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1 **The soil as an ecosystem**

2 Jean-François Ponge*

3

4 **Abstract**

5 Can soil be considered as just a component of terrestrial ecosystems and agroecosystems or is it an
6 ecosystem in itself? The present piece of opinion suggests that we should refer to the original
7 definition of the ecosystem given by Tansley and apply it to the soil viewed as a multi-scale
8 assemblage of ecological systems.

9

10 **Introduction**

11 The concept of ecosystem services generated an overabundant literature over the last 20 years. In more
12 than a thousand publications (1,560) indexed by ISI Web of Science™ (last update November 29,
13 2014) soil was considered as the main provider of ecosystem services. Agricultural and forest
14 production, protection against erosion and flooding, water stocking, fixation of atmospheric carbon
15 and nitrogen are among the most often cited ecosystem services provided by soil. If soil renders so
16 many services to mankind this questions the manner we consider it from a scientific, conservational or
17 economical point of view. Can soil be considered as just a component of terrestrial ecosystems and
18 agro-ecosystems or is it an ecosystem in itself? Published articles using the expression “soil
19 ecosystem” showed a two-fold increase in the last three years. This census also revealed that the
20 concept of ecosystem applied to the soil was not novel and was even familiar to the scientific
21 community: the earliest paper (Auerbach 1958) was published in the prestigious journal “Ecology”,
22 the official organ of the Ecological Society of America. Let us examine the problem in the light of
23 present-day knowledge on soils and ecosystems.

24 **The ecosystem concept, from Tansley to now**

25 The word “ecosystem” appears for the first time in a seminal paper by Tansley (1935) who defines it
26 as a system (in physicist sense) including “the whole complex of organisms inhabiting a given region”
27 but also, and this was the novelty, “the whole complex of physical factors forming what we call the
28 environment of the biome – the habitat factors in the widest sense.” Tansley indicates explicitly that
29 no limit of size or nature can be attributed to ecosystems, even if the examples cited in his paper
30 concern mainly vegetation, his best known subject. With this paper, Tansley introduced an
31 epistemological break in ecological science, still based at that time on Clements’ thought (Clements
32 1916), who considered the “plant society” as a “complex organism”, not considering the physical
33 environment. In that frame, the soil was only the physical support of vegetation. Thereafter, the
34 ecosystem concept remained relatively poorly used by ecologists, as was the case for European
35 (continental) plant ecologists, who preferred to turn to phytosociology, building and describing units

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36 (associations, alliances, etc.), copied on the Linnean classification of living organisms (species,
37 genera, families, etc.).

38 Odum (1953) replaced the ecosystem concept in the frame of bioenergetics, applying
39 principles of thermodynamics in an endeavour to assess transfers of matter and energy on a
40 quantitative base. He defined the ecosystem as a “natural unit that includes living and non-living parts
41 interacting to produce a stable system in which the exchange of materials between the living and non-
42 living parts follows circular paths”. Stability became an important attribute because it allowed for the
43 first time the ecosystems to be discerned, modelled and mapped by a larger scientific community.
44 Odum’ views were largely popularized in Europe by Duvigneaud (1974, 1980) and were seminal to
45 the development of the International Biological Programme (IBP). According to Odum, the ecosystem
46 is the basic unit of Nature, quasi self-sufficient because it only needs energy sources (lastly solar
47 energy) to maintain its equilibrium. This means a neat restriction from Tansley’s definition, since
48 independence (even though relative) from the immediate environment is a prerequisite. This vision of
49 the ecosystem became rapidly successful, because it allowed to compute mass and energy balance, by
50 making inventories of organisms living at the inside of a well-determined envelope, and measuring
51 respiration, nutrient uptake, productivity and other ecosystem’s attributes. Such basic units can also be
52 used as quantifiable monitoring units, hence the successful development of methods and concepts for
53 “ecosystem management.” According to Odum’ views, putting limits to ecosystems (not on the paper
54 but on the field) is a delicate work, because one has to accept or reject some frontier visible on the
55 field (forest edge, river, pond shore, cliff, etc.) as determining the “independence” of the ecosystem.
56 According to this concept, which was dominant for a long time in ecology, soil cannot be considered
57 as an ecosystem, because it relies entirely on vegetation for organic matter inputs, the “fuel” of its
58 inhabitants.

