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Advances in measuring soil health

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Contents

Series list x
Acknowledgements xvii
Introduction xviii

Part 1 Measuring soil biological activity

1 Assessing soil health by measuring fauna 3
Felicity Crotty, Royal Agricultural University, UK

- 1 Introduction 3
- 2 The impact of mesofauna on the soil habitat 7
- 3 Mesofauna in agriculture 9
- 4 Mesofauna in grasslands 11
- 5 Mesofauna in woodlands 12
- 6 Mesofauna as bioindicators 14
- 7 Conclusion 16
- 8 Where to look for further information 16
- 9 References 17

2 Quantifying earthworm community structures as indicators of soil health 25
Jacqueline L. Stroud, formerly Rothamsted Research, UK

- 1 Introduction 25
- 2 Earthworms, soil health and management 26
- 3 Challenges in collecting data on earthworms 27
- 4 Developing improved assessment of earthworms 28
- 5 Results and discussion 31
- 6 Conclusion 36
- 7 Where to look for further information 36
- 8 References 36

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3 Characterisation of fungal communities and functions in agricultural soils 41
Andy F. S. Taylor, The James Hutton Institute and University of Aberdeen, UK; and Thomas Freitag, Lucinda J. Robinson and Duncan White, The James Hutton Institute, UK

1 Introduction 41
2 Challenges in characterising fungal communities 42
3 Molecular characterisation of fungal communities 44
4 Proxies for fungal abundance 48
5 Case study: investigating soil fungal communities 50
6 Conclusion 57
7 Future trends in research 58
8 Where to look for further information 61
9 References 61

Part 2 Measuring soil physical and chemical properties

4 Advances in visual soil evaluation techniques 71
Mansonia Pulido-Moncada, Aarhus University, Denmark; Bruce C. Ball, formerly Scotland's Rural College (SRUC), UK; and Wim M. Cornelis, Ghent University, Belgium

1 Introduction 71
2 Assessing soil structural quality by visual soil evaluation techniques 73
3 Methods based on topsoil examination (spade methods) 75
4 Methods based on soil profile examination 85
5 Dissemination of visual soil evaluation techniques and their future trends in research 92
6 Case study I: VESS and sustainable agricultural assessment and management 94
7 Case study II: visual techniques to assess soil structure application and contribution to agriculture in Africa 96
8 Summary 100
9 Where to look for further information 101
10 References 102

5 Imaging soil structure to measure soil functions and soil health with X-ray computed micro-tomography 111
Alexandra Kravchenko and Andrey Guber, Michigan State University, USA

1 Introduction 111
2 X-ray computed micro-tomography scanning 113

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3 Soil health-related structure characteristics that can be obtained via X-ray computed micro-tomography 115
4 Image analysis software 118
5 Image processing 118
6 Thresholding 120
7 Potential indicators of soil health that can be derived from X-ray computed micro-tomography 121
8 Where to look for further information 129
9 References 130

6 Geophysical methods to assess soil characteristics 139
Ho-Chul Shin, Rothamsted Research, UK; Guillaume Blanchy, Lancaster University, UK; Ian Shield, Peter Fruen, Timothy Barraclough and Christopher W. Watts, Rothamsted Research, UK; Andrew Binley, Lancaster University, UK; and William R. Whalley, Rothamsted Research, UK

1 Introduction 139
2 Geophysical properties of soil 142
3 Electromagnetic induction 144
4 Electrical resistivity 152
5 Acoustic-to-seismic coupling 159
6 Conclusion 166
7 Where to look for further information 167
8 Acknowledgements 168
9 References 168

7 Advances in techniques to assess soil erodibility 175
R. J. Rickson, E. Dowdeswell Downey, G. Alegbeleye and S. E. Cooper, Cranfield University, UK

1 Introduction 175
2 Factors affecting soil erodibility 175
3 Assessment of soil erodibility 181
4 Future trends in research 195
5 Conclusion 203
6 Where to look for further information 204
7 References 204

8 Advances in measuring mechanical properties of soil in relation to soil health 215
Muhammad Naveed, University of West London, UK

1 Introduction 215
2 Soil rheology 218
3 Cone penetration resistance 222

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4 Uniaxial confined compression test 225
5 Miniature indentation test 231
6 Indirect tensile strength test 233
7 Conclusion 235
8 Future research 236
9 References 236

9 Advances in near-infrared (NIR) spectroscopy to assess soil health 241
Francisco J. Calderón, Oregon State University, USA; Andrew J. Margenot, University of Illinois at Urbana-Champaign, USA; and Scarlett Bailey, National Resources Conservation Service - National Soil Survey Center, USA

1 Introduction 241
2 Infrared spectroscopy for the analysis of soils and soil health 242
3 Near-infrared (NIR) spectroscopy for the analysis of soil properties 244
4 Using near-infrared (NIR) spectroscopy in practice: methodology 247
5 Using near-infrared (NIR) spectroscopy in practice: results and discussion 248
6 Conclusion and future trends 257
7 Where to look for further information 258
8 References 258

10 Spectral mapping of soil organic carbon 263
Bas van Wesemael, Université catholique de Louvain, Belgium

1 Introduction 263
2 Pilot studies of spectral SOC mapping 266
3 Challenges for SOC mapping over large extents 270
4 Synthetic bare soil images 275
5 Case study 277
6 Summary and future trends 278
7 Where to look for further information 279
8 References 280

Part 3 From measurement to management

11 Developing soil health indicators for improved soil management on farm 289
Elizabeth Stockdale, NIAB, UK; Paul Hargreaves, Scotland's Rural College (SRUC), UK; and Anne Bhogal, ADAS Gleadthorpe, UK

