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1 **Commentary paper**

2

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

5

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7

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19

Abstract

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

This commentary paper is divided into four main sections:

- a) The contentious nature of soil organic matter.
- b) Soil biological quality/fertility.
- c) Soil classification.
- d) Which agricultural practices can be defined as sustainable?

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

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

Highlights

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

53 1. Introduction

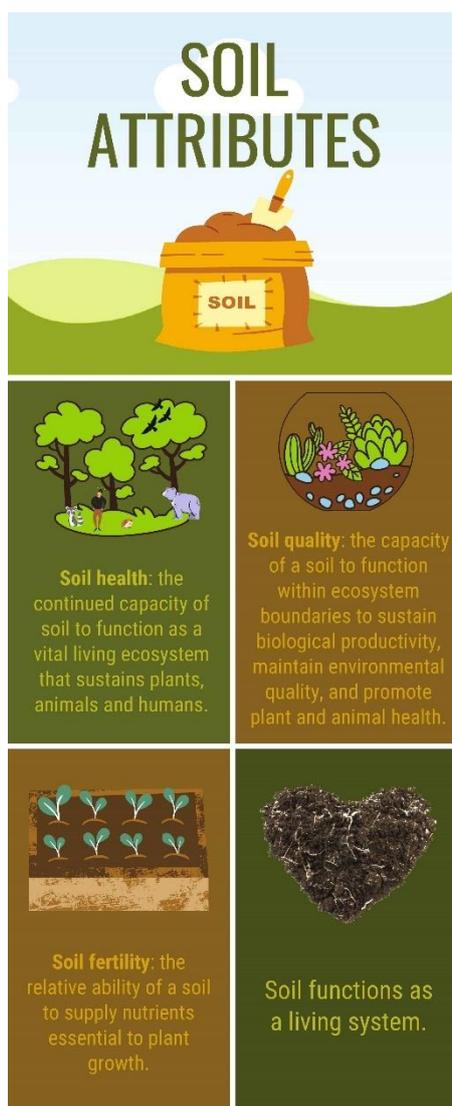
54

55 Soils are one of our most valuable resources and are fundamental natural capitals at the
56 base of all trophic chains. In agricultural systems, management practices that ensure high
57 production often have negative repercussions on soil health, quality and fertility (Fig. 1). A
58 high number of physicochemical, microbiological and biochemical parameters are responsible
59 for the fertility of a soil (Cheik & Jouquet, 2020; Jiang et al., 2020). However, because of the
60 challenge of considering them altogether, only the most informative and reliable ones can be
61 selected. Soil biological properties are very sensitive to small-scale changes occurring in a
62 soil compared to soil physicochemical parameters. To ensure the long-term sustainability of
63 cropping systems, both the status of soil organisms and crops need to be taken into account
64 (de Vries and Wallenstein, 2017; Pelosi and Römbke, 2018). In this commentary paper, the
65 specific biological indicators of soil health will be discussed together with soil
66 physicochemical parameters and suggestions for soil classification. The core assumption is
67 that healthy soils provide an optimal environment for soil organisms that stimulate plant
68 physiological and biochemical responses to stress (Pinstrup-Andersen and Pandya-Lorch,
69 1998; Soussana et al., 2019).

70 The overall message is the urgency of better understanding the effects of soil
71 management practices on the structure of soil microbial and animal communities, and on plant
72 health and production. A high number of physicochemical, biological and biochemical
73 parameters are responsible for the fertility of a soil. However, due to the impossibility of
74 considering all of them, it is inevitable to select the most informative and reliable ones (Gil-
75 Sotres et al., 2005). Generally, the physicochemical parameters are of scarce utility as
76 indicators, as they are altered often when soils are subjected to drastic disturbances (Filip,
77 2002). On the other side, soil biochemical properties are more sensitive to smaller changes
78 occurring in a soil (Yakovchenko et al., 1996; Wallenstein & Vilgalys, 2005; Muscolo et al.,
79 2015). The selection of biological indicators closely related to soil microbial dynamics is
80 essential for the quantification of soil quality and its resilience to stresses, two basic requisites
81 of soil fertility (Duru et al., 2015; Hopkin, 2008; Schloter et al., 2018; Vogel et al., 2018;
82 Veen et al., 2019). The indicators adopted could provide reliable and easy-to-interpret
83 information on soil and plant status, as they are little affected by the fluctuations related to the
84 season and topographic effects.

85 Carrying out a representative soil sampling, measuring soil biological indicators,
86 proposing a correct soil classification, and integrating all data in a holistic framework can
87 facilitate the inclusion of soil health, quality and fertility in management decisions made by
88 farmers, land managers, and crop advisers. Understanding the effects of agricultural
89 management practices on soil health, soil microorganisms/animals, and plants is important,
90 but soil health should be included as a factor when management decisions are made by
91 farmers, land managers, and crop advisers.

92



93

94 **[Figure 1. HERE]**

95

96 Despite significant data gaps, there is growing evidence that unsustainable agricultural
97 practices not only negatively affect the health and quality of the soils needed to sustain
98 healthy crops and provide nutrient-rich foods, but they can also significantly affect the

99 integrity and resilience of the ecosystem as a whole. To ‘break’ the above-cited vicious circle,
100 sustainable solutions are required to facilitate the conservation of soils. But, in order to
101 understand which soils are or can be sustainably managed, soil classification criteria are
102 essential. The founders of the soil classification linked the different units to precise
103 pedogenetic processes (FAO-UNESCO, 1974) to be able to define the functioning of each
104 unit. The advantages of knowing the position of a cultivated field on the map of the
105 distribution of the world's soils remain minimal for the farmer. Scale and micro-
106 morphological or purely local factors intervene and affect the functionality of the soil map.
107 Generally, farmers do not know the name of the soils they are cultivating. Not even many
108 scientists who study natural ecosystems know the name of the soils in which they grow plants
109 or raise livestock.

110 This article is focused on the most advanced and updated research on the processes
111 occurring at the interface between soil physicochemical aspects, plant roots and soil
112 microorganisms/animals in sustainable agrosystems, and on practices to establish sustainable
113 soils and preserve their fertility. An examination of the published literature has revealed that:

114

- 115 a) soil humus formation, soil compaction and degradation, soil-plant-atmosphere
116 interactions, root development and rhizosphere processes, vegetation types and
117 phytosociology, signaling among plants and organisms, and plant nutrient balance
118 have all crucial roles in making a soil really sustainable;
- 119 b) a conspicuous part of soil physical, chemical and biological fertility in
120 agroecosystems can be attributed to the action of soil microorganisms, with a
121 substantial contribution of soil animals;
- 122 c) a new paradigm for soil classification is necessary for creating the conditions for
123 soils to be sustainable and able to provide ecosystem services.

124

125 In this article, all these aspects are considered in a holistic view, with agrosystems
126 considered as living systems where soil, vegetation, fauna and microorganisms co-evolve and
127 are reciprocally influenced (paragraph 6). In living soils, the key role of microorganisms in
128 agrosystems should be seriously taken into account in land management strategies, focusing
129 not exclusively on crop yield and quality, but also on soil fertility restoration and
130 environmental safety. Moreover, the role of soil fauna, especially considering their

131 interactions with microorganisms and plant roots, can surely contribute to the long-term
132 sustainability of agricultural soils.

133 The aim of this commentary paper is therefore to reveal the complex interactions between
134 soil physical and chemical properties (on which classification is mainly based), soil microbial
135 diversity, and plant health in sustainable agroecosystems. Nowadays, agricultural activity,
136 rather than considering just productivity, is focused on the quality of products, natural
137 resource stewardship and environmental aspects, moving toward sustainable management
138 techniques. The sustainable, judicious and efficient use of soils is thus essential to support
139 continued agricultural production and quality. Focusing on sustainable soil use management
140 and food production, this new type of agriculture can perfectly fit within the background of
141 natural resources challenge, where positive mutual interactions between soil microorganisms
142 and cultivated plants play a key role.

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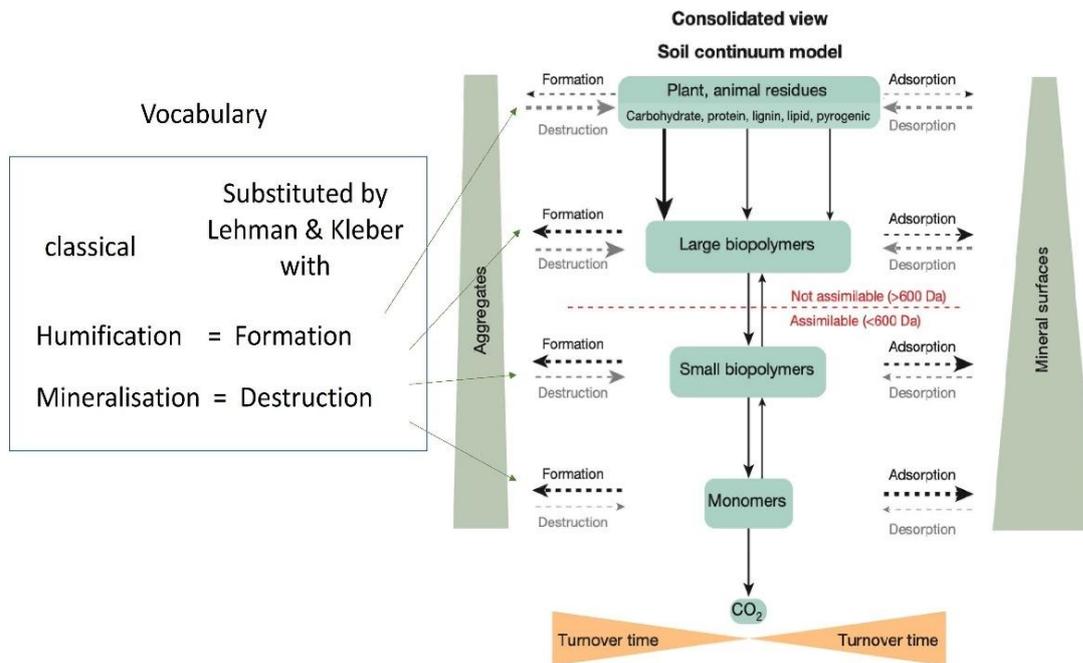
144

