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Dynamics of Carbon and Nutrients in a Successional Forest Sequence in the Mesopotamian Espinal (Argentina)

C. Mendoza[1], N. Ayala[1], M. Antivero[1], C. Italiano[2], E. Giardina[2] and A. Di Benedetto[2,3*]

[1]Faculty of Science and Technology, U.A.D.E.R., Route 11, Km. 10.5, Oro Verde, Entre Ríos, Argentina.
[2]Faculty of Agronomy, University of Buenos Aires, San Martín Avenue 4453 (C1417DSE), Buenos Aires, Argentina.
[3]Faculty of Agricultural Sciences, National University of Mar del Plata, Route 226, Km. 73.5 (B7620ZAA), Balcarce, Buenos Aires Province, Argentina.

Authors' contributions

This work was carried out in collaboration between all authors. Authors CM, ADB and EG designed the study and wrote the manuscript. Authors NA, MA and CI recorded data, performed the statistical analysis and managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

The Mesopotamian Espinal has been recently modified in several areas of Entre Ríos province (Argentina) due to the advance of the agricultural frontier, producing an important reduction in forest area. Inappropriate forest management had early transformed the native and primary forests into degraded or secondary forests. Deforestation and land abandonment have led to the development of a sequence of successional forest stages. The aim of this work was to assess the effects of forest succession changes on soil properties and nutrients contents of a successional forest sequence in the Mesopotamian Espinal (Argentina) which would be associated with livestock production. To reach proposed objectives, ten soil samples were collected from the depth of 0-10 (A-horizon) and

**Corresponding author: E-mail: dibenede@agro.uba.ar;*

30-40 cm (B-horizon) from 4 sites in three forest successional sequence. An initial forest (IF) (approximately 20 years at the beginnings of this study), a secondary forest (SF) (mixed forest with trees of between 60 and 80 years old) and a mature forest (MF) with minimal signals of degradation were studied. Results showed soil texture changes during the successional forest process with higher clay and coarse sand but lower silt and fine sand values at the IF stage than MF state. In the same way, an increase in organic matter (as much in the humic- as in the fulvic-fraction) and in most nutrient (nitrogen, phosphorus, calcium, magnesium and potassium) were found. Data showed that whenever forest reach to mature state, soil quality indicators would explain part of the higher plant productivity.

Keywords: Forest regeneration; soil organic carbon; soil quality indicators; soil nutrient accumulation.

1. INTRODUCTION

The Mesopotamian Espinal has been recently modified in several areas of Entre Ríos province due to the advance of the agricultural frontier. Inappropriate forest management had early transformed the native and primary forests into degraded or secondary forests. Deforestation and land abandonment have led to the development of a sequence of successional forest stages, which leads to a mature stable forest [1].

After a land is cleared for agriculture and later abandoned, ecosystems undergo a series of directional changes, a process called secondary succession. The most conspicuous of such changes are those related to vegetation composition and structure, but other ecosystem properties, such as soil structure and nutrient composition are also affected [2]. Soil processes, by being closely correlated with plant changes, are expected to be associated with successional dynamics and carbon sequestration but the relative importance and interactions between soil type, previous land use and forest cover type differed with soil depth [3]. Documenting the changes in soil properties during succession has been an active area of research in both temperate [4] and lowland tropical areas [5], but other ecosystems, such as the Mesopotamian Espinal remain little studied.

Soil properties are considered one of the major factors that affect the distribution patterns of forest types. Soil properties from each preceding community, which increase in organic matter and profile development, together with modification of the light environment, are the two main explanations for succession [6]. Soil organic matter is recognized to be one of the most reactive components of soil and is extremely important to maintaining soil fertility and productivity [7]. Soil humus is mainly derived from the biochemical degradation of plant and animal residues and microbial activity [8] and is generally divided into three classes of materials based on their alkaline and acidic solubilities: fulvic acid, humic acid and humin [9,10]. Humic acids play essential biological, chemical and physical role in soils and improve soil conditions for plant growth, while humin was the main carbon-related stocks in forest chronosequences [11]. On the other hand, the soil fulvic fraction acts as a focal point of interacting the variables such as soil nitrogen and humic fraction [12]. Carbon inputs and nutrient availability are known to affect soil organic carbon stocks as well [13].