1 Introduction 289
2 Frameworks from policy and practice where soils are considered 292
3 Approaches to monitoring soil quality/health in agricultural systems 296
4 Case study: developing a practical and relevant soil health toolkit for UK agricultural soils 305

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5 Conclusion and future trends 320
6 Where to look for further information 323
7 Acknowledgement 324
8 References 324

12 Developing decision support systems (DSS) for farm soil and crop management 329
Matt Aitkenhead, The James Hutton Institute, UK

1 Introduction 329
2 Spatial data and sensor requirements for DSS 331
3 Models and software for DSS 334
4 DSS user interface design, actuators and systems 336
5 Decision support or decision-making? 339
6 What reasons are there for low uptake of DSS? 340
7 What will DSSs of the future look like? 343
8 Summary 345
9 Where to look for further information 346
10 References 347

Index 355

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Introduction

The UN Agency's Intergovernmental Technical Group on Soils (ITPS) has defined healthy soil as 'the ability to sustain productivity, diversity and environmental services of terrestrial ecosystems'. Understanding and measuring the different dimensions of soil health is key to sustain agricultural productivity and protect environmental resources. There has been a wealth of research on developing better analytical techniques to measure the biological, physical and chemical properties of soils. This volume reviews these developments and their implications for better management of soils. Chapters in Part 1 examine advances in measuring soil biological activity such as earthworms and fungi as indicators of soil health. Part 2 addresses developments in measuring soil physical properties through advances in visual, imaging and geophysical techniques, as well as the methods used to measure chemical properties such as soil organic carbon. Part 3 of the book looks at how measurement can be translated into farming practice through soil health indicators and decision support systems.

Part 1 Measuring soil biological activity

Part 1 opens with a chapter on assessing soil health by measuring fauna. Chapter 1 provides examples of the impact of soil fauna on soil health within different ecosystems and how the soil habitat changes in relation to this biodiversity. It focuses specifically on mesofauna in agriculture, grasslands, woodlands and as bioindicators, before concluding with an overview of how the development of mesofauna as bioindicators is important in establishing a healthy soil.

The next chapter reviews quantifying earthworm community structures as indicators of soil health. Chapter 2 begins by describing the three epigeic, endogeic and anecic groups of earthworms before going on to discuss the importance of these earthworms in soil health and management. The challenges in collecting data on earthworms are also discussed, specifically focusing on the resources required and the ability to accurately identify earthworm species. This is followed by a section on developing improved assessment methods for earthworms by farmers. The chapter concludes by highlighting how important it is to develop earthworm observation networks in the future.

Chapter 3 focuses on the characterisation of fungal communities and functions in agricultural soils. The chapter begins by highlighting the challenges in characterising fungal communities, such as investigating species-rich communities and our knowledge of fungal community structure, spatial distribution and sampling issues. The chapter then discusses molecular

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characterisation of fungal communities followed by a review of the range of proxies for fungal abundance. The chapter includes a case study on the practicalities of investigating soil fungal communities, emphasising the importance of fungal communities in soil health.

Part 2 Measuring soil physical and chemical properties

Soil structure is a complex and dynamic property that constitutes a key aspect of soil health. Soil structure assessment can be evaluated in the field by visual soil evaluation techniques. The first chapter of Part 2 discusses advances in these techniques which have been a focus of significant international research. Chapter 4 reviews the development and protocols of selected topsoil and soil profile methods to show differences in methodological approaches, and includes guidance on selection of the appropriate method for particular situations. Two case studies show how visual techniques can be used to improve management of soil, and to assess and monitor soil health in developing countries.

The use of non-invasive imaging techniques offers new approaches to characterize soil health, complementing information from traditional soil structure analyses. Chapter 5 discusses imaging soil structure using X-ray computed micro-tomography (X-ray μCT) to assess soil health and functioning. Imaging techniques are particularly suitable for characterising soil pore architecture which drives processes such as water and gas fluxes, chemical transport as well as soil biota activity. The chapter shows how the technique can be used to measure features such as macroporosity, pore connectivity, pore shape and solid-to-pore distance. It includes examples of the application of pore measurement for soil characterization and practical advice on methods to use.

Chapter 6 explores the use of geophysical methods to assess soil physical characteristics. The chapter begins by reviewing geophysical properties of soil such as clay and organic matter content. It then moves on to discuss methods such as electromagnetic induction (EMI), electrical resistivity and acoustic-to-seismic coupling and their applications in measuring soil properties such as water content and rates of soil drying. The chapter shows how these methods can be used to monitor soil health and identify within-field variations required for successful application of precision farming.

Soil erodibility is the susceptibility of soil to the erosive forces of rain splash, runoff and wind. Chapter 7 surveys advances in techniques to assess soil erodibility, beginning by examining the factors that affect soil erodibility, including soil properties, land use and management practices and the effect of soil amendments and conditioners. The chapter then summarises the various techniques that can be used to assess soil erodibility, including both static and dynamic laboratory and field tests. The chapter concludes with an overview of future research needs in developing improved methods to assess soil erodibility.

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The next chapter focuses on advances in measuring mechanical properties of soil in relation to soil health. Chapter 8 begins by discussing soil rheology, showing how a rotational rheometer test can be used to measure the microstructural stability of soil. Cone penetration resistance tests and their importance in characterising the variability of soil strength within the soil are also discussed. A section on a uniaxial confined compression test is also included, followed by an analysis of miniature indentation tests and how they can be used to determine the mechanical properties of soil at the millimetre scale. The use of indirect tensile strength tests is also examined, before the chapter concludes by emphasising the importance of measuring both soil mechanical properties and soil matric potential.