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

146

147 Lehmann and Kleber (2015) reject the concept of humus and claim that: “*Government-*
148 *funded research programs must therefore preferentially support science that bridges the gap*
149 *between detailed and fine-scale mechanistic research at the plant-soil interface and field-*
150 *scale research relevant to those who manage soils for their multiple ecosystem services”*. In
151 their "Soil continuum model - Consolidated view" (Fig. 2) they replaced "humification" and
152 "mineralization" with the less precise terms of "formation" and "destruction". Stevenson
153 (1994) founded the organic matter science accurately describing large to small molecules and
154 their specific properties in a model very similar to the one presented as a novelty in 2015 by
155 Lehman and Kleber. With the intention of strengthening our position in defense of humus, we
156 report in Appendix 1 the thought of “The first major critique of the humification concept”
157 (Lehmann and Kleber, 2015). It seems to us that Waksman (1936) predicted soil depletion as
158 a consequence of denying the concept of "Humus as an organic system". The recent
159 acknowledgement of the supramolecular nature of soil humus substances (Drosos et al., 2018;
160 Piccolo, 2002; Pinton et al., 2007) allows to devise a fractionation procedure, called
161 Humeomics, that enables a detailed characterization of the structure of humic molecules in
162 soil. The molecular mass of humic molecules can be increased with repercussions on the
163 amount of carbon stored in the soil (Piccolo et al., 2019).

164



165

166

[Figure 2. HERE]

167

168 As for "fine-scale mechanistic research", it reminds us of those who would like to eat the
 169 pills that astronauts carry into space, instead of real legumes or cooked meats. It may even
 170 happen that they do not understand why they do not feel good in the long term. The concept
 171 gets closer when we consider the mass of neurons composing our brains. Via the process of
 172 categorization, the brain transforms only some sensory stimulation into information. Only
 173 some of the wavelengths of light striking our retinas are transformed into seen objects, and
 174 only some of the changes in air pressure registered in our ears are heard as words or music. To
 175 categorize something is to render it meaningful (Barrett, 2009). The same neurons produce
 176 different thoughts in response to a specific evolution of the entire brain system, that becomes
 177 increasingly rich in interconnexions and information. In figurative terms, the functioning of
 178 the soil is similar to that of a brain, but instead of generating thought in a living net of
 179 neurons, it builds a real complex ecosystem of interconnected living beings in continuous co-
 180 evolution.

181

182 3. Soil physicochemical quality and changes in soil organic matter

183

184 One of the main worldwide agricultural problems is the decline in soil fertility, mainly
 185 due to the reduction of soil biodiversity, and of nutrient and water content. Agricultural soils

186 are particularly susceptible to this problem, as they are based on the purposeful simplification
187 of the relationships between the plant and other components of the natural habitat. This
188 simplification should make agricultural ecosystems easier to control, but instead it creates
189 conditions of extreme weakness for plant life. Many studies have shown that the conversion
190 of natural land to agriculture, together with the agricultural intensification that enhances soil
191 organic matter (SOM) depletion, makes the greatest contribution to soil biodiversity loss
192 (Giller et al., 1997; Six et al., 2004; Sofa et al., 2014a; Vitti et al., 2015; Sofa et al., 2020a).
193 The large-scale use of pesticides may also have direct or indirect effects on soil biodiversity,
194 but the lack of data has resulted in contradictory research results (EASAC - European
195 Academies Science Advisory Council, 2018; Silva et al., 2018). SOM, especially its stabilized
196 fraction (humus in chemical sense), plays a crucial role in climate change mitigation and
197 adaptation (Shukla et al., 2020). Amount and types of SOM are principally determined by the
198 continuous physical and chemical action of soil organisms. Soil fauna and microbes are
199 crucial for breaking down, transforming and decomposing SOM (Filser et al., 2016). For this
200 reason, studies focused on understanding soil microorganism-SOM and macrofauna-SOM
201 interactions are needed, and guidelines for future experimentation and best regenerative
202 practices to exploit soil multifunctionality have to be developed, tested and validated.

203 Soils and crops are vulnerable to climate change and environmental stress, and will be
204 more and more in the near future. Many crops are endangered by increasing water shortage,
205 often due to changes in rainfall frequency, and rise of soil aridity and desertification,
206 eventually resulting in deteriorated soil structure and critically low levels of SOM, macro- and
207 micronutrients, all of which essential for water provision and plant growth (Matson et al.,
208 1997; Sofa et al., 2019a). The frequent and strong soil tillage, typical of intensive agriculture,
209 significantly affects the stability of soil microaggregates, that have a key role in SOM
210 stabilization and support long term carbon sequestration, being more stable than
211 macroaggregates (Filser et al., 2016). This triggers a detrimental vicious circle which
212 ultimately leads to an increase in the use of mineral fertilizers and pesticides, and needs
213 continuous and strong soil tillage to replace the burrowing and aggregating activity of soil
214 animals, again increasing SOM loss (Silva et al., 2019). In brief, such soils become mere
215 “containers” for plant roots and function as a carbon source, worsening the greenhouse effect
216 even further.

217 Healthy, fertile soils are rich in SOM built of carbon that living plants remove from the
218 atmosphere through photosynthesis. SOM fuels the soil organisms which improve soil

219 structure and recycle mineral elements that plants take up as nutrients (FAO and ITPS, 2015;
220 Mechri et al., 2017). But soils release carbon, too. The frequent use of tillage and fertilizers,
221 characteristic of modern conventional agriculture, has accelerated SOM degradation, releasing
222 more carbon into the atmosphere. The last IPCC report (Shukla et al., 2020) concludes that,
223 globally, cropland soils have lost 20-60% of their original SOM content. On top of those
224 losses, modern agriculture consumes a lot of fossil fuels to pull plows and manufacture the
225 synthetic nitrogen fertilizers that farmers rely on to coax large harvests from degraded soils.
226 Additionally, restoring soil health would help mitigate the effects of climate change.
227 Increasing the amount of SOM enhances its ability to hold water. Improving soil structure
228 would reduce erosion and retain more rainfall, where it can better sustain crops - especially
229 during drought-stressed years (Sofo et al., 2019b). In addition to benefiting the climate, less
230 fertilizer use will reduce off-farm water pollution (Silva et al., 2019). Land management
231 choices also affect the amount of carbon stored in trees, plants and soil (FAO, 2020). The last
232 IPCC report (Shukla et al., 2020) estimates that serious changes in forestry and agriculture to
233 curtail deforestation and improve soil management could reduce global emissions by 5 to 20
234 percent. While this won't solve the climate problem, it would represent a significant down
235 payment on a global solution.

236 What is it really important to monitor in a soil? Certainly, a comprehensive and in-depth
237 analysis of soil characteristics is required. To do this, correct soil sampling (e.g., by analyzing
238 composite soil samples taken at different soil depths in specific soil horizons) and/or an
239 appropriate pedological excavation are essential. This can allow the definition of physical soil
240 properties (accumulation of salts, soil compaction, reduction of macropores, soil hydraulic
241 conductivity - vertical and horizontal water infiltration), soil macroporosity (with macropores
242 analysis and their shape and size, both relevant for water infiltration), soil moisture,
243 preferably measured by sensors in different soil horizons during the year. Other important
244 parameters for defining soil fertility are the root status, evaluation of the healthy status of the
245 roots and of root morphology (root density, root diameter, amount of white, suberized and
246 dead roots, etc.), microscopic analysis of the roots to observe eventual physical damage of the
247 roots (e.g., necrotic parts, increased lignification, etc.). Among chemical parameters, a key
248 role for the fertility of agricultural soils is played by soil nutrients (particularly nitrogen and
249 phosphorus) and the presence/absence of soil contaminants, such as heavy metals, pesticides
250 and hydrocarbons. Soil gas analyses are also relevant, as the determination of carbon dioxide,
251 nitrogen oxides and methane (and oxygen too, even if it cannot be easily detected) by means

252 of gas chromatographic techniques or portable laser-based trace gas analyzers will allow us to
253 distinguish between anaerobic and aerobic micro-environments, with the latter able to
254 promote several plant diseases due to pathogenic microbial attacks.

