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1 **Review paper**

2

3 **Soil quality and fertility in sustainable agriculture, with a**
4 **contribution to the biological classification of agricultural soils**

5

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7

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Abstract

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36 Soils and crops are nowadays particularly vulnerable to climate change and environmental
37 stresses. In many agrosystems, soil biodiversity and the ecosystem services soil provides are
38 under threat from a range of natural and manmade drivers. Agricultural soils are perturbed by
39 the agronomic practices so far adopted, that disrupt soil trophic networks to a large extent, and
40 make soils less and less productive in the long term. In this scenario, sustainable soil uses aimed
41 at improving plant/root status, growth and development play a crucial role, as they have been
42 found to enhance the biological capacity of agricultural soils.

43 This review paper is divided into five parts:

44

- 45 a) The contentious nature of soil organic matter. A few points in Lehmann and Kleber's
46 article may mislead thinking but this doesn't necessarily mean that they were right.
- 47 b) Soil physicochemical quality and changes in soil organic matter.
- 48 c) Soil biological quality/fertility. Soils are alive, organic, full of life.
- 49 d) Soil classification. The concepts contained in the first three points were well known
50 to the fathers of pedology. Unfortunately, their principles have been lost over time.
- 51 e) Which agricultural practices can be defined as sustainable?

52

53 The published literature was analyzed within a holistic view, with agrosystems considered
54 as living systems where soil, vegetation, fauna and microorganisms co-evolve and are
55 reciprocally influenced. Ultimately, this review will suggest a better stewardship of agricultural
56 soils as a natural capital.

57

58 **Keywords:** conservation and sustainable agriculture; plant-microorganisms-soil interactions;
59 soil classification; soil ecology; soil organic matter; soil quality and fertility.

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65 **Highlights**

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- 67 • A crucial question: what it is really a sustainable agricultural soil?
- 68 • Is it possible to adopt a different paradigm of soil classification?
- 69 • The decline in soil fertility is mainly due to the reduction of soil biodiversity and organic
70 matter content.
- 71 • Biodiversity and fertility are two sides of the modern concept multifunctional
72 agricultural soils.
- 73 • A better stewardship of agricultural soils as a natural capital is urgent and necessary.

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75

76 **1. Introduction**

77

78 Soils are one of our most valuable resources and are fundamental natural capitals at the
79 base of all trophic chains. In agricultural systems, management practices that ensure high
80 production often have negative repercussions on soil health, quality and fertility (Fig. 1). A high
81 number of physicochemical, microbiological and biochemical parameters are responsible for
82 the fertility of a soil (Cheik & Jouquet, 2020; Jiang et al., 2020). However, because of the
83 challenge of considering them altogether, it is inevitable to select the most informative and
84 reliable ones. Soil biological properties are very sensitive to small-scale changes occurring in a
85 soil, compared to soil physicochemical parameters. To ensure the long-term sustainability of
86 cropping systems, both the status of soil organisms and crops need to be taken into account. In
87 this review paper, the specific biological indicators of soil health will be discussed together
88 with soil physicochemical parameters and suggestions for soil classification. The core
89 assumption is that healthy soils provide an optimal environment for soil organisms that
90 stimulates plant physiological and biochemical responses to stress. The overall message is the
91 urgency of better understanding the effects of soil management practices on the structure of soil
92 microbial and animal communities and on plant health and production. The selection of
93 biological indicators closely related to soil microbial dynamics could be essential for the
94 quantification of soil quality and its resilience to stresses, two basic requisites of soil fertility.
95 The indicators adopted could provide reliable and easy-to-interpret information on soil and
96 plant status, as they are little affected by the fluctuations related to the season and the
97 topographic effects. Carrying out a representative soil sampling, measuring soil biological

98 indicators, carrying out a correct soil classification, and integrating all data in a holistic
99 framework can facilitate the inclusion of soil health, quality and fertility in management
100 decisions made by farmers, land managers, and crop advisers.

101 Healthy soils provide an environment for soil organisms and plants that minimizes stresses.
102 The latter can be quantified with biological indicators. A high number of physicochemical,
103 biological and biochemical parameters are responsible for the fertility of a soil. However, due
104 to the impossibility of considering all of them, it is inevitable to select the most informative and
105 reliable ones (Gil-Sotres et al., 2005). Generally, the physicochemical parameters are of scarce
106 utility as indicators, as they are altered often when soils are subjected to drastic disturbances
107 (Filip, 2002). On the other side, some soil biochemical properties are sensitive to smaller
108 changes occurring in a soil (Yakovchenko et al., 1996; Wallenstein & Vilgalys, 2005; Muscolo
109 et al., 2015). These indicators should be a measure that provides reliable and easy to interpret
110 information and they should not be affected by the fluctuations related to the season and the
111 positional effect, because this could prevent the identification of changes because of
112 perturbations, damages or environmental stresses (Arshad & Martin, 2002). Moreover, to have
113 a clear picture, soil indicators should be combined with plant indicators of stress. Understanding
114 the effects of agricultural management practices on soil health, soil microorganisms/animals,
115 and plants is important, but soil health should be included as a factor when management
116 decisions are made by farmers, land managers, and crop advisers.

117

118 ***[Figure 1. HERE]***

119

120 Despite significant data gaps, there is growing evidence that unsustainable agricultural
121 practices not only negatively affect the health and quality of the soils needed to sustain healthy
122 crops and provide nutrient-rich foods, but they can also significantly affect the integrity and
123 resilience of the ecosystem as a whole. To 'break' the above-cited vicious circle, sustainable
124 solutions are required to facilitate the conservation of soils. But, in order to understand which
125 soils are or can be sustainably managed, the criteria of soil classification are essential. The
126 founders of the soil classification had linked the different units to precise pedogenetic processes
127 (FAO-UNESCO, 1974) to be able to define the functioning of each unit. The advantages of
128 knowing the position of a cultivated field on the map of the distribution of the world's soils
129 remain minimal for the farmer. Scale and micro-morphological or purely local factors intervene
130 and affect the functionality of the soil map. Generally, farmers do not know the name of the

131 soils they are cultivating. Not even many scientists who study natural ecosystems know the
132 name of the soils in which they grow plants or raise cattle. In the laboratory, for example, when
133 experimenting on different plants to know their ability to grow or produce, no one ever
134 imagined that soil could exist as a real living, interacting complete (and quite independent)
135 system.

136 This article is focused on the most advanced and updated research on the processes
137 occurring at the interface between soil physicochemical aspects, plant roots and soil
138 microorganisms/animals in sustainable agrosystems, and on the practices and ways to establish
139 sustainable soils and preserve their fertility. The analysis of published literature highlighted
140 that:

141

- 142 a) soil humus formation, soil compaction and degradation, soil-plant-atmosphere
143 interactions, root development and rhizosphere processes, vegetation types and
144 phytosociology, signaling among plants and organisms, and plant nutrient balance
145 have all crucial roles in making a soil really sustainable (paragraphs 2 and 3);
- 146 b) a conspicuous part of soil physical, chemical and biological fertility in
147 agroecosystems can be attributed to the action of soil microorganisms, with a
148 substantial contribution of soil animals (paragraph 4);
- 149 c) a new paradigm for soil classification is nowadays necessary for creating the
150 conditions for soils to be sustainable and able to provide ecosystem services
151 (paragraph 5).

152

153 In this article, all these aspects are considered in a holistic view, where agrosystems are
154 considered as living system where soil, vegetation, fauna and microorganisms co-evolve and
155 are reciprocally influenced (paragraph 6). In living soils, the key role of microorganisms in
156 agrosystems should be seriously taken into account in land management strategies, focusing
157 not exclusively on crop yield and quality, but also on soil fertility restoration and environmental
158 safety. Moreover, the role of soil fauna, especially considering their interactions with
159 microorganisms and plant roots, can surely contribute to the long-term sustainability of
160 agricultural soils.

161 On this basis, the aim of this review paper is to reveal the complex interactions between
162 soil physical and chemical properties (on which classification is mainly based), soil microbial
163 diversity, and plant health in sustainable agroecosystems (crop soils). Nowadays, agricultural

164 activity, rather than considering just productivity, is focused on the quality of products, natural
165 resource stewardship and environmental aspects, moving toward sustainable management
166 techniques. The sustainable, judicious and efficient use of soils is thus essential to support
167 continued agricultural production and quality. Focusing on sustainable soil use management
168 and food production, this new type of agriculture can perfectly fit within the background of
169 natural resources challenge, where positive mutual interactions between soil microorganisms
170 and cultivated plants play a key role.

171

172

173 **2. The contentious nature of soil organic matter**

174

175 Lehmann and Kleber (2015) reject the concept of humus and claim that: “*Government-*
176 *funded research programs must therefore preferentially support science that bridges the gap*
177 *between detailed and fine-scale mechanistic research at the plant–soil interface and field-scale*
178 *research relevant to those who manage soils for their multiple ecosystem services*”. In their
179 "Soil continuum model - Consolidated view" (Fig. 2) they replaced "humification" and
180 "mineralization" with the less precise terms of "formation" and "destruction". Stevenson
181 (1994), quoted in their article, founded the organic matter science accurately describing large
182 to small molecules and their specific properties in a model very similar to the one presented as
183 a novelty by Lehman and Kleber. With the intention of strengthening our position in defense of
184 humus, we report in Appendix 1 the astonishing Outlook of another book (Waksman, 1936)
185 that Lehmann and Kleber (2015) cite as “The first major critique of the humification concept”.
186 It seems to us instead that this brilliant scientist predicted soil depletion as a consequence of
187 denying the concept of "Humus as an organic system".

188

189 ***[Figure 2. HERE]***

190

191 As for "fine-scale mechanistic research", it reminds us of those who would like to eat the
192 powders that astronauts carry into space, instead of real legumes or cooked meats. Then maybe
193 they complain that they are not so healthy. Atoms make up the brain, but thoughts come from
194 the combination of so much knowledge that alone it gushes out and establishes alternative paths,
195 which are construction, not simple mechanical movements of electrons.

196

197
198 **3. Soil physicochemical quality and changes in soil organic matter**
199

200 One of the main worldwide agricultural problems is the decline in soil fertility, mainly due
201 to the reduction of soil biodiversity, and of nutrient and water content. Agricultural soils are
202 particularly susceptible to this problem, as they are based on the purposed simplification of the
203 relationships between the plant and other components of the natural habitat. This simplification
204 should make agricultural ecosystems easier to be controlled, but it creates conditions of extreme
205 weakness for plant life and, in fact, is nothing else than a dream. Many studies have shown that
206 the conversion of natural land to agriculture, together with the agricultural intensification that
207 enhances soil organic matter (SOM) depletion, makes the greatest contribution to soil
208 biodiversity loss (Giller et al., 1997; Six et al., 2004; Sofa et al., 2014; Vitti et al., 2015; Sofa
209 et al., 2020). The large-scale use of pesticides may also have direct or indirect effects on soil
210 biodiversity, but the lack of data has resulted in contradictory research results (EASAC, 2018;
211 Silva et al., 2019). SOM, especially its stabilized fraction (humus in chemical sense), plays a
212 crucial role in climate change mitigation and adaptation (IPCC, 2019). Amount and types of
213 SOM are principally determined by the continuous physical and chemical action of soil
214 organisms. Soil fauna and microbes are crucial for shredding, transforming and decomposing
215 SOM (Filser et al., 2016). For this reason, studies focused on understanding soil
216 microorganisms-SOM and macrofauna-SOM interactions are needed, and guidelines for future
217 experimentation and best regenerative practices to exploit soil multifunctionality have to be
218 developed, tested and validated.