Chapter 9 reviews advances in near-infrared (NIR) spectroscopy to assess soil health. Infrared absorbance frequencies of soil constituents such as organic matter and clay minerals form the basis for developing reliable calibrations for predicting soil health indicators (SHI). Diffuse reflectance spectroscopy in the near-infrared (NIR: 350-2500 nm) region offers a relatively rapid, non-destructive and high-throughput alternative to wet chemistry measurements of soil health. To demonstrate the potential for using NIR for soil health measurements, this chapter describes the use of a NIR spectral dataset of diverse United States soils (n=709) from the USDA NRCS National Soil Survey Center to develop chemometric prediction models of representative SHI: total organic C (TOC), aggregate stability, clay content, and β-glucosidase activity. Future directions for NIR prediction of SHI and infrared spectroscopy-based soil health assessment are also discussed.

The final chapter of Part 2 examines spectral mapping of soil organic carbon. Chapter 10 first reviews recent pilot studies testing the potential of this technique. The chapter then focuses on the challenges in large-scale application of spectral mapping when the soil and parent material are heterogeneous and surface conditions are unknown. To deal with these constraints, the chapter assesses the calibration of spectral models based on large spectral libraries, the surface conditions that disturb the soil signal and a time series of images in order to delimit cropland fields and increase the extent of bare soil that can be mapped. A case study developing a soil organic carbon prediction map derived from the spectra of a Sentinel-2 image and calibrated using the LUCAS spectral library is also included.

Part 3 From measurement to management

Chapter 11 concentrates on developing soil health indicators for improved soil management. It starts by discussing the use of current indicators for soil health, such as land use capability and suitability approaches, environmental quality monitoring and concepts derived from food quality management. The

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chapter includes a case study on developing a practical toolkit of soil health indicators for UK farmers to rapidly assess biological, chemical and physical measures of soil health. The chapter concludes by emphasising the importance of developing these soil health indicators for better soil quality management in the future.

The final chapter of the book examines developing decision support systems for farm soil management. Chapter 12 provides a review of the potential role of decision support systems (DSS) and current systems. Different aspects of agricultural DSS design, implementation and operation are covered. These aspects include spatial planning, the need for and use of sensor technology, modelling and software components, system-operator interfaces. The also discusses what is needed to make DSS more successful and widely used in agriculture.

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Chapter 1

Assessing soil health by measuring fauna

Felicity Crotty, Royal Agricultural University, UK

1 Introduction
2 The impact of mesofauna on the soil habitat
3 Mesofauna in agriculture
4 Mesofauna in grasslands
5 Mesofauna in woodlands
6 Mesofauna as bioindicators
7 Conclusion
8 Where to look for further information
9 References

1 Introduction

Soil biodiversity, including abundance, species diversity, genetic diversity and functional diversity of fauna living within the soils, is an important aspect of soil health. Soil biodiversity can also act as an indicator of soil health, with a functioning biodiverse soil food web exemplifying a healthy soil which will be able to deliver many ecosystem services (the benefits provided by the ecosystem). The biodiversity of soil animal communities may exceed aboveground biodiversity by several orders of magnitude in many habitats (Anderson, 2009). Conserving soil biodiversity is key to improving and sustaining soil health, through maintaining nutrient cycles, decomposition and plant growth within the soil habitat (Firbank et al., 2008; Handa et al., 2014; Crotty et al., 2015). Soil quality and soil health, have been used frequently and interchangeably within the scientific literature. Initially, soil health was considered in relation to organic agriculture (Howard, 1947), but since the early 1990s and the seminal work by Doran and Zeiss (2000), soil health has been thought of as 'the continued capacity of a soil to function as a vital living system'. Soil health is broader, covering multiple soil functions with greater emphasis on the whole soil ecosystem, as a changing interlinked network. The response of diversity, abundance and function of soil organisms to soil management constitutes an important aspect of soil quality (Mbuthia et al., 2015). A healthy soil provides

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many ecosystem services; these include provisioning services (such as food, timber and fibre); regulating services (modifying water quality, flooding or climate); and supporting services (such as soil formation, photosynthesis and nutrient cycling) (Millennium Ecosystem Assessment, 2005). These ecosystem services are driven by the soil fauna, particularly the cycling of mineral nutrients and water regulation. These decomposers provide the basis for soil fertility through recycling plant material and mineralizing soil nutrients (Zhang et al., 2017). Tibbett et al. (2020), reviewed potential threats to soil biodiversity and found in 70% of the papers investigated, that a decline in soil health is directly related to soil biodiversity loss.