255

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

257

258 Soils host a quarter of our planet's biodiversity, but most of it remains unknown (Sofa et
259 al., 2010; Wall et al., 2010; Fierer, 2017; Sofa et al., 2020a). One gram of soil may contain up
260 to one billion bacterial cells, tens of thousands of taxa, up to 200 million of fungal hyphae,
261 and a wide range of invertebrates like earthworms, springtails and nematodes (Wagg et al.,
262 2014), that are all part of a complex and interconnected food web (Lavelle et al., 2014; Wall
263 et al., 2015; Williamson et al., 2017). The health of all multicellular organisms (including
264 plants, animals, and humans) and their surrounding ecosystems are interconnected through a
265 subset of microbial organisms found in the plant and soil compartments, particularly in the
266 rhizosphere. Plants nurture an entire world of soil organisms that feed and protect the plants
267 according to aboveground-belowground, plant-soil feedbacks (PSFs) that have different
268 spatio-temporal scales and are greatly affected by climate-related factors (Ponge, 2013; Veen
269 et al., 2019).

270 The diverse communities of telluric bacteria and fungi keep the soil healthy and fertile
271 and determine the main biogeochemical processes that make life possible on Earth (Dastgerdi
272 et al., 2020; Sweeney et al., 2020; Wilpiseski et al., 2019). They play fundamental roles in
273 driving many ecosystem processes on which the functioning of terrestrial ecosystems
274 depends, including soil formation, nutrient and water cycling, climate regulation, carbon
275 storage, production of food, medicine and fibre, disease and pest control, and greater
276 resilience to global change (Bardgett & Van der Putten, 2014; Lavelle et al., 2014). While soil
277 biodiversity represents an important biological and genetic resource for biotechnological
278 innovation with benefits to society, it is increasingly threatened by different forms of land
279 degradation (FAO, 2020; FAO and ITPS, 2015). Soil biodiversity is vulnerable to many
280 human disturbances, including intensive and non-sustainable agricultural practices, land use,
281 climate change, nitrogen-enrichment, soil pollution, invasive species, and sealing of soil
282 (Orgiazzi et al., 2015). Soil microorganisms' dynamics (e.g., mobility, growth, nutrient
283 absorption and respiration), mainly responsible for soil fertility and quality (Bünemann et al.,
284 2018), are strongly affected by the soil management (Enwall et al., 2007; Jeanbille et al.,

285 2016; Sofa et al., 2020a, 2020 b). When the soil microbial biocenosis is significantly altered,
286 cultivated plants are more susceptible to diseases and display stunted growth. In this respect,
287 correct agronomic techniques (fertilisation, irrigation, soil tillage, etc.) become instruments to
288 recover the disrupted equilibrium. However, the functionality and metabolism of soil
289 microorganisms are related to soil quality and fertility, as they influence and, at the same
290 time, are influenced by the soil carbon and nitrogen contents, bacteria being an essential part
291 of carbon and nitrogen cycling processes (de Vries and Shade, 2013; Mooshammer et al.,
292 2014; de Vries & Wallenstein, 2017; Li et al., 2018). Microbial interactions play a critical role
293 not only in regulating ecological functions and processes but ultimately in determining the
294 health of plants, animals and humans as components of terrestrial ecosystems (Fierer, 2017;
295 Sofa et al., 2020b; Stevenson et al., 2020). Having co-evolved with a plethora of
296 microorganisms, plants benefit from microbial symbiosis, while simultaneously facing
297 challenges from pathogens.

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

318 microbes to top predators, include trophic chains (Pollierer et al., 2019) by which fresh
319 organic matter is transformed in humus (Lehmann and Kleber, 2015) at a rate increasing with
320 the number and complementarity of functional niches of soil animals (Heemsbergen et al.,
321 2004).

322 It is essential to link biodiversity measures with specific soil functions and plant status
323 under particular environmental contexts, particularly in agrosystems (Ramirez et al., 2015).
324 For instance, while some soil functions are driven by a diverse set of organisms that
325 contribute to functional resilience (e.g., decomposition), other soil functions involve a more
326 specific set of organisms (e.g., nitrifiers, bio-control agents) which make them more
327 vulnerable to biodiversity loss. Wagg et al. (2014) showed that soil biodiversity loss or
328 simplification of soil community composition can impair multiple ecosystem functions,
329 including plant diversity, decomposition, nutrient retention, and nutrient cycling. A better
330 understanding of the pivotal roles of soil organisms in mediating soil-based ecosystem
331 services, as affected by ecosystem management approaches and practices adapted to socio-
332 ecological contexts, is also central to guiding biodiversity-friendly agricultural intensification
333 (Lal, 2015; FAO, 2020).

334

335

336 **5. Soil classification**

337

338 *5.1. Crucial historical legacies*

339

340 In this section we summarize the historical legacies of two masters of soil classification,
341 Dokuchaev Vasily Vasilyevich (1846-1903), considered the founder of the soil classification
342 in Europe, and Hans Jenny (1899–1992), one of the greatest American pedologists, a Swiss
343 who ended up working in California at Berkeley University.

344

345 1) From "Zones verticales des sols, zones agricoles, sols du Caucase" (Dokuchaev, 1900),
346 cited in "A l'aube de la Science du sol" (Legros, 2019):

347

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

- 350 b) Climate and corresponding vegetation are the main factors responsible for the
 351 organization of soils on a global scale.
- 352 c) At the field scale, climatic variability does not have to be considered, while
 353 topography and variability of the geological substrate can still modify soils.
- 354 d) Dokuchaev and his students also observed that there were exceptions to climate
 355 zonality. Local environmental factors play a predominant role and mask the role of
 356 climate. It will take many years to conceptually resolve this problem, as evidenced
 357 by the changes in vocabulary introduced on the subject over time. Currently we
 358 distinguish between “zonal” soils, that are part of the climatic zonality, “azonal”
 359 soils, whenever the rock outcrops directly, and “intra-zonal” soils, whose
 360 characteristics are linked to special conditions, such as excess water or salt.

361

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

363

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

369 b) The initial state of the soil system has been designated as parent material. Climate
 370 (cl), Organisms (o), Topography (r), Parent material (p), and Time (t) completely
 371 describe the soil system. The total change of any soil property depends on all the
 372 changes of the soil-forming factors following a fundamental equation:

373

374 (1) $s = f(cl, o, r, p, t, \dots)$, where: s stands for “soil property”, f for "function of," or
 375 "dependent on", dots show that, besides the variables listed, additional soil formers may
 376 have to be included. In a more precise differential mathematical formula, the equation (1)
 377 becomes:

378

$$379 \quad (2) \quad ds = \left(\frac{\partial s}{\partial cl}\right)_{o,r,p,t} dcl + \left(\frac{\partial s}{\partial o}\right)_{cl,r,p,t} do + \left(\frac{\partial s}{\partial r}\right)_{cl,o,p,t} dr + \left(\frac{\partial s}{\partial p}\right)_{cl,o,r,t} dp + \left(\frac{\partial s}{\partial t}\right)_{cl,o,r,p} dt$$

380

381 c) In selecting cl , o , r , p , and t as the independent variables of the soil system, we do
 382 not assert that these factors never enter functional relationships among themselves.

383 We emphasize the fact that the soil formers may vary independently and may be
384 present in a great variety of combinations, either in nature or under experimental
385 conditions. To find out the role played by each soil-forming factor, it is necessary
386 that all the remaining factors be kept constant. A serious practical difficulty in
387 solving Equation (1) in the field arises from the requirement of keeping the soil
388 formers constant. In laboratory experiments on soil formation, we can exercise rigid
389 control of the conditioning variables (e.g., temperature, moisture, etc.) and thus
390 obtain sets of data that leave no doubt as to the functional relationship between
391 them. Under field conditions, considerable variation in the magnitude of the
392 variables cannot be avoided, in consequence of which we arrive at scatter diagrams
393 rather than perfect functions. Statistical considerations must be introduced, and the
394 resulting equations possess the character of general trends only. Even so, the gain in
395 scientific knowledge fully justifies the mode of approach.

396

397 5.2. Soil and vegetation

398

399 A major problem with the current system of soil classification is that it is difficult for
400 non-specialists to use and understand. Perhaps it is possible to take an example from botanists
401 and the synthetic methods they have prepared. There are several aspects that vegetation and
402 soil coverings have in common:

- 403 a) both are "covers", both correspond to a continuous layer that shows changes inside
404 and outside perceptible to the human eye. If there is more water in the system, for
405 example, the vegetation changes and also the underlying soil; external change can
406 also be seen from satellite; the internal change (structure) is noticed by the naked
407 eye with some training. Of course, the more the water (or other main ecological
408 factors) balance differs, the more the change is visible;
- 409 b) in both, the whole cover can be broken down into sub-layers. For example, for
410 vegetation we speak of arboreal, shrubby and herbaceous layers; for the soil of
411 organic, organic-mineral and mineral horizons;
- 412 c) in both cases, circumscribing spatial sub-units (horizontal or vertical) is not so
413 simple, because the transition from one to the other unit is rarely abrupt; very often
414 it is gradual and nuanced. It is normal for this to happen, because in the two cases

415 the factors involved in the distribution of the plant and animal species that inhabit
416 these two coverages are interdependent and evolving.

