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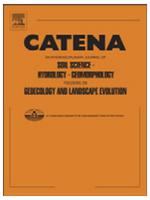

Progressive and regressive soil evolution phases in the Anthropocene

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ABSTRACT

Soils have a substantial role in the environment because they provide several ecosystem services such as food supply or carbon storage. Agricultural practices can modify soil properties and soil evolution processes, hence threatening these services. These modifications are poorly studied, and the resilience/adaptation times of soils to disruptions are unknown. Here, we study the evolution of pedogenetic processes and soil evolution phases (progressive or regressive) in response to human-induced erosion from a 4000-year lake sediment sequence (Lake La Thuile, French Alps). Erosion in this small lake catchment in the montane area is quantified from the terrigenous sediments that were trapped in the lake and compared to the soil formation rate. To access this quantification, soil processes evolution are deciphered from soil and sediment geochemistry comparison. Over the last 4000 years, first impacts on soils are recorded at approximately 1600 yr cal. BP, with the erosion of surface horizons exceeding 10 $t\cdot km^{-2}\cdot yr^{-1}$. Increasingly deep horizons were eroded with erosion accentuation during the Higher Middle Ages (1400–850 yr cal. BP), reaching 1000 $t\cdot km^{-2}\cdot yr^{-1}$, and leading to the remobilization of carbonated and poorly weathered material, hence rejuvenating soil development. Erosion exceeded the soil formation rate and constituted a regression in the development of soils. The tolerable erosion limit is thus defined for erosion from 25 to 30 $t\cdot km^{-2}\cdot yr^{-1}$. Beyond this limit, the sustainability of the agroecosystem is limited and ecosystem services decrease. Afterwards, pedogenesis evolved again from progressive (700–300 yr cal. BP) to regressive (300 yr cal. BP-today) phases. Erosion was less important during the last 700 years than during the Middle Ages but with the same weathering stages, indicating that soils were deeply affected during the Middle-Age and have yet not recovered. Our results highlight the importance of the human factor in the pedogenesis over last millennia and suggest that the studied agro-ecosystem entered the Anthropocene 1400 years ago.

1. Introduction

The intensification of agricultural practices and their increasing pressure on agroecosystems are known to modify soil properties and pedogenetic processes (Matson, 1997; Grieve, 2001; Dupouey et al., 2002; Bojko and Kabala, 2016). The first evidence of human settlements/agriculture in the Alps dates from the Neolithic period (Martin et al., 2008; Dotterweich, 2013). The natural evolution of soils was probably disturbed from this period, which began with fire deforestation (Gobet et al., 2003; Colombaroli et al., 2013; Valese et al., 2014). Indeed, the removal of vegetation cover results in the destabilization of slopes and increased erosion fluxes downstream (Edwards and Whittington, 2001). Nowadays, the triggered loss of soil represents a threat to mountain economies (food supply), the water quality and carbon storage (Pimentel, 2006). The effects of this threat on soil properties, soil quality and ecosystem services from a long-term perspective and the resilience of mountain soils to disruption for a given management are poorly known. A better understanding on how soils function and react to disruptions is crucial to predict their evolution and adapt our management for future generations (Arshad and Martin, 2002).

Pedogenesis results from a succession of processes, which depend on soil the forming factors: climate, relief, living organisms (including humans and their activities), parent material and time (Jenny, 1941).

Abbreviations: E, erosion; V, volume; SF, soil formation; ST, soil thickness; SL, soil loss; TS, terrigenous sediment; SY, sediment yield; DD, dry density (for sediment); BD, bulk density (for soil); M_{sed}, mass of sediment; NCIR, non-carbonate ignition residue; OM, organic matter; TOC, total organic carbon.

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This evolution is characterized by different positive and negative phases (Pallmann, 1947; Erhart, 1967; Duchaufour, 1970; Huggett, 1998). Different meanings of regression, including qualitative and quantitative, are possible. The nature of soils can change, such as by rejuvenating, leading to a regression of the pedogenesis state without regressing in terms of depth (Pallmann, 1947; Duchaufour, 1970; Egli and Poulenard, 2016). Erosion is a natural process, and tolerable erosion is necessary to ensure the sustainability of systems. Sustainable management must prevent erosion from exceeding soil formation rate to avoid the regression and degradation of soils (Verheijen et al., 2009; Dotterweich, 2013). Regression can also mean that the gradual evolution of a soil is disrupted during its development and that its degree of evolution regresses (Jäger et al., 2015).

Most of the soils in the Alps initially formed following glacial retreat from bedrock or superficial deposits (Alewell et al., 2015; Jäger et al., 2015; Le Roy et al., 2015). Weathering that was reinforced by vegetation settlement allowed a thin layer of soil to develop and grow. This process can currently be observed and dated from chronosequences that have been studied at the front of glaciers (Huggett, 1998; Egli et al., 2001). These observations of pedogenesis on short time scales (10 to 100 years) can also be observed with long-term field experiments and recent well-dated modifications of land use (Arshad and Martin, 2002; Montagne et al., 2016). The contexts of pristine soils i.e. non-human-affected soils, are difficult to access at this latitude for comparison. Nonetheless, the study of current soils is necessary to understand their evolution. Current soils work as boundary conditions: they are the final point of their evolution. Soils have a memory and exploitable properties to reconstruct past soils but are not often suitable chronometers because of chemical and physical transfers (Huggett, 1998).