Accumulation of available nutrients in the soil is a key process of heathland-to-forest succession that significantly improves plant nutrient availability but leads to only minor changes in carbon/nutrient ratios and humus quality Measures of soil nutrient availability such as concentrations of nitrogen and phosphorus are important indicators of terrestrial productivity [14]. The chemical composition is an essential part in unravelling the dynamics of organic matter in the soil. Substantial efforts have been made to characterize the chemical composition of forest A-horizons, whereas detailed information on the composition of subsoil-soil organic matter in natural ecosystems remains scarce [15].

The aim of this work was to assess the effects of forest succession change on soil properties of a successional forest sequence in the Mesopotamian Espinal (Argentina) which would be associated with livestock production.

2. MATERIALS AND METHODS

The Espinal is an Argentine eco-region located between 28° and 40°S latitude, to the South of the Chaqueño Park, covering approximately 330,000 km^2 and forms an arch that surrounds the Pampas Grassland eco-region. The Mesopotamian Espinal, in Entre Ríos province, comprises forests belonging to the Espinal phytogeographic Province, especially in Ñandubay district. The study was conducted in the Villaguay Department (covering an area of 1,600 km^2 in Entre Ríos province, Argentina).

The climate of the Villaguay Department is humid temperate. Annual mean precipitation is 1,000 mm $year^{-1}$, with an important inter-annual variability, but with peaks of rainfall in autumn and spring, although a recently simulation for long-term weather data showed a progressive rainfall change [16]. Mean annual temperature is about 16°C, with the mean temperature of the coldest (July) and hottest (February) months being 11° and 25°C, respectively. Temperature changes gradually from season to season; however, there may be days with minimum temperatures below 10°C in summer and with maximum values of 30°C in winter [1].

Vegetation is characterized by dominant xerophilous tree species such as *Prosopis. nigra* (Griseb.) Hieron, *P. affinis* Spreng, *Acacia caven* (Molina) Molina, *Celtis ehrenbergiana* (Klotzsch) Liebm., *Aspidosperma quebracho-blanco* Schltdl., *Geoffroea decorticans* Burkart, *Prosopis affinis, Schinus longifolius* (Lindl.) Speg., *Scutia buxifolia* Reissek, *Trithrinax campestris* (Burmeist.) Drude and Griseb among other characteristic species.

The present study was carried out in three different forests of the Mesopotamian Espinal (Argentina) located in a similar environment (weather, soils and topography). For details see Mendoza et al. [1]. Considerations were taken to circumscribe the successional pattern as the main source of variation. All stands, (0.5 ha^{-1} each) have no logging activity. They are situated in a 20 km range and represent different successional stages.

The forests selected had the following characteristics:

a) Initial forest (IF): Monospecific forest of *A. caven*, originated by colonization of this species in a cropland abandoned in 1998 (approximately 20 years at the beginnings of this study).
b) Secondary forest (SF): Mixed forest dominated by *P. affinis*, with the presence of other characteristic species, such as *A. caven* and *C. ehrenbergiana*, which includes trees of between 60 and 80 years old.
c) Mature forest (MF): Mixed old-growth forest, dominated by *P. nigra*, with the presence of *A. caven*, *P. affinis* and *C. ehrenbergiana*. This forest presents minor signals of degradation.