219 Soils and crops are vulnerable to climate change and environmental stress, and they will
220 be more and more in the next future. Many crops are endangered by increasing water shortage,
221 often due to changes in rainfall frequency, and rise of soil aridity and desertification, eventually
222 resulting in deteriorated soil structure and critically low levels of SOM, macro- and
223 micronutrients, all of which essential for water provision and plant growth (Matson et al., 1997;
224 Sofa et al., 2019a). The frequent and strong soil tillage, typical of intensive agriculture,
225 significantly affects the stability of soil microaggregates, that have a key role in SOM
226 stabilization and support long term carbon sequestration, being more stable than
227 macroaggregates (Filser et al., 2016). This triggers a detrimental vicious circle which ultimately
228 leads to an increase in the use of mineral fertilizers and pesticides, and needs continuous and
229 strong soil tillage to replace the burrowing and aggregating activity of soil animals, again

230 increasing SOM loss (Silva et al., 2019). In brief, such soils become mere “containers” for plant
231 roots and function as a carbon source, worsening the greenhouse effect even further.

232 Healthy, fertile soils are rich in SOM built of carbon that living plants remove from the
233 atmosphere through photosynthesis. SOM fuels the soil organisms which improve soil structure
234 and recycle mineral elements that plants take up as nutrients (FAO, 2015, 2017). But soils
235 release carbon, too. The frequent use of tillage and fertilizers, characteristic of modern
236 conventional agriculture, has accelerated SOM degradation, releasing more carbon into the
237 atmosphere. The last IPCC report (IPCC, 2019) concludes that, globally, cropland soils have
238 lost 20 percent to 60 percent of their original SOM content. On top of those losses, modern
239 agriculture consumes a lot of fossil fuels to pull plows and manufacture the synthetic nitrogen
240 fertilizers that farmers rely on to coax large harvests from degraded soils. Additionally,
241 restoring soil health would help mitigate the effects of climate change. Increasing the amount
242 of SOM enhances its ability to hold water. Improving soil structure would reduce erosion and
243 retain more rainfall, where it can better sustain crops - especially during drought-stressed years
244 (Adriano Sofo et al., 2019a). In addition to benefiting the climate, less fertilizer use will reduce
245 off-farm water pollution (Silva et al., 2019). Land management choices also affect the amount
246 of carbon stored in trees, plants and soil (FAO, 2018). The last IPCC report (IPCC, 2019)
247 estimates that serious changes in forestry and agriculture to curtail deforestation and improve
248 soil management could reduce global emissions by 5 to 20 percent. While this won't solve the
249 climate problem, it would represent a significant down payment on a global solution.

250 What is really important to monitor in a soil? For sure, a comprehensive analysis and in-
251 depth analysis of soil characteristics. For doing this, a correct soil sampling (e.g. by analyzing
252 of composite soil samples taken at different soil depths) and/or an appropriate pedological
253 excavation are essential. This can allow the definition of physical soil properties (accumulation
254 of salts, soil compaction, reduction of macropores, soil hydraulic conductivity - vertical and
255 horizontal water infiltration), soil macroporosity (with macropores analysis and their shape and
256 size, both relevant for water infiltration), soil moisture, preferably measured by sensors at
257 different soil depths during the year. Other important parameters for defining soil fertility are
258 the root status, evaluation of the healthy status of the roots and of root morphology (root density,
259 root diameter, amount of white, suberized and dead roots, etc.), microscopic analysis of the
260 roots to observe eventual physical damage of the roots (e.g., necrotic parts, increased
261 lignification, etc.). Soil gas analyses are also relevant, as the determination of CO₂, NO_x and
262 CH₄ (and O₂ too, even if it cannot be easily detected) by means of GS-chromatographic

263 techniques or portable laser-based trace gas analyzers. This will allow to distinguish between
264 anaerobic and aerobic micro-environments, with these latter able to promote several plant
265 diseases due to pathogenic microbial attacks.

266

267

268 **4. Soil biological quality/fertility**

269

270 Agricultural soils are a natural capital of enormous importance that provides the foundation
271 for food production and, in terms of the human lifespan, are not a renewable resource. For this
272 reason, they must be preserved for the future. Soils host a quarter of our planet's biodiversity,
273 but most of it remains unknown (Wall et al., 2010; Fierer, 2017; Antonelli et al., 2020; Sofo et
274 al., 2020). One gram of soil may contain up to one billion bacterial cells, tens of thousands of
275 taxa, up to 200 million of fungal hyphae, and a wide range of invertebrates like earthworms,
276 springtails and nematodes (Wagg et al., 2014), that are all part of a complex and interconnected
277 food web (P. Lavelle et al., 2014; Wall et al., 2015; Williamson et al., 2017). The health of all
278 multicellular organisms (including plants, animals, and humans) and their surrounding
279 ecosystems are interconnected through a subset of microbial organisms found in the plant and
280 soil compartments, particularly in the rhizosphere. Plants nurture an entire world of soil
281 organisms that feed and protect the plants according to aboveground-belowground, plant-soil
282 feedbacks (PSFs) that have different spatio-temporal scales and are greatly affected by climate-
283 related factors (Ponge, 2013; Veen et al., 2019).

284 The diverse communities of telluric bacteria and fungi keep the soil healthy and fertile and
285 determine the main biogeochemical processes that make life possible on Earth (Dastgerdi et al.,
286 2020; Sweeney et al., 2020; Wilpieszski et al., 2019). They play fundamental roles in driving
287 many ecosystem processes on which the functioning of terrestrial ecosystems depends on,
288 including soil formation, nutrient and water cycling, climate regulation, carbon storage,
289 production of food, medicine and fibre, disease and pest control, and greater resilience to global
290 change (Bardgett & Van Der Putten, 2014; P. Lavelle et al., 2014). While soil biodiversity
291 represents an important biological and genetic resource for biotechnological innovation with
292 benefits to society, it is increasingly threatened by different forms of land degradation (FAO,
293 2015; FAO, 2017). Soil biodiversity is vulnerable to many human disturbances, including
294 intensive and non-sustainable agricultural practices, land use, climate change, nitrogen-
295 enrichment, soil pollution, invasive species, and sealing of soil (Orgiazzi et al., 2015). Soil

296 microorganisms' dynamics (e.g., mobility, growth, nutrient absorption and respiration), mainly
297 responsible for soil fertility and quality (Bünemann et al., 2018), are strongly affected by the
298 soil management (Enwall et al., 2007; Jeanbille et al., 2016; Sofo et al., 2020a). When the soil
299 microbial biocenosis is significantly altered, cultivated plants are more susceptible to diseases
300 and display stunted growth. In this view, correct agronomic techniques (fertilisation, irrigation,
301 soil tillage, etc.) become instruments to recover the disrupted equilibrium. However, the
302 functionality and metabolism of soil microorganisms are related to soil quality and fertility, as
303 they influence and, at the same time, are influenced by the soil C and N contents, bacteria being
304 an essential part of C and N cycling processes (de Vries and Shade, 2013; Mooshammer et al.,
305 2014; de Vries & Wallenstein, 2017; Li et al., 2018). Microbial interactions play a critical role
306 not only in regulating ecological functions and processes but ultimately in determining the
307 health of plants, animals and humans as components of terrestrial ecosystems (Fierer, 2017;
308 Sofo et al., 2020b; Stevenson et al., 2020). Having co-evolved with a plethora of
309 microorganisms, plants benefit from microbial symbiosis, while simultaneously facing
310 challenges from pathogens.

311 Microbial communities are regulated by the activity of soil animals, among which
312 ecosystem engineers play an essential role (Lavelle, 2002). Earthworms, ants, termites (in arid
313 tropical countries) contribute significantly to the creation of an interconnected pore network
314 (Pagenkemper et al., 2015) into which air and water are circulating (Pla et al., 2017), and which
315 are hot spots of microbial activity (Hoang et al., 2016). They also contribute to the creation of
316 soil aggregates (Lavelle et al., 2020), offering a dynamic habitat to microbial colonies (Gupta
317 & Germida, 2015) and preventing loss of carbon, water and nutrients (Pulleman & Marinissen,
318 2004). Soil engineers and their associated microbiome produce metabolites which exert a
319 hormonal effect on plants (Muscolo et al., 1996) and act as signals which stimulate the defence
320 metabolism of plants (Blouin et al., 2005). Soil animals of smaller size, although not directly
321 involved in the physical transformation of the soil, are they main regulating agents of the
322 microbial compartment. By feeding on fungi and bacteria they contribute to maintain the
323 microbial biomass in an active state (Kaneda & Kaneko, 2008), decrease competition among
324 microbial strains by feeding preferentially on those growing faster (Newell, 1984). Although
325 still in need of research, it can be expected that selective grazing of microbial colonies by tiny
326 soil animals (nematodes, protozoa, microarthropods, enchytraeids) increases soil microbial
327 biodiversity locally, as this has been repetitively shown to occur with grassland vegetation
328 under moderate herbivore grazing (review in Metera et al., 2010). It has even been suggested

329 that some soil animals would consume preferentially microbial pathogens and thus could
330 contribute to decrease soil pathogenicity (Friberg et al., 2005). Soil food webs, from microbes
331 to top predators, include trophic chains (Pollierer et al., 2019) by which fresh organic matter is
332 transformed in humus (Lehmann & Kleber, 2015), and that at a rate increasing with number
333 and complementary of functional niches of soil animals (Heemsbergen et al., 2004).

334 It is essential to link biodiversity measures with specific soil functions and plant status
335 under particular environmental contexts, particularly in agrosystems (Ramirez et al., 2015). For
336 instance, while some soil functions are driven by a diverse set of organisms that contribute to
337 functional resilience (e.g. decomposition), other soil functions involve a more specific set of
338 organisms (e.g. nitrifiers, bio-control agents) which make them more vulnerable to biodiversity
339 loss. (Wagg et al., 2014) showed that soil biodiversity loss or simplification of soil community
340 composition can impair multiple ecosystem functions, including plant diversity, decomposition,
341 nutrient retention, and nutrient cycling. A better understanding of the pivotal roles of soil
342 organisms in mediating soil-based ecosystem services, as affected by ecosystem management
343 approaches and practices adapted to socio-ecological contexts, is also central to guiding
344 biodiversity-friendly agricultural intensification trajectories (Barrios, 2007; FAO, 2018).

345

346

347 **5. Soil classification**

348

349 *5.1. Crucial historical legacies*

350

351 Before moving on to a new proposal of soil classification, let's summarize the crucial
352 historical legacies of two masters of soil classification, Dokuchaev Vasily Vasilyevich (1846-
353 1903), considered the founder of the soil classification in Europe, and Hans Jenny (1899–1992),
354 one of the greatest American pedologists, a Swiss who ended up working in California at
355 Berkeley University.

356

357 1) From "Zones verticales des sols, zones agricoles, sols du Caucase" (Dokuchaev, 1900),
358 cited by Jean-Paul Legros in "A l'aube de la Science du sol" (Legros, 2019):

359

360 a) Climate, biological agents, rock, topography and duration are the factors of soil
361 differentiation, or the factors of pedogenesis.

- 362 b) Climate and corresponding vegetation are the main ones responsible for the
 363 organization of soils on a global scale.
- 364 c) At the field scale, climatic variability does not have to be considered while topography
 365 and variability of the geological substrate can still modify soils.
- 366 d) Dokuchaev and his students had also observed that there were exceptions to the
 367 climate zonality. Locally, this or that environmental factor plays a preponderant role
 368 and masks the role of climate. It will take many years to conceptually resolve this
 369 problem, as evidenced by the changes in vocabulary introduced on the subject over
 370 time. All the reflections carried out lead us to distinguishing between “zonal” soils,
 371 that are part of the climatic zonality, “azonal” soils, whenever the rock outcrops
 372 directly, and “intra-zonal” soils, whose characteristics are linked to special conditions,
 373 such as excess water or salt.

374

375 2) In “Factors of soil formation - A System of Quantitative Pedology” (Jenny, 1941):

376

377 a) The soil system is an open system; substances may be added to or removed from it.
 378 Every system is characterized by properties that we may designate by symbols, such
 379 as s_1, s_2, s_3, s_4, s_5 , etc. For example, s_1 may indicate nitrogen content, s_2 acidity, s_3
 380 apparent density, s_4 amount of calcium, s_5 pressure of carbon dioxide, etc. Any
 381 system is defined when its properties are stated.