One of the most important features of the soil is that the fauna are immersed in the environment they live in, surrounded by their food, living space and excretion products (Crotty, 2011). This is why soil fauna have such a large impact on the ecosystem services provided by the soil. Soil biodiversity is also recognised as one of the cornerstones for soil security, as it is one of the seven main functions (McBratney et al., 2014), as well as the presence of life within the soil being necessary for the soil to be considered soil (Coleman, 2008). Soils are the most species-diverse habitat on the Earth (Bender et al., 2016), and there are more microorganisms residing in a teaspoon of soil than there are humans globally. To visualise this quantification, for example, microbial biomass in 1 ha of soil, 20 cm depth, weighs approximately 1 tonne (Kaczmarek, 1984), equivalent to the weight of 17 sheep (Schon et al., 2011b), while protozoa can be calculated to weigh approximately 400 kg per ha (Ekelund and Ronn, 1994) (or six sheep). Mesofauna (springtail and mites) vary greatly in numbers and biomass across habitats but have been found to equate to around 52 kg per ha (Crotty, 2011; Crotty et al., 2016) (almost one sheep), whilst nematode biomass equates to 317 kg per ha (Crotty, 2011; Crotty et al., 2016) or five sheep. However, earthworms account for the majority of soil fauna biomass, with weights calculated to reach 1.5 tonnes per ha (Crotty et al., 2016) and over 2.5 million individuals per ha, equivalent to 24 sheep. Therefore, there is a greater biomass of soil fauna residing below ground (equivalent to 53 sheep) than there would be sheep grazing above ground, with conventional stocking densities around 16 sheep per ha (Schon et al., 2011b). These calculations are for arable soils, and in a grassland soil the fauna biomass can be up to 10 times these amounts. This gives an indication of the importance of soil biodiversity that is often overlooked due to the focus of researchers on just one group of soil organisms rather than the whole soil food web. A decline in soil biodiversity has implications for soil health, as it impedes the soil's ability to perform ecosystem service functions and lowers its innate resistance, resilience to perturbations and the capacity to recover from these perturbations (Tibbett et al., 2020).

The structure of the soil profile has a large influence over the habitable space for soil fauna, particularly mesofauna and macrofauna. As large pores

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are less abundant than pores with smaller diameters, large animals have access to fewer crevices than smaller animals (Kampichler, 1999), leading to the abundance of a vast array of mesofauna of different diameters. Mesofauna are one of the most abundant and diverse groups of animal fauna within the soil, mainly consisting of springtails (Collembola), mites (Acari), Enchytraeidae and other primitive arthropods (Protura, Diplura, Symphyla) with less than 2 mm body width (Swift et al., 1979) (Fig. 1). Mesofauna are an important component of litter transformation, processing organic inputs through the detrital food web. Collembola are found within the fossil record as one of the earliest examples of terrestrial life, almost 400 million years ago (Brown, 2001), and although they are different species to those of modern soils, the functionality of the soil food web was likely to be similar to today. Springtails and mites can be frequently found at large abundances of 150 000 per m^2, independent of the above-ground biome (Coleman and Crossley, 2003). Diversity of species can also be high, with up to 100 species of springtails and mites found within the same site (or soil

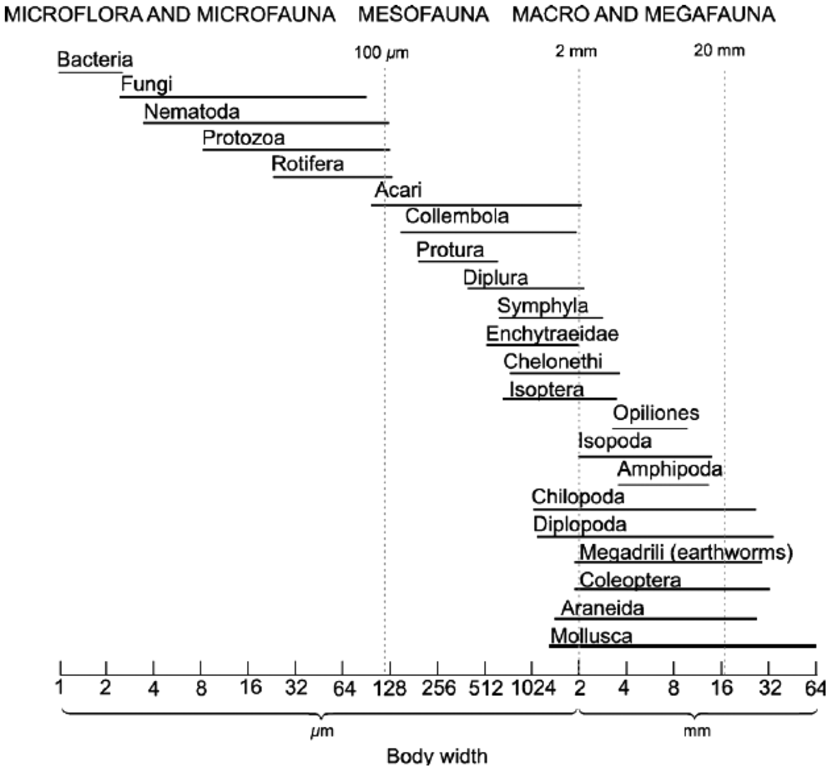

Figure 1 Size classification of soil organisms according to body width (from Swift et al., 1979).

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sample). Springtails are mainly microbivorous and have an important role in controlling microbiological populations, selectively grazing, having an impact on plant litter decomposition processes and affecting the formation of soil microstructures (Rusek, 1998). Mites are more diverse functionally than springtails, with small microbivorous or saprotrophic species as well as large predatory species. Mites also have greater differences in life strategy, with Oribatid species more likely to be found in stable environments due to their slower (K-strategists) lifecycles compared to Prostigmata that are often found in disturbed environments and have rapid development, fast growth cycles and greater fecundity (R-strategist). Enchytraeidae worms are also part of the mesofauna and are found in large abundances in highly organic (peat) soils. These soils have limited nutrient cycling and decomposition due to cold temperatures and/or waterlogging and are fairly acidic, limiting the diversity of soil fauna living within them. Enchytraeidae worms exert a large influence on the soil structure and promote decomposition and nutrient accumulation in their casts, while also redistributing nutrients throughout the soil profile (van Capelle et al., 2012).

