9

Actions and Feedback: Consequences for Soil Management

9.1. Emergence of an eco-evolutionary understanding of the functioning of soils

Ecology is gradually recognizing that ecological and evolutionary dynamics (in the Darwinian sense) are concomitant and interacting (see Chapter 8 and Figure 9.1). This means, for example, that the functioning of an ecosystem influences the availability of mineral nutrients, which exerts selection pressures on the plants that will develop, through evolutionary mechanisms, adaptations, enabling better exploitation of minerals and increasing their competitive ability against other plants. In turn, these new adaptations will enable plants to modify the availability of nutrients in the soil and the functioning of the ecosystem as a whole [BAR 16, BOU 11]. We now believe that it is very important to study this type of eco-evolutionary feedback because it is clear that evolutionary dynamics, for example the time required for an adaptation to appear in a population under the influence of a new selection pressure, are faster than originally imagined. This type of dynamics can have significant implications for human societies. For example, if a new plant variety is cultivated on large surfaces because it is resistant to a pathogen, this new variety constitutes a selection pressure for the pathogen that tends to rapidly (a few years) evolve resistance, which provides feedbacks by decreasing the yields of the variety. On a more fundamental level, these arguments also show that the properties of ecosystems as they are currently observed depend on these eco-evolutionary

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dynamics and that these properties cannot be fully understood without taking into account these dynamics. All these arguments push for developing research at the interface between evolutionary ecology and ecosystem ecology [FUS 07].

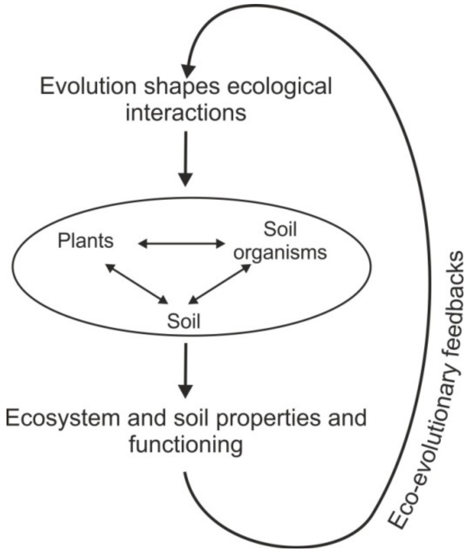

Figure 9.1. *Eco-evolutionary dynamics in soils. Darwinian evolution shapes the ecological interactions between plants, soil and soil organisms and thus shapes the characteristics of soil and plant organisms. As a result, evolution influences the general properties of soils (e.g. the amount of organic matter) and ecosystems (e.g. primary production). It is an iterative process: the ecological properties of soils, both biotic and abiotic, serve as a general setting for natural selection and evolution, so that soils provide feedback to evolutionary processes*

This type of approach is also very relevant for soils and their functioning. An initial observation is that too often soil ecologists have not addressed evolutionary issues [BAR 07], at least in part because soil ecology is traditionally closer to functional ecology and the "abiotic pole of ecology" than to evolutionary ecology [NOB 04]. Nevertheless, eco-evolutionary dynamics are likely to play an important role in soil functioning and their response to change (climate change, land-use change, agriculture, pollution, etc.). Many studies are already going in this direction for subterranean–air interactions. For example, a theoretical model shows how the ability of plants to influence the decomposition of soil organic matter (through litter quality or rhizospheric priming effect) changes the atmospheric deposition of these nutrients, which subsequently determines their availability [BAR 14]. This feedbacks to the carbon stock in the soil and primary production. Similarly, Donavan *et al.* [DON 11] summarized the knowledge acquired on the fact that the diversity of the traits of leaves (e.g. leaf thickness or leaf nitrogen content) is under various selection pressures. This in turn influences litter decomposition and soil functioning.

What is true for belowground–aboveground relationships is probably true for all ecological processes within soils that involve or do not involve plants.