417 We know that using the characteristic species of the phytosociological units to map the
418 forest vegetation, the part of the forest occupied by undefined vegetation types becomes larger
419 than that occupied by known vegetation types (Zanella and Géhu (Directeur), 1994). In fact,
420 to define vegetation units, lists of particular species are needed; these characteristic species
421 are not the most common in each vegetation unit (if they were the most common, they would
422 also be present elsewhere). Thus, by definition, a large part of an area covered by
423 phytosociological units lacks the characteristic species. This prevents phytosociology from
424 best expressing its operationality. A map of the distribution of vegetation units is always
425 ambiguous and nuanced in many transitional places (Bartoli, 1966; Susmel, 1980, 1959). The
426 founding principle (Braun-Blanquet, 1964; Clements, 1936) says that the species lists are
427 repetitive in the space, and therefore it is possible to put a name on each list and produce
428 vegetation maps. We know, however, that for ecological reasons, plant lists can only be
429 partially repetitive. The species respond to the environment and form an unlimited number of
430 combinations that are constantly evolving in space and time (Tansley, 1935). To make an
431 ecosystem survey, in which a given group of plants and animals coevolve, people have to
432 place themselves in the center of an ecologically homogeneous environment. Unfortunately,
433 detecting such ecological homogeneity remains a subjective matter, also because the success
434 of this coexistence can only be discovered in the future, during the succession of an
435 ecosystem.

436

437 *5.3. Classical soil classification*

438

439 Foresters considered mainly the organic surface part of the soil, calling it the “humus
440 form”, P.E. Müller in Jabiol et al. (2005), whilst agronomists concentrated mostly on the
441 mineral part of the soil (which also contained the organic part buried with the cultivation)
442 which they called “soil”. While foresters selected morpho-functional traits, agronomists
443 focused on climate (USDA) and physical-chemical composition, texture, structure, thickness
444 of various diagnostic horizons (USDA and other National and International classifications),
445 with the scope to provide mineral elements and nutrients for crops. Foresters tried to link
446 humus forms to the floristic composition or soil animal lists (Hartmann, 1965; Hartmann and
447 Marcuzzi, 1970; Klinka et al., 1981) and the ability to regenerate the forest (Toutain, 1981;

448 Bernier and Ponge, 1994; Camaret et al., 2000; Ponge, 2009; Bernier, 2018). Agronomists, on
449 the other hand, linked soil types to the specific climate and needs of crops (Jenny, 1941;
450 Birkeland, 1999; Beaudette et al., 2013; Brenna and Tabaglio, 2013; Berdugo et al., 2020).
451 Each country built its own classifications.

452 For the soil, the need for unification was necessary when international organizations
453 wanted to map soils at planet level. A summary of the history of soil classification can be
454 found in the FAO-website portal. The FAO-Unesco Soil Map of the World (1974) is
455 structured in 10 Volumes composed of a common Legend (Volume 1) and nine sections
456 corresponding to different areas of our planet ([http://www.fao.org/soils-portal/data-hub/soil-](http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/)
457 [maps-and-databases/faunesco-soil-map-of-the-world/en/](http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/)). The authors of the cartography
458 tried to respect the principles mentioned above (5.1. Crucial historical legacies). In FAO-
459 UNESCO (1974) we can read: “*The number of soil units which compose the legend of the Soil*
460 *Map of the World is 106. The legend sheets present these soil units in an order which reflects*
461 *the general processes of soil formation. The basic principles which underlie the separation of*
462 *these soil units and their definitions are discussed in Chapter 3. Areas of "non soil" are*
463 *shown on the map as miscellaneous land units.*” It sounded very promising. Unfortunately,
464 the agreement was only apparent. It hid strong differences of thought that later revealed
465 themselves in the construction of different national operational classification systems. The
466 USA built their own classification (Soil Survey Staff, 1975, 1999, 2003, 2010, 2014, 2015;
467 Soil Science Division Staff, 2017), FAO and IUSS another (Jahn et al., 2006; WRB, 2006;
468 IUSS Working Group WRB, 2007; IUSS Working Group WRB, 2010; IUSS Working Group
469 WRB, 2015; Charzyński et al., 2017), and many states operated independently in their
470 countries, often agronomists on one side and foresters on the other, for example in France
471 (Afes, 2009). In Italy, for historical reasons, the classification of soils depends on the region
472 in which it is practiced: in the North West, the French system prevails, even for humus forms,
473 in the North East, the German or USDA systems are adopted but an ancient Austrian system
474 (Hartmann and Marcuzzi, 1970) was until recently used for humus forms, and in the Central-
475 South often the USDA is preferred sometimes that of IUSS Working Group, while for humus
476 it is not uncommon to refer to a Canadian manual (Klinka et al., 1981).

477 Even worse, when there are more than three variables interacting, and in the soil there are
478 dozens, a natural system ends up in chaotic and unpredictable movement (Mayr, 1942;
479 Lorenz, 1963). Soil profiles, as other natural systems, are all different and impossible to
480 classify through a list of characters subdivided in categories as foreseen by Jenny (1941). It is

481 thus impossible to give a name to the soil by fixing the position of a diagnostic horizon in the
482 profile, or the color of this horizon using a panel of reference colors (Munsell), or the content
483 of clay of this horizon. Each variable depends of so many other variables that, in a given point
484 in the field, the combination of them is very large and unpredictable (Equation 1 or 2).
485 However, soil scientists decided to separately improve existing classifications. The result was
486 that the national classifications diverged over time, making it impossible to merge them into a
487 single reference.

488 For some years now, the specialists of the different classification schools have been
489 organizing joint outings, such as soil classification IUSS activities. The best attempt to make
490 the classification easier to understand to other natural science specialists is that of the Soil
491 Survey Staff (Staff Soil Survey, 2015), which proposed a beautiful Illustrated Guide to Soil
492 Taxonomy (version 2) based on the American system. The corresponding model of the World
493 Reference Base Working Group was published in 2018 (Blum et al., 2018). What is most
494 surprising in these manuals is the almost absence of information on soil biology, zero pages in
495 the Staff Soil Survey (2015), four pages in the Blum et al. (2018), even if the “fathers” of soil
496 science put soil organisms in second position, after the climate. And we know how much the
497 climate itself is connected to the living beings of our planet, which have modified it to make it
498 suitable for their development (Lenton et al., 2016).

499

500 *5.4. Is there a way to classify soil that is useful and also accessible to non-specialists?*

501

502 To classify the soil in a simple way, it is necessary to define from the outset the purpose
503 of the classification and the “limits of the boxes” in which it is useful to put the soils. The
504 Unified Soil Classification System (USCS), for example, is a standardized method used in
505 engineering and geology to describe the texture and grain size of a soil. It can be applied to
506 most unconsolidated materials and is represented by a two-letter symbol. A similar “logical”
507 model is already used for agricultural soils. The owner of a crop sends the soil sample to the
508 laboratory which does the analysis and classifies that soil for that specific crop, and reports
509 how much nutrients are missing to optimize its production. Although you may disagree on the
510 principle that knowing what plants are made of makes possible to calculate what needs to be
511 put into the soil (Fusaro, 2015; Lowenfels, 2017), with adjustments of doses and nutrients
512 distributed over time, and crop rotation, the method works. There is now an important amount
513 of research results on the biological quality of the soil. Some of the thousands of articles on

514 the subject include historical context (Magdoff and Weil, 2004; Wander et al., 2019);
515 European references (Parisi, 1974, 2001; Chaussod, 1996; Balbo et al., 2006; Ponge et al.,
516 2013) and climate change implications (Brussaard et al., 2007; Bispo et al., 2018; Yin et al.,
517 2020).

518 In few words, a QBS index (Biological Quality of the Soil) is calculated by sampling soil
519 animals, especially arthropods and worms. These animals are sorted into functional groups
520 and studied in different types of soils. It can be seen if one soil is richer in functional
521 biodiversity (which guarantees the functioning of the soil, with the right proportion between
522 mites and springtails, for example) than another (Angelini et al., 2002; Ruiz-Camacho, 2011;
523 Nuria et al., 2011). Similarly, soil microorganisms are classified into functional groups
524 designed to reflect soil management (Torsvik and Øvreås, 2002; Nesme et al., 2016).

525 In summary, there are many useful ways to classify the soil, but none which satisfy what
526 the founders of the soil science wished, that is to understand the soil on a planetary level and
527 to appreciate how this system was distributed/developed on the planet in harmony with life.
528 There is perhaps a way to get to this; not to attempt to circumscribe the infinite final soil
529 types, but to identify a small number of soil-forming processes to which more soil types are
530 arbitrarily assigned.

531

532 5.5. Soil and humus

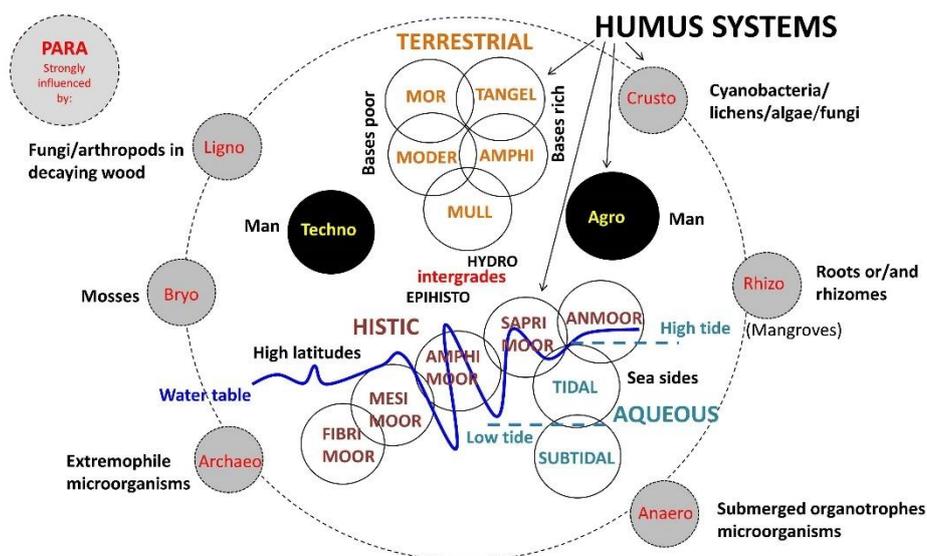
533

534 When an artificial crop system is compared to a forest, things change. We think of a
535 whole system composed of species that have historically come together to collaborate and
536 optimize energy resources. Forest managers call the attempt to mathematically imitate the
537 achievement of a balanced forest ecosystem in terms of age, number and size of trees as
538 "normalization" (Susmel, 1980; Phillips et al., 2004; Pan et al., 2011; Oldeman, 2012;
539 Reinmann and Hutya, 2017; Hasan et al., 2017; Mahdavi et al., 2019). The cycle concerns a
540 part of the forest surface, a mosaic piece that regenerates when an old tree die and leads to the
541 stability of the forest mosaic as a whole. The number of trees on the surface under renewal
542 must decrease exponentially following a known curve with parameters related to the species
543 and called the "norm". Soil plays a fundamental role in the cycle, and it is the superficial part
544 of the soil profile composed of organic (O or H) and organo-mineral (A) horizons that
545 changes most rapidly, the whole profile following within a much longer time (Achat et al.,

546 2015; Baldrian, 2017; Bernier and Ponge, 1994; Osman, 2013; Poeplau et al., 2020;
547 Takahashi et al., 2019; Zanella et al., 2001, 2018a).