Awareness of soil biodiversity and its importance in ecosystem function has been increasing exponentially over the last few decades. Recently, the European Soil Biodiversity Atlas (Jeffery et al., 2010) and the Global Soil Biodiversity Atlas (Orgiazzi et al., 2016) have been published, as well as the

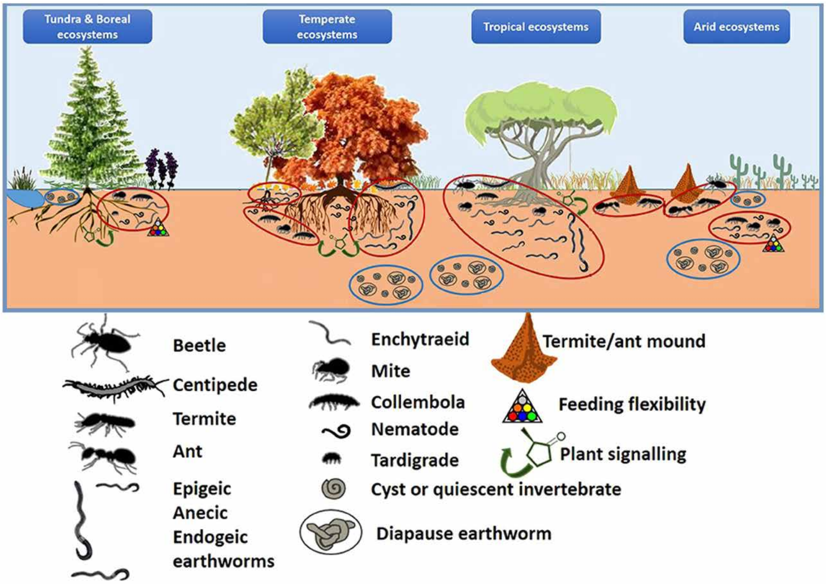

Figure 2 Illustration of how soil biodiversity and activity differ across biomes and within the soil profile; red ellipses indicate activity hotspot within the soil food web; blue ellipses indicate inactivity (adapted from Briones, 2018).

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creation of the Global Soil Biodiversity Initiative (launched in 2011) with tri-annual conferences discussing the topic. However, the interactions occurring within the soil between soil fauna and how they exemplify soil health remain unclear; making the soil more biodiverse does not directly equate to making a soil healthier. Throughout this chapter, examples will be provided of the impact of soil fauna on soil health within different ecosystems and how the soil habitat changes in relation to this biodiversity. Soil mesofauna can be found globally from the equator to the poles, although the diversity and activity of the mesofauna change in relation to the above-ground habitat; this is due to the amount of food available to the fauna and the stability of the ecosystem. Soil fauna are most active in temperate ecosystems, where there is a large input of plant litter and organic matter throughout the year; however, a large diversity of organism can still be found in tundra, boreal and arid ecosystems, although more fauna may be inactive (Fig. 2).

2 The impact of mesofauna on the soil habitat

Soil fauna, as well as being surrounded by the food that they eat, are also surrounded by the habitat they live within and have a far greater impact on this habitat in comparison to other organisms in other ecosystems. Soil mesofauna will comminute and fragment plant litter (Fig. 3), processing plant debris

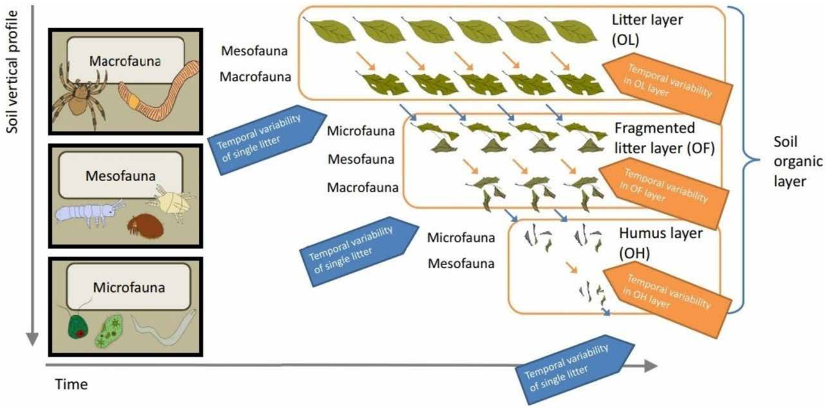

Figure 3 Change in plant litter after decomposition enhanced by the action of soil fauna, the main actors highlighted at each level of fragmentation. Adapted from Fujii et al. (2020), due to the nature of the soil habitat, soil fauna effectively live in 'a house made out of food'; therefore, consumption of food changes not just the availability of food resources but the composition of resources, of which each is affected by the temporal variability of single litter species and the whole layer. For example, a decreasing litter volume during decomposition will negatively affect mesofauna and macrofauna, but the increase in surface area during fragmentation can positively affect microfauna (Fujii et al., 2020).

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Index

Abiotic soil parameters 51
Acidification 9
Acoustic-to-seismic coupling Model 161–163
Agarose gel 53
Aggregate-size distribution 180
Aggregate stability 180, 248
Agile approach 344, 345
Agrantec.com 29
Agricultural intensification 10
Agriculture and Horticulture Development Board (AHDB) 305
Airborne sensors 267
Allolobophora chlorotica (endogeic earthworms) 25, 28
Amplicon libraries preparation 53–54
Anecic earthworms 25
APEX. *see* Swiss-Belgian Airborne Prism Experiment (APEX) sensor
Arbuscular mycorrhizal (AM) fungi 45
Archie's law 142
Artificial neural networks (ANNs) 265
  use of 203
Assessing soil health by measuring fauna
  agriculture, mesofauna in 9–11
  bioindicators, mesofauna as 14–15
  grasslands, mesofauna in 11–12
  mesofauna on soil habitat, impact of 7–9
  woodlands, mesofauna in 12–14
Astigmata 10
ASTM pinhole test 187
AVISO 118

