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A Perspective on Chemistry and Society

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Chemical Innovation for Sustainable Agriculture by Investing in Soil Health

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Claudio Screpanti is an agronomist working in Syngenta R&D organization in Switzerland. He has several years of experience in agricultural research. He obtained his PhD in agronomy from the University of Bologna, Italy in 2003. He carried out additional studies in molecular biology and genetic engineering at the University of Louvain-la-Neuve, Belgium. Later, Claudio joined the Syngenta R&D organization, covering different scientific roles always in relation to soil biology. In 2018 he became a Syngenta Fellow, a company award recognizing outstanding scientific achievements. In his current role, Claudio leads the Soil Health Centre in Stein (Switzerland) and acts as Syngenta soil expert looking at the behavior and effects of new small molecules in the soil-crop systems. The aim is to support the discovery and development of new and more sustainable crop protection solutions.

Agriculture and Current Challenges

There is an increasing urgency for a more resilient and sustainable way to produce food, feed and fibers. Science and technologies can play a pivotal role in these endeavors. A broad array of new promising technologies is steeply growing in the farming area spanning from precision agriculture techniques, advanced modeling and predictive approaches to optimize inputs, new crop breeding programs up to microbiome harnessing to improve crop performance and resilience against the major climatic and pest threats.[1,2]

Beside this technological panoply, there is an emergent trend towards new and exciting opportunities to support sustainable agriculture using chemical innovation. In the following paragraphs, new perspectives on how chemistry can contribute and support food production in the context of some of the major challenges of this century will be presented.

Soil Health and Priorities for the Global Challenges

More than 95% of food comes from soil. However, there is an increasing concern about the rapid degradation of soil resources. New actionable programs have been put in place to preserve this non-renewable resource.[3] Soil health, as an emerging concept, has gained increasing attention in several scientific, social, and political areas in recent years. Soil health can be defined as "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health".[4] New policies aiming at preserving soil were promoted in several geographies like Switzerland, EU and beyond.[5–7]

Using soil health as criterion to drive innovation in agriculture requires a solid evaluation framework to profile any new and promising technology.[8–10] Identifying the best approach to measure soil health is still a matter of debate,[8–11] here, a framework suitable for crop protection R&D is presented. Three major priorities reflecting the global challenges are considered: promote soil biodiversity, preserve soil from major threats and mitigate climate changes (as indicated in Fig. 1). These priorities enable to identify eight targets to evaluate the impact of new technologies.

Several enabling technologies and agronomical management practices have been disclosed as impactful to support and improve the soil health addressing one or more of the highlighted targets,[4,11,12] yet in this context, the potential role of chemical-based technologies has been often neglected and discounted, even though a tremendous role is played by natural small molecules on a multitude of processes below ground.[13–15] It is worth mentioning the striking and not yet

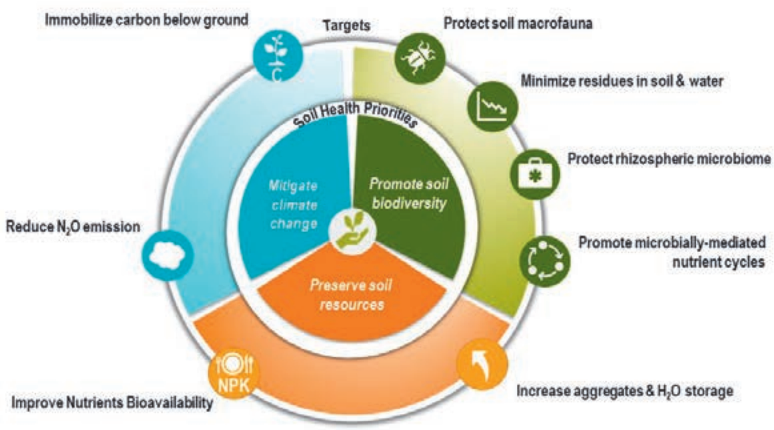

Fig.1. Framework with soil health priorities and associated targets.

fully uncovered chemical diversity that can be found below ground with thousand different chemical features isolated from the roots of different plant species.[14,16] The next section aims to provide a historical perspective of the role of chemistry in the soil and crop sciences and how it evolved in the last centuries. Such perspectives will help to highlight possible trajectories for the chemical innovation for future agriculture.