382 b) The initial state of the soil system has been designated as parent material. Climate
 383 (cl), Organisms (o), Topography (r), Parent material (p), and Time (t) completely
 384 describe the soil system. The total change of any soil property depends on all the
 385 changes of the soil-forming factors following a fundamental equation: $s = f(cl, o, r,$
 386 $p, t, \dots)$, where: s stands for “soil property”, f for “function of,” or “dependent on”,
 387 dots show that, besides the variables listed, additional soil formers may have to be
 388 included. In a more precise differential mathematical formula, the equation becomes:

389

$$390 \quad ds = \left(\frac{\partial s}{\partial cl} \right)_{o, r, p, t} dcl + \left(\frac{\partial s}{\partial o} \right)_{cl, r, p, t} do + \left(\frac{\partial s}{\partial r} \right)_{cl, o, p, t} dr + \left(\frac{\partial s}{\partial p} \right)_{cl, o, r, t} dp + \left(\frac{\partial s}{\partial t} \right)_{cl, o, r, p} dt$$

391

392 c) In selecting cl, o, r, p , and t as the independent variables of the soil system, we do not
 393 assert that these factors never enter functional relationships among themselves. We
 394 emphasize the fact that the soil formers may vary independently and may be obtained

395 in a great variety of constellations, either in nature or under experimental conditions.
 396 To find out the role played by each soil-forming factor, it is necessary that all the
 397 remaining factors be kept constant. A serious practical difficulty in solving $s = f(cl,$
 398 $o, r, p, t, \dots)$ in the field arises from the requirement of keeping the soil formers
 399 constant. In laboratory experiments on soil formation, we can exercise rigid control
 400 of the conditioning variables (e.g., temperature, moisture, etc.) and thus obtain sets of
 401 data that leave no doubt as to the functional relationship between them. Under field
 402 conditions, considerable variation in the magnitude of the variables cannot be
 403 avoided, in consequence of which we arrive at scatter diagrams rather than perfect
 404 functions. Statistical considerations must be introduced, and the resulting equations
 405 possess the character of general trends only. Even so, the gain in scientific knowledge
 406 fully justifies the mode of approach.

407

408 5.2. Soil and vegetation

409

410 We know colleagues who study forest ecosystems both in Italy and in France. When for
 411 research reasons it becomes necessary to describe or classify the soil, they feel lost. It is only
 412 partially true that they do not take the time to study the soil. They are generally well-trained to
 413 classify vegetation, for instance, even it is not their specialization. We have already discussed
 414 with them: they attempted to classify the soil referring to soil classification manuals (national
 415 and international issues). For being sure whether their classification was right, they always had
 416 to ask a specialist intervention, and many times they were wrong with some parameters and
 417 names. This doesn't surprise us: soil is a very complex part of an ecosystem. But there must be
 418 means of making it accessible to everyone. Although not quite completely, botanists have made
 419 themselves understand when classifying vegetation. There are several aspects that vegetation
 420 and soil coverings have in common:

421

- 422 a) both are "covers", both correspond to a continuous layer that shows changes inside
 423 and outside perceptible to the human eye. If there is more water in the system, for
 424 example, the vegetation changes and also the underlying soil; external change can
 425 also be seen from satellite; the internal change (structure) is noticed by the naked eye
 426 with some training. Of course, the more the water (or other main ecological factors)
 427 balance differs, the more the change is visible;

- 428 b) in both, the whole cover can be broken down into sub-layers. For example, for
429 vegetation we speak of arboreal, shrubby and herbaceous layers; for the soil of
430 organic, organic-mineral and mineral horizons;
- 431 c) in both cases, circumscribing spatial sub-units (horizontal or vertical) is not so
432 simple, because the transition from one to the other unit is rarely abrupt; very often
433 it is gradual and nuanced. It is normal for this to happen, because in the two cases the
434 factors involved in the distribution of the plant and animal species that inhabit these
435 two coverages are manifold, interdependent and evolving.

436

437 We know that using the characteristic species of the phytosociological units to map the
438 forest vegetation, the part of the forest occupied by undefined vegetation types becomes larger
439 than that occupied by known vegetation types (Zanella 1993, 1998; Zanella et al., 1994). In
440 fact, to define vegetation units, lists of particular species are needed; these characteristic species
441 are not the most common in each vegetation unit (if they were the most common, they would
442 also be present elsewhere). Thus, by definition, a large part of an area covered by
443 phytosociological units lacks of characteristic species. This prevents phytosociology from best
444 expressing its operationality. A map of the distribution of vegetation units is always ambiguous
445 and nuanced in many transitional places (Bartoli, 1966; Susmel, 1959, 1980). The founding
446 principle (Braun-Blanquet, 1964; Clements, 1936) says that the species lists are repetitive in
447 the space and therefore it is possible to put a name on each list and produce vegetation maps.
448 We know, however, that for ecological reasons, plant lists can only be partially repetitive. The
449 species respond to the environment and form an invaluable number of combinations that are
450 constantly evolving in space and time; they follow the local becoming of every area of fractal
451 size on planet Earth. To establish the composition of the phytosociological units, people use
452 multivariate statistical analysis programs. Depending on the number of surveys, the locations
453 chosen for the investigation and the temporal period in which the counting of the species is
454 carried out, the result changes (Zanella, 1990).

455 On the phytosociological side, however, the observation remains that we could not do
456 better: the best vegetation maps are the phytosociological ones. This is possible because the
457 phytosociological surveys are carried out within "ecologically homogeneous" areas. To make a
458 survey, people don't have to choose a random point, but to place themselves in the center of an
459 ecologically homogeneous environment. At the International Station of Phytosociology of
460 Bailleul (France) we discussed this aspect many times with professor Jean-Marie Géhu, the heir

461 of the works of Braun-Balquet. It was his main fundamental, unforgettable teaching. "Keep this
462 principle in mind, never give it up, you seem to be wasting time, but you are gaining a lot of it:
463 choose carefully the environment in which you are taking the survey, it must be as homogeneous
464 as possible considering the purposes of your work; work objectives define the size of your
465 survey". We used to reply: "But then, professor, the detection becomes subjective". He replied
466 almost enraged: "Precisely for this reason you must be very careful and well explain to everyone
467 where you are taking the survey and why!". He was right: without ecological homogeneity,
468 ecosystems cannot be circumscribed and mapped. And it remains a subjective matter, indeed.
469 We will see why here down, after describing what happened to the soil classification.

470 Soil classification has its own story. Already at the start two very different classifications
471 were born: simplifying, foresters considered the most organic surface part of the soil, calling it
472 "humus form", P.E. Müller in (Jabiol et al., 2005); agronomists concentrated on the most
473 mineral part of the soil (which also contained the organic part buried with the processing) which
474 they called "soil". While foresters selected morpho-functional traits, agronomists focused on
475 climate (USDA) and physical-chemical composition, texture, structure, thickness of various
476 diagnostic horizons (USDA and other National and International classifications), with the scope
477 to provide mineral elements and nutriment for crops. Foresters tried to link humus forms to
478 the floristic composition or soil animal lists (Hartmann, 1965; Hartmann and Marcuzzi, 1970;
479 Klinka et al., 1981) and the ability to regenerate the forest (Toutain, 1981; Bernier and Ponge,
480 1994; Camaret et al., 2000; Ponge, 2009; Bernier, 2018). Agronomists, on the other hand, linked
481 soil types to the specific climate and needs of crops (Jenny, 1941; Birkeland, 1999; Beaudette
482 et al., 2013; Brenna and Tabaglio, 2013; Berdugo et al., 2020). Each country built its own
483 classifications.

484

485 5.3. Classical soil classification

486

487 For the soil, the need for unification was necessary when international organizations
488 wanted to map soils at planet level. An exciting summary of the history of soil classification
489 can be found in the FAO-website portal. The FAO-Unesco Soil Map of the World (1971-1981)
490 is structured in 10 Volumes composed of a common Legend (Volume 1) and nine sections
491 corresponding to different areas of our planet (Fig. 3).

492

493 **[Figure 3. HERE]**

494

495 The first volume corresponds to a legend necessary to understand all the maps. We copied
496 pasted in Appendix 2 some pages of this legend. They well illustrate the difficulties that have
497 been overcome by the authors of this monumental work.

498 The authors of the cartography tried to respect the principles mentioned above (5.1. Crucial
499 historical legacies). In FAO-UNESCO (1974) we can read: *“The number of soil units which
500 compose the legend of the Soil Map of the World is 106. The legend sheets present these soil
501 units in an order which reflects the general processes of soil formation. The basic principles
502 which underlie the separation of these soil units and their definitions are discussed in Chapter
503 3. Areas of “non soil” are shown on the map as miscellaneous land units.”* It sounded very
504 promising. But the disagreement among soil scientists produced a scientific near-disaster.
505 Agreement was only apparent, and hid strong differences of thought that later revealed
506 themselves in the construction of different national operational classification systems. The USA
507 built their own classification (Soil Survey Staff, 1975, 1999, 2003, 2010, 2014, 2015; Soil
508 Science Division Staff, 2017), FAO and IUSS another (Jahn et al., 2006; WRB, 2006; IUSS
509 Working Group WRB, 2007; IUSS Working Group WRB, 2010; IUSS Working Group WRB,
510 2015; Charzyński et al., 2017), and many states operated independently in their countries, often
511 agronomists on one side and foresters on the other, example in France (Afes, 2009). In Italy,
512 for example, for historical reasons, the classification of soils depends on the regions in which it
513 is practiced: in the North West, the French one prevails, even for humus forms, in the North
514 East, the German or USDA ones are adopted but the Austrian one for humus forms, and in the
515 Central-South often the USDA is preferred, sometimes that of IUSS Working Group, while for
516 humus it is not uncommon to refer to a Canadian manual.

517 Even worse, when there are over three variables interacting, and in the soil there are dozens,
518 a natural system end up in a chaotic and unpredictable movement (Mayr, 1942; Lorenz, 1963).
519 Soil profiles, as other natural systems, are all different and impossible to classify through a list
520 of characters subdivided in categories. Jenny had foreseen it too (Jenny, 1941) - resumed in 5.1.
521 Crucial historical legacies. It is thus impossible to give a name to the soil fixing the position of
522 a diagnostic horizon in the profile, or the color of this horizon using a panel of reference colors
523 (Munsell), or the content of clay of this horizon. Each variable depends of so many other
524 variables that in a given point in the field the combination of them is very large and
525 unpredictable. However, soil scientists decided to separately improve existing classifications.

526 The result was that the national classifications diverged over time, making it impossible to
527 merge them into a single reference.

528 For some years now, the specialists of the different classification schools have been
529 organizing joint outings, such as soil classification IUSS activities. The best attempt to make
530 the classification easier to understand to other natural science specialists is that of the Soil
531 Survey Staff (Staff Soil Survey, 2015), which proposed a beautiful Illustrated Guide to Soil
532 Taxonomy (version 2) obviously based on the American system. The corresponding model of
533 the World Reference Base Working Group was published in 2018 under the title of Essentials
534 of Soil Science - Soil formation, functions, use and classification (Blum et al., 2018). What is
535 most surprising in these manuals is the almost absence of information on soil biology (zero
536 pages in the American Guide, 4 pages in the WRB Essentials), even if the “fathers” of soil
537 science put it in the second position, after the climate. And we know how much the climate
538 itself is connected to the living beings of our planet, which have modified it to make it suitable
539 for their development (Lenton et al., 2016).

540

541 *5.4. Is there a way to classify soil that is useful and also accessible to non-specialists?*

542

543 To classify the soil in a simple way, it is necessary to define from the beginning the purpose
544 of the classification and the “limits of the boxes” in which it is useful to put the soils. The
545 Unified Soil Classification System (USCS), for example, is a standardized method used in
546 engineering and geology to describe the texture and grain size of a soil. It can be applied to
547 most unconsolidated materials and is represented by a two-letter symbol. A similar “logical”
548 model is already used for agricultural soils, automated. The owner of a crop sends the soil
549 sample to the laboratory that does the analysis and classifies that soil for that specific crop, and
550 reports how much nutrients are missing to optimize its production. Although you may disagree
551 on the principle that knowing what plants are made of (Fusaro, 2015; Lowenfels, 2017) makes
552 possible to calculate what needs to be put into the soil, with arrangements over time and crop
553 changes, the method works. There is now an important amount of work on the biological quality
554 of the soil. Some among thousands of articles, historical context (Magdoff and Weil, 2004;
555 Wander et al., 2019); European references (Parisi, 1974, 2001; Chaussod, 1996; Balbo et al.,
556 2006; Ponge et al., 2013); climate change implications (Brussaard et al., 2007; Bispo et al.,
557 2018; Yin et al., 2020).