Ten soil samples were collected from the depth of 0-10 (A-horizon) and 30-40 cm (B-horizon) from 4 sites. The soil chemical properties (A- and B-horizons) of composed samples of different forest plots were determined in triplicate. Organic matter (OM), carbon status (C), electrical conductivity (EC), and pH were analyzed in a 1:5 (v/v) water extract. Nutrient concentration analysis were made only for B-horizon and included nitrogen (N) (Kjeldahl method), phosphorus (P) (colorimetrically), potassium (K), calcium (Ca), sodium (Na) and magnesium (Mg) (atomic absorption) according to Sparks et al. [17]. The cation-exchange capacity (CEC) was determined with 1 M ammonium acetate at pH = 7. Both humic and fulvic acids were extracted from soils using the alkaline extraction proposed by the International Humic Substances Society [18]. Bulk density was measured as a ratio of mass of oven dry soil to the volume of soil before drying.

The experimental design was a completed randomized block. Data were subjected to analysis of variance and means were separated by Tukey tests ($P < .05$).

3. RESULTS

Soil texture changed during the successional forest process. In the initial stage (IF) we found higher clay and coarse sand than the mature forest (MF), but the last showed higher silt and fine sand values (Table 1).

Significant differences in chemical properties (ph and electrical conductivity) and carbon capture between subsoil horizons along the three successional forest stages tested were found (Table 2). Significant differences in favor of A-horizon for all chemical properties tested were found as well. On the one hand, EC increased in the A-horizon between the IF and MF stages while decreased from the B-horizon. A pH decreased in both subsoiled horizons as forest developed were found. Organic matter and humic acids increased between IF and MF in both horizons but carbon status increased in the same way only in the A-horizon. Fulvic acids increased from IF and MF in both horizons. Although bulk density only was recorded at B-horizon, data showed a significant decrease as forest advanced from IF to MF.

B-horizon nutritional status was shown in Table 3. Main nutrients such as N, P, Ca, Mg and K increased between IF, and MF successional sequence while Na decreased it. The cation exchange capacity for B-horizon showed the same pattern than the main cations (Table 3).

4. DISCUSSION

In general, the criteria for judging the regeneration success of disturbed ecosystems have been based on inspection of visual above ground indicators; soil components, in most cases, have received little attention [19]. The development of a forest successional sequence in the Mesopotamian Espinal is common to northeast Argentina [1], but little is known about how such changes affect soil properties. We evaluated the changes in soil properties at the 0- to 10- (A-horizon) and 30- to 40-cm (B-horizon) depths during this conversion in three chrono-sequences (initial forest, secondary forest and mature forest).

Soil structure can be defined as the arrangement of primary mineral and organic particles of soil into secondary units called aggregates. Therefore, soils can be seen as a heterogeneous mixture of primary particles (sand, silt and clay), which are organized at several hierarchical levels of complexity by means of interface processes that link these particles [20]. Soil texture plays a key role in below ground C storage in forest ecosystems and strongly influences nutrient availability and retention. Long-term preservation of organic C in soils has been demonstrated to occur mainly to the silt- and clay-size fractions [21]. Although little on the textural composition of soils in a chrono-sequence has been published, our results showed an increase in silt and fine sand but a decrease in clay and coarse sand between the initial forest and the mature one (Table 1). N and C losses in disturbed soils are influenced by soil texture with higher losses on sandy soils and with a positive relationship between clay percentage and soil organic matter [22].

Li et al. [23] demonstrated the significant impacts of natural succession in an old-growth forest on the soil nutrient properties and organic matter. These authors indicated that changes in soil properties along the forest succession gradient might be a useful index for evaluating the successional stages of the subtropical forests. Soil nutrient concentrations, particularly N and P, are important indicators of terrestrial productivity [15]. On the other hand, Li et al. [23] showed that soil C increases according to plant productivity increases, soil recovery is much slower than vegetation changes.

Soil organic matter (SOM) is recognized to be one of the most reactive components of soil and is extremely important to maintaining soil fertility and productivity [8]. The recovery of soil organic matter and changes to soil pH displayed distinct spatial heterogeneity due to the surface micro-topography (mounds and furrows) created by contours ripping of rehabilitation sites. At least, our results showed a pH decreased from Mesopotamian Espinal successional sequence of forest development (Table 2), probably associated with nutrient retention by vegetation and litter in agreement with previous reports [5,19,24].

