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Landscape-scale analysis of cropping system effects on soil quality in a context of crop-livestock farming

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ABSTRACT

Crop-livestock systems are complex farming systems in which many agricultural practices are combined. Sustainable management of soils in these farming systems requires comprehensive assessment of soil quality and consideration of soil properties and functions in an integrated way. This study evaluated soil quality in a 12-km^2 watershed that contains intensive crop-livestock farming systems typical of western France and characterized by high animal density and the co-existence of annual crops (cereals and forages, sometimes in rotation with temporary grasslands) and permanent grasslands. Physical (bulk density, aggregate stability), chemical (pH, copper, organic carbon, nitrogen, available phosphorus, C:N) and biological properties (bacterial and fungal abundance and diversity) of the soil were measured in the upper 15 cm of soil at 164 sampling points. Cropping systems at each point were described in detail from farm surveys, which collected data on crop rotations, manure and crop-residue management, fertilizer application and tillage. The variability in soil properties and the impact of cropping systems were quantified at the watershed scale. The percentage of variance of soil properties explained by the cropping system ranged from 6 to 47%, reaching 47%, 36% and 29% for aggregate stability after a fast wetting test, total nitrogen and organic carbon, respectively. Soil biological properties were explained less, but significantly so, by the cropping system as well. Soil properties were combined into a soil quality index. Among variables, crop rotation influenced soil quality the most, much more than manure application. Permanent grasslands and crop rotations with temporary grasslands had significantly higher soil quality indices than annual crops. This approach requires further development to analyze trade-offs among soil properties in crop-livestock systems.

1. Introduction

Agriculture faces many challenges in terms of food production, climate change and natural-resource management and protection. Agroecology addresses some of these challenges with a range of agricultural practices involving the sustainable use of natural resources (Altieri et al., 1983). Among these natural resources, soil is non-renewable, plays a key role in supporting agricultural production and has several functions, including water regulation, nutrient cycling, habitat support and climate regulation (Schulte et al., 2014). Agricultural soils are currently exposed to numerous threats, such as erosion, compaction, loss of soil organic matter and loss of soil biodiversity, which decrease their ability to function and to provide ecosystem services (Schwilch et al., 2016). Alternative field-management practices to improve soil organic matter and soil structure include manure application, long-term grasslands, pulse-crop rotations, winter cover crops, reduced tillage, and incorporation of crop residues (Lal, 1991; Blanco-Canqui et al., 2006; Morvan et al., 2007).

Given these threats, the concept of soil quality is relevant when assessing and monitoring the “capacity of soil to function” (Karlen et al., 1997), i.e., to provide ecosystem services (Andrews et al., 2004). The capacity of a soil to function can be assessed by analyzing its relevant chemical, physical or biological properties (Karlen et al., 1997; Bastida et al., 2006). Wienhold et al. (2004) classified soil indicators as either inherent or dynamic, with environmental factors determining both the former (e.g. parent material, depth to bedrock) and, along with management practices, the latter (e.g. bulk density, pH, organic matter content, biological activity) (Gregorich et al., 1998). Physical and chemical indicators remain the main indicators used to assess soil quality, but biological indicators have been more recently developed

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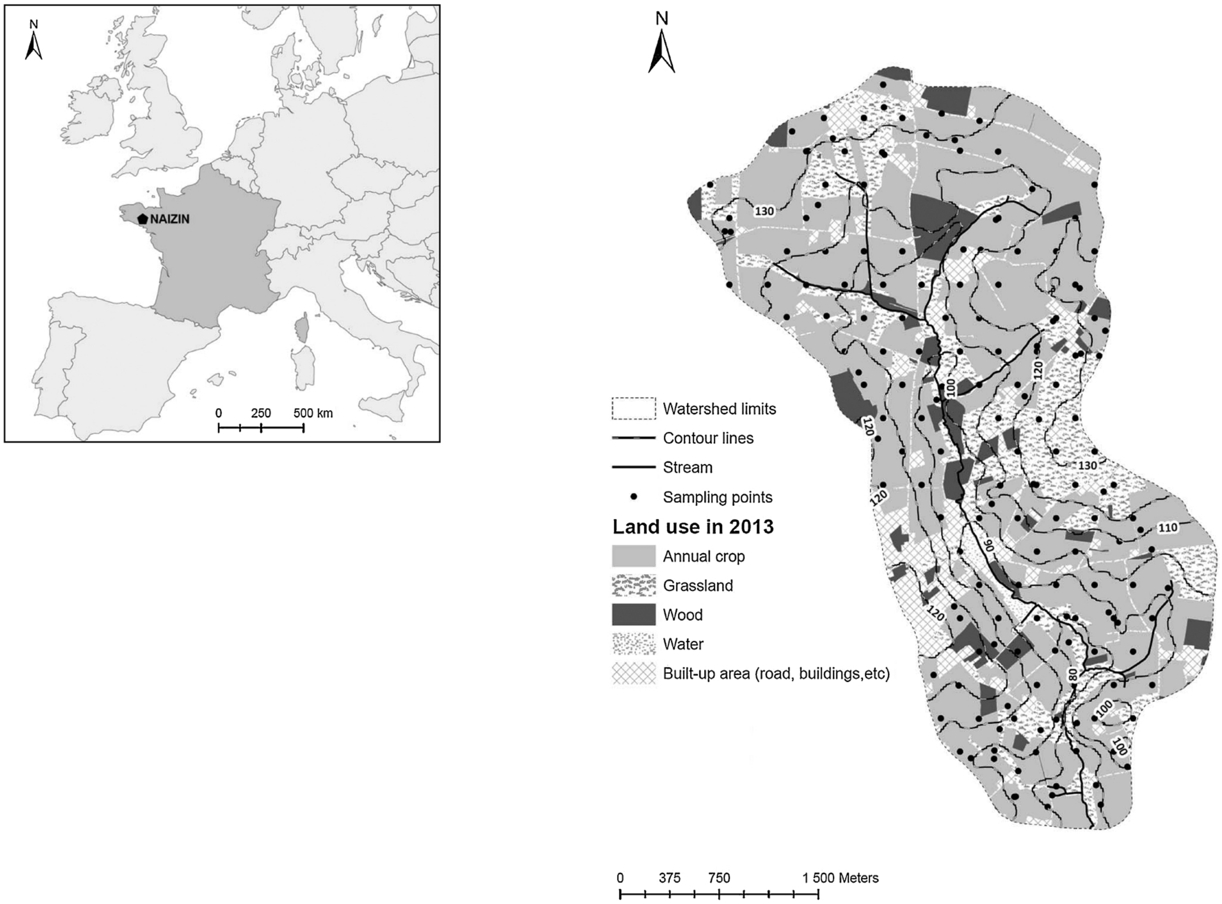