Soil and Chemistry: A Historical Perspective.

The importance of chemistry in soil and the relevance for crop production goes back to the nineteenth century with the first attempts by von Thaer in Germany,[17] Davy in England,[18] and Boussingault in France[19] to shed light on the essential role of soil to support plant growth by providing nutrients. Later Way unveiled the ability of soil to exchange ions and the underlying the ion-sorption processes;[20] and then together with Liebig's work[21] they set up the foundations for the soil fertilization and ultimately contributed to the soil fertility concept. Other milestones followed in the twentieth century and marked the contribution of the chemical innovation in the agriculture particularly with the Haber-Bosch process through which it became possible to synthesize ammonia from atmospheric nitrogen with the help of iron-based catalyst, paving the way for modern agriculture and use of synthetic fertilizer.[22]

From the 1950s onwards chemical innovation sustained a growing crop protection industry with many – among others – soil-applied agrochemicals.[23] This innovation led to a significant increase in labor and land productivity[24] as well as in food security.[25,26]

Whilst the past technological efforts were devoted to more abundant and safer foods, the future emerging direction points to the urgent needs of more sustainable food production addressing the major interconnected global challenges like climate change[27] and biodiversity and soil losses.[3] Thus, this historical perspective leads to enquiry how chemical innovation can support sustainable agriculture by targeting soil health?

Chemical Innovation Targeting Soil Health

As indicated in Fig. 1, the framework for implementing soil health science in crop protection R&D identified eight major targets. For succinctness purpose, only a few of them will be discussed in this section.

Minimizing residues of future chemical crop protection solutions is one of the highest priorities to support soil health. To this end, information about the environmental degradability of early chemical leads should be available as early as possible and drive a rational chemical design. Therefore, new alternative predictive approaches able to provide swiftly and in a high-throughput manner indications about degradation are highly valuable.[28,29] A few recent investigations harvested some encouraging results, the published approach hinged on the fast evaluation of the degradation kinetics of a wide range of compounds on activated sludge systems and used this to predict soil half-lives from studies with a regulatory setting. Satisfactory predictions across a wide range of agrochemicals were observed and were superior to other approaches relying on other available predictive models.[28]

Protecting the soil microbial community and promoting the microbial nutrient cycles hold great potential. In this respect the naturally occurring below-ground chemicals particularly in the rhizosphere – the thin interface between plant roots and near soil – represents unique and fascinating examples of 'Chemistry-in-action' underpinning a vast range of biological interactions and biogeochemical processes with a fundamental ecological relevance and exceedingly important agronomical implications. Plants strongly contribute to such a 'Chemical parade' by deploying up to 50% of their photosynthates in the rhizosphere[14] as primary or secondary metabolites (Fig. 2). They regulate several interactions as plant-plant; microbes-plant, plant-pest and nutrient assimilation.

Chemical signals like flavonoids are involved in the plant-microbe interactions and the recruitment of beneficial N-fixing rhizobial bacteria by the leguminous plants. Benzoxazinoids are multifunction molecules acting as phytosiderophores for iron assimilation and also mediate the recruitment of other beneficial microorganisms[30] or attract herbivore insects.[31]

Similarly, soil microorganism use signals to communicate and coordinate growth and other behavior features like competitions, symbiosis, or diseases. Several recent studies showed that rhizosphere microorganisms can produce antimicrobials like DAPG (2,4-diacetylphloroglucinol), PHZ (phenazines) and PRN (pyrrolnitrin) which can be active against pathogens causing different soil borne-diseases.[13,32] Soil microorganisms release also other classes of molecules acting as phytohormone compounds (*i.e.* auxins, gibberellins, and cytokinins) which influence the development and other physiological processes in plants.

If an anthropomorphic consideration would be allowed here, it could be stated that plants speak chemistry and use small molecules to call for food, cry for help and compete for space.