Soil organisms, macrofauna (e.g. earthworms) and microorganisms, participate in many ecological interactions:

– among soil organisms (including plant roots);

– between soil organisms and the physico-chemical properties of soil.

These organisms have been shaped by eco-evolutionary dynamics, which are at the origin of the ecological interactions that determine the current functioning of the soil. For example, during their evolution, soil bacteria have developed a high efficiency in breaking down highly diversified organic compounds produced by plants and microorganisms themselves. This involves the production of various metabolites and the regulation of this production (e.g. through "quorum sensing") [RED 02]. In turn, the evolution of these dead organic matter exploitation capabilities influences soil carbon stocks and various ecosystem properties. Many soil organisms (bacteria, fungi, protozoa, nematodes, etc.) have very short generation times, which can potentially enable them to evolve very rapidly. It is likely that all processes impacting soils (changes in land uses, long-term climate change, changes due to seasonal climate cycles, tillage) trigger evolutionary dynamics that have barely been studied. When changes in composition and activity are observed in a microbial community, for example bacteria, following a disturbance, these changes are largely due to the fact that some bacteria become active and their populations increase. However, some of these changes may also be due to evolutionary dynamics with the appearance of new bacteria based on combinations of genes and alleles that did not exist before the disturbance. Understanding evolutionary dynamics in which soils are involved may seem like a fascinating but rather theoretical research topic that cannot lead to concrete applications in terms of soil management and agriculture. This judgment must be strongly revised. On the one hand, understanding evolutionary dynamics can give very strong arguments for using ecological interactions. Thus, if we understood the evolutionary causes of the generally positive effect of earthworms on plant growth, we could more easily use earthworms in agriculture. On the other hand, the rapidity of evolutionary dynamics increases the impact of the evolutionary consequences of soil management so that these consequences must be taken into account to develop a fully integrative ecological soil engineering. Finally, humans directly select cultivated plants so that the integration of eco-evolutionary feedback involving soil, soil organisms and the selection of cultivated plants is likely to be an important lever towards the development of more sustainable agriculture in the spirit of ecological engineering.

9.2. Towards ecological and evolutionary soil engineering

The knowledge acquired in general ecology and soil ecology suggests a new type of engineering, ecological engineering, which is based not on human technologies fueled by fossil energies (“conventional” engineering) but on natural processes [ODU 62]. The strategy of ecological engineering is to couple human interventions that generally involve the use of technologies with the self-organization of ecosystems [ODU 03]. This coupling enables optimal performance, while avoiding significant energy expenditure, since work – in the physical sense – is outsourced by biodiversity and the ecological functions it supports. However, in anthropized ecosystems, such as agro-ecosystems, “gross” ecosystem services perceived by society are the result of human actions and biodiversity-based ecological processes. The proportion of work achieved, on the one hand, through human interventions and on the other hand, through ecological processes supported by biodiversity is difficult to determine [BAR 17].

In an engineering approach, the objective is to provide a solution to a problem (problem-solving) according to a procedure that begins with a diagnosis of the situation, the design of a solution, the mobilization of tools and their implementation in the field. Ecological engineering differs from conventional engineering in all respects as discussed below.

Like soil physico-chemical analyses, which have been used for a long time in soil diagnostics, advances in ecology now make it possible to access standardized methods for characterizing the biological quality of soils. They are based on the analysis of the diversity and structure of biological communities and the identification of bioindicators [BIS 17, COR 99, VEL 07]. These indicators are useful for characterizing at a given time the quality of soils impacted by different practices. By repeating the use of these indicators over time, it is then possible to establish the past trajectory of soil quality and possibly to extrapolate the observed trend to predict its future state. Soil quality analyses are possible by comparing these results with standards integrating the physico-chemical characteristics of soils, which we now know represent major biodiversity filters [RAN 13]. Having managers that take ownership of such soil biological characterization tools is clearly a major challenge [BIS 17].

