O., De Deyn, G.B., van der Ploeg, M. 2022. Soil microbiota as game-changers in restoration of degraded lands. Science 375, 990, doi: 10.1126/science.abe0725

Dalton, M., McMahon, J., Kennedy, M.A., Repper, R., Al Shilali, S.E., AlBalawi, Y., Boyer, D.D., Thomas, H. 2022. The Middle Holocene 'funerary avenues' of North-West Arabia. The Holocene 32 (3),183–199, doi: 10.1177/09596836211060497

Delgado-Baquerizo, M. 2022. Simplifying the complexity of the soil microbiome to guide the development of next-generation SynComs. Journal of Sustainable Agriculture and Environment, 1, 9–15, doi: 10.1002/sae2.12012

Dorison, A. 2022. Ancient agriculture on lava flows: Using LiDAR and soil science to reassess pre-hispanic farming on Malpais landforms in West Mexico. Journal of Ethnobiology 42 (2), 131–151, doi: 10.2993/0278-0771-42.2.131

dos Santos, O.A.L., Backx, B.P., Abumousa, R.A., Bououdina, M. 2022. Environmental Implication associated with the development of nanotechnology: From synthesis to disposal. Nanomaterials, 12, 4319, doi: 10.3390/nano12234319

Dwidevi, S.L., Garcia-Oliveira, A.L., Govindaraj, M., Ortiz, R. 2023. Biofortification to avoid malnutrition in humans in a changing climate: Enhancing micronutrient bioavailability in seed, tuber, and storage roots. Frontiers in Plant Science, 14, 119148, doi: 10.3389/fpls.2023.1119148

Escribà-Gelonch, M., Butler, G.D., Goswani, A., Tran, N.N., Hessel, V. 2023. Definition of agronomic circular economy metrics and use for assessment for a nanofertilizer case study. Plant Physiology and Biochemistry, 196, 917–94, doi: 10.1016/j.plaphy.2023.02.042.

Fischer, S., Hilger, T., Piepho, H.-P., Jordan, I., Karungi, J., Towett, E., Shepherd, K., Cadish, G. 2020. Soil and farm management effects on yield and nutrient concentrations of food crops in East Africa. Science of the Total Environment, 716, 137078, doi: 10.1016/j.scitotenv.2020.137078

Frumkin, A., Comay, O. 2021. The last glacial cycle of the southern Levant: Paleoenvironment and chronology of modern humans. Journal of Human Evolution 160, 102609, doi: 10.1016/j.jhevol.2019.04.007

Gomes Zuppa de Andrade, V.H., Redmile-Gordon, M., Groenner Barbosa, B.H., Dini Andreote, F., Würdig Roesch, L.F., Satler Pylro, V. 2021. Artificially intelligence soil quality and health indices for "next generation" food production systems. Trends in Food Science & Technology, 107, 195–200, doi: 10.1016/j.tifs.2020.10.018

Hartemink, A.E. 2016. Chapter two - The definition of soil since the early 1800s. Advances in Agronomy, 73–126, doi: 10.1016/bs.agron.2015.12.001

Hjort, J., Streletskiy, D., Dore, G., Wu, Q.B., Bjella, K., Luoto, M. 2022. Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment 3, 24–38, doi: 10.1038/s43017-021-00247-8

Huang, S., Yamaji, N., Ma, J.-F. 2022. Zinc transport in rice: how to balance optimal plant requirements and human nutrition. Journal of Experimental Botany, 73, 1800–1808, doi: 10.1093/jxb/erab478

Huey, S.L., Mehta, N.H., Konieczynki, E.M., Bhargava, A., Friessen, V.M., Krisher, J.T., Mbuya, M.N.N., Monterrosa, E., Nyangaresi, A.M., Boy, E., Mehta, S. 2022. Bioaccessibility and bioavailability of biofortified food and food products: Current evidence. Critical Reviews in Food Science and Nutrition doi: 10.1080/10408398.2022.2142762

Husted, S., Minutello, F., Pinna, A., Le Tougaard, S., Møs, P., Kopittke, P.M. 2023. What is missing to advance foliar fertilization using nanotechnology? Trends in Plant Science, 28, 90–104. doi: 10.1016/j.tplants.2022.08.017

