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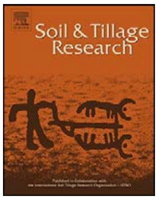

Review

Tillage and soil ecology: Partners for sustainable agriculture

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ABSTRACT

Much of the biodiversity of agroecosystems lies in the soil. The functions performed by soil biota have major direct and indirect effects on crop growth and quality, soil and residue-borne pests, diseases incidence, the quality of nutrient cycling and water transfer, and, thus, on the sustainability of crop management systems. Farmers use tillage, consciously or inadvertently, to manage soil biodiversity. Given the importance of soil biota, one of the key challenges in tillage research is understanding and predicting the effects of tillage on soil ecology, not only for assessments of the impact of tillage on soil organisms and functions, but also for the design of tillage systems to make the best use of soil biodiversity, particularly for crop protection. In this paper, we first address the complexity of soil ecosystems, the descriptions of which vary between studies, in terms of the size of organisms, the structure of food webs and functions. We then examine the impact of tillage on various groups of soil biota, outlining, through examples, the crucial effects of tillage on population dynamics and species diversity. Finally, we tackle the question of the design of tillage systems to enhance biological control in cultivated fields. Identification of the optimal tillage system requires a global consideration of soil management, rather than an analysis focusing on tillage alone, taking into account soil ecology. Organic residue management, the prevention of compaction, crop rotation and the timing of cultivation must all be considered together, taking into account their impact on pest populations and on the natural enemies of pests and ecosystem engineers. This approach requires more detailed research and careful experimental design than traditional comparisons of conventional and reduced tillage systems. We propose the development of population modeling in cultivated fields, as the available ecological models rarely include parameters linked to the soil management system.

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1. Introduction

Soil is the most diverse and important ecosystem on the planet. A tremendous number of biological processes continually active in soils are of crucial importance for the maintenance of other ecosystems in the continental biosphere. Most of the biodiversity of agroecosystems lies in the soil (Young and Crawford, 2004), and the functions performed by soil biota have large, direct and indirect effects on crop growth and quality, soil and residue-borne pests, disease incidence, the quality of nutrient cycling and water transfer and the sustainability of soil productivity. They also determine the resistance and resilience of agroecosystems to abiotic disturbance and stress (Brussaard et al., 2007).

The rationale of sustainable crop management systems is based on the achievement of multicriterion objectives: crop yield is only one of a number of factors to be considered when evaluating the functioning of a crop management system. Consequently, the soil is no longer seen purely as a medium for plant growth, but also as a habitat for a number of organisms. A fundamental consequence of this change in approach is that ecological concepts and theories are now required for the design of new tillage systems, together with a knowledge of soil science, agronomy, ecophysiology and soil mechanics.

Farmers use tillage, consciously or inadvertently, to manage soil biodiversity. However, several literature reviews (e.g. House and Parmelee, 1985a,b; Stinner and House, 1990; Kladivko, 2001; Lakshman et al., 2006; Miura et al., 2008) have highlighted the difficulties involved when trying to identify trends concerning the effect of tillage on soil biota. The identification of keys to help us to understand and predict the relationships between tillage regime and soil ecology therefore remains an important challenge in tillage research. When taking up this challenge, two key points must be addressed.

1. Firstly, improvements in the assessment of the impact of tillage on soil organisms and functions are required. Unlike above-ground biodiversity, soil biodiversity can mostly be managed only indirectly, through tillage and other cropping practices (crop rotation, organic and mineral fertilization), complicating the design of new crop management systems.
2. Secondly, we need to determine which tillage systems make the best use of soil biodiversity. Given the large number of functions of soil biota, we require biodiversity to fulfill many services, and tillage must be designed such that those services are optimized, even if the intrinsic value of soil biodiversity is, in many cases, difficult to assess (Brussaard et al., 2007).

This paper will focus on these two points, after a short presentation of the conceptual framework for soil biota studies. We will not deal here with weed control by tillage, focusing only on the soil microflora and fauna and the biological control of crop pests.

2. The soil ecosystem

2.1. Diversity of soil biota

The complexity of soil biota may be characterized in several ways, the most commonly used method being based on organism size. Excluding plant roots, soil biota consist of the soil microflora (bacteria, fungi, green algae, etc.) and the soil fauna. The soil fauna is also usually divided into three groups, on the basis of mean organism size and adaptation to life in either the water-filled pore space or the air-filled pore space (Cochran et al., 1994; Lavelle, 2000). The organisms of the soil microfauna are generally less than 0.2 mm long. This group consists mostly of protozoa and nematodes, predominantly living in the water-filled pore space. The mesofauna consists of organisms 0.2–2 mm in length, living in the air-filled pore space of the soil and within the litter. The mesofauna includes microarthropods (e.g. acarids, springtails) and enchytraeid worms (small Oligochaeta). The macrofauna consists of individuals more than 2 mm in length, including termites, earthworms and large arthropods.

Soil biota may also be described through the structure of soil food webs (Moore, 1994). For instance, considering the detritus microfoodweb, the microflora and microfauna break down the organic matter. The protozoa, nematodes and microarthropods forage on fungi and bacteria and have their own predators, which in turn serve as a food resource for organisms at higher levels. This approach to studying soil biota highlights the importance of cultivated areas for biodiversity conservation: organisms living in agricultural soils are part of larger food webs, serving as a reservoir of food for animals belonging to higher orders in the food web. For instance, in organic rice-based cropping systems, recent studies have shown that spiders depend on detritivores for food during fallow periods (Sidsgaard, 2000). It has been suggested that, given the low prey quality of pest species, alternative preys serve as important food supplement for spiders and other beneficial organisms. Thus, changes in crop management practices, such as direct drilling, mechanization or the replacement of manual weed control by chemicals, may have a significant impact on spiders and other beneficial organisms.

It is also possible to classify soil organisms according to their function. For instance, considering the role of soil fauna in nutrient cycling in agro-ecosystems, Lavelle (1997) suggested classifying invertebrates into three functional groups, based on the nature of their relationship with the microflora and their ability to create various structures. The first functional group defined consists of the organisms of the aforementioned *microfoodweb*, corresponding to the part of the general soil foodweb linking microorganisms to their predators. This group corresponds principally to the part of the microfauna predating on bacteria and fungi, and their predators. These organisms create no structures. The second functional group consists of the mesofauna and large arthropods and was described by Lavelle as *litter transformers*. These organisms ingest purely organic material, physically fragmenting the litter and releasing fecal pellets with an important role in microbial activity ("external rumen digestion", Aira et al., 2003). These digestion processes release nutrients, which may subsequently be reabsorbed by the decomposers. The fecal pellets are also involved in the stabilization of soil structure and aggregation (Balesdent et al., 2000). The final functional group consists of *ecosystem engineers*, most of which are members of the macrofauna: earthworms (endogeic and anecic species), termites and ants. These organisms create diverse organomineral structures and interact with microorganisms through an internal rumen-type digestion. They alter the physical and chemical conditions in the soil, modifying the flow of water and nutrients, thereby indirectly affecting the growth and development of other living organisms, including the crop, in particular. Ecosystem engineers not only contribute to soil aggregation by releasing fecal pellets and casts, they also make a major contribution to soil structure, by creating nests or digging burrows, thereby affecting air, water and nutrient transfers and root development and function.

These different ecological groups exert several functions in the soil, thereby controlling the efficiency of several ecosystem services (e.g. the capacity of the soil to degrade pesticides (Holtze et al., 2008), the biological control of numerous pathogens (Bailey and Duczek, 1996) and nutrient cycling (Sooksa-nguan et al., 2009)).