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Short communication

Studying the complexity of the secondary succession process in the soil of restored open mine lignite areas; the role of chemical template

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ABSTRACT

The unfolding of the secondary succession process in the soil of open mine areas reclaimed with *Triticum aestivum* (wheat) was analyzed by using a polyphasic approach. The study was conducted in five wheat fields with post-reclamation age 0, 5, 10, 15 and 20 years. Also data from control wheat fields outside the mining area were used. From the total of 77 variables 21 were used as surrogates to depict the succession course. These were organized in four spheres; (a) soil chemical composition (b) microbial community structure (c) catabolic activity of microbial community and (d) enzymatic activity in soil. To model the entire succession process the significant correlations among individual variables regardless of origin were analyzed by network analysis. Further, the results of the analysis informed the elaboration of a conceptual model by using Structural Equation Modeling (SEM). Although local configurations of variables were clearly imprinted on the network analysis phase graph, network parameters indicated dominance of the global network topology over local. The succession course is described as a moderately complex, well organized system, while the unfolding of the secondary processes in the four organization spheres followed almost co-directional pathways. The model formulated by SEM was a strongly reduced one, with many strong pair-wise relationships. Our results partially support the idea that the soil chemical background operates as a template overriding the structure of the microbial community and the enzymatic and catabolic activities.

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1. Introduction

The idea that ecological systems are complex, self-organized entities is widespread. In this respect, Proulx and Parrott (2008) took complexity as innate property of a system which is optimized in the course of self-organization process and nominated it indicator of ecological integrity, while Parrott (2010) described ecological systems as complex, adaptive and dynamic networks of interacting components that should be studied in a context of non-equilibrium dynamics. Earlier ecological complexity was discussed in terms of species richness, connectance, interaction strength and evenness (Pimm 1984). Recently Cadenasso et al. (2006) introduced the term “biocomplexity” to account for the degree to which the ecological system encompassing biological, social and physical components shows spatially explicit heterogeneity, organizational connectivity and historical contingency. This definition addresses what are the components of the system, how they organized (spatial heterogeneity), how they interact (connectivity) and how they change over time (contingency). Specifically, contingency refers not only to direct relationships and effects but also to indirect effects, legacies, memory of past states of the system etc.

In the case of soil habitats that are characterized by enhanced heterogeneity (Fitter et al., 2005), distinct substructures are readily identifiable with variables referring either to stoichiometry, or enzymatic activity or even to biocommunity, offering the possibility to discuss multiple aspects of complexity. According to Beare et al. (1995) soil consists of a number of biologically relevant spheres, that exhibit distinct though somewhat overlapping properties. The idea of spheres could be extended and identified with substructures such as (a) the chemical composition of the soil, (b) the structure and (c) the catabolic activity of the microbial community and (d) the enzymatic activity in soil. Among them, the subset of physicochemical variables—including mineralogy, pH, porosity, and availability in macro- and micronutrients, is considered major determinant of soil functions, influencing differentially the various subgroups of the microbial community (e.g. Stockdale et al., 2006). More to the point, Stockdale et al. (2006) put forward that the physicochemical variables operate in concert, thus, the entire soil physicochemical setup can be viewed as a template on which organisms and ecological systems operate.

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However, apart from the combination of the physicochemical variables, other parameters such as the type and the diversity of the above-ground vegetation and the management practices exert regulatory effects on the biomass and the structure of the soil microbial community (Schutter and Dick, 2002; Spedding et al., 2004; Sun et al., 2004).

In order to study complexity, we focused on data describing a secondary successional course because not only many factors are involved in succession but they also operate in concert either synergistically or competitively (Meiners et al., 2015). For instance, the composition of the new plant community depends on seed limitation, among others, which subsequently depends on the availability of seeds and safe sites for germination and establishment. The data analyzed in the present study were collected from open-mine areas reclaimed with *Triticum aestivum* before 0, 5, 10, 15 and 20 years. Results on the dynamics of the structural and activity patterns displayed by the soil microbial community along the secondary succession process taking place in these areas were previously reported by Mastrogianni et al. (2014). In this paper, we recoil on the same dataset and discuss issues relating to the complexity patterns associated with the self-organization process which according to Zeng et al. (2005) unfolds in reclaimed areas. Precisely, the issues addressed in this study were twofold: a) to examine the extent to which the chemical template determines the structure of the other organization spheres (structure and catabolism of microbial community, enzymatic activity) and b) to test whether the soil variables were organized as to function in concert albeit originated from different organization spheres.