548 The need to have one international system for classification of all humus forms is quite
549 recent. Unification began in July 2003, with a meeting in Trento (Italy) of 26 European
550 specialists with the specific aim of arriving at a European proposal for the classification of
551 humus forms. The need for unification arose from the necessity to accurately calculate the
552 carbon cycle at the level of several European countries. The profile of a natural soil is very
553 complex, and it is not enough to take samples at predefined depths to know the amount of
554 carbon that it stores. It is better to subdivide the soil into horizons and then take a sample in
555 each of them. With ½ or more of the carbon being concentrated in the organic and organo-
556 mineral horizons, which correspond to the humus forms, it was decided to try to classify them
557 in a standardized way. In 2018, the summary of the work (Fig. 3) was collected in three
558 Applied Soil Ecology special issues (Zanella and Ascher-Jenuell, 2018a, 2018b, 2018c).

559



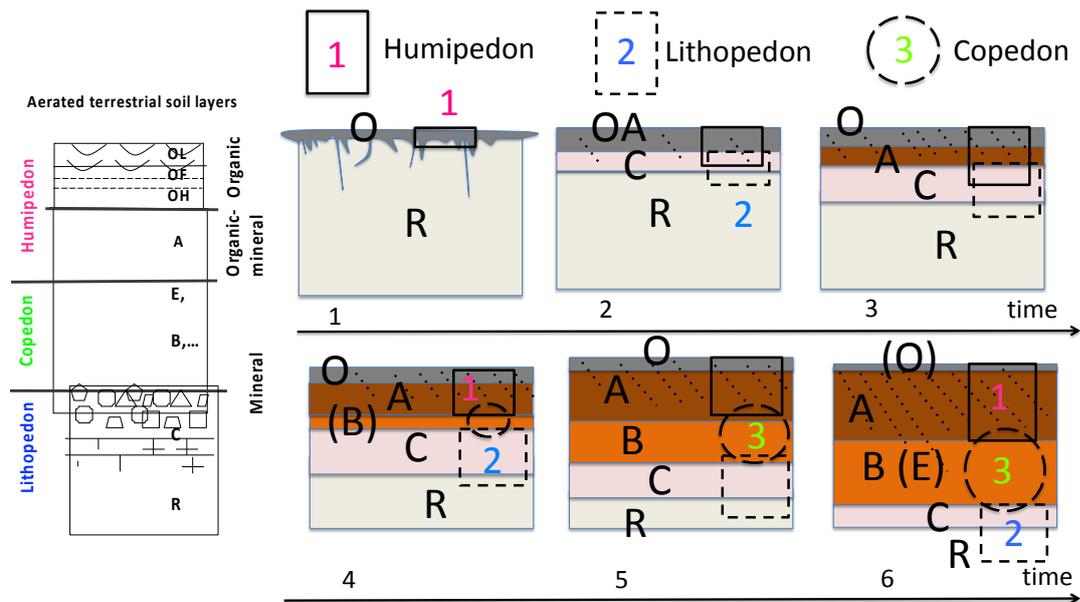
560

561 **[Figure 3. HERE]**

562

563 The soil develops and changes with the system that contains it, and depending on the
564 space-time scale with which one looks at it (Zanella et al., 2018e, 2018b). It seems like a
565 trivial matter; in reality it changes the perspective with which one has to look at the soil when
566 wanting to classify it. One way to classify soil taking into account its dynamics is to break it
567 down into three layers which are evolving and influencing each other but which remain and
568 can be classified independently (Fig. 4).

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[Figure 4. HERE]

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Living organisms organize the superficial part of the Earth's crust into layers that are visible to the naked eye. If we consider the soil as a living ecosystem, it begins with the colonization process of the rock by microorganisms (time 1 on Fig. 4). In time 2, we can see an organic matter that begins to bond with the mineral one and form aggregates (OA horizon), and the rock fragments generating an initial Lithopedon (C). In time 3, the organo-mineral aggregates become well amalgamated and form a structured A horizon. In time 4, a new layer called Copedon begins to form between well-developed Humipedon and Lithopedon; it arises from the interaction of them. In time 5, Copedon (horizon B) increases in volume and takes on a mature form. In time 6, we arrive at a complete, mature soil profile, where the Copedon can also present an E horizon.

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It is possible to break down the soil profile into three main sections: Humipedon (organic O and/or organic-mineral A horizons); Copedon (mineral horizons E and/or B); Lithopedon (mineral horizons C and R). The advantage is that of being able to study these parts of the soil as if they were relatively independent (Zanella et al., 2018d). In the natural environment, the formation of the soil profile can stop at the Humipedon stage (in films of microorganisms on bare rock, or in soil crust), or also comprise a Lithopedon (sometimes very thick in soils at high altitude, such as Rendzina or Rakers, for example), or form an additional Copedon (as in the most common mature soils) which may be very deep in tropical soils (Fig. 4, time 5 and 6); eroded soils often lost their whole Humipedon.

592 Moving on to classification, morpho-functional diagnostic horizons were chosen for each
593 Humipedon. As an example, the Mull system contains those humus forms that are able to
594 integrate into an organic-mineral horizon all the litter annually produced by the ecosystem in
595 which they develop. As consequence, all the humus forms belonging to a Mull system are
596 characterized by 1. the absence of the last stage of litter transformation (corresponding to a
597 diagnostic horizon called OH, made of organic thin fragments, mixed with small animal
598 droppings) and 2. the presence of an organic-mineral A horizons made of zoogenic large
599 aggregates. In the same way, other morpho-functional, organic and organo-mineral, zoogenic
600 and non-zoogenic horizons were defined to classify each Humipedon in five Terrestrial
601 humus systems (Mull, Moder, Mor, Amphi and Tangel). In each humus system the relative
602 thickness of the diagnostic horizons allows to individuate 3-4 finer humus forms.

603 TerrHum, a free available Android app, can help to remember the diagnostic characters
604 and horizons (<https://play.google.com/store/apps/details?id=fr.inra.terrhum>) corresponding to
605 each humus system and forms. The same reasoning was done for submerged (Histic) tidalic
606 seaside (Aqueous) and initial, or man-modified, or artificial (Para) humus systems. The
607 classification method is very similar to that described in the FAO-UNICEF map legend: to
608 circumscribe a soil ecosystem at the top of the Earth crust, that grows over time and evolves
609 following a pedogenetic process, dependent on those same soil forming-factors reported in the
610 preceding Crucial historical legacies. The recognition of morpho-functional elements then
611 makes it possible to identify humus systems and forms.