Understanding the hidden language of crops particularly below ground can be a way forward to synthetize natural

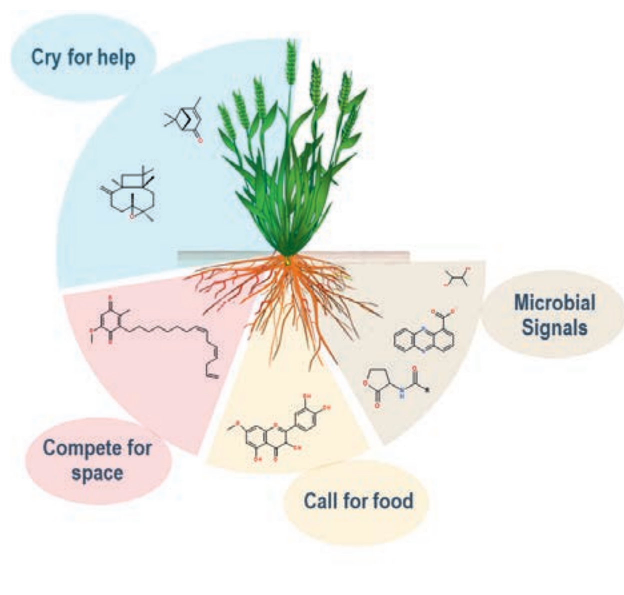

Fig. 2. Naturally above- and below-ground chemicals produced by plants and microbes and controlling several processes.

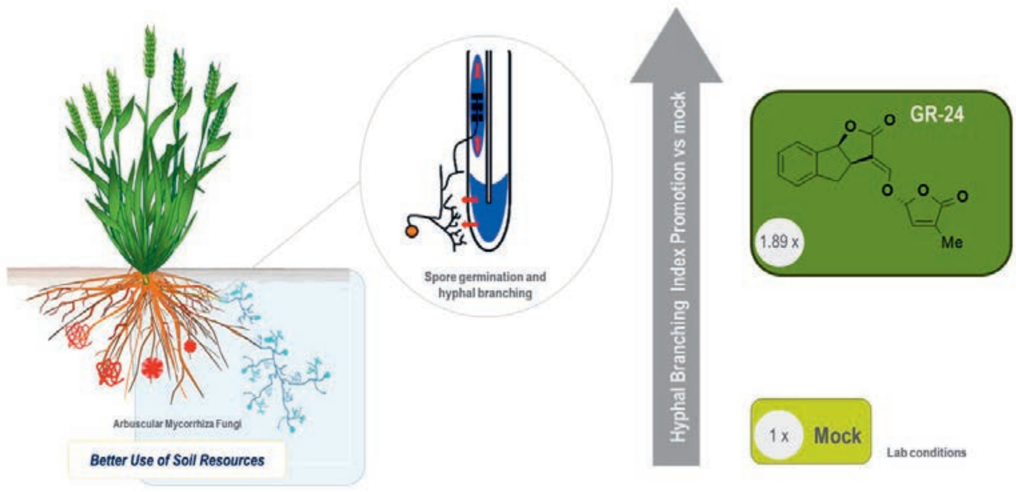

Fig. 3. Strigolactones derivatives induce hyphal branching in mycorrhizae, an important step in the establishment of the symbiosis between the fungus and the root of the plant host.

molecule or invent and optimize new compounds inspired by the natural chemical signals.

An example of innovation in this area is represented by strigolactones. Strigolactones are terpenoid-derived natural molecules acting as phytohormones and controlling several physiological and development processes in planta. They act also as potent rhizosphere signals with many potential applications in modern agriculture.[33] Interestingly, they are involved in the establishment of relevant symbiotic interactions between crops and arbuscular mycorrhizae and/or rhizobium. Moreover, new evidence suggests that strigolactones can influence the composition of the root microbiome.[34] The role of strigolactones on the promotion of mycorrhization is particularly relevant for soil health. Arbuscular mycorrhizae are considered keystone taxa supporting many important ecosystem processes like carbon, nitrogen and phosphorus cycles, biodiversity soil structure promotion.[35,36] Recent studies showed how synthetic mimics of strigolactones are active to promote key steps in the symbiotic relationship (Fig. 3).[37,38]

Successful total synthesis of natural strigolactones like sunflower-specific heliolactone[39,40] and orobanchol in rice[41] represent interesting chemical leads to promote soil health.