The origin of stabilized SOM about above ground and below ground biomass is poorly known; while the highest C and N concentrations are usually recorded near the soil surface compared to greater depths [25], a high proportion of soil C is present in subsoil horizons below the A-horizon [26]. Between 30 and 63% of the SOM is stored below 30 cm, making subsoil-SOM an important source and sink in the global carbon cycle. Nevertheless, detailed information on the composition of subsoil-SOM remains scarce. Regardless of soil type, results indicate that the chemical composition of the extractable subsoil-SOM significantly differ from topsoil-SOM in the maritime broadleaved forests studied by Vancampenhout et al. [16]. While topsoil-SOM mainly differs according to nutrient status, subsoil-SOM shows high relative amounts of soil lipids or polysaccharides for coarse and fine textured loamy soils respectively [15]. In early successional stages (IF) which showing low SOM, fine sand content and the percentage of fine roots probably acted as co-drivers enhancing soil aggregate stability while silt content decreased it (Tables 1 and 2) in agreement with Erktan et al. [27].

Humus are one of the most active forms of soil organic carbon. Zhang-Jun et al. [10] indicated that the percentage of humus increased with vegetation succession. Both, the soil humic fraction and soil fulvic fraction are responsible for the buffer soil properties but the presence of phosphate ions may strongly change natural buffer capacity of humic acids by shifting

Table 1. Textural composition of the B-horizon in soils with different successional stages: a) initial successional stage (IF); b) in an intermediate secondary forest (SF); and c) in a mature forest (MF). Different capital letters indicate significant differences (P < .05) between the three successional forest stages

Successional sequence	Silt (%)	Clay (%)	Coarse sand (%)	Fine sand (%)
IF	23.90[b]	50.12[a]	1.42[a]	17.36[b]
SF	25.60[b]	49.10[a]	0.99[b]	17.10[b]
MF	29.73[a]	42.37[b]	0.44[c]	20.74[a]

Table 2. Chemical and physical properties of subsoil horizons (A and B) from soils with different stages: a) initial successional stage (IF); b) in an intermediate secondary forest (SF); and c) in a mature forest (MF). Different lower case letters indicate significant differences (P < .05) between the three successional forest stages. Different capital letters indicate significant differences (P < .05) between horizons for each successional forest stage

Successional sequence	C (%)	OM (%)	Humins (%)	Fulvic acids (%)	pH	EC (dS m^{-1})	Bulk density (g cm^{-3})
IF-A	2.90[cA]	3.42[cA]	0.945[cA]	0.191[aB]	7.93[aA]	0.18[bB]	
SF-A	4.56[bA]	4.11[bA]	1.134[aA]	0.173[bB]	7.19[bB]	0.26[aB]	
MF-A	5.89[aA]	6.08[aA]	1.278[aA]	0.158[cB]	6.11[cB]	0.32[aA]	
IF-B	1.59[aB]	2.09[bB]	0.350[bB]	0.212[bA]	8.08[aA]	0.39[aA]	1.10[a]
SF-B	1.27[aB]	2.53[bB]	0.335[bB]	0.201[bA]	8.10[aA]	0.34[aA]	0.71[b]
MF-B	1.04[bB]	3.18[aB]	0.495[aB]	0.270[aA]	6.96[bA]	0.15[bB]	0.41[c]

Table 3. Nutrients concentrations of subsoil B-horizon from soils with different stages: a) initial successional stage (IF); b) in an intermediate secondary forest (SF); and c) in a mature forest (MF). Different lower case letters indicate significant differences (P < .05) between the three successional forest stages