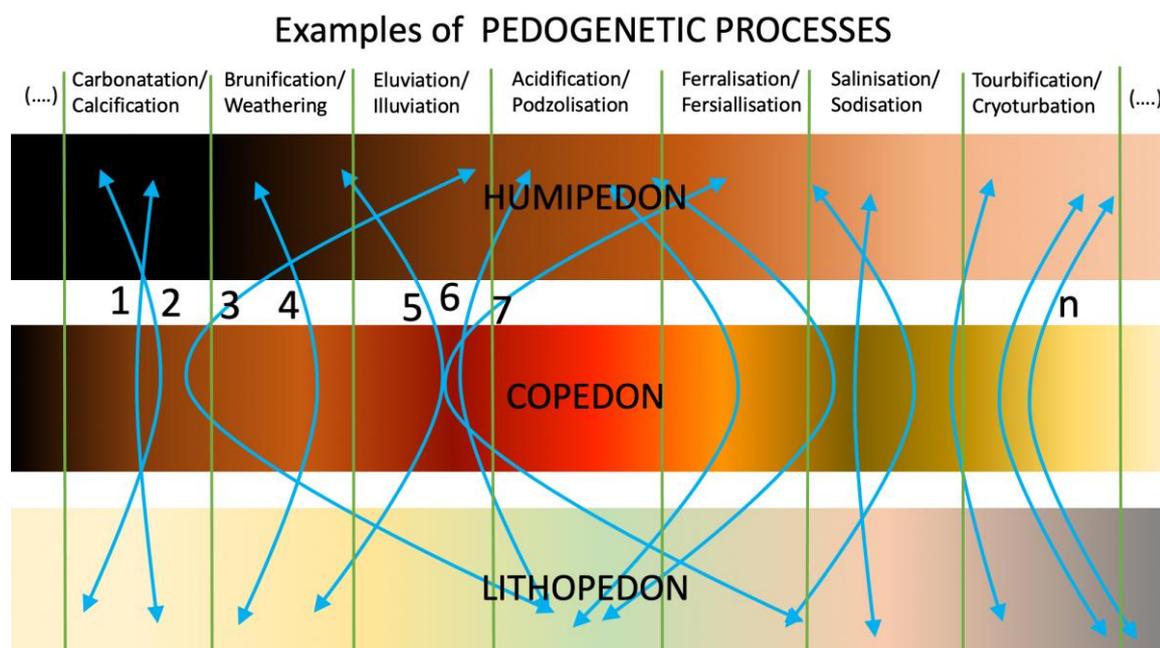
612 To obtain a classification of the whole soil profile, it would be enough to do the same
613 proceeding for the Copedon and Lithopedon, and to identify some morpho-functional
614 diagnostic horizons corresponding to given processes of pedogenesis. This work is already
615 present and explicitly reported in the FAO-UNICEF first world soil maps. As if the soil could
616 not correspond to a real ecosystem, recent classifications have given up looking for a purpose
617 in the evolution of the soil.. We think it is a serious fundamental error, which generates
618 confusion and misunderstanding. We suggest assigning the classic pedogenesis processes to
619 Copedon, in order to recover much of the classification work that is also found in recent soil
620 classifications (examples: Eluviation/Illuviation, with the formation of an E horizon in
621 missing the finished in Bt clay and genesis of a Luvisol profile; Podzolization, with formation
622 of Bhs or/and Bs horizons and genesis of a profile of Podzol; Brunification/weathering, with
623 formation of Bw horizons and genesis of a profile of Cambisols, and so on). It is a question of

624 returning to the origin of Pedology, where pedogenesis processes were established, and which
 625 implies that the soil is a real evolving ecosystem.

626 A classification of the Lithopedon would help to distinguish parent material from
 627 substrate. In addition, Lithopedon physical and chemical qualities certainly influence the
 628 cycles of nutrients, carbon, air and water in the soil (Cremeens et al., 1994; Gupta et al.,
 629 2008). (Juilleret et al., 2014; Moragues-Quiroga et al., 2017) Juilleret et al. (2014) suggest to
 630 implement four “subsolum materials” in the WRB as qualifiers; Moragues-Quiroga et al.
 631 (2017) suggest to survey potential geochemical tracers of exchange processes at the water-
 632 mineral interface, suggest to differentiate surface organic compartment, upper horizons with
 633 presence of atmosphere-derived particles, lower horizons characterized by a mineralogical
 634 composition pointing to ancient events.

635 In Figure 5, the subdivisions (which are rarely abrupt) within the three soil layers
 636 (Humipedon, Copedon and Lithopedon) are expressed with colors. The arrows correspond to
 637 the interrelationships between the subsystems (Humi- Co- and Litho-pedon) of the soil. These
 638 have their own dynamics which are partly independent of the whole, but which can be
 639 detected with the naked eye by looking for signs of co-evolution (pedological processes),
 640 which ultimately generate each particular soil profile.

641



642

643 *[Figure 5. HERE]*

644

645 The forms of humus are directly linked to particular groups of soil animals (Ponge, 2003,
646 2013; Zanella et al., 2018b) and agents of biodegradation which are in turn linked to soil
647 microorganisms (Sofa et al., 2014, 2019; Bispo et al., 2018; Bayat et al., 2018; Karimi et al.,
648 2018, 2019; Liang et al., 2019). This connection could have very important consequences on
649 the management of forest and agricultural soils to stop the climate from warming. The
650 ultimate goal could be to integrate in the new classification all those data relating to biological
651 functioning that are now collected by people who already practice a non-specialized soil
652 classification.

653 From another point of view, which is the one concerning agricultural soil, soil that
654 produces food for humans and domesticated animals, it was thought that to
655 transform/modify/till such type of soil was an economically very profitable action. At the time
656 of maximum expansion of the technological revolution of agriculture, Hans Jenny became
657 aware of the possible misunderstanding, and in 1980 defined soil as follows: “Soil is more
658 than farmer’s dirt, or a pile of good topsoil, or engineering material; it is a body of nature that
659 has its own internal organization and history of genesis” (Jenny, 1980). In a letter to Science
660 of the same year, he even wrote: “Because of a possible climatic warm-up, we do not wish
661 accelerate humus oxidation and the concomitant flux of carbon dioxide from soil into the
662 atmosphere... The humus capital, which is substantial, deserves to be maintained because
663 good soils are a national asset”.

664

665

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

667

668 *6.1. Conventional or sustainable agriculture?*

669

670 Nowadays, agricultural production is at risk due to many adverse abiotic and biotic
671 factors. Furthermore, climate change can potentially decrease the effectiveness of plant
672 defence mechanisms and increase the risk of diseases through excess growth and
673 physiological alteration of cultivated plants (Vitti et al., 2016). In terms of increased
674 temperature and extreme precipitation regimes, whether aridity or flooding, climate change
675 will have detrimental agricultural consequences due to the interrelations between climate,
676 land and water use, soil degradation and landscape changes (Dale, 1997; Tsiafouli et al.,
677 2015). Nowadays, food security is an increasing concern in a growing number of countries.

678 This situation calls for a relevant appraisal of factors that could affect crop production. One of
679 the factors promoting a sustainable food production system is soil biodiversity (Sofo et al.,
680 2020b). Unfortunately, despite the promotion of sustainable soil management by the Global
681 Soil Partnership since 2012, in many cases soil management is still focused on directly
682 managing soil fertility, rather than on protecting soil biodiversity as a whole or single species
683 individually, although soil biodiversity is known to be a main agent of soil fertility (Altieri et
684 al., 2015).

685 The application of pesticides, herbicides and mineral fertilizers, typical of conventional
686 agriculture, cannot be considered an eco-friendly approach for crop production and defence,
687 as their overuse can provoke water contamination, air and water pollution, and release of
688 harmful residues and by-products into the soils (Blouin 2018; Korkina and Vorobeichik 2018;
689 Van Groenigen et al., 2019). A decrease in soil quality due to conventional soil management
690 negatively influences important ecosystem processes, like nutrient cycling and carbon
691 sequestration (Blouin et al., 2005; Bampa et al., 2019). On the other side, sustainable
692 agriculture offers new chances to mitigate the effects of climate change. In sustainable
693 agroforestry systems, management practices are able to increase carbon inputs into the soil
694 and possibly reduce greenhouse gases (GHGs) emissions due to some revised field
695 operations, e.g. by irrigation, use of recycled water, pest and disease management,
696 fertilization, and soil and plant farming systems (Mutuo et al., 2005). In turn, carbon
697 enrichment increases biological activity by improving soil structure, as well as soil moisture
698 and nutrient content that are beneficial to plant growth and production (Marinari et al., 2000).
699 As Lago et al. (2020) recently indicated, there is clear evidence that more environmentally
700 friendly land management represents a promising strategy to increase soil carbon
701 sequestration.

702

703 *6.2. Soil and vegetation coevolve*

704

705 Soil functions as a living system. Climate, organisms, topography, parent material and
706 time completely describe the soil system. Soil and vegetation co-evolve implementing other
707 living beings and creating the well-known zonation of biomes of planet Earth. In recent years,
708 soil quality has been recognized to play a double role in the entire agroecosystem: it is
709 important for a good production as well as for a healthy environment (Doran and Zeiss, 2000).
710 In conventional agriculture, still adopted by most farmers, frequent soil tillage strongly

711 reduces the complexity and diversity of soil microbiota (Adl et al., 2006). For this reason,
712 conventional, non-sustainable agronomic practices should evolve into a more sustainable
713 management addressed to ameliorate the ecological networks and nutrient cycles, in which
714 soil microorganisms are involved. The adoption of sustainable soil management practices and
715 organic agriculture can be eco-friendly and include safe methods to ameliorate plant
716 physiological status, reduce plant disease incidence, and increase yield and quality without
717 side damages to the environment and human health. For instance, it would be possible to
718 adopt a sustainable approach that enriches the soil with biocontrol microorganisms with
719 action against pests (El-Tarabily and Sivasithamparam, 2006), plant-growth-promoting
720 microorganisms able to promote plant growth and development (Abhilash et al., 2016), and
721 microorganisms able to increase the availability and uptake of essential nutrients in plants,
722 e.g. mycorrhiza for phosphorus and nitrogen-fixing bacteria for nitrogen (Bolan, 1991).

723 In this scenario, the advantages of the adoption of a sustainable management (or
724 conservation and regeneration agriculture), that includes no/minimum tillage, cover crop
725 application, incorporation of grass and crop residues into the soil, and endogenous and
726 exogenous soil carbon inputs (Palm et al., 2014) can be a key factor to enhance soil
727 quality/fertility and production in a sustainable way, preserving natural resources and
728 avoiding detrimental effects on the environment. Such benefits include a high level of soil
729 microbial genetic/functional diversity and complexity both in the soil (bulk soil and
730 rhizosphere) and in the plant (phyllosphere, carposphere, and endosphere), a faster carbon and
731 nitrogen turnover, higher levels of SOM and soil water content, and better soil physical and
732 chemical characteristics (Fausto et al., 2018). Inappropriate or exploitative crop
733 agroecosystems represent a key threat for soil degradation through erosion, nutrient depletion
734 or structural collapse (Didden et al., 1994). Increasing our knowledge on biochemical
735 processes of soil microorganisms and animals involved in carbon and nitrogen dynamics, that
736 influence in turn their availability for plants (Shaffer et al., 2001), will lead to optimized
737 management strategies for a multifunctional concept of agriculture.