BBRO. *see* British Beet Research Organisation (BBRO)
Bead beating 53
Benchtop ƒÊCT scanners 115
Berlese tullgren funnels 14
β-glucosidase enzymes 248
BioBio project 27
Bioinformatic analysis 54–55
Biological factors 178–179
Biotic soil parameters 51
British Beet Research Organisation (BBRO) 305
Butt Close 158

CAI. *see* Cellulose absorption index (CAI)
Calcium carbonate equivalent ($CaCO_3$) 201
Cation exchange capacity 180
Cellulose absorption index (CAI) 274
'Centralised' hubs 34
Central West Soil Structure Classification 74
Cereal monocultures 11
Clay content 248
Clay dispersion 184–185
CMD Mini-Explorer 146
Coefficient of vulnerability (Kv) 198
Collembola 5
Compression index 229
Cone penetrometer 223
Confined compression test 236
Conservation agriculture 11, 26
Coprophagy 8
CoreVESS 97
Cornell Soil Health Assessment 300, 303, 304
Crop establishment methods 9
Crop rotation 336
Crumb or aggregate coherence test (D6572) 184
CTAB extraction buffer 53
Cumulative sensitivity function 149

DADA2 packages 54
Data mining techniques 264
Decision support systems (DSS) development
  decision-making 339–340
  future trends 343–345
  models and software 334–336

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- overview of 329–331
- reasons for low uptake of 340–343
- spatial data and sensor requirements 331–332
  - sensors used 332–334
- user interface design 336–337
  - actuators and systems 337–338

Different erosion processes, accounting for 196–197
Digging soil pits, process of 28
Digital soil mapping (DSM) 264, 346
Dipole-dipole array 154–155
Dirac delta 154
DNA
- extraction 52–53
- metabarcoding 44

Double hydrometer test (D4221) 184
Double Spade method 83
Drop/shatter test 80
Drying and wetting cycles 197
DSM. *see* Digital soil mapping (DSM)
DSS. *see* Decision support systems (DSS)
Dynamic cone penetrometer 224
Dynamic laboratory techniques 184

Earthworms, three stages of development
- application 28
- co-development phase 28
- Pilot study 28

Electrical conductivity 142
Electrical resistivity 142
EM4Soil 150
EMagPy 150
Enchytraeidae 10
Enchytraeidae worms 6
Endogeic earthworms 25
Epigeic earthworms 25
Erosion function apparatus (EFA) 188
EU Horizon-2020 project 296
European Journal of Soil Science 31
European Soil Biodiversity Atlas 6
External parameter orthogonalization (EPO) approach 273

Faecal pellets 8
'Fair' Sq scores 97
FAL method 74
Farmland earthworm populations
- ecological group analysis 32
- global participation 32
- typical field abundance 32
- UK earthworm ecological groups 32
- UK farmland earthworm abundances 32
- World farmland earthworm abundance 32

Faunal voids 8
Field-generated barcodes 44
Field test kits 190
Fitness for Purpose 293
Flow shear stresses 187–188
Food and Agriculture Organisation 291
Food quality 295
Fosters field 31
Fractals 201–202
Frequency-domain electromagnetic induction (FDEM) 145
Fungal abundance, proxies for 48–50
Fungal communities
- and functions in agricultural soils, characterisation of
  - case study 50–57
  - challenges in 42–44
  - fungal abundance, proxies for 48–50
  - molecular characterisation of 44–48
- molecular characterisation of 44–48
- nationwide analysis of 55–57

Fungal-feeding nematodes 12
Fungi 41

Gapeworm (*Syngamus trachealis*) 26
Gaussian three-dimensional blur filter 120
Geophysical methods to assess soil characteristics
- acoustic-to-seismic coupling 159–166
- electrical resistivity 152–159
- electromagnetic induction 144–152
- geophysical properties of soil 142–144

Geospatial soil sensing system (GEOS3) 276
Global Soil Biodiversity Atlas 6
Global thresholding procedures 120
GPS positioning 338
GrassVESS. *see* VESS variant for grasslands (GrassVESS)
Görbing method 76

Hand grinding 53
Herbivory 11
Heterostigmata 10
Hjulström curves 176–177
Hooke's law 219, 220
Hoosfield spring barley 34
Horizontal dipole mode (H) 145
Hypha 47

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ImageToolsWinR100 118
Internal transcribed spacer (ITS) region 45
International databases 44
International Soil Tillage Research Organisation (ISTRO) 74

Jet Erosion Device (JEd) 188
Jet Erosion Test (JET) 188

KE. *see* Kinetic energy (KE)
'K' erodibility index 196
K-factor 191
Kinetic energy (KE) 224
KORE interface 337, 338

Lamé's second parameter 159
Land degradation assessment in drylands (LADA) project 84
Land potential knowledge system (LandPKS) 293
Laser Doppler vibrometer (LDV) 162
Laser granulometry 186
Linear viscoelastic (LVE) range 219, 220
Local PLSR model 265
Love waves 144
Low-cost hand-held spectroscopy 333
LUCAS spectral library 271, 272, 277
Lumbricus rubellus (epigeic earthworms) 25
Lumbricus terrestris (anecic earthworms) 25, 28
Lung worms (*Metastrongylus* spp.) 26
LVE. *see* Linear viscoelastic (LVE) range