59 Since IBP studies, which stimulated a large array of inventories and balance sheets of the
60 living world, from Equator to Poles, from the deep ocean to the highest mountains, the ecosystem
61 concept became popular and well suited to the media, in the same manner and for the same reasons as
62 the concept of biodiversity, notably after the Rio World conference (1992). Ecological research came
63 in hand with this media coverage of concepts previously handled with caution by the scientific
64 community. Most spectacular developments concerned the recognition of the non-independence of the
65 units acknowledged as basic units by Odum and followers. The thorough study of terrestrial
66 environments allowed ascertaining the interdependence and the permanent renewal of “motifs”
67 composing forests, watersheds, landscapes and, above all, the enormous share of stochasticity issuing
68 from dispersal, immigration and extinction of living organisms. The ecosystem cannot be considered
69 in isolation, each organism ensuring the functions for which it has been “programmed”, but rather
70 becomes an entity largely open to the outside and eminently changing (Tilman 1999). The realization
71 of changes taking place at the global scale, in particular the greenhouse effect and its spectacular and
72 still unresolved ecological consequences, contributed to open the “Pandora’s box” of the Odum’
73 ecosystem. This urged some scientists to reject the ecosystem concept and propose new paradigms
74 taking into account stability, disturbance and spatial scale. O’Neill (2001) speaks of “ecological
75 systems” which are “composed of a range of spatial scales, from the local system to the potential
76 dispersal range of all the species within the local system.”

77 The ecosystem concept has been also at the heart of the controversy between “reductionism”
78 and “holism” in ecology or, in more fashioned terms, between “community” and “ecosystem” ecology,
79 as exemplified in the excellent book of Golley (1996) on the subject, to which the reader is referred.
80 Far from settling the debate in this piece of opinion it is just worth to recall that Tansley was justly

81 reluctant of both the reductionism of Gleason (1926) and the holism of Clements (1916), basing his
 82 arguments on the fact that the part and the whole had the same importance if we want to fully
 83 understand how properties emerge in the universe (see Ponge 2005 for a review). This “merry-go-
 84 round” overview should not be closed without paying homage to the Russian scientist and philosopher
 85 Vladimir Ivanovitch Vernadsky, who was the first to give a scientific basis to the unity of living and
 86 non-living matter (Lapo 2001).

87 **The soil as an embedded and embedding ecosystem**

88 The philosopher and physicist Sir Arthur Koestler described the concept of the “holon”, corresponding
 89 to embedded functional units, allowing us to understand how an organism functions in a self-regulated
 90 manner (Koestler 1969). Above organisms (the subject he had to present in the course of a biological
 91 congress held in Alpbach, Austria, 1968), Koestler described the universe as a series of environments
 92 infinitely embedded in a hierarchical manner. His hierarchical concept was highly successful in
 93 biology, filling a gap in the knowledge of self-regulating systems, and even though he remained better
 94 known for his philosophic work, landscape ecology was largely inspired from Koestler’s “holon”
 95 concept. This vision adds to our view of the universe a dimension which could be named “vertical”,
 96 mimicking the fractal dimension popularized by Mandelbrot (1983). It offers the advantage of
 97 allowing travel through the scales of perception that the scientist discover when dissecting a system
 98 which he(she) is studying or acting on. Koestler’s concept implies that one cannot consider a level of
 99 perception without taking into account the level immediately above it. This was shown in an elegant
 100 manner to apply to the soil in a paper by Coleman et al. (1992), to which E.P. Odum himself
 101 participated. The hierarchically nested structure of detrital food-webs was a focus topic of Andrei
 102 Pokarzhevskii’s soil science, a concept this author applied fruitfully to the bio-indication of soil
 103 pollution (Pokarzhevskii 1996).