Izydorczyk, G., Ligas, B., Mikula, K., Witek-Krowiak, A., Moustakas, K., Chojnacka, K. 2021. Biofortification of edible plants with selenium and iodine – a syst,ematic literature review. Science of the Total Environment, 754, 141983 doi: 10.1016/j.scitotenv.2020.141983

Kennedy, S.A., Kelloway, S.J. 2021. Heavy metals in archaeological soils the application of portable X-ray fluorescence (pXRF) spectroscopy for assessing risk to human health at industrial sites. Advances in Archaeological Practice 9, 2, 145–159, doi: 10.1017/aap.2020.52

Kwak, J.I., An, Y.-J. 2021. Post COVID-19 pandemic: Biofragmentation and soil ecotoxicological effects of microplastics derived from face masks. Journal of Hazardous Materials, 416, 126169. doi:10.1016/j.jhazmat.2021.126169

Ladegaard-Pedersen, P., Achilleos, M., Dörflinger, G., Frei, R., Kristiansen, K., Frei, K.M. 2020. A strontium isotope baseline of Cyprus. Assessing the use of soil leachates, plants, groundwater and surface water as proxies for the local range of bioavailable strontium isotope composition. Science of the Total Environment 708, 134714, doi: 10.1016/j.scitotenv.2019.134714

Le, T.N.Q., Tran, N.N., Escribà-Gelonch, M., Serra, C.A., Fisk, I., McClements, D.J., Hessel, V. 2021. Microfluidic encapsulation for controlled release and its potential for nanofertilizers. Chemical Society Reviews, 50, 11979, doi: 10.1039/D1CS00465D

Liu, F., Wu, H.Y., Zhao, Y.G., Li, D.C., Yang, J.L., Song, X.D., Shi, Z., Zhu, A.X., Zhang, G.L. 2022. Mapping high resolution National Soil Information Grids of China. Science Bulletin 67, 328–340, doi: 10.1016/j.scib.2021.10.013

Moekel, C., Breivik, K., Nøst, T.H., SAnkoh, A., Jones, K.C., Sweetman, A. 2020. Soil pollution at a major West African E-waste recycling site: Contamination pathways and implications for potential mitigation strategies. Environment International, 137, 105563, doi: 10.1016/j.envint.2020.105563

Naylor, D., Sadler, N., Bhattacharjee, A., Graham, E.B., Anderton, C.R., McClure, R., Lipton, M., Hofmockel, K.S., Jansson, J.K. 2020. Soil microbiomes under climate change and implications for carbon cycling. Annual Review of Environmental Resources, 45, 29–59, doi: 10.1146/annurev-environ-012320-082720

Needham, A., Wisher, I., Langley, A., Amy, M., Little, A. 2022. Art by firelight? Using experimental and digital techniques to explore Magdalenian engraved plaquette use at Montastruc (France). PLoS ONE e0266146, doi: 10.1371/journal.pone.0266146

Oldfield, E.E., Eagle, A.J., Rubin, R.L., Rudek, J., Sanderman, J., Gordon, D.R. 2022. Crediting agricultural soil carbon sequestration. Science, 375, 122–1225, doi: 10.1126/science.abl799

Orengo, H.A., Garcia-Molsosa, A. 2019. A brave new world for archaeological survey: Automated machine learning-based potsherd detection using high-resolution drone imagery. Journal of Archaeological Science 112, 105013, doi: 10.1016/j.jas.2019.105013

Poggio, L., de Sousa, L.M., Batjes, N.H., Heuvelink, G.B.M., Kempen, B., Ribeiro, E., Rossiter, D. 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. SOIL 7, 217–240, doi: 10.5194/soil-7-217-2021

Scalenghe, R., Barello, F., Saiano, F., Ferrara, E., Fontaine, C., Caner, L., Olivetti, E., Boni, I., Petit, S. 2015. Material sources of the Roman brick-making industry in the I and II century A.D. from Regio IX, Regio XI and Alpes Cottiae. Quaternary International 357, 189–206, doi: 10.1016/j.quaint.2014.11.026