Macrofauna 8
MAFF. *see* Ministry for Agriculture, Food and Fisheries (MAFF)
Management for Soil Biology and Soil Health (SBSH) 305
MAVI 118
Maxwell's model 219
Mean weight diameter (MWD) 194, 246
Mechanical properties
  cone penetration resistance 222–223
    equipment 223–225
    location and timing 225
    results 225
  future research 236
  indirect tensile strength test 233–235
  miniature indentation test 235
    results 233
    soil hardiness and elasticity measurements 231–233
  overview of 215–218
  with processes and functions 215, 216
  soil rheology 218–219
    amplitude sweep test 219–221
    results 221–222
  uniaxial confined compression test 225–226
    compression properties derivation 227–229
    factors affecting compression properties 229–231
    semi-logarithmic diagram 226–227
Megapascals (MPa) 222, 223
Mesostigmata. *see* Predatory mites
'Microbial loop' effect 9
MicroLEIS-DSS 336
Mid-infrared (MIR) 244
Mini 3D soil profile 88–89
MinION 45
Ministry for Agriculture, Food and Fisheries (MAFF) 223
MIR. *see* Mid-infrared (MIR)
Mites 6
Monoclonal antibodies 48
Mothur pipeline packages 54
MPa. *see* Megapascals (MPa)
Multiple scatter correction (MSC) 255
Multi-temporal approach 276
MWD. *see* Mean weight diameter (MWD)
Mycelial disruption 48
MySeq platform 45

National Center for Biotechnology Information (NCBI) 44
National Cooperative Soil Survey Soil Characterization Database 247
National Soils Inventory of Scotland (NSIS) 50
Natural Resources and Conservation Service (NRCS) 241, 242, 247, 297, 303
NBR2. *see* Normalized burn ratio 2 (NBR2) index
NDVI 267, 268, 273, 279
Near-infrared (NIR) spectroscopy
  future trends 257–258
  overview of 241–242
  in practice
    infrared absorbance interpretation 250–252
    methodology 247–248
    relationship among SHI 248–250
    SHI prediction 252–257
  soil properties analysis 244–245

    - component *vs*. function 245–246
    - minor mass component 245
    - operation *vs*. *in situ* SHI 246
    - wet chemistry measurement accuracy 246–247
  - soils analysis and health 242–244
- Next-generation sequencing (NGS) 44
- NIR. *see* Near-infrared (NIR) spectroscopy
- Non-governmental organisation collaborators 97
- Normalising and pooling libraries 54
- Normalized burn ratio 2 (NBR2) index 275, 277, 278
- Normalized soil moisture index (NSMI) 273–274
- NRCS. *see* Natural Resources and Conservation Service (NRCS)
- NSMI. *see* Normalized soil moisture index (NSMI)
- Numeric Visual Evaluation of Subsoil Structure (SubVESS) 90–92

- OPAL earthworm survey 27
- Operational taxonomic unit (OTU) 44, 54–55
- Oribatids 10
- Otsu method 121
- Oxford Nanopore Technologies 45

- Pacbio 45
- Partial least squares (PLS) model 244, 255, 256
- Particulate organic matter (POM) 128–129
  - particles 114
- 'Pedo-transfer functions' (PTFs) 192
- Peerklamp method 74
- 'Peerlkamp' Visual Method 78
- Penetrometers 222
- Permanent pasture 11
- Permanganate-oxidizable carbon (POXC) 247, 254
- Perpendicular orientation (PRP) 145
- Phospholipid fatty acids (PLFA) 49
- Phthiracaridae Oribatid mites 8
- Pinhole dispersion (D4647/D4647M) 184
- PLS. *see* Partial least squares (PLS) model
- Pocket penetrometers 223
- Poduromorpha Collembola 12
- Polycyclic aromatic hydrocarbons (PCBs) 26
- Poor man's tropical rainforest 13
- Pore water extraction (D4542), analysis of 184
- POXC. *see* Permanganate-oxidizable carbon (POXC)
- Practical Guide for Participative Evaluation of Soil Quality (PGPE) 92
- Predatory mites 12
- Profil Cultural method 74, 86–88
- Prostigmata 10
- Proximal sensing techniques 267
- Public Health Act 1875 293
- P-wave 144
- pyGIMLi 150

- Quantifying earthworm community structures
  - collecting data on earthworms, challenges in 27–28
  - developing improved assessment of 28–31
  - soil health and management 26–27
- Quantitative PCR (qPCR) 49

- Rainfall and run-off combined 188–189
- Rainfall simulation 186–187
- 'Rainfall simulation survival index' (RSSI) 201
- Rapid Diagnosis of Soil Structure (DRES) 92
- Ratio of performance to deviation (RPD) 277
- Rayleigh waves 144
- Rivers (Prevention of Pollution) Act 1876 293
- RMSE. *see* Root mean square error (RMSE)
- Rock fragments/stone cover, percentage of 177
- Root mean square error (RMSE) 255, 257
- RPD. *see* Ratio of performance to deviation (RPD)
- Runoff simulation. *see* Flow shear stresses

- Sandy loam soil 233
- SBSH. *see* Management for Soil Biology and Soil Health (SBSH)
- SBSH programme 309, 316–318
  - soil indicators selected by 314
- SCMAP. *see* Soil composite mapping processor (SCMAP)
- SCORPAN co-variates 264
- Scottish Environment Protection Agency (SEPA) 223
- Sentinel-2B image 277, 278
- SEPA. *see* Scottish Environment Protection Agency (SEPA)
- Shear wave 144
- SHI. *see* Soil health indicators (SHI); Soil Health Institute (SHI)
- Short-grass vegetation 12
- SimPEG 150
- #60minworms pilot study 29