558 In few words, a QBS index (Biological Quality of the Soil) is calculated by sampling soil
559 animals, especially arthropods and worms. These animals are sorted into functional groups and
560 the quality of these groups is studied in different types of soils. It can be seen if one soil is richer
561 in functional biodiversity (which guarantees the functioning of the soil, with the right proportion
562 between mites and springtails, for example) than another (Angelini et al., 2002; Ruiz-Camacho,
563 2011; Nuria et al., 2011). Similarly, soil microorganisms are classified into functional groups
564 and designed to improve soil management (Torsvik and Øvreås, 2002; Nesme et al., 2016).
565 Some of the countless scientific articles (Fierer et al., 2007; Uroz et al., 2016; Finn et al., 2017;
566 Banerjee et al., 2018; Pennanen et al., 2019). There are even references for the public, with
567 practices of use of microorganisms, including symbionts: (Lowenfels and Lewis, 2010;
568 Lowenfels, 2014, 2017). There are also manuals for the classification of soil health, through the
569 analysis of its physical, chemical and biological components, one example among many
570 (Gugino et al., 2009). Some constructive criticisms among a countless number of works
571 (Magdoff and Weil, 2004; Bellon-Maurel et al., 2010; Datta et al., 2016; Fine et al., 2017; Roper
572 et al., 2017; Cano et al., 2018; Bünemann et al., 2018).

573 There are many useful ways to classify the soil, then, but none of them seems to satisfy
574 what the founders of the soil science wished. They wanted to understand the soil on a planetary
575 level, to appreciate how this system was distributed/developed on the planet in harmony with
576 the planet life. Is there a way to achieve this?

577

578 5.5. *Soil and humus*

579

580 When an artificial crop system is compared to a forest, things change. We should think to
581 nourishing elements cycle for a whole system composed of species that have historically come
582 together to collaborate and optimize energy resources. Forest managers call the attempt to
583 mathematically imitate a natural forest-becoming as "normalization" (Susmel, 1980; Phillips et
584 al., 2004; Pan et al., 2011; Oldeman, 2012; Reinmann and Hutryra, 2017; Hasan et al., 2017;
585 Mahdavi et al., 2019). The cycle concerns a part of the forest surface, a mosaic piece that
586 regenerates when an old tree die. It has been described and leads to the stability of the forest
587 mosaic as a whole. The number of trees on the surface under renewal must decrease
588 exponentially following a known curve with parameters related to the species and called
589 "norm". Soil plays a fundamental role in the cycle, and it is rather the Humipedon (Zanella et
590 al., 2018c) that changes over time, the whole profile following within a much longer time

591 (Bernier and Ponge, 1994; Osman, 2013; Achat et al., 2015; Baldrian, 2017; Zanella et al.,
592 2018a; Takahashi et al., 2019; Poeplau et al., 2020).

593 The need to have one for all and international humus forms classification is quite recent.
594 Unification began in July 2003, with a meeting in Trento (Italy) of 26 European specialists with
595 the specific aim of arriving at a European proposal for the classification of humus forms. The
596 need for unification arose from the necessity to accurately calculate the carbon cycle at the level
597 of several European countries. The profile of a natural soil is very complex, and it is not enough
598 to take samples at predefined depths to know the amount of carbon that it stores. It was better
599 to subdivide the soil into horizons and then take a sample in each of them. The 2/3 of the carbon
600 being concentrated in the organic and organo-mineral horizons, which correspond to the humus
601 forms, it was decided to try to classify them in a standardized way. In 2018 the summary of the
602 works (Fig. 4) was published in 19 articles that make up 2 special issues of the Applied Soil
603 Ecology Journal, volumes 122a and 122b (Zanella and Ascher-Jenuß, 2018a, b). It was
604 accompanied by another 58 in-depth articles in a third special issue, volume 123 (Zanella and
605 Ascher-Jenuß, 2018c).

606

607 ***[Figure 4. HERE]***

608

609 If the soil acts as a living being, it develops and changes with the system that contains it,
610 and depending on the space-time scale with which one looks at it, it changes its appearance
611 (Zanella et al., 2018d). It seems like a trivial matter; in reality it changes the perspective with
612 which one has to look at the soil wanting to classify it. One way to classify soil taking into
613 account its dynamics is to break it down into three layers which are evolving influencing each
614 other but which remain and can be classified independently (Fig. 5).

615

616 ***[Figure 5. HERE]***

617

618 Living organisms organize the superficial part of the Earth's crust into layers that are visible
619 to the naked eye (a necessary condition for the soil to be classified in the field with the naked
620 eye; in general, a magnification of 10 times is also recommended). If we consider the soil as a
621 living system, it begins with the colonization process of the rock by microorganisms (Time 1
622 on Fig. 6). In time 2, we can see an organic matter that begins to bond with the mineral one and
623 form aggregates (OA horizon), and the rock fragments generating an initial Lithopedon (C). In

624 time 3, the organo-mineral aggregates become well amalgamated and form a structured A
625 horizon. In time 4, a new layer called Copedon begins to form between well-developed
626 Humipedon and Lithopedon; it arises from the interaction of them. In time 5, Copedon (horizon
627 B) increases in volume and takes on a mature form. In time 6, we arrive at a complete, mature
628 soil profile, where the Copedon can also present an E horizon.

629 Each soil horizon gets its own relative independence: since it is built by living beings and
630 develops by its-own, it can also be considered a subsystem contained in a larger complete soil
631 system. As the complexity of the body of a living organism may be reduced in its different
632 organs, it is thus possible to break down the soil profile into horizons contained in three “organ-
633 like” parts: Humipedon (organic horizons OL, OF and OH and organic-mineral A); Copedon
634 (mineral horizons E and/or B); Lithopedon (mineral horizons C and R). The advantage is that
635 of being able to study these parts of the soil as if they were independent, this is done with
636 organs, when you want to understand how an organism works. In the natural environments, the
637 formation of the soil profile can stop at Humipedon (soil Crust, layer of microorganisms on
638 bare rock) stage, or also get a Lithopedon (high altitude, soils such as Rendzina or Rakers, for
639 example), or form an additional Copedon (the most common adult soils) which may be even
640 very large in comparison to Lithopedon and Humipedon (in tropical soils in general); soil can
641 also lose its Humipedon later on (eroded soils), or possess only a Lithopedon (moon soils, for
642 example, that lack of life).

643 Moving on to classification, morpho-functional boxes were chosen for the humus forms.
644 For example: humus forms of a Mull system are all those in which the litter disappears within
645 one year. Which translated into a morpho-functional field parameter becomes: to create an OH
646 horizon (last stage of litter transformation by soil organisms, a layer of organic dust/thin
647 fragments, mixed with small animal droppings) takes at least one-year time. Thus, it was
648 decided that when there is no OH horizon, the humus form should belong to a Mull system.
649 Once a precise definition of the OH horizon made, the classification of the Mull system was
650 available and easy to use in the field. A similar reasoning was made for the other humus
651 systems: Moder = with OH, and with gradual transition towards an A horizon on acidic parent
652 material; Amphi = with OH, and with gradual transition to an A horizon on non-acidic parent
653 material; Mor = with nozOF and / or with clear transition between organic and mineral horizons;
654 Tangel = with an A horizon that shows less than half the thickness of OH. In each system the
655 different humus forms are only a matter of measurable thicknesses of the diagnostic horizons.
656 A free available iOS or Android app may help to remember the diagnostic characters and to

657 classify the topsoil. The same reasoning was done for Histic (submerges topsoils), Aqueous
658 (tidalic seaside topsoils) and Para (initial, very young and pioneer, or man-modified and
659 artificial topsoils) systems. The underlying principle is very similar to that described in the
660 FAO-UNICEF map legend: we have tried to circumscribe a surface volume of the earth's crust
661 that grows over time and evolves as a system (called pedogenetic processes by soil scientists),
662 dependent on those same soil forming-factors reported in the preceding Crucial historical
663 legacies (section 5.1.).

664 To obtain a classification of the soil also on a biological basis, it would be enough to do
665 the same proceeding for the Copedon and Lithopedon, that is to identify some a priori boxes,
666 corresponding to the different processes of pedogenesis connected to them. In practice it is only
667 a question of cutting from the classical classification of the soil what could be Humipedons,
668 assigning the remaining horizons to a process of formation and evolution, which despite being
669 partly dependent on the one taking place in Humipedon, has its own relative autonomy and is
670 easy to identify in the field (e.g. Eluviation, with the formation of an E horizon in missing the
671 finished in Bt clay). In Figure 6, the subdivisions (which are rarely abrupt) within the three soil
672 layers are expressed with colors. The arrows correspond to soil systems moving within these
673 layers. It is the latter that together originate the soil but they have their own dynamics partly
674 independent of the soil.

675 Reviewers asked for a table summarizing the thinking expressed in this part of the article.
676 It is true that we do not even know what needs to be done to get out of the impasse. A biological
677 classification of the soil on a DNA basis could probably clarify the living essence of the soil
678 (Table 1).

679

680 ***[Figure 6. HERE]***

681

682 The forms of humus are directly linked to particular groups of soil animals (Ponge, 2003,
683 2013; Zanella et al., 2012, 2018b) and agents of biodegradation which are surely in turn linked
684 to soil microorganisms (Sofo et al., 2014, 2019; Bispo et al., 2018; Bayat et al., 2018; Karimi
685 et al., 2018, 2019; Liang et al., 2019). This connection could have very important consequences
686 on the management of forest and agricultural soils to stop climate from warming. The ultimate
687 goal could be to integrate in the new classification all those data relating to biological
688 functioning that are now collected by people who already practice a non-specialized soil
689 classification (section 5.4).

690 From another point of view, which is the one concerning agricultural soils, that produce
691 food not only for humans, it was thought that to transform/modify and work at will the soil was
692 a scientific and profitable action. Originally it was never thought that the soil was a system to
693 be protected due to its historical biological structure and composition. Hans Jenny became
694 aware of the possible misunderstanding and in 1980 published a book (Jenny, 1980) on the
695 basis of a very modern definition of soil: “Soil as an Object of Nature - Soil is more than
696 farmer’s dirt, or a pile of good topsoil, or engineering material; it is a body of nature that has
697 its own internal organization and history of genesis”. In a letter to Science of the same year he
698 even wrote: “Because of a possible climatic warm-up, we do not wish accelerate humus
699 oxidation and the concomitant flux of carbon dioxide from soil into the atmosphere... The
700 humus capital, which is substantial, deserves to be maintained because good soils are a national
701 asset”.

702

703

704 **6. Which agricultural practices can be defined sustainable?**

705

706 *6.1. Conventional or organic agriculture?*

707

708 Nowadays, agricultural production is at risk due to many adverse abiotic and biotic factors.
709 Furthermore, climate change can potentially decrease the effectiveness of plant defence
710 mechanisms and increase the risk of diseases through excess growth and physiological
711 alteration of cultivated plants (Vitti et al., 2016). In terms of increased temperature and extreme
712 precipitation regimes, whether aridity or flooding, climate change will have detrimental
713 agricultural consequences due to the interrelations between climate, land and water use, soil
714 degradation and landscape changes (Dale, 1997; Tsiafouli et al., 2015a). Nowadays, food
715 security is an increasing concern in a growing number of countries. This situation calls for a
716 relevant appraisal of factors that could affect crop production. One of the factors promoting a
717 sustainable food production system is soil biodiversity (Sofu et al., 2020b). Unfortunately,
718 despite the promotion of sustainable soil management by the Global Soil Partnership since
719 2012, in many cases soil management is still focused on directly managing soil fertility, rather
720 than on protecting soil biodiversity as a whole or single species individually, although soil
721 biodiversity is known to be a main agent of soil fertility (Altieri et al., 2015).