738

739 *6.3. Sustainable agriculture application and monitoring*

740

741 Addressing knowledge gaps of sustainable practices is of fundamental importance as an
742 entry point to improve growing techniques and for understanding wider soil processes, such
743 as consequences of land use or climatic change on both biodiversity and soil ecosystem

744 services. The research should be focused on developing an ecological and holistic approach
745 that combines traditional soil health assessment with sensitive indicators of the effects of the
746 soil environment on soil microbial and faunal communities and cultivated plants, such as
747 community dynamics (taxonomic, genetic, functional and metabolic) and plant stress
748 physiology, mostly assessed by growth/yield, hormone levels and photosynthetic capacity
749 (e.g., photosystem II activity). The sustainable approach will lead to a better understanding of
750 the effects of management practices on soil organisms and plants. In the long-term, soil health
751 should be included as a factor when management decisions are made by farmers, land
752 managers and crop advisers. The studies should not be designed for a systematic monitoring
753 of the differential effects of each component of sustainable practices such as soil cover,
754 manuring, reduced pesticide use or reduced tillage (Hobbs et al., 2008), but with these
755 practices in combination, in order to have an overall vision of the agrosystem, and how to
756 manage it sustainably (Fig. 6). In this view, the metagenomics (that is the microbial identities
757 and functional gene information) and the metaphenomics (that is the product of the combined
758 genetic potential of the microbiome and resources) of bacteria or fungi (Fierer, 2017; Jansson
759 and Hofmockel, 2018) would allow to define the microbial communities living in the different
760 soil layers. The DNA/RNA-based identification of specific alive and active bacterial/fungal
761 taxa, according to their functional distinction (aerobic/anaerobic,
762 saprophytic/parasitic/pathogenic, autotrophic/heterotrophic) can be of key importance for
763 defining the microbiological fertility of a soil and its response to agricultural practices
764 (Crecchio et al., 2004; Badagliacca et al., 2020). Identification by DNA fingerprinting,
765 originally developed for the identification of poorly culturable microbial strains, has become a
766 rapid and cost-effective method of current use in agricultural soils. It has been extended to the
767 current assessment of nematode communities (Wang et al., 2008) and its application to other
768 soil fauna is promising, although still not in current use (Orgiazzi et al., 2015). Finally,
769 eventual pathogenic organisms and mycorrhization index should be monitored, identifying
770 probable microbial pathogens and/or anaerobic microorganisms by a culture based-approach
771 (*Phytophthora*, *Clostridium*, *Bacillus*, etc.) and presence and types of mycorrhiza, including
772 DNA analysis of eventual pathogenic microorganisms during the growing season.

773 The application of endogenous and exogenous carbon inputs would be necessary for
774 improving soil status. Using specific commercial products containing biostimulants and
775 biocontrol agents to improve physicochemical and microbiological properties of the soils,
776 could increase resistance against eventual pathogens and enrich soil microbial communities.

777 The application of compost, manure, soil management techniques for facilitating water
 778 horizontal movement in the soil, use of decompacting plants (e.g., *Raphanus* spp. or other
 779 Brassicaceae) would facilitate water vertical movement in the soil, both directly (Whelan et
 780 al., 2013) and through a favorable influence on earthworms (Pérès et al., 1998). On this basis,
 781 sustainable management is a key factor for increasing the functionality and diversity of soil
 782 biota that enhance soil biological fertility. This amelioration leads to a higher soil quality,
 783 stability and multifunctionality, positively affecting plant physiological status and crop
 784 productivity.



785

786 **[Figure 6. HERE]**

787

788 Over the last decades, intensive agricultural practices (e.g., continuous soil tillage, high
 789 inputs of mineral fertilizers, application of low-quality irrigation water, removal of pruning
 790 residues) have determined the loss of soil fertility and the depletion of soil organic matter
 791 (SOM), with negative effects on both productivity and soil conservation (Bonanomi et al.,
 792 2011). Many conventional agronomic practices have a negative impact on SOM (Arrouays
 793 and Pelissier, 1994), the soil microbiome (Lupatini et al., 2017) and soil trophic networks
 794 (Tsiafouli et al., 2015), causing a decline in fertility: soil leveling (with consequent
 795 elimination of the organic horizon in many areas of the plant), deep tillage with a surface

796 carryover of mineral horizons (non-organic), soil sterilization with destruction of
797 microbiological diversity, the continuous and massive use of herbicides, mineral fertilizers
798 and pesticides with biocidal action, and so on. Sustainable agronomic practices foresee a
799 reworking of agronomic management which includes the reduction of the use of mineral
800 fertilizers and pesticides (including cupric products), the rationalization of irrigation, the
801 management - and not the elimination - of spontaneous vegetation and the contribution of
802 different types of organic matter to restore the ecosystem complexity and heterogeneity,
803 without leaving aside a careful analysis of the fields and the state of the plants, of the
804 environmental conditions (pedological, microbiological, orographic and microclimatic), and,
805 above all, of the agronomic and ecological history of the fields. The correct use of
806 formulations of materials of natural origin, specially designed and processed according to the
807 different cultivation and business conditions, can quickly re-establish the trophic balance and
808 soil-plant compatibility, reactivating the nourishment of the crops and increasing their
809 resistance to pathogens and parasites. Thus, soils rich in organic matter, or regularly fertilized
810 organically with compost and vegetable residues (possibly not coming from the same crop),
811 have a greater microbiological biodiversity. Crop rotation with phylogenetically distant
812 species, the practice of fallow and crop associations make it possible to prevent or eliminate
813 the decrease in soil fertility, and the use of graft carriers with tree crops can be helpful to
814 mitigate problems of replanting of the same species. The crop succession, the inter-cropping
815 of different species, the use of rootstocks phylogenetically distant from the cultivated variety
816 make it possible to overcome the problems related to the decline in soil fertility. A very
817 effective sustainable technique appears to be the use of compost tea, infused or more
818 commonly fermented with compost, which has already been the subject of growing scientific
819 and applicative interest for several years (Scheuerell and Mahaffee, 2002; St. Martin et al.,
820 2020; Vилlecco et al., 2020). The technique is based on the use of different compost, specially
821 selected (and sometimes, according to the needs of the plant, combined with non-composted
822 organic substance), placed in infusion under aerobic conditions.

823

824 *6.4. Soil functions as a living system*

825

826 Nowadays, there is evidence that sustainable management practices (e.g. no-tillage,
827 supply of organic fertilizers, mulching of pruning residuals and cover crops, reduction or even
828 suppression of pesticide use) can contribute to re-carbonize soils and reduce soil CO₂

829 emissions, recover soil fertility, and increase yield. In sustainable agrosystems, because of the
830 composition of the recycled biomass (pruning residuals, leaf fall, cover crops) and of newly
831 supplied (e.g. compost, manure), a huge amount of nutrients is released if external supply of
832 mineral fertilizers could successfully be replaced. However, considering processes
833 determining nitrogen availability (organic matter mineralization, leaching, cover crops uptake,
834 etc.), interactions among nutrients (e.g., antagonistic effects), variability of soil moisture, and
835 mineral nutrition, particular attention is required. Sustainable agriculture can give benefits to
836 plant growth, such as increased biomass and productivity, enhanced photosynthesis and
837 carbohydrate allocation, better regulation of root respiration and higher defenses against pests
838 and diseases, with more soil microorganisms and fauna, and thus more efficient trophic
839 networks. Mycorrhizal fungi, being involved in many ecosystem services (Stevenson et al.,
840 2020), are important in many types of soil. Besides well-known negative effects of
841 conventional practices (Verbruggen et al., 2010), in over-exploited, conventionally managed
842 agricultural landscapes, habitat loss and fragmentation prevent dispersal and are major threats
843 to mycorrhizas (Longo et al., 2016).

844 Human societies benefit from a multitude of ecosystem services from both natural and
845 managed ecosystems, to which soil organisms make a crucial and distinctive (Stevenson et al.,
846 2020). Unfortunately, it is well recognized that humans are changing the global environment
847 at an unprecedented rate. An increasing proportion of the world's population is urban or
848 suburban. For this reason, the demand to extend cultivated areas in cities is increasing,
849 prompting to establish, restore and sustain urban ecosystems. In these new anthropogenic
850 environments, the application of organic inputs and bio-products, included in sustainable
851 agricultural practices, can be crucial for plants' survival. Sustainable agriculture can cause
852 recreational, human health, economic and environmental benefits. The latter also includes
853 lower GHGs emissions because of reduced use of synthetic fertilizers and pesticides, lower
854 leaching losses to groundwater (e.g., nitrates and nitrites), and no eutrophication of ponds and
855 streams because of excess phosphorus and nitrogen. Comparisons of soil biota across wild,
856 rural and urban habitats have revealed dramatic differences between sustainably managed and
857 conventionally managed areas, with the lowest biodiversity in the latter (Stevenson et al.,
858 2020).