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SL. *see* Swelling line (SL)
SMAF. *see* Soil Management Assessment Framework (SMAF)
SNV. *see* Standard normal variate (SNV)
SOC. *see* Soil organic carbon (SOC)
Soil aggregation 217
Soil biodiversity 3
Soil chemistry 179–180
Soil composite mapping processor (SCMAP) 276
Soil compression characteristics 228, 230
Soil-dwelling earthworms 26
Soil erosion plots 190–192
Soil functions and soil health, imaging soil structure to measure
  image analysis software 118
  image processing 118–120
  potential indicators 121–129
  soil health-related structure characteristics 115–117
  thresholding 120–121
  X-ray computed micro-tomography scanning 113–115
Soil fungal communities, investigating 50–51
Soil Health 360, 324
Soil health derived from X-ray CT, potential indicators of
  macroporosity 121–123
  pore connectivity 123–125
  pore shape 125–126
  soil particulate organic matter 128–129
  solid-to-pore distance 126–128
Soil health indicators (SHI) 242, 245, 246, 250
Soil health indicators for soil management
  frameworks from policy and practice
    environmental quality monitoring 293–295
    food quality measurement 295–296
    land use capability and suitability approaches 292–293
  future trends 320–322
  overview of 289–292
  soil quality monitoring/agricultural systems health 296–297
    guidance to support soil management 304–305
    indicators identification 297–300
    interpretation framework development 300–303
    result presentation 303–304
  UK agriculture, practical and relevant soil health toolkit
    building stakeholder engagement 316–318
    evaluation in practice 318–320
    principles to practice 305
    selecting indicators 311–315
    setting benchmarks and thresholds 315–316
    underpinning approach 309–311
Soil Health Institute (SHI) 323
Soil infiltration capacity and rate 178
SoilJ plugin 118
Soil Management Assessment Framework (SMAF) 303
Soil matric potential 225
Soil organic carbon (SOC), spectral mapping
  case study 277–278
  challenges
    calibration using soil spectral libraries 270–272
    dealing with surface conditions 272–275
  future trends 278–279
  overview of 263–266
  pilot studies 266–270
  synthetic bare soil images 275–277
Soil organic matter (SOM) 178, 201, 269
SOILpak 74, 84
SOILpak Scoring Procedure 89–90
Soil penetration strength 163
Soil penetrometers 224
Soil permeability 178
Soil properties 290
Soil quality 291
Soil quality scoring procedure (SQSP) 74, 77–78
Soil shear strength 178
Soil texture 176–177
SOM. *see* Soil organic matter (SOM)
Sonication 189, 192
The Spade Analysis 74
Spade diagnosis method 76
Spade methods
  from ‘The Peerlkamp method’ to ‘VESS’ method 78–83
  from ‘The Spade Diagnosis’ to ‘The Spade Analysis’ 76–77
  Visual Soil Assessment (VSA) 84–85
Spatial variability in erodibility, accounting for 195–196
Species-rich communities, characterising 42–43
Spectroscopy 333

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'Spectrotransfer Function' (STF) 201
Springtails 5
Standard normal variate (SNV) 255
Static field techniques 183–184
Sterol ergosterol 48
St-number 78
Stress-strain curve 216, 217
S-wave 144
Swelling line (SL) 227
Swiss-Belgian Airborne Prism Experiment (APEX) sensor 267
Synchrotron facilities 115

Tall-grass vegetation 12
Techniques to assess soil erodibility, advances in
  assessment of 181–189
  dynamic field tests 189–195
  factors affecting 175–176
  future trends in research 195–203
  land use and management practices 180–181
  soil properties 176–180
Temporal variability in erodibility, accounting for 196
Tensile strength (TS) 233–235
#30minworms co-development 30
3DMA-Rock 118
330 ha Rothamsted Research Farm 30–31
Tillage 9–10
Total organic C (TOC) 248, 254, 255
Tractor-mounted sensor 333
TS. *see* Tensile strength (TS)
Twitter hub @wormscience 29
2D *vs*. 3D aggregate layers 199

UAS. *see* Unmanned aerial systems (UAS)
UAS-borne spectrometers 271
UAV. *see* Unmanned aerial vehicle (UAV)
UK farmland earthworm populations and tillage 33
UK Government's 25-Year Environment Plan 291, 292
United States Department of Agriculture (USDA) 241
UNITE fungal sequence database 45
Universal Soil Loss Equation/USLE model 179
Unknown fungus 46
Unmanned aerial systems (UAS) 265
Unmanned aerial vehicle (UAV) 331, 345
USDA. *see* United States Department of Agriculture (USDA)
USDA Natural Resources Conservation Service (NRCS) 112

VCL. *see* Virgin compression line (VCL)
Vermicompost 26
Vertical dipole mode (V) 145
Vertisols 89
VESS. *see* Visual evaluation of soil structure (VESS)
VGStudioMAX 118
Virgin compression line (VCL) 227
Visible-near-infrared (Vis-NIR) spectroscopy 201
Visual evaluation of soil structure (VESS) 78
  and sustainable agricultural assessment and management 94–96
  variant for core samples 80–81
  variant for grasslands 81–82
Visual Soil Assessment (VSA) 74, 84–85
Visual soil evaluation techniques, advances in
  assessing soil structural quality 73–75
  dissemination of 92–94
  soil profile examination, methods based on 85–92
  topsoil examination, methods based on 75–85
Visual techniques
  to assess soil structure application 96–100
  contribution to agriculture in Africa 96–100

Warren Field 158
Water-drop testing technique 186
Water Erosion Prediction Project (WEPP) 179, 182
Water-stable aggregates (WSA) 180
Weed seed bank 10
Wet sieving 185–186
Whole-farm analysis 35
Whole Profile Assessment 74
#WorldWormWeek 30
Worm club 26

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