104 However, the hierarchical concept of the soil ignores the existence of constant back and forth
 105 streams through the embedded scales thus defined. In particular, the “holon” concept does not take
 106 into account the reversibility and instability of embedding, as soon as “ecosystems” are considered,
 107 which are far from machines made of clearly discernible elements. As an example, take a look to
 108 North American Douglas fir forests of the Pacific Coast, where our most common European
 109 earthworm, *Lumbricus terrestris*, unknown in New World until European colonization, now
 110 proliferates at the end of a two-century “Conquest of the West” (Cameron et al. 2012). In its original
 111 environment, the western coniferous forest, Douglas fir is a keystone species, imposing a millenary
 112 cycle to the forest ecosystem, renewal being mainly ensured by fire. Douglas fir accumulates a huge
 113 amount of hard-to-decay litter, impeding any natural regeneration despite an enormous stock of
 114 nitrogen and other favourable nutrients, available only through the mycorrhizal network of the adult
 115 (to which seedlings are still not or cannot be connected). Only fire is able to make these nutrients
 116 available to seedlings, in the absence of burrowing earthworm species. The arrival of *Lumbricus*
 117 *terrestris*, a soil engineer burrowing and feeding activities of which are known to favour a rapid
 118 turnover of main nutrients in forests (Ponge 2003, 2013), will change the environmental conditions
 119 prevailing in the soil of western coniferous forests. In line with the abovementioned mechanism it can
 120 be postulated that woody landscapes of the western US will evolve to a large extent in the next
 121 decades. If we follow the views taken true by Koestler and followers, what is embedded in what in
 122 Douglas fir forests? Previously dependent on the arboreal cover, the soil becomes, at least during the
 123 time of seedling establishment, the master chief of the ecosystem, upsetting equilibria rather than
 124 relying on them.

125 What is the place of the soil in a non-hierarchic concept of embedded ecosystems? By the
 126 diversity of its biotic (plant roots included) and non-biotic components, its gaseous and water
 127 compartments, the functions it ensures through its various interactions (e.g. trophic networks, mineral
 128 weathering, decomposition, humification) and its visible upper and lower limits (from surface litter to
 129 parent rock), the soil is indeed an ecosystem, belonging to the universal category of open systems
 130 (Ashby 1956). By its living character, well established by Gobat et al. (2010), and the services it
 131 renders to the Planet (Lavelle et al. 2006), the soil is indeed an ecosystem in the sense given to this
 132 term by Tansley in 1935. Soils are naturally embedded in Odum' terrestrial ecosystems (forests,
 133 meadows, etc.), from which they are essential parts, functionally speaking, and their "memory"
 134 (Schaefer 2011). During forest renewal (before and during the start of a new cohort of trees), soil
 135 acquires even a dominant role (Ponge et al. 1998). Although physically embedded in the ecosystem
 136 sensu Odum, the soil can, at least at key moments of its development, be embedding it functionally.

137 Other ecosystems exist and are in turn embedded in the soil. We can cite the root tip, or the
 138 organo-mineral aggregates. For instance, growing root tips are the seat of numerous interactions (the
 139 microbial loop) between plants (exuding organic compounds), microbes (deriving energy and carbon
 140 from the plant, mineralizing humus and weathering mineral matter), and animals (feeding on microbes
 141 and mineralizing the microbial biomass), allowing the plant to take up and assimilate nutrients very
 142 efficiently (Bonkowski 2004). Soil aggregates, originating from faunal, root and microbial activity, are
 143 seats of carbon sequestration and render the soil and as a consequence crop production able to sustain
 144 global changes (Six et al. 2004). Numerous other examples exist, gathered and detailed in Gobat et al.
 145 (2010), which establish the existence of numerous ecosystems at the inside of the soil ecosystem, even
 146 if the term "ecosystem" has rarely if any been used for designating them.

147 The ecosystem concept can be fruitfully applied to the soil, making it a matter of study in
 148 itself for ecosystem as well as community ecologists. Moreover, considering the soil as an ecosystem
 149 can be important for future land management strategies. It is common view that soil is a substrate for
 150 crops, but also for roads and buildings, without addressing it as the place where most organisms live
 151 and die. This urges the diversity and integrity of soil biological functions to be protected worldwide as
 152 a necessary condition of mankind survival.

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