In the context of climate change, reducing greenhouse gas emission is an unavoidable challenge requiring the involvement of public and private organizations. According to a recent ICPP report[42] about 23% of greenhouse emissions derive from agriculture and other land uses. Nitrogen fertilization is of massive importance for crop production at farm level and it is associated with nitrous oxide release. This is a potent greenhouse gas accounting for about one third of the total agriculture and other land use greenhouse emissions.[43] The current consensus is that fertilization practices and other interventions are the most effective approaches to control the soil N-cycle and reduce greenhouse gas emissions.[27] However, small molecules can have profound and specific effects on different steps of the soil N-cycle. A broad range of natural or synthetic compounds – encompassing several agrochemicals – have been shown to interact directly with different steps of the soil N-cycle.[44–46] The soil N-cycle is a multi-step process mediated by microbes.[46] Any shift in one step will also have indirect consequences on N pools' partitioning and thus on other cycle steps. To manage the soil N-cycle effectively, it is necessary to consider the processes' holistic nature and control N availability, leaching, and emissions.

Conclusive Remarks

Since the inception of the agriculture sciences in the nineteenth century, chemistry has been at the cornerstone of crop productivity, nutrients, and soil fertility concepts. Chemical innovation supported almost two centuries of exceptional development in agriculture securing access to food, feed and fibers.

Yet, today climate change and other global challenges are threating our food production system. Therefore, a more resilient and sustainable agriculture is urgently needed. A way forward is through the promotion of soil health. Although the concept is open to many definitions and interpretations, three clear priorities can be used to drive the innovation: promoting soil biodiversity, preserving soil resources from major threats and mitigating climate change. New chemical solutions can address these targets. An exciting and very promising venue for innovation lies with new non-cidal molecules miming rhizosphere signals controlling important biogeochemical processes with a tremendous agronomical relevance. Knowing and mastering the chemical lexicon of the plants can support a healthy crop by promoting a healthy soil.

To build the future using wisdom gained from the past, the following quote from Liebig sounds timely "Perfect Agriculture is the true foundation of all trade and industry – it is the system of Agriculture cannot be formed without the application of scientific principles; for such a system must be based on an exact acquaintance with the means of nutrition of vegetables , and with the influence of soils and action of manure upon them . This knowledge we must seek from chemistry".[21]

The Swiss Chemical Society is leading the way with many new and thrilling initiatives.[47] For instance, by establishing and promoting new thematic communities like Chemistry and the Environment, Green & Sustainable Chemistry and Chemical Ecology; without doubt important steps to reap future benefits.

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[1] P. Trivedi, J. E. Leach, S. G. Tringe, T. Sa, B. K. Singh, *Nat. Rev. Microbiol.* **2020**, *18*, 607, https://doi.org/10.1038/s41579-020-0412-1.
[2] A. Walter, R. Finger, R. Huber, N. Buchmann, *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 6148, https://doi.org/10.1073/pnas.1707462114.
[3] FAO, GSBI, SCBD, EC, Report, Rome, **2020**.