722 The application of pesticides, herbicides and mineral fertilizers, typical of conventional
723 agriculture, cannot be considered an eco-friendly approach for crop production and defence, as
724 their massive use can provoke water contamination, air and water pollution, and release of
725 harmful residues and by-products into the soils (Blouin 2018; Korkina and Vorobeichik 2018;
726 Van Groenigen et al., 2019). A decrease in soil quality due to conventional soil management
727 negatively influences important ecosystem processes, like nutrient cycling and carbon
728 sequestration (Blouin et al., 2005; Bampa et al., 2019). On the other side, sustainable,
729 conservation, and/or regeneration agriculture offers new chances to mitigate the effects of
730 climate change. In sustainable agroforestry systems, management practices are able to increase
731 carbon (C) inputs into the soil and possibly reduce greenhouse gases (GHGs) emissions due to
732 some revised field operations, e.g. by irrigation, use of recycled water, pest and disease
733 management, fertilization, and soil and plant farming systems (Mutuo et al., 2005). In turn,
734 carbon enrichment increases biological activity by improving soil structure, as well as soil
735 moisture and nutrient content that are beneficial to plant growth and production (Marinari et
736 al., 2000). As Lago et al. (2020) recently indicated, there is clear evidence that more
737 environmentally friendly land management represents a promising strategy to increase soil C
738 sequestration.

739

740 *6.2. Soil and vegetation coevolve*

741

742 Soil functions as a living system. Climate, organisms, topography, parent material and time
743 completely describe the soil system. Soil and vegetation co-evolve implementing other living
744 beings and creating the well-known zonation of biomes of planet Earth. In recent years, soil
745 quality has been recognized to play a double role in the entire agroecosystem: it is important
746 for a good production as well as for a healthy environment (Doran & Zeiss, 2000). In
747 conventional agriculture, still adopted by most farmers, frequent soil tillage strongly reduces
748 the complexity and diversity of soil microbiota (Adl et al., 2006). For this reason, conventional,
749 non-sustainable agronomic practices should evolve in a more sustainable management
750 addressed to ameliorate the ecological networks and nutrient cycles, in which soil
751 microorganisms are involved. The adoption of sustainable soil management practices and
752 organic agriculture can be eco-friendly and safe methods to ameliorate plant physiological
753 status, reduce plant disease incidence, and increase yield and quality without side damages to
754 the environment and human health. For instance, it would be possible to adopt a sustainable

755 approach that enriches the soil with biocontrol microorganisms with action against pests (El-
756 Tarably & Sivasithamparam, 2006), plant-growth-promoting microorganisms able to promote
757 plant growth and development (Abhilash et al., 2016), and microorganisms able to increase the
758 availability and uptake of essential nutrients in plants, e.g. mycorrhiza for P (Bolan, 1991) and
759 nitrogen-fixing bacteria for N (Shu et al., 2012).

760 In this scenario, the advantages of the adoption of a sustainable management (or
761 conservation and regeneration agriculture), that includes no/minimum tillage, cover crop
762 application, incorporation of grass and crop residues into the soil, and endogenous and
763 exogenous soil carbon inputs (Palm et al., 2014) can be a key factor to enhance soil
764 quality/fertility and production in a sustainable way, preserving natural resources and avoiding
765 detrimental effects on the environment. Such benefits include a high level of soil microbial
766 genetic/functional diversity and complexity both in the soil (bulk soil and rhizosphere) and in
767 the plant (phyllosphere, carposphere, and endosphere) (Fig. 7), a faster C and N turnover, higher
768 levels of SOM and soil water content, and better soil physical and chemical characteristics
769 (Fausto et al., 2018). Inappropriate or exploitative crop agroecosystems represent a key threat
770 for soil degradation through erosion, nutrient depletion or structural collapse (Fedoroff, 1987).
771 Increasing our knowledge on biochemical processes of soil microorganisms and animals
772 involved in C and N dynamics, that influence in turn their availability for plants (Didden et al.,
773 1994; Shaffer et al., 2001), will lead to optimize management strategies for a multifunctional
774 concept of agriculture.

775

776 **[Figure 7. HERE]**

777

778 Addressing knowledge gaps of sustainable practices is of fundamental importance as an
779 entry point to improve growing techniques and for understanding wider soil processes, such as
780 consequences of land use or climatic change on both biodiversity and soil ecosystem services.
781 The research should be focused on developing an ecological and holistic approach that
782 combines traditional soil health assessment with sensitive indicators of the effects of the soil
783 environment on soil microbial and faunal communities and cultivated plants, such as
784 community dynamics (taxonomic, genetic, functional and metabolic) and plant stress
785 physiology, mostly assessed by growth/yield, hormone levels and photosynthetic capacity (e.g.,
786 photosystem II activity). The sustainable approach will lead to a better understanding of the
787 effects of management practices on soil organisms and plants. In the long-term, soil health

788 should be included as a factor when management decisions are made by farmers, land managers
789 and crop advisers. The studies should not be designed for a systematic monitoring of the
790 differential effects of each component of sustainable practices such as soil cover, manuring,
791 reduced pesticide use or reduced tillage (Hobbs et al., 2008), but with these practices in
792 combination, in order to have an overall vision of the agrosystem, and how to manage it
793 sustainably (Fig. 8). In this view, the metagenomics (that is the microbial identities and
794 functional gene information) and the metaphenomics (that is the product of the combined
795 genetic potential of the microbiome and resources) of bacteria or fungi (Fierer, 2017; Jansson
796 & Hofmockel, 2018) would allow to define the microbial communities living in the different
797 soil layers. The DNA/RNA-based identification of specific alive and active bacterial/fungal
798 taxa, according to their functional distinction (aerobic/anaerobic,
799 saprophytic/parasitic/pathogenic, autotrophic/heterotrophic) can be of key importance for
800 defining the microbiological fertility of a soil and its response to agricultural practices
801 (Crecchio et al., 2004; Badagliacca et al., 2020). Identification by DNA fingerprinting,
802 originally developed for the identification of poorly culturable microbial strains, has become a
803 rapid and cost-effective method of current use in agricultural soils (Johnson et al., 2003). It has
804 been extended to the current assessment of nematode communities (Wang et al., 2008) and its
805 application to other soil fauna is promising, although still not in current use (Orgiazzi et al.,
806 2015). Finally, eventual pathogenic organisms and mycorrhization index should be monitored,
807 identifying probable microbial pathogens and/or anaerobic microorganisms by a culture based-
808 approach (*Phytophthora*, *Clostridium*, *Bacillus*, etc.) and presence and types of mycorrhiza,
809 including DNA analysis of eventual pathogenic microorganisms during the growing season.

810 The application of endogenous and exogenous carbon inputs would be necessary for
811 improving soil status. Using specific commercial products containing biostimulants and
812 biocontrol agents to improve physicochemical and microbiological properties of the soils, could
813 increase resistance against eventual pathogens and enrich soil microbial communities. The
814 application of compost, manure, soil management techniques for facilitating water horizontal
815 movement in the soil, use of decompacting plants (e.g., *Raphanus* spp. or other Brassicaceae)
816 would facilitate water vertical movement in the soil, both directly (Whelan et al., 2013) and
817 through a favorable influence on earthworms (Pérès et al., 1998). On this basis, a sustainable
818 management is a key factor for increasing the functionality and diversity of soil biota, that
819 enhance soil biological fertility. This amelioration leads to a higher soil quality, stability and
820 multifunctionality, positively affecting plant physiological status and crop productivity.

821

822 **[Figure 8. HERE]**

823

824 Over the last decades, intensive agricultural practices (e.g., continuous soil tillage, high
825 inputs of mineral fertilizers, application of low-quality irrigation water, removal of pruning
826 residues) have determined the loss of soil fertility and the depletion of soil organic matter
827 (SOM), with negative effects on both productivity and soil conservation (Bonanomi et al.,
828 2011). Many conventional agronomic practices have a negative impact on SOM (Arrouays &
829 Pelissier, 1994), the soil microbiome (Lupatini et al., 2017) and soil trophic networks (Tsiafouli
830 et al., 2015b), causing a decline in fertility: soil leveling (with consequent elimination of the
831 organic horizon in many areas of the plant), deep tillage with a surface carryover of mineral
832 horizons (non-organic), soil sterilization with destruction of microbiological diversity, the
833 continuous and massive use of herbicides, mineral fertilizers and pesticides with biocidal action,
834 and so on. Sustainable agronomic practices foresee a reworking of agronomic management
835 which includes the reduction of the use of mineral fertilizers and pesticides (including cupric
836 products), the rationalization of irrigation, the management - and not the elimination - of
837 spontaneous vegetation and the contribution of different types of organic matter to restore the
838 ecosystem complexity and heterogeneity, without leaving aside a careful analysis of the fields
839 and the state of the plants, of the environmental conditions (pedological, microbiological,
840 orographic and microclimatic), and, above all, of the agronomic and ecological history of the
841 fields. The correct use of formulations of materials of natural origin, specially designed and
842 processed according to the different cultivation and business conditions, can quickly re-
843 establish the trophic balance and soil-plant compatibility, reactivating the nourishment of the
844 crops and increasing their resistance to pathogens and parasites. Thus, soils rich in organic
845 matter, or regularly fertilized organically with compost and vegetable residues (possibly not
846 coming from the same crop), have a greater microbiological biodiversity. Crop rotation with
847 phylogenetically distant species, the practice of fallow and crop associations make it possible
848 to prevent or eliminate the decrease in soil fertility, and the use of graft carriers with tree crops
849 can be helpful to mitigate problems of replanting of the same species. The crop succession, the
850 inter-cropping of different species, the use of rootstocks phylogenetically distant from the
851 cultivated variety make it possible to overcome the problems related to the decline in soil
852 fertility. A very effective sustainable technique appears to be the use of compost tea, infused or
853 more commonly fermented with compost, which has already been the subject of growing

854 scientific and applicative interest for several years (Scheuerell & Mahaffee, 2002; St. Martin et
855 al., 2020; Vilecco et al., 2020). The technique is based on the use of different compost,
856 specially selected (and sometimes, according to the needs of the plant, combined with non-
857 composted organic substance), placed in infusion under aerobic conditions.

858

859 *6.3. Soil functions as a living system*

860

861 Nowadays, there are evidences that sustainable management practices (e.g. no-tillage,
862 supply of organic fertilizers, mulching of pruning residuals and cover crops, reduction or even
863 suppression of pesticide use) can contribute to re-carbonize soils and reduce soil CO₂ emissions,
864 recover soil fertility, and increase yield. In sustainable agrosystems, because of the composition
865 of the recycled biomass (pruning residuals, leaf fall, cover crops) and of newly supplied (e.g.
866 compost, manure), a huge amount of nutrients is released if external supply of mineral fertilizers
867 could successfully be replaced. However, considering processes determining N availability
868 (organic matter mineralization, leaching, cover crops uptake, etc.), interactions among nutrients
869 (e.g. antagonistic effects), variability of soil moisture, and mineral nutrition, a particular
870 attention is required. Sustainable agriculture can give benefits to plant growth, such as increased
871 biomass and productivity, enhanced photosynthesis and carbohydrate allocation, better
872 regulation of root respiration and higher defenses against pests and diseases, with more soil
873 microorganisms and fauna, and thus more efficient trophic networks. Mycorrhizal fungi, being
874 involved in many ecosystem services (Stevenson et al., 2020), are important in many types of
875 soil. Besides well-known negative affects of conventional practices (Verbruggen et al., 2010),
876 in over-exploited, conventionally managed agricultural landscapes, habitat loss and
877 fragmentation prevent dispersal and are major threats to mycorrhizas (Longo et al., 2016).