Fig. 1. Map of the study area.

(Bastida et al., 2008). Recent advances in soil molecular biological methods make it possible to include microbial diversity indicators in soil quality approaches (Lemanceau et al., 2015; Bouchez et al., 2016). Considered separately, each soil indicator provides partial information about soil quality and its effects on one aspect of soil functions. Soil quality assessment frameworks have been developed to normalize and combine several indicators into a soil quality index (Andrews et al., 2004). These frameworks can compare soil quality among sites and provide an integrated view of soil quality (Wienhold et al., 2006; Karlen et al., 2008).

Numerous studies have demonstrated a positive influence on soil chemical, physical and biological properties of certain agricultural practices, such as reducing tillage (Liebig et al., 2004), using organic fertilizers (Edmeades, 2003), incorporating crop residues into the soil (Kumar and Goh, 2000) and introducing cover crops or grasslands into crop rotations (Griffiths et al., 2010). These practices can mutually reinforce soil functions, but can also benefit one or more functions at the expense of others (Power, 2010). For example, minimum tillage can increase soil organic matter content and water infiltration in topsoil (Rasmussen, 1999) but can negatively affect nutrient cycling (Brennan et al., 2014). Additionally, impacts of individual agricultural practices on soil quality have been extensively studied; however, to our knowledge, interactions among several agricultural practices within a cropping system have been investigated far less. The use of organic fertilizers can increase soil organic carbon (SOC) content and improve soil physical properties but can also cause excessive nutrient enrichment and alter water quality, depending on the other agricultural practices implemented in the field (Ugarte et al., 2014). Thus, the challenge is to develop a more systemic assessment of agricultural practices to comprehensively manage soil functions.

Mixed crop-livestock systems, integrating crop and livestock production at the farm or the landscape level (Schiere et al., 2002) are complex agricultural systems in which a variety of agricultural practices are combined and differing degrees of interactions exist among system components (crop, grassland, animals) (Moraine et al., 2014). Depending on farm specialization and intensification, a diversity of cropping systems with distinct combinations of agricultural practices, including manure application and introduction of grasslands (pastures or hayfields) into the crop rotation, may co-exist in a given crop-livestock area (Akkal-Corfini et al., 2014). Integrated assessment of soil quality in these areas is highly topical since specialized crop and livestock systems have been demonstrated to have negative effects on the environment, especially on soils (Pimentel et al., 2005; Soussana and Lemaire, 2014), and optimized crop-livestock systems are key agroecological models (Bonaudo et al., 2014). From this perspective, better knowledge about effects on soil quality of combining management practices within cropping systems in crop-livestock areas is needed. Sustainable management of soils in cultivated areas requires transitioning to comprehensive assessment of soil quality and using integrated approaches to consider soil properties and functions (Andrews et al., 2004).

In this study, we assessed impacts of cropping systems on soil quality in mixed crop-livestock systems at the landscape scale. Within the framework of soil quality assessment, this study is based on measuring dynamic physical, chemical and biological soil indicators in a variety of cropping systems in a 12-km^2 watershed containing intensive crop-livestock farming systems typical of western France. These areas are characterized by high animal density and the co-existence of annual crops and grasslands. Soil quality indicators were selected in relation to soil functions of interest for agroecosystem sustainability (biomass production, maintaining soil biodiversity) (Rakkar et al., 2017) and for crop-livestock systems in this specific area (nutrient recycling and