[4] J. W. Doran, *Agri. Ecosyst. Environ.* **2002**, *88*, 119, https://doi.org/10.1016/S0167-8809(01)00246-8.
[5] U. Steiger, P. Knüsel, L. Rey, 'Nationales Forschungs programm NFP 68 Gesamtsynthese*s',* **2019**.
[6] L. Montanarella, P. Panagos, *Land Use Policy* **2021**, *100*, 104950, https://doi.org/10.1016/j.landusepol.2020.104950.
[7] E. L. Ng, J. Zhang, *Sustainability* **2019**, *11*, 3697, https://doi.org/10.3390/su11133697.
[8] E. K. Bünemann, G. Bongiorno, Z. Bai, R. E. Creamer, G. De Deyn, R. de Goede, L. Fleskens, V. Geissen, T. W. Kuyper, P. Mäder, M. Pulleman, W. Sukkel, J. W. van Groenigen, L. Brussard, *Soil Biol. Biochem.* **2018**, *120*, 105, https://doi.org/10.1016/j.soilbio.2018.01.030.
[9] N. Fierer, S. A. Wood, C. P. B. de Mesquita, *Soil Biol. Biochem.* **2021**, *153*, 108111, https://doi.org/10.1016/j.soilbio.2020.108111.
[10] J. Lehmann, D. A. Bossio, I. Kögel-Knabner, M. C. Rillig, *Nat. Rev. Earth Environ.* **2020**, *1*, 544, https://doi.org/10.1038/s43017-020-0080-8.
[11] C. E. Norris, G. M. Bean, S. B. Cappellazzi, M. Cope, K. L. H. Greub, D. Liptzin, E. L. Rieke, P. W. Tracy, C. L. S. Morgan, C. W. Honeycutt, *Agronomy J.* **2020**, *112*, 3195, https://doi.org/10.1002/agj2.20234.
[12] J. A. Stenberg, *Trends Plant Sci.* **2017**, *22*, 759, https://doi.org/10.1016/j.tplants.2017.06.010.
[13] V. Venturi, C. Keel, *Trends Plant Sci.* **2016**, *21*, 187, https://doi.org/10.1016/j.tplants.2016.01.005.
[14] N. M. van Dam, H. J. Bouwmeester, *Trends Plant Sci.* **2016**, *21*, 256, https://doi.org/10.1016/j.tplants.2016.01.008.
[15] H. Massalha, E. Korenblum, D. Tholl, A. Aharoni, *Plant. J.* **2017**, 90, 788, https://doi.org/10.1111/tpj.13543.
[16] P. Pétriacq, A. Williams, A. Cotton, A. E. McFarlane, S. A. Rolfe, J. Ton, *Plnat. J.* **2017**, *92*, 147, https://doi.org/10.1111/tpj.13639.
[17] A. D. Thaer, 'The principles of agriculture', Bangs, Brother & Company, **1852**.
[18] H. Davy, 'Elements of Agricultural Chemistry in a Course of Lectures for the Board of Agriculture', B. Warner, **1821**.
[19] J.-B. Dumas, J. B. Boussingault, 'The chemical and physiological balance of organic nature: an essay', Saxton & Miles, **1844**.
[20] D. L. Sparks, 'Encyclopedia of Water: Science, Technology, and Society', **2019**, pp. 1-11.
[21] J. F. von Liebig, L. P. B. Playfair, 'Organic chemistry in its applications to agriculture and physiology', J. Owen, **1841**.
[22] V. Smil, *World Agriculture* **2011**, *2*, 9.
[23] R. Hance, 'Soils and crop protection chemicals', British Crop Protection Council, **1984**.
[24] V. Smil, 'Energy and civilization: a history', MIT Press, **2018**.
[25] E. C. Oerke, *J. Agricultural Sci.* **2006,** *144*, 31, https://doi.org/10.1017/S0021859605005708.
[26] J. Popp, K. Hantos, *Stud. Agricultural Econ.* **2011**, *113*, 47.
[27] K. Paustian, J. Lehmann, S. Ogle, D. Reay, G. P. Robertson, P. Smith, *Nature* **2016**, *532*, 49, https://doi.org/10.1038/nature17174.
[28] K. Fenner, C. Screpanti, P. Renold, M. Rouchdi, B. Vogler, S. Rich, *Environ. Sci. Technol.* **2020**, *54*, 3148, https://doi.org/10.1021/acs.est.9b05104.