859 Regardless of practical challenges, there is untapped potential for sustainable agricultural
860 practices to influence environmental outcomes, citizens' consciousness and market's trends
861 soon (Scotti et al., 2015; Stevenson et al., 2020). The results of many recent studies encourage

862 the use of sustainable agricultural practices able to enhance soil fertility (Diacono and
863 Montemurro, 2010; Kassie et al., 2013; Scotti et al., 2015). The ultimate goal is to convince
864 farmers to adopt a sustainable farming system as a whole, and not just as individual
865 elements/practices, in order to promote good-quality production without negative effects on
866 the environment. For achieving this, the approaches should not be ‘top down’, but they must
867 be ‘bottom up’, where farmers and citizens help to co-design and co-deliver soil management
868 and food production systems (Ajayi, 2007; Kassie et al., 2013). It is time to switch to a
869 modern and multifunctional concept of agriculture based not only on the production but above
870 all on product quality, environmental protection, resource saving and promotion of human
871 health.

872

873 *6.5. Soil is organized into layers*

874

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

883 Microorganisms and plants condition the Humipedon. Mineralogical aspects and more
884 related to soil physics are more decisive in Copedon. The geological history of the soil and
885 the cycles of some minerals are much more important in Lithopedon. The time separates the
886 studies of these three soil layers, handing them over to specialists who meet periodically to
887 make the right synthesis. The soil is a single body that reacts as if it were composed of
888 superimposed organs. Soil classification must take this crucial aspect into account.
889 Humipedon reacts over the years and up to a few decades; Copedon takes from decades to
890 hundreds of years; the Lithopedon centuries to millennia.

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

895 Agrosystems (crop soils) correspond to artificially simplified natural systems (in general
896 Mull Humipedons). When artificialization is extreme, we talk about Techno systems
897 (hydroponic or compost are examples of that). These phrases hide an underestimated truth of
898 intrinsic value. Agro-systems are not alternative systems, but old systems reorganized by man
899 (Zanella et al., 2018f). The soil system incessantly tries to return to its original organization,
900 made of different overlapping layers, but the work of using its stored energy takes it back
901 annually in time. At the end of a conventional exploitation process there is a soil poor in
902 organic matter and life, an original mother rock of the soil. We must no longer think we can
903 move, manipulate, destroy, create soil as if it were an object and then expect it to work as a
904 living system to render service to us.

905 If the purpose of conventional agriculture is to build new soils, then we need to think
906 about building Copedons between Humipedons and Lithopedons, not destroying this
907 historical organization. Ask us what these layers really are (studying natural references) and
908 how they can be built in compliance with natural and biological laws. It is perhaps possible to
909 build new Humipedons. This is what we try to do with composts or hydroponic solutions. We
910 can try to make them better, more like existing Humipedons. The other possibility is organic
911 farming. The right method should be very similar to the one proposed by Masanobu Fukuoka
912 in his famous book “Natural Way of Farming” (Fukuoka, 1985) to intervene as little as
913 possible. Understand how it works and accompany the movement, changing the cards in the
914 game as little as possible. It is difficult and, for this reason, it is the right way, and it needs a
915 scientific preparation of high naturalistic/biological level.

916

917 *6.6. Agriculture, human health and environment*

918

919 We offer the propositions that:

- 920 a) Intensive agriculture should be abandoned;
- 921 b) agriculture should produce enough food for an increasing number of humans.

922 Is it possible to produce enough food and to stay in good health all over planet Earth? For
923 knowing this, other two parameters should be considered:

- 924 a) the need for a global management of Earth resources, like a United Nations
925 Organization that would decide democratically;

926 b) the regulation of birth rate might be achieved with a calculation of Earth's bearing
927 capacity (shared ecological footprint) within the framework of a humanity that
928 shares resources better than today.

929

930 6.7. Agroforestry

931

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

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

943

944

945 7. Conclusions and future insights

946

947 In this commentary paper, we presented cross-disciplinary and holistic approaches
948 applied to agricultural soils. Converting the conventional management systems of agricultural
949 land into more sustainable and environment-preserving systems has become urgent.
950 Conventional vegetable and fruit production, because of the unavoidable lack of resources
951 (particularly soil and water), is going to be economically and environmentally
952 disadvantageous, while, on the other side, organic farming, whose benefits and costs are
953 controversial, is not always self-sustaining and durable, and it cannot cover the enormous and
954 increasing world demand. For avoiding this dilemma, the productive systems should be
955 directed towards the principles of an innovative, sustainable, regeneration and conservative
956 agriculture, which includes rationally the existing and innovative agro-technological practices,
957 such as no- or minimum soil tillage, on-site nutrient input and recycling, adequate irrigation
958 and rational management of crop residues. This innovative approach, aimed to keep

959 production at a high level and cultivating lastingly, can render a wide range of benefits to
960 farmers and the environment. In addition, better understanding the role of soil fauna in such
961 systems has a key role to adapt management strategies and mitigating GHGs emissions.
962 Furthermore, the role of soil organisms (both microbes and animals) to ecosystem services
963 and their close relationship with soil organic matter has been often overlooked, while it
964 should be seriously taken into account in future land management strategies.

965 The world's soils are rapidly deteriorating because of soil erosion, nutrient depletion and
966 other threats, but sustainable practices and technologies can reverse this trend. One key point
967 from the new IPCC report (Shukla et al., 2020) is that conventionally tilled soils erode over
968 100 times faster than they form and that land degradation represents "one of the biggest and
969 most urgent challenges" that humanity faces. Humans have degraded roughly one-third of the
970 world's topsoil, and about 3.2 billion people - more than a third of humanity - already suffer
971 from the effects of degraded land. Continuing down this path does not bode well for feeding a
972 growing world population. Barriers to adopting regenerative farming systems include force of
973 habit, lack of knowledge about new practices and real and perceived economic risk during the
974 transition. The benefits of rebuilding healthy, fertile soil are clear. Economic benefits of land
975 restoration average 10 times the costs. Thus, sustainable agriculture appears to have a big
976 economic, social and political impact (Baggaley et al., 2020). We trust that sustainable
977 agriculture will contribute to understand how important the soil as a living matrix is for both
978 climate regulation and plant production. A better grasp of how soil organisms interact with
979 organic matter turnover and stabilization will open novel ways for the sustainable
980 management of soils. It is time to take soil seriously in consideration and to rethink
981 humanity's relationship to the environment and particularly to soil. In their article, Kopnina et
982 al. (2018) hope for change from an anthropocentric mentality based on human-centered values
983 and things to a more comprehensive vision that includes non-human living beings and things,
984 such as environmental life-support systems. Thus, it would be necessary to promote a general
985 law of soil protection, as soil produces food and sustains all ecosystems, independently from
986 human need to economically grow. People need to change agriculture and land use, and we all
987 wish to have 'more sustainable' soils, the only basis for a healthier world.

988

989

990 **References**

991

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1676 **Tables**

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1678 **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 impasse.
	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). USDA attempt to approach a larger audience (ecologists, environmental scientists, etc.).
	Essentials of Soil Science - Soil formation, functions, use and classification (2018). WRB attempt to open to other disciplines.
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.

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1697 **Figure legends**

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1700 **Figure 1.** The three key attributes of soil, considered as a living system.

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1702 **Figure 2.** From “The contentious nature of soil organic matter”. Figure entitled:

1703 Reconciliation of current conceptual models for the fate of organic debris into a consolidated

1704 view of organic matter cycles and ecosystem controls in soil (Lehmann and Kleber, 2015).

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1706 **Figure 3.** The FAO-Unesco Soil Map of the World, a first immense effort to synthetize the
1707 distribution of the soil on our planet. On the right the cover of Volume I, which is identical in
1708 the other volumes, only changes the squared that frame the described section. Notice the
1709 design, which recalls the horizons of the soil, but also soil, vegetation and atmosphere, or an
1710 interlocking of concentric circles typical of a modern ecological vision. Just beautiful, with
1711 the maps scattered as if in a vacuum.

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1713 **Figure 4.** The 20 humus systems of the classification published by the Humus Group are
1714 divided into: 6 young or very particular natural systems (Para); 2 systems closely linked to
1715 man, one semi-natural (Agro) and one completely built by man (Techno); 5 terrestrial systems
1716 containing 17 humus forms; 5 Histic systems containing 16 humus forms; 2 Aqueous systems
1717 containing 3 humus forms. In total, the forms of humus described are 36 (not reported in the
1718 figure).

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1720 **Figure 5.** On the left, the "layers" that can be identified in the soil profile. On the right, the
1721 phases of formation of the soil profile.

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1723 **Figure 6.** Soil is more complex than we think. It is almost as if it were an underground forest,
1724 much more concentrated and with less air than that which lives above the ground. We can
1725 imagine it composed of three layers in which it evolves without being perceptible in its
1726 dynamic state. Perhaps the blue arrows can represent the real processes of soil forming
1727 generating the large groups of soils (corresponding to theoretical main pedogenetic processes)
1728 described by the modern IUSS Working Group.

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1730 **Figure 7.** Major benefits of the adoption of sustainable agricultural practices. Examples of the
1731 sustainable agricultural practices explained in the text.

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1734 **Appendices**

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1736 **Appendix 1.** Quotation from Waksman, S. A. (1936). *HUMUS. Origin, chemical composition*
1737 *and importance in nature.* The Williams & Wilkins Company. The whole "outlook" of the
1738 authors can be found here: <https://soilcarboncoalition.org/files/Waksman-Humus.pdf>,

1739 particularly at pages 397-398.