878 Human societies benefit from a multitude of ecosystem services from both natural and
879 managed ecosystems, to which soil organisms make a crucial and distinctive (Stevenson et al.,
880 2020). Unfortunately, it is well recognized that humans are changing the global environment at
881 an unprecedented rate. An increasing proportion of the world's population is urban or suburban.
882 For this reason, the demand to extend cultivated areas in cities is increasing, prompting to
883 establish, restore and sustain urban ecosystems. In urban ecosystems, the selection of cultivated
884 or ornamental plant species to use on roofs and walls, has often been based primarily on their
885 ability to cope with the harsh conditions of the urban rooftop environment (e.g., high wind and
886 irradiance, lack of organic material and nutrients, intermittent drought) (Fig. 9). In these new

887 anthropogenic environments, the application of organic inputs and bio-products, included in
888 sustainable agricultural practices, can be crucial for plants' survival. Sustainable agriculture can
889 cause recreational, human health, economic and environmental benefits. The latter also includes
890 lower GHGs emissions because of reduced use of synthetic fertilizers and pesticides, lower
891 leaching losses to groundwater (e.g., nitrates and nitrites), and no eutrophication of ponds and
892 streams because of excess phosphorus and nitrogen. Comparisons of soil biota across wild, rural
893 and urban habitats have revealed dramatic differences between sustainably managed and
894 conventionally managed areas, with the lowest biodiversity in the latter (Antonelli et al., 2020).

895

896 ***[Figure 9. HERE]***

897

898 Regardless of practical challenges, there is untapped potential for sustainable agricultural
899 practices to influence environmental outcomes, citizens' consciousness and market's trends
900 soon (Scotti et al., 2015; Stevenson et al., 2020). The results of many recent studies encourage
901 the use of sustainable agricultural practices able to enhance soil fertility (Diacono &
902 Montemurro, 2010; Kassie et al., 2013; Scotti et al., 2015). The ultimate goal is to convince
903 farmers to adopt a sustainable farming system as a whole, and not just as individual
904 elements/practices, in order to promote good-quality production without negative effects on the
905 environment. For achieving this, the approaches should not be 'top down', but they must be
906 'bottom up', where farmers and citizens help to co-design and co-deliver soil management and
907 food production systems (Ajayi, 2007; Kassie et al., 2013). It is time to switch to a modern and
908 multifunctional concept of agriculture based not only on the production but above all on product
909 quality, environmental protection, resource saving and promotion of human health.

910

911 *6.4. Soil is organized into layers*

912

913 The complexity is such that the time distinguishes at least three groups of layers in the soil:
914 Humipedon, Copedon and Lithopedon. Microorganisms and plants condition the Humipedon
915 evolution by generating a known series of systems that starts on mineral substrate and divides
916 in two series, in submerged environment (Archeo, Anaero, Histo and Aqueous systems) and
917 out of water in aerated sites (Crusto, Bryo, Rhizo, main Terrestrial systems) (Zanella et al.,
918 2018d). Animals interact with microorganisms and plants in each system. Each system is
919 structured around particular organisms and which have coevolved for millions of years.

920 Microorganisms and plants condition the Humipedon. Mineralogical aspects and more
921 related to soil physics are more decisive in Copedon. The geological history of the soil and the
922 cycles of some minerals are much more important in Lithopedon (Zanella et al., 2018). The
923 time separates the studies of these three soil layers, handing them over to specialists who meet
924 periodically to make the right synthesis. The soil is a single body that reacts as if it were
925 composed of superimposed organs. Soil classification must take this crucial aspect into account.
926 Humipedon reacts over the years and up to a few decades; Copedon takes from decades to
927 hundreds of years; the Lithopedon centuries to millennia.

928 We must no longer think we can move, manipulate, destroy, create soil as if it were an inanimate
929 object. Soil has its own internal, historical and precious organization: what we need to do is
930 discover it and use it well. It is necessary to understand these processes well before intervening
931 with means that risk destroying the "superimposed organs" of the soil.

932 Agrosystems (crop soils) correspond to artificially simplified natural systems (in general
933 Mull Humipedons). When artificialization is extreme, we talk about Techno systems
934 (hydroponic or compost are examples of that). These phrases hide an underestimated truth of
935 intrinsic value. Agro-systems are not alternative systems, but old systems reorganized by man.
936 The soil system incessantly tries to return to its original organization, made of different
937 overlapping layers, but the work of using its stored energy takes it back annually in time. At the
938 end of a conventional exploitation process there is a soil poor in organic matter and life, an
939 original mother rock of the soil. We must no longer think we can move, manipulate, destroy,
940 create soil as if it were an object and then expect it to work as a living system to render service
941 to us. It's like catching a lion in an African savannah, taking it to the Alps and feeding it roe
942 deer. This would not work. Or rather, it would work, like in a zoo, but spending energy to create
943 and keep alive another unbalanced system; it would be better to preserve original systems and
944 try to coevolve with them.

945 If the purpose of conventional agriculture is to build new soils, then we need to think about
946 building Copedons between Humipedons and Lithopedons, not destroying this historical
947 organization. Ask us what these layers really are (studying natural references) and how they
948 can be built in compliance with natural and biological laws. It is perhaps possible to build new
949 Humipedons. This is what we try to do with composts or hydroponic solutions. We can try to
950 make them better, more like existing Humipedons. The other possibility is organic farming.
951 The right method should be very similar to the one proposed by Masanobu Fukuoka in his
952 famous book "Natural Way of Farming" (1985): to intervene as little as possible. Understand

953 how it works and accompany the movement, changing the cards in the game as little as possible.
 954 It is difficult and, for this reason, it is the right way, and it needs a scientific preparation of high
 955 naturalistic/biological level.

956

957 *6.5. Agriculture, human health and environment*

958

959 Obviously:

- 960 a) agricultural practices should comply with respect for human health and the
 961 environment;
 962 b) a starving humanity is not in good health.

963

Could it be possible?

964 Atavistically, in Italy it is said that it is not possible to have a drunk wife (who was more
 965 often a husband) and a full barrel; in French Brittany, where butter is always on the table, it is
 966 repeated that it is not possible to have butter and butter money together. A review on the subject,
 967 with also a recipe for pasta with tomato sauce, can be found in this article (Zanella et al., 2018).
 968 Yet we have to put the two obvious things together. Here new parameters intervene that are
 969 beyond the scopes of this article, such as the need for a global management of the planet's
 970 resources, like a United Nations Organization that really works, like the Senate Assembly in
 971 the film Star Wars (Fig. 10). Who decides among other things and democratically to regulate
 972 births, with a calculation of Earth's bearing capacity (shared ecological footprint) within the
 973 framework of a humanity that divides resources between humans better than what it is doing
 974 today? Are these only dreams?

975

976 ***[Figure 10. HERE]***

977

978 *6.6. Agroforestry*

979

980 This is also an important point, not detached from the previous one. The agro-forestry use
 981 of the lands of our planet is often presented as an ecological and sustainable method of
 982 exploitation both internationally and nationally. The concept is acceptable. It is known how
 983 trees increase the volume of the ecosystem, with helpful implications in the air and soil parts of
 984 the ecosystem (Jose, 2009; Altieri et al., 2015; Marsden et al., 2019; Wang et al., 2020).

985 What must be avoided is that it becomes a disguised method of stealing more land from
986 the forest. Since the part already taken (1/2) does no longer satisfy a humanity in search of food,
987 we operate on the part that remains transforming it into an agricultural forest. If the process is
988 conceivable for the ecological exploitation of those parts of the forest (equatorial and otherwise)
989 which have already been converted into cultivated fields and then abandoned, it should be
990 banned in the still forests, whether they are treated with tall trees or coppices.

991

992

993 **7. Conclusions and future insights**

994

995 The world's soils are rapidly deteriorating because of soil erosion, nutrient depletion and
996 other threats, but sustainable practices and technologies can reverse this trend. One key point
997 from the new IPCC report (IPCC, 2019) is that conventionally tilled soils erode over 100 times
998 faster than they form and that land degradation represents “one of the biggest and most urgent
999 challenges” that humanity faces. The role of soil organisms (both microbes and animals) to
1000 ecosystem services and their close relationship with soil organic matter is often overlooked,
1001 while it should be seriously taken into account in future land management strategies. In an
1002 agrosystem, from an ecological point of view, understanding the relationship between local
1003 changes (e.g., soil microorganisms/fauna) and global effects (e.g., soil quality/fertility, soil
1004 environmental importance, global change) - the so-called “local to global” concept - aims
1005 relevant and innovative.

1006 Converting the conventional management systems of agricultural land into more
1007 sustainable and environment-preserving systems has become urgent. Conventional vegetables
1008 and fruit production, because of the unavoidable lack of resources (particularly soil and water),
1009 is going to be economically and environmentally disadvantageous, while, on the other side,
1010 organic farming, whose benefits and costs are controversial, is not always self-sustaining and
1011 durable, and it cannot cover the enormous and increasing world demand. For avoiding this
1012 dilemma, the productive systems should be directed towards the principles of an innovative,
1013 sustainable, regeneration and conservative agriculture, which includes rationally the existing
1014 and innovative agro-technological practices, such as no- or minimum soil tillage, on-site
1015 nutrient input and recycling, adequate irrigation and rational management of crop residues. This
1016 innovative approach, aimed to keep production at a high level and cultivating lastingly, can
1017 render a wide range of benefits to farmers and the environment (Fig. 8). In addition, better

1018 understanding the role of soil fauna in such systems has a key role to adapt management
1019 strategies and mitigating GHGs emissions.

1020 Today humans have degraded roughly one-third of the world's topsoil, and about 3.2
1021 billion people - more than a third of humanity - already suffer from the effects of degraded land.
1022 Continuing down this path does not bode well for feeding a growing world population. Barriers
1023 to adopting regenerative farming systems include force of habit, lack of knowledge about new
1024 practices and real and perceived economic risk during the transition. The benefits of rebuilding
1025 healthy, fertile soil are clear. According to a 2018 United Nations report that reviewed global
1026 land degradation, economic benefits of land restoration average 10 times the costs. So,
1027 sustainable agriculture appears to have a big economic, social and political impact (Baggaley
1028 et al., 2020). In this review, we tried to present cross-disciplinary and holistic approaches
1029 applied to agricultural soils. We trust that sustainable agriculture will contribute to understand
1030 how important the soil as a living matrix is for both climate regulation and plant production. A
1031 better grasp of how soil organisms interact with organic matter turnover and stabilization will
1032 open novel ways for the sustainable management of soils. It is time to take soil seriously in
1033 consideration and to rethink humanity's relationship to the soil. People need to change
1034 agriculture and land use, and we all wish to have 'more sustainable' soils, the only basis for a
1035 healthier world.

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For Peer Review

Tables

Table 1. Historical legacies.

Historical legacies	
Dokuchaev (1900)	Climate, biological agents, rock, topography and duration are the factors of soil differentiation, or the factors of pedogenesis
	Climate and corresponding vegetation are the main ones responsible for the organization of soils on a global scale
	At the field scale, climatic variability does not have to be considered while topography and variability of the geological substrate can still modify soils
	There were exceptions to the climate zonality. Locally, this or that environmental factor plays a preponderant role and masks the role of climate. “Zonal” soils, that are part of the climatic zonality; “azonal” soils, whenever the rock outcrops directly; and “intra-zonal” soils, whose characteristics are linked to special conditions, such as excess water or salt
Jenny (1941)	The soil system is an open system
	The initial state of the soil system has been designated as parent material
	In selecting climate (cl), biological agents (o), rock (r), topography (p) and duration (t) as the independent variables of the soil system, we do not assert that these factors never enter functional relationships among themselves.
Soil and vegetation	Soil and vegetation correspond to a continuous layer that shows changes inside and outside perceptible to the human eye
	Both soil and vegetation covers can be broken down into sub-layers
	Circumscribing spatial sub-units (horizontal or vertical soil and vegetation sub-units) is not so simple, because the transition from one to the other unit is rarely abrupt; very often it is gradual and nuanced
	We know that using the characteristic species of the phytosociological units to map the forest vegetation, the part of the forest occupied by undefined vegetation types becomes larger than that occupied by known vegetation types
	It is crucial to choose carefully the environment in which you are taking the survey, it must be as homogeneous as possible considering the purposes of your work; work objectives define the size of your survey
Need of unification	The need for unification is necessary when international organizations wanted to map soils at planet level
	The number of soil units which compose the legend of the Soil Map of the World is 106. The legend sheets present these soil units in an order which reflects the general processes of soil formation. The basic principles which underlie the separation of these soil units and their definitions are discussed in Chapter 3. Areas of "non soil" are shown on the map as miscellaneous land units
	The disagreement among soil scientists produced a scientific near-disaster
	When there are over three variables interacting, and in the soil there are dozens, a natural system end up in a chaotic and unpredictable movement

	Illustrated Guide to Soil Taxonomy (2015)
	Essentials of Soil Science - Soil formation, functions, use and classification (2018)
Soil as living system	Living organisms organize the superficial part of the Earth's crust into layers that are visible to the naked eye
	Each soil horizon gets its own relative independence: since it is built by living beings and develops by its-own, it can also be considered a subsystem contained in a larger complete soil system
	To classify the soil means to circumscribe a surface volume of the earth's crust that grows over time and evolves as a system (called pedogenetic processes by soil scientists), dependent on those same soil forming-factors
	Topsoils are directly linked to particular groups of soil animals. This connection could have very important consequences on the management of forest and agricultural soils to stop climate from warming
Jenny (1980)	Because of a possible climatic warm-up, we do not wish accelerate humus oxidation and the concomitant flux of carbon dioxide from soil into the atmosphere... The humus capital, which is substantial, deserves to be maintained because good soils are a national asset
Solution?	A biological classification of the soil on a DNA basis could probably clarify the living essence of the soil

Figures legends

Figure 1. The three key attributes of soil, considered as a living system.