[29] F. Lunghini, G. Marcou, P. Azam, M. H. Enrici, E. Van Miert, A. Varnek, *SAR and QSAR in Environ. Res.* **2020**, *31*, 493, https://doi.org/10.1080/1062936X.2020.1776387.
[30] S. Rasmann, T. C. J. Turlings, *Curr. Opin. Plant Biol.* **2016**, *32*, 62, https://doi.org/10.1016/j.pbi.2016.06.017.
[31] L. Hu, P. Mateo, M. Ye, X. Zhang, J. D. Berset, V. Handrick, D. Radisch, V. Grabe, T. G. Köllner, J. Gershenzon, C. A. M. Robert, M. Erb, *Science* **2018**, *361*, 694, https://doi.org/10.1126/science.aat4082.
[32] F. Dennert, N. Imperiali, C. Staub, J. Schneider, T. Laessle, T. Zhang, R. Wittwer, M. G. A. van der Heijden, T. H. M. Smits, K. Schlaeppi, *FEMS Microbiol. Ecol.* **2018**, *94*, fiy075, https://doi.org/10.1093/femsec/fiy075.
[33] A. De Mesmaeker, C. Screpanti, R. Fonné-Pfister, M. Lachia, A. Lumbroso. H. J. Bouwmeester, *Chimia* **2019**, 73, 549, https://doi.org/10.2533/chimia.2019.549.
[34] E. B. Aliche, C. Screpanti, A. De Mesmaeker, T. Munnik, H. J. Bouwmeester, *New Phytol.* **2020**, *227*, 1001, https://doi.org/10.1111/nph.16489.
[35] M. G. A. van der Heijden, F. M. Martin, M. A. Selosse, I. R. Sanders, *New Phytol.* **2015**, *205*, 1406, https://doi.org/10.1111/nph.13288.
[36] S. Banerjee, K. Schlaeppi, M. G. A. van der Heijden, *Nat. Rev. Microbiol.* **2018**, *16*, 567, https://doi.org/10.1038/s41579-018-0024-1.
[37] K. Akiyama, S. Ogasawara, S. Ito, H. Hayashi, *Plant Cell Physiol.* **2010**, *51*, 1104, https://doi.org/10.1093/pcp/pcq058.
[38] L. Borghi, C. Screpanti, A. Lumbroso, M. Lachia, C. Gübeli, A. De Mesmaeker, *Plant and Soil* **2021**, 1, https://doi.org/10.1007/s11104-021-04943-8.
[39] M. Yoshimura, R. Fonné-Pfister, C. Screpanti, K. Hermann, S. Rendine, M. Dieckmann, P. Quinodoz, A. De Mesmaeker, *Helv. Chim. Acta* **2019**, *102*, e1900211, https://doi.org/10.1002/hlca.202000017.
[40] S. Woo, C. S. P. McErlean, *Org. Lett.* **2019**, *21*, 4215, https://doi.org/10.1021/acs.orglett.9b01402.
[41] B. Zwanenburg, H. Regeling, C. W. van Tilburg-Joukema, B. van Oss, P. Molenveld, R. de Gelder, P. Tinnemans, *Eur. J. Org. Chem.* **2016**, *2016*, 2163, https://doi.org/10.1002/ejoc.201600132.
[42] P. R. Shukla, J. Skeg, E. C. Buendia, V. Masson-Delmotte, H. O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, S. van Diemen, 'ICCP Report', **2019**.
[43] C. A. Kinney, K. W. Mandernack, A. R. Mosier, *Soil Biol. Biochem.* **2005**, *37*, 837, https://doi.org/10.1016/j.soilbio.2004.07.044.
[44] M. Zhang, Z. Xu, Y. Teng, P. Christie, J. Wang, W. Ren, Y. Luo, Z. Li, *Sci. Total Environ.* **2016**, *543*, 636, https://doi.org/10.1016/j.scitotenv.2015.11.053.
[45] P. A. Karas, C. Baguelin, G. Pertile, E. S. Papadopoulou, S. Nikolaki, V. Storck, F. Ferrari, M. Trevisan, A. Ferrarini, F. Fornasier, S. Vasileiadis, G. Tsiamis, F. Martin-Laurent, D. G. Karpouzas, *Sci. Total Environ.* **2018**, *637*, 636, https://doi.org/10.1016/j.scitotenv.2018.05.073.
[46] D. Moreau, R. D. Bardgett, R. D. Finlay, D. L. Jones, L. Philippot, *Funct. Ecol.* **2019**, *33*, 540, https://doi.org/10.1111/1365-2435.13303.
[47] A. De Mesmaeker, *Chimia* **2021**, *75*, 119, https://doi.org/10.2533/chimia.2021.119.