Sediment archives are useful to find old soil footprints and reconstitute their temporal evolution, especially in a context of intense human activities and with long-term perspectives. One of the most prominent and trackable consequences of human practices on the environment is the erosion of soils (Foley, 2005; Pimentel, 2006). Lake sediments can store erosion products, which are thus a component of soils when erosion is active (Edwards and Whittington, 2001; Arnaud et al., 2012). Sediment archives are also relevant to stratigraphically define the Anthropocene (Blum and Eswaran, 2004; Crutzen, 2006; Waters et al., 2016). If changes in the stratigraphy are a consequence of pedogenesis modification (Erhart, 1967), the Anthropocene should be locally defined by the effects of humans on soil evolution. The quantification of erosion from lake sediment sequences has been investigated by several authors (Zolitschka, 1998; Enters et al., 2008; Massa et al., 2012; Foucher et al., 2015), but few studies have attempted to decipher the soil evolution from lake sediments (Mourier et al., 2010; Giguet-Covex et al., 2011; Arnaud et al., 2012; Jäger et al., 2015). This quantification enables us to determine the intensity of the disruption that triggered the loss of soil and the tolerable erosion in the catchment according to the difference from the soil formation rate, which could be a local definition of the Anthropocene (Verheijen et al., 2009; Li et al., 2009; Alewell et al., 2015).

Lake La Thuile, which is located in the French pre-Alps, provides a long sedimentary sequence that spans the entire Late-glacial and Holocene periods. A high-resolution multi-proxy (sedimentological, palynological, and geochemical) analysis of the uppermost 6.2 m (Bajard et al., 2016) revealed a mainly lacustrine origin for the sediment during the late and mid-Holocene periods (12,000–4000 yr cal. BP), and the forest that was established around the lake prevented erosion on these slopes. The sedimentary filling of the lake during the late Holocene period was mainly a consequence of human-induced erosion in response to land-use changes (Bajard et al., 2016). The first human effects in the landscape were identified ca. 3300 cal. BP with a decrease in the forest cover and subsequent slight increase in terrigenous input. Thus, we choose to first focus on the last 12,000 years and then on the last 4000 years by combining both quantitative and qualitative approaches of pedogenetic processes and their resilience to human-induced modifications. Combining analyses of the soils in the catchment and those of lake sediment should enable us to: i) characterize the erosion products in relation to pedogenetic sources, ii) quantify the erosion in terms of the soil thickness and iii) model the soil formation to assess the sustainability of the system.

2. Materials and methods

2.1. Study site

Lake La Thuile (45°31′50.63″N, 6°3′39.9″E) is a small lake (0.06 km^2) in the montane zone in the southern of the Bauges Massif at 874 m a.s.l. in the Northern French Alps (Fig. 1a). This lake has an oval shape (approximately 465 m by 156 m), and its maximum depth reaches 8 m. The catchment around the lake rises up to 1209 m a.s.l. and covers an area of 1.6 km^2. Except for the gentle grazed slopes near the lake and the village of La Thuile, most of the catchment area is currently forested (Fig. 1b). The lake is fed by two main temporary streams that flow during snow melt and long rainfalls. The northern stream begins in a small gully area. The lake is of glacial origin and is part of the Lake Bourget catchment through the Leysse River. The climate is temperate, with an annual temperature from 6 to 8 °C and annual precipitation from 1500 to 1700 mm (Zamolo, 1980). Rainfall is concentrated in winter. The lake can be ice-covered during cold winters.

The catchment area is mainly underlain by carbonate rocks. Hard micritic limestones (Jurassic Tithonic formation) that consist of massive strata cover the southeastern area of the catchment (Fig. 1c). Intercalations of calcareous formations with Berriasian marls and shales and Valanginian spathic limestones (Geologic map 1/50,000, Montmélian sheet) cover most of the area (Fig. 1c). Quaternary glacial deposits are found in the northwestern area of the catchment and at the outlet of the lake.

The surroundings of the lake are occupied by grasslands and pastures. The northern and eastern sides of the catchment are covered by woodland, with planted resinous trees (*Picea abies*) to the north and hardwoods elsewhere. Old terraces, maybe as a consequence of hedge, are always visible in the landscape. Old photography from the beginning of the 20th century show that the current meadows replaced cereal cultures and that forest was less extensive at that time with pastures on the upper shores of the lake (Fig. 2).

2.2. Soil characterization and sampling

Five soil profiles (THU01, THU02, THU03, THU04 and THU06) and two augers observations (THU05 and THU07) were realized to characterize the major soil types in the catchment (Fig. 1). These profiles were chosen according to their topography, geology and land use to be representative of most soils in the catchment. THU05 developed on a small alluvial fan. Auger observations were performed to confirm the expansion of a given soil unit and to increase the sampling representativeness.

The soil profiles were described by horizons with common descriptors, including color (Munsell Color, 2000), texture, structure, roots, coarse elements, and matrix reaction to an acid solution. The FAO (Food and Agriculture Organization) soil classification (WRB - FAO, 2014) and the Guidelines for soil description (FAO, 2006) were used for horizon and soil denomination (Fig. 3). One sample was collected from each horizon for further laboratory analyses.

2.3. Sediment sequence and chronology

An 18-m-long sediment sequence (THU10, IGSN: IEFRA00BB - *IGSN codes refer to an open international database, www.geosamples.org*) was retrieved from the deepest part of Lake La Thuile and described in Bajard et al. (2016).