Figure 2. From “The contentious nature of soil organic matter”. Figure entitled: Reconciliation of current conceptual models for the fate of organic debris into a consolidated view of organic matter cycles and ecosystem controls in soil (Lehmann & Kleber, 2015).

Figure 3. The FAO-Unesco Soil Map of the World, a first immense effort to synthesize the distribution of the soil on our planet. On the right the cover of Volume I, which is identical in the other volumes, only changes the squared that frame the described section. Notice the design, which recalls the horizons of the soil, but also soil, vegetation and atmosphere, or an interlocking of concentric circles typical of a modern ecological vision. Just beautiful, with the maps scattered as if in a vacuum.

Figure 4. The 20 humus systems of the classification published by the Humus Group are divided into: 6 young or very particular natural systems (Para); 2 systems closely linked to man, one semi-natural (Agro) and one completely built by man (Techno); 5 terrestrial systems containing 17 humus forms; 5 Histic systems containing 16 humus forms; 2 Aqueous systems containing 3 humus forms. In total, the forms of humus described are 36 (not reported in the figure).

Figure 5. On the left, the "layers" that can be identified in the soil profile. On the right, the phases of formation of the soil profile.

Figure 6. Soil is more complex than we think. It is almost as if it were an underground forest, much more concentrated and with less air than that which lives above the ground. We can imagine it composed of three layers in which it evolves without being perceptible in its dynamic state. Perhaps the blue arrows can represent the large groups of soils described by the modern IUSS Working Group, and give an idea of this concept.

Figure 7. Bubble charts of the values of bacterial relative abundance in rhizosphere, endosphere, phyllosphere and carposphere (leaf and fruit surface, respectively) at class level of

olive plants. Each bubble represents a bacterial taxon filled with a specific colour, the size of which is proportional to the summary level of this taxon in the examined samples. The increasing scale of the total reads, represented by the smaller bubbles to the bigger ones, is displayed above each bubble chart. The arrows indicate the degree of bacterial transfer among the different compartments. Endosphere is the poorest in terms of microbial abundance and diversity, because of the highly selective environment. Kindly contribution by Alba Mininni.

Figure 8. Major benefits of the adoption of sustainable agricultural practices. Examples of the sustainable agricultural practices explained in the text.

Figure 9. Urban green roofs. (Top row) from left to right: green roofs in old buildings (Milan, Italy); vertical forest skyscraper (Milan, Italy); garden terraces (San Francisco, USA). (Central row) from left to right: “food roof” with vegetables (Trani, Italy); Mohri Garden at Roppongi Hills (Tokio, Japan); green roof of Kyoto railway station (Japan). Pictures by Adriano Sofo.

Figure 10. The Senate Building, also known as the Senate Rotunda, Senate Tower, Convocation Center, or Senate Dome, was the building on Coruscant in the center of the Senate District which served as the seat of the Galactic Senate from the end of the Great Sith War until the end of the Old Republic, also serving as the seat of the Imperial Senate during the Galactic Empire, with the Grand Convocation Chamber at its heart. The designers claimed that any weapon capable of destroying the Chamber would also have to be powerful enough to destroy the entire planet, making the facility invulnerable against sabotage or orbital bombardment (from: https://starwars.fandom.com/wiki/Senate_Building/Legends).

Appendices

Appendix 1. Quotation from Waksman, S. A. (1936). *HUMUS. Origin, chemical composition and importance in nature*. The Williams & Wilkins Company. The whole “outlook” of the authors can be found here: <https://soilcarboncoalition.org/files/Waksman-Humus.pdf>, particularly at pages 397-398.

Appendix 2. Pages 10 to 14 of the Volume I of the FAO-Unesco Soil Map of the World. Using an electronic tool, it is easy to enlarge the quoted parts and read them. Otherwise, just open the site <http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/> and download the whole volume.

For Peer Review

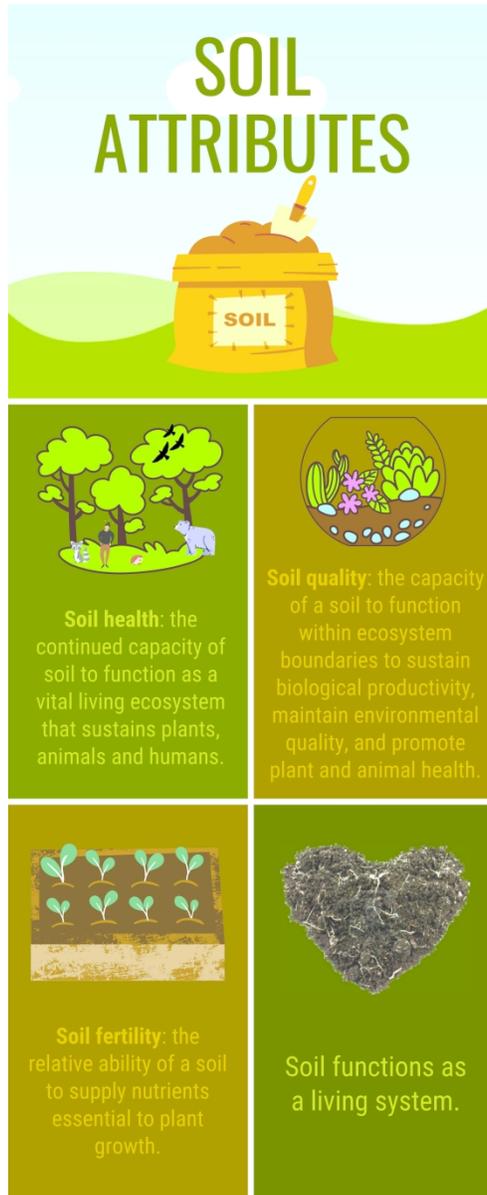


Figure 01

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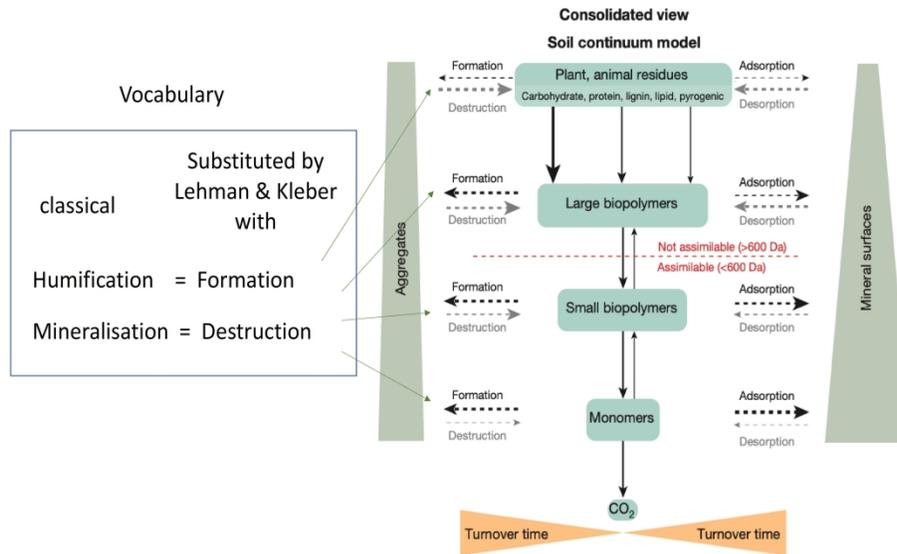


Figure 02

338x190mm (300 x 300 DPI)

<http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/>

Volume I Legend
Volume II North America
Volume III Mexico and Central America
Volume IV South America
Volume V Europe
Volume VI Africa
Volume VI South Asia
Volume VI North and Central Asia
Volume X Southeast Asia
Volume X Australasia

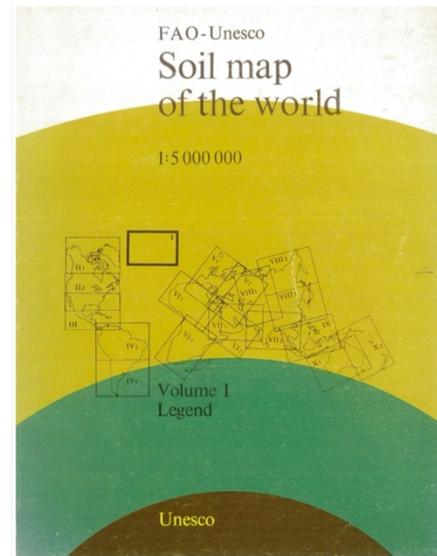


Figure 03

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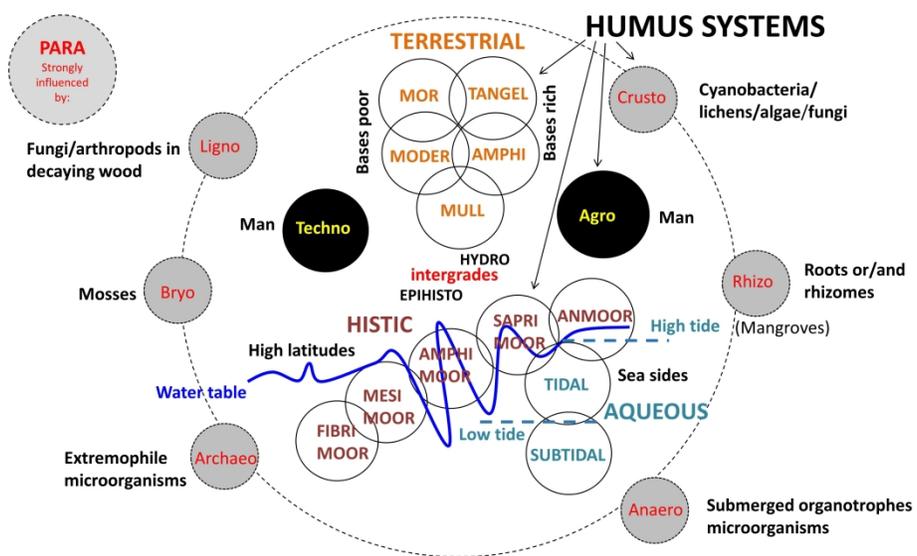