The analysis of soil quality, the knowledge of the impact of agricultural practices on this quality and the prospective approach of extrapolating the trajectory of this quality are intended to identify appropriate ecological engineering actions. In the field of soil management, it is generally a question of promoting the ecosystem services delivered by soils (agricultural production, climate regulation, regulation of water flows and its quality, etc.) and the sustainability of the provision of these services. More specifically, ecological engineering aims to promote soil quality, that is, its fertility (ability to provide quality products in sufficient quantities) and its stability (resistance, resilience) in a context of global change, in particular by increasing the stock of organic matter to promote water retention, cation exchange capacity and soil structure [LAL 06]. In cases where the soils are degraded, it can enable their restoration, for example by:

– the revegetation of a garbage dump [LEI 16];

– phytostabilization and phyto-extraction during heavy metal contamination [WON 03];

– phyto-extraction assisted by microorganisms [LEB 08] or earthworms [JUS 12, SIZ 09];

– the degradation of organic pollutants by earthworms [CON 08] and microorganisms [VAR 17]. It can also be used to build new soils and substrates through the action of plants and earthworms [DEE 16]. These Technosols can also be interesting for the conservation of various soil organisms in adverse environments such as urban green spaces [VER 17].

New tools may be required to achieve such management objectives. Like conventional engineering, which consists of manufacturing mechanical and chemical tools, ecological engineering proposes to adapt organisms of interest to the goal to be achieved, by selecting the most interesting traits from diverse organisms or by creating new varieties of organisms capable of carrying out certain functions with high efficiency. An example of this is the selection of plants with traits that contribute to the recruitment of populations of soil organisms that are beneficial to the nutrition and health of the host plant.

Finally, the implementation of ecological or conventional engineering solutions in the field will depend on the human and environmental contexts, and more specifically on the regulations, the budget, the space available and the acceptable risk of failure [BER 15, BLO 13].

However, in some cases, it will be difficult to envisage “improving” the functioning of the ecosystem and the most reasonable strategy for taking advantage of the ecosystem services provided by an ecosystem will then be to conserve its biodiversity. We will also opt for this conservation option when the ecosystem environment is subject to strong disturbances that could destabilize it. This type of option will likely apply when:

– the financial resources for intervention are limited and cannot allow both the introduction of conventional technology and its maintenance;

– the surface area that can be mobilized to implement the engineering solution is vast, making it possible to withstand relatively low engineering efficiency per unit area as it is powered by local solar energy;

– the acceptable range of potential trajectories taken by the ecosystem is wide and therefore the risk of obtaining a really unfavorable trajectory is low.

At the other extreme, a problem can be solved by conventional engineering solutions, which relies on human technologies and fossil fuels. This approach will be preferred where financial resources are high, space is limited or where risk of failure is high.

Two intermediate options can be proposed. When biodiversity is reduced, with functionally important species disappearing, we can encourage their return by their own means, for example with the establishment of ecological corridors that will ensure a sustainable flow of individuals, genes and matter in the long term. When biodiversity is reduced and the dispersal capacities of organisms are not sufficient for the active dispersion of these organisms via a corridor, it is then possible to resort to passive dispersion: humans can manipulate soil organisms by transporting them to the site of interest or by introducing inoculants into the soil (e.g. inoculation of rhizobia on legumes, mycorrhizal fungi on angiosperms or earthworms to restore a compact soil with the bio-organic fertilization technique, FBO®) [BER 15, BLO 13].

One of the major challenges of ecological engineering is integrating the evolutionary dimension of the manipulated organisms. The conceptual framework proposed by the eco-evolutionary dynamics mentioned at the beginning of the chapter should thus be explored. Soil management, particularly in agroecology, involves a regular reassessment of the state of the ecological system being managed, in order to estimate the consequences of management activities and to adapt the operational objectives to the ecological trajectory taken by the system and according to the evolutionary trajectory taken by the involved organisms. This adaptive management must also integrate the dynamics of the social issues to which the manager must respond. It must therefore be based on a participatory approach involving all the relevant stakeholders (managers, development agents, researchers, etc.).

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