Successional sequence	Nutrients						CEC (meq 100 g^{-1})
	N (%)	P (ppm)	Ca (meq 100 g^{-1})	Mg (meq 100 g^{-1})	K (meq 100 g^{-1})	Na (meq 100 g^{-1})	
IF-B	0.73[c]	0.31[c]	13.71[c]	3.30[b]	0.31[b]	1.10[a]	18.93[c]
SF-B	0.89[b]	1.05[b]	17.94[b]	4.52[a]	1.22[a]	0.52[b]	33.65[b]
MF-B	1.11[a]	1.58[a]	21.93[a]	4.77[a]	1.47[a]	0.58[b]	40.81[a]

buffering maximum toward higher pH values. Consequently, the buffer capacity of these compounds and humic acids-rich soils is also high [11]. The soil fulvic fraction acts as a focal point of interacting the variables such as soil N and humic fraction [12] while the humic fraction reacting with metals [28]. Our results indicate that both humic and fulvic fractions increased between IF and MF in the Mesopotamian Espinal as much in the A-horizon as B-horizons (Table 2). The significance of these data is enhanced by the fact that the changes in humic and fulvic fractions during a forest chrono-sequence is scarce.

A large proportion of the organic residues that reach the soil is mineralized, these include leaves, stems, flowers, fruits, and other plant structures, which releasing both organic and inorganic nutrients that can be reabsorbed by plants. The release rate of nutrients in each forest ecosystem, determining its nutritional status [1]. Accumulation of available nutrients in the soil is a key process in heathland-to-forest succession that significantly improves plant nutrient availability but leads to only minor changes in carbon/nutrient ratios and humus quality [29].

Barret and Burke [30] indicated that N retention of forest soils is often limited by organic substrate availability, but few studies have explicitly tested the relationship between soil carbon content and nitrogen retention. Potential carbon mineralization and N immobilization increased with increasing soil organic matter content because soil organic carbon content accounted for 58% of the variation in potential rates of N immobilization. In one of the few reports available, Banning et al. [2] showed that recovery of soil nitrogen was faster than soil carbon. Our results are not in agreement because N (Table 2) and carbon (Table 3) increased 1.52 and 2.03 times respectively along the three successional forest stages tested. On the other hand, Banning et al. [2] indicated that there is a potential for a net loss of soil nutrients due to rapid decomposition under conditions of revegetation for which, losses of N are often greater than losses of other nutrients. In this way, Frouz et al. [24] showed that available Ca and Na availability decreased during succession. Once again, our results showed an increase in 1.52, 5.09, 1.60, 1.45, 4.74 times for N, P, Ca, Mg and K respectively (Table 3) as Espinal forest recovery as far as to reach the mature stage. Bautista-Cruz and del Castillo [5] and Jia et al. [31] showed that the highest rates of soil C sequestration and the highest drop in exchangeable K, Mg, and Ca concentrations took place the first 15 year of forest development in agreement with our results in the Mesopotamian Espinal forest (Table 3).

Two contrasting hypotheses have also been put forward to explaining the impact of changes in nutrient availability on soil organic carbon decomposition. The first hypothesis, also known as the stoichiometry hypothesis, assumes that microbial decomposition is driven by the relative availability of nutrients. In N-limited decomposer systems increased C input, resulting in a higher C-to-N ratio should slow down decomposition, whereas N input resulting in a lower C-to-N ratio should increase decomposition and decrease soil C sequestration. The second hypothesis, which is known as the ‘microbial mining hypothesis’, states that increased nutrient availability slows down decomposition of recalcitrant C by suppressing microbial activities which break down recalcitrant litter compounds such as lignin to acquire N. According to this hypothesis, excess N should increase ecosystem C stocks in systems where litter inputs contain recalcitrant compounds, but decrease it where litter inputs are dominated by more decomposable compounds [13]. The present Mesopotamian Espinal forest data cannot let to dismiss any of these hypotheses, which it is the matter for future research.

5. CONCLUSIONS

The Mesopotamian Espinal successional sequence in a disturbed initial forest to a mature one showed soil changes, in agreement with previous reports on forest from other geographic localization. The organic matter, fulvic and humic acids content, and nutrient content increase across the forest successional sequence would be explaining part of the higher plant productivity found in a mature forest state.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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