Sear, D.A., Allen, M.S., Hassall, J.D., Maloney, A.E., Langdon, P.G., Morrison, A.E., Henderson, A.C.G., Mackay, H., Croudace, I.W., Clarke, C., Sachs, J. P., Macdonald, G., Cisneros-Dozal, L.M., Fonville, T. 2020. Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought. Proceedings of the National Academy of Sciences of the United States of America 117(16), 8813–8819, doi: 10.1073/pnas.1920975117

Shah, G.M., Amin, M., Shahid, M., Ahmad, I., Khalid, S., Abbas, G., Imran, M., Naeem, M.A., Shahid, N. 2022. Toxicity of ZnO and Fe_2O_3 nano-agro-chemicals to soil microbial activities, nitrogen utilization, and associated human health risks. Environmental Sciences Europe, 34, 106, doi: 10.1186/s12302-022-00687-z

Snoeck, C., Ryan, S., Pouncett, J., Pellegrini, M., Claeys, P., Wainwright, A.N., Mattielli, N., Lee-Thorp, J.A., Schulting, R.J. 2020. Towards a biologically available strontium isotope baseline for Ireland. Science of the Total Environment 712, 136248, doi: 10.1016/j.scitotenv.2019.136248

Su, Y., Zhou, X., Meng, H., Xia, T., Liu, H., Rolshausen, P., Roper, C., McLean, J.E., Zhang, Y., Keller, A.A., Jassby, D. 2022. Cost-benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. Nature Food, 3, 1020–1030. doi: 10.1038/s43016-022-00647-z.

Szpak, P. 2014. Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices. Frontiers in Plant Science 5, 288, doi: 10.3389/fpls.2014.00288

Teuber, S., Ahlrichs, J.J., Henkner, J., Knopf, T., Kuhn, P., Scholten, T. 2017. Soil cultures - The adaptive cycle of agrarian soil use in Central Europe: an interdisciplinary study using soil scientific and archaeological research. Ecology and Society 22 (4), 13, doi: 10.5751/ES-09729-220413

Villarino, S.H., Pinto, P., Jackson, R.B., Pineiro, G. 2021. Plant rhizodeposition: A key factor for soil organic matter formation in stable fractions. Science Advances 7, eabd3176, doi: 10.1126/sciadv.abd3176

Villarino, S.H., Pinto, P., Jackson, R.B., Pineiro, G. 2021. Plant rhizodeposition: A key factor for soil organic matter formation in stable fractions. Science Advances, 7, eabd3176. doi: 10.1126/sciadv.abd3176

Wang, B.R., An, S.S., Liang, C., Liu, Y., Kuzyakov, Y. 2021. Microbial necromass as the source of soil organic carbon in global ecosystems. Soil Biology & Biochemistry 162, 108422, doi: 10.1016/j.soilbio.2021.108422

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., Von Lützow, M., Marin-Spiotta, E., Van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.-J., Kögel-Knabner, I. 2019. Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. Geoderma, 333, 149–162, doi: 10.1016/j.geoderma.2018.07.026

Williams, R., Taylor, G., Orr, C. 2020. pXRF method development for elemental analysis of archaeological soil. Archaeometry 62 (6), 1145–1163, doi: 10.1111/arcm.12583

Winkler, K., Fuchs, R., Rounsevell, M., Herold, M. 2021. Global land use changes are four times greater than previously estimated. Nature Communications 12, 2501, doi: 10.1038/s41467-021-22702-2

Zhou, Y., Li, X.H., Liu, Y.S. 2021. Cultivated land protection and rational use in China. Land Use Policy 106, 105454, doi: 10.1016/j.landusepol.2021.105454

Zwetsloot, M.J., van Leeuwen, J., Lemmerik, L., Martens, H., Simó Josa, I., Ven de Broek, M., Debeljak, M., Rutgers, M., Sandén, T., Wall, D.P., Jones, R.E., Creamer, R.E. 2021. Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. European Journal of Soil Science, 72, 1640–1654, doi: 10.1111/ejss.13051