2. Materials and methods

2.1. The data set

Data were gathered from restored post-mining areas refilled with leftover materials in the lignite district of Prolemaida (Western Macedonia, Greece). Restored fields were reclaimed with *T. aestivum* (wheat) before 0, 5, 10, 15 and 20 years. Moreover, data were collected from control fields outside the mining area that were cultivated also with wheat for the last 30 years. To avoid landscape effects the studied fields were confined within a rather homogeneous area. Three texture variables (percentages of silt, clay, sand), 14 chemical variables (Organic C (SOM), organic N, C/N, P, K, Mg, Fe, Zn, Mn, Cu, Ca, Cd, Co, Ni), three variables representing the activity of enzymes involved in the C, N and P cycles (b-glycosidase, urease, alkaline phosphatase), 29 Phospholipid Fatty Acids (PLFAs) variables standing for the structure of the microbial community and 31 Biolog variables (substrates) figuring the Community Level Physiological Profile (CLPP) accounting for microbial activity, were assessed. A detailed description of the sites, sampling, samples treatment and methods for variables' determination is given in Mastrogianni et al. (2014). According to our previous findings (Mastrogianni et al., 2014), most variables oscillated randomly during the succession course while a limited number (21 out of 77) changed systematically. Since the goal of this paper was to study the dynamics of the succession patterns, our analyses were based on these 21 variables (Table S1; Supplementary material) which were taken as surrogates shaping the succession fingerprints of the soil chemical, enzymatic, structural and activity profiles. Because all variables were not expressed in the same scale, prior to any analysis, data were standardized in the range 0–1 to eliminate the scale effect.

2.2. Data analysis

To depict the overall succession history and to obtain metrics directly related to complexity, we explored interactions among individual variables regardless of the sphere in which each participated by applying network analysis techniques. The analysis was started from significant pairwise correlations among variables and provided measures about the structural features of the network based on the adjacent matrices and produced graphs (Hanneman and Riddle, 2005). In this study, nodes represented surrogate variables and ties stand for significant correlation coefficients among them. For the analysis of patterns the UCINET 6 package was used (Borgatti et al., 1999). Details on network analysis and metrics, and their significance on exploring network structure are presented on Supplementary Material (Table S2).

To address the statistical validity of the network analysis, a set of regression models were fitted by the method of Structural Equation Modeling (SEM). In practice, SEM pairs prior knowledge

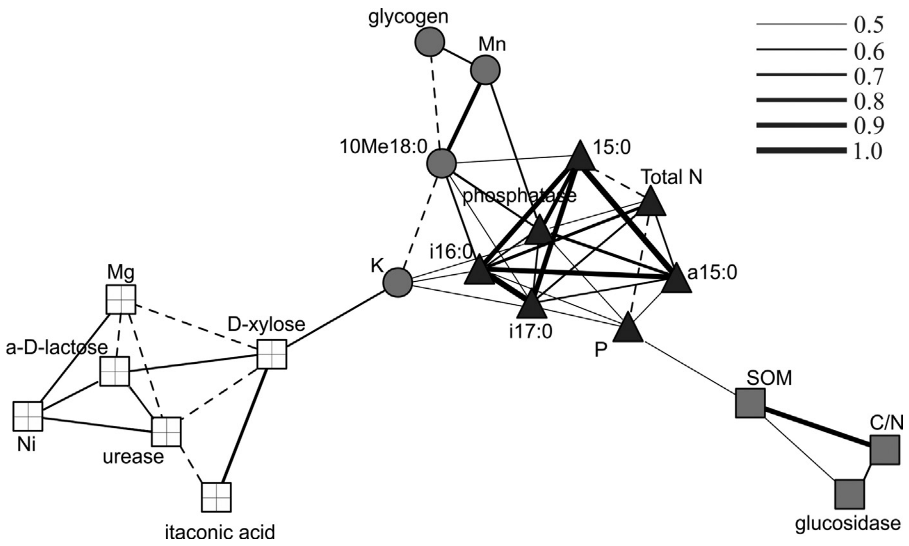

Fig. 1. The network of relationships among the soil surrogate variables regardless of sampling location plotted on the phase space of the two first PCoA axes. Different node shapes (cross-square, circle, triangle, empty square) denote different factions and different node colors (white, grey, black) correspond to different structurally equivalent clusters. Solid and dashed lines indicate significant and non-significant relationships respectively while the strength of the arrows corresponds to the value of the respective correlation coefficients. The statistical significance of the relations was post-checked against data applying a SEM model.

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