Figure 04

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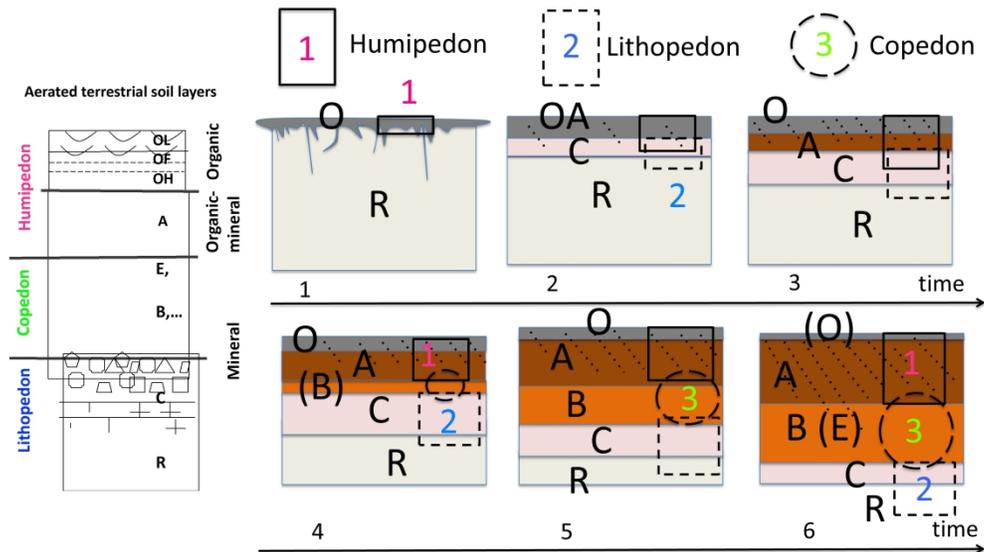


Figure 05

338x190mm (300 x 300 DPI)

Soil dynamic units

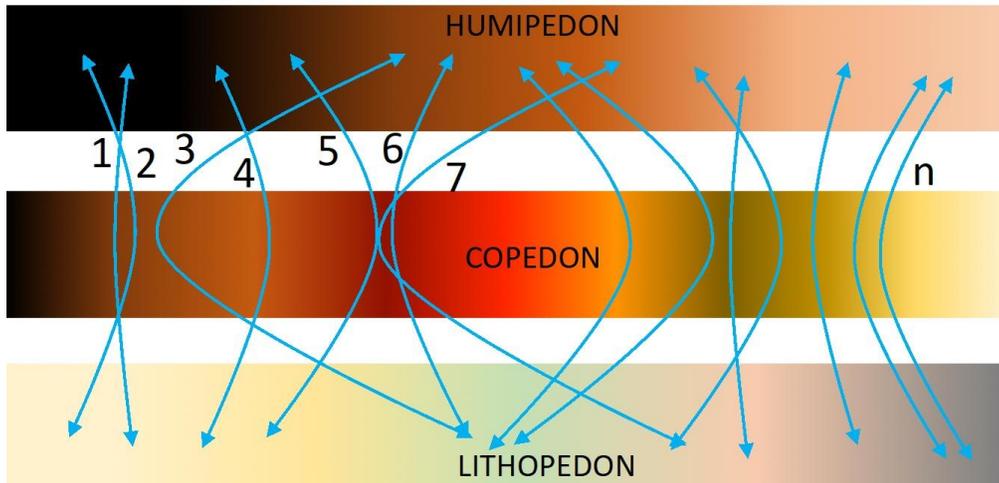


Figure 06

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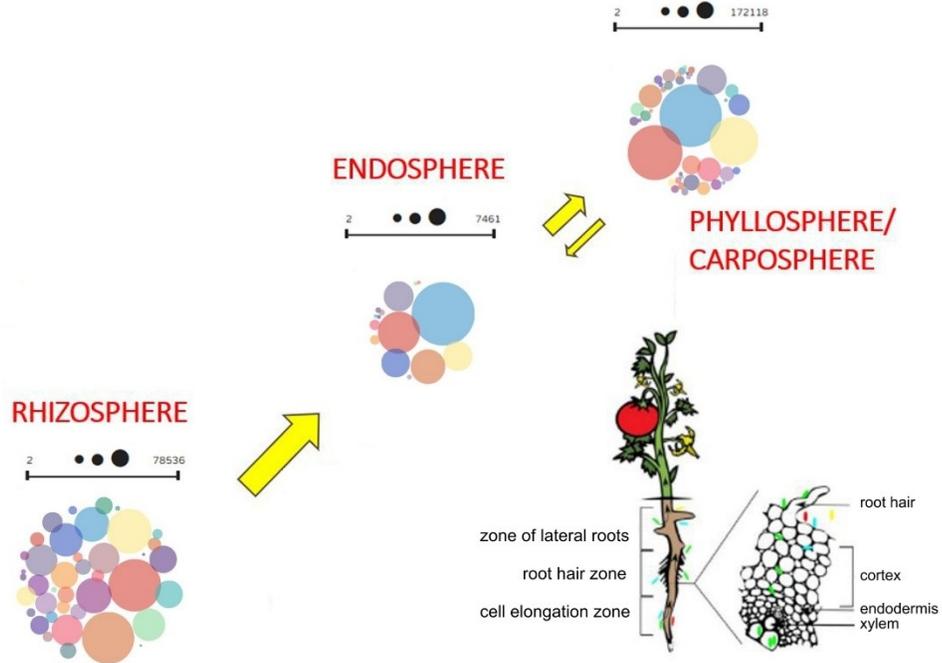


Figure 07

132x90mm (220 x 220 DPI)

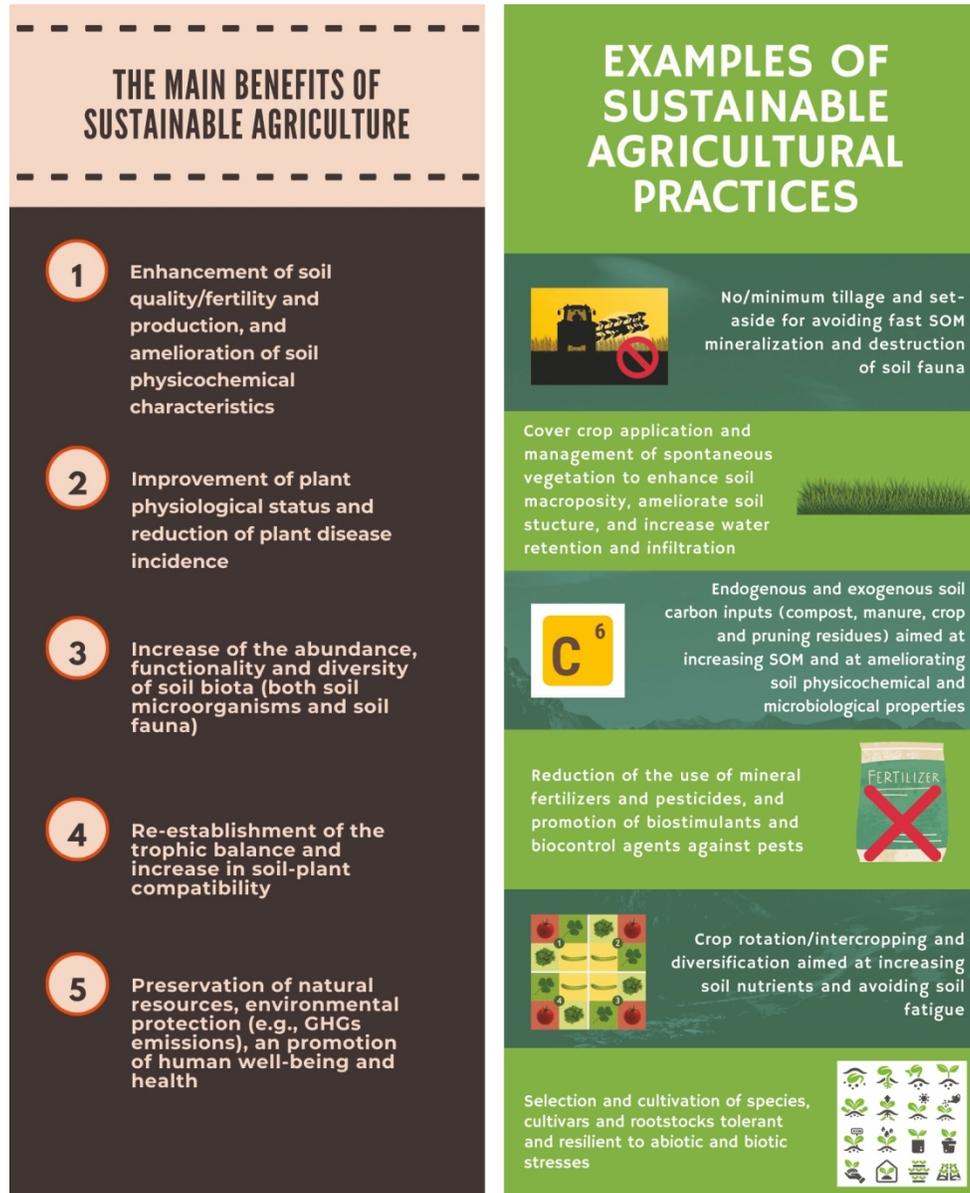


Figure 08

432x529mm (96 x 96 DPI)



Figure 09

426x282mm (300 x 300 DPI)



Figure 10

338x190mm (300 x 300 DPI)

Appendix 1

“The study of humus, including not only its chemical nature but also its formation, decomposition, and importance in soil processes, in plant nutrition, and in industrial utilization, involves many specific problems which are closely concerned with various phases of plant and animal life. The physicist, the chemist, the botanist, and the micro- biologist can all contribute to the solution of the numerous complicated problems involved in the formation and utilization of humus.

The soil is influenced in numerous ways by the humus content. Such physical characteristics of the soil as its structure, texture, moisture holding capacity, and temperature are modified by the presence and abundance of humus. As a result of the various chemical and physicochemical reactions between humus and the inorganic constituents, the acidity of the soil, its colloidal condition and its base exchange capacity are greatly affected. A considerable amount of the important elements, carbon, nitrogen, phosphorus, sulfur, and iron remain stored up in the soil humus for considerable periods of time. During decomposition of the humus, these elements become liberated as CO_2 , NH_3 , PO_4 , SO_4 , and, being available for plant growth, influence soil fertility. Because of its high combustion value, humus is an excellent source of fuel; many deposits of economic importance have accumulated in aquatic environments and where the amounts of bases and mineral nutrients are insufficient to pay-or decomposition.

Knowledge of the abundance and chemical nature of humus, of its variation in composition under different conditions of formation and transformation, and of the changes that it undergoes as a result of treatment is extremely important in determining the value of a given soil for crop production. This is true especially of soils rich in humus, such as forest soils, in which the natural humus type determines the system of forest management. The importance of humus in human economy seldom receives sufficient emphasis. Suffice to say that it probably represents the most important source of human wealth on this planet. Nature has stored in and upon the earth, in the form of humus, the source of a vast amount of readily available energy, a large part of the carbon needed for life processes, and most of the combined nitrogen, so much needed for plant growth. The study of humus thus involves problems in various fields of science: a) in chemistry, embracing the chemical composition of humus and its numerous constituents, the interaction of the organic with the inorganic soil complexes, and the chemical characteristics of humus in relation to the chemical composition of the plant and animal residues from which it originated; b) in physics and physical chemistry, including an investigation of the relationship of humus to those soil properties. which influence plant development; c) in microbiology, dealing, on the one hand, with the formation of humus, and on the other with its decomposition; d) in soil fertility and plant physiology, concerning the liberation of the nutrient elements contained in the humus, and the direct relationships of humus to plant nutrition. Aside from these, numerous special problems arise in studying the utilization of humus, both for agricultural and industrial purposes.

Humus can thus be considered as a natural body, related to: a) the soil or the surface weathered layer of the earth, to which it gives characteristic properties and in the formation of which it plays a prominent role; b) the majority of plants which have their roots in the humus, from which they derive directly or indirectly a large part of their nutrients and to which they continuously contribute, and c) the majority of microorganisms, which find in humus a natural habitat, from which they derive their energy and nutrients and in the formation and transformation of which they exert the dominant influence”.

Appendix 1. Quotation from Waksman, S. A. (1936). *HUMUS. Origin, chemical composition and importance in nature.* The Williams & Wilkins Company. The whole “outlook” of the authors can be found here: <https://soilcarboncoalition.org/files/Waksman-Humus.pdf>, particularly at pages 397-398.

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