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Hypoxic and acidic — Soils on mofette fields

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ABSTRACT

Mofette fields are areas characterized by CO_2 that ascends from the earth mantle to the surface owing to volcanic activities. Geogenic CO_2 may almost completely make up the soil atmosphere on mofette fields, inducing fundamental effects on both the vegetation and soils. Mofette fields are thus a natural laboratory to study the effects of increased CO_2 concentrations in the soil atmosphere. Plants adapt physiologically or anatomically to the specific gas budget on mofette fields, forming a typical, often azonal, mofette vegetation. Soil formation and development are similarly controlled by the gas budget. The acidifying effect of CO_2 induces low soil pH, accelerated silicate weathering and leaching of base cations. Formation of secondary Fe and Mn oxides is decreased under partial to total O_2 exclusion, and the oxides remain poorly crystalline. Reduced Fe minerals may be stable in a CO_2 atmosphere. Soil organic matter accumulates on mofette fields and stays in unaltered and less decomposed state, as bioturbation is diminished and microbial communities shift to anaerobic and acidophilic ones, utilizing geogenic CO_2 instead of plant-derived C. Several soil properties and functions are controlled by CO_2 that acts as a soil-forming factor. Thus, we suggest to emphasize its effects more distinctly in soil classification by a ‘mofettic’ qualifier applicable to all soil reference groups of the WRB classification.

Contents

1. Introduction

Soil gas emissions are common in seismic and volcanic areas. Apart from CO_2 (mofettes), also SO_2 and H_2S (solfatares), CH_4 (mud volcanoes) and hot water vapour (fumaroles) are the most common soil gases (Etiope et al., 2004a, 2004b; Heinicke et al., 2009; Martinelli and Panahi, 2003; Pfanz et al., 2004), with Ar, H_2, He and N_2 at trace levels (Bräuer et al., 2011). The gases are released from ascending magma owing to temperature and pressure release and find their way to the surface through cracks and fissures. Aside from water vapour, CO_2 is the most important gas occurring in volcanic exhalations. Carbon dioxide dissolves out of the ascending magma, and on its way upward, gas molecules coalesce to form larger bubbles. Depending on the path length, pressure and temperature, the flux of CO_2 can be large (Sparks, 1978). In some cases, CO_2 is dissolved in ascending water and reaches the surface together with the water phase, a system called a mineral spring (i.e., a wet mofette). Carbon dioxide diffusing upward in dry, undissolved state, forms so-called dry mofettes independent of whether it degasses through dry soil or through a water body.

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In general, geogenic CO_2 emanations can be spotted either by a modified vegetation (Pfanz et al., 2004, 2007; Vodnik et al., 2002a, 2002b), by corpses of dead animals (Pfanz, 2008) or by atmospheric abnormalities (Kies et al., 2015). Vegetation is either much smaller than in control areas, more chlorotic, with less flowers and viable seeds, or is defined by its azonal character. In the latter case, plants grow far outside their normal growth distribution patterns. Swamp or mire species may thus be found within fertilized fodder meadows. Their anatomical or physiological ability to compete with hypoxia or even anoxia gives them a decisive competitive advantage.

Mofettes co-occur worldwide with seismic structures and in pre- and post-volcanic areas. In Europe, they can be found in Germany (Eifel, Rhön, Teutoburg Forest, Neckar valley, NW Franconia), in the Czech Republic (Cheb basin), Slovenia (Radenci area), Italy (Toscany), Iceland, Greece, Hungary, Romania (Hargitha Mountains) and France (Massif Central). Worldwide they are found for instance within the caldera of the Yellowstone volcano or in the Inyo crater range, in the Cascades range (USA), in geothermal fields of New Zealand, Kamchatka and Indonesia (Djeng Plateau).

Apart from other soil-forming factors, soils on mofette fields are at first affected by increased CO_2 concentrations in the soil atmosphere. Generally and irrespective of mofette fields, the soil atmosphere is enriched in CO_2, relative to the above-ground atmosphere. This is a consequence of biological processes such as root respiration, rhizomicrobial respiration, decomposition of plant residues, the priming effect induced by root exudation or by addition of plant residues, and basal respiration by microbial decomposition of soil organic matter (SOM) (Kuzyakov, 2006). The CO_2 concentration in the soil atmosphere commonly amounts to <5% (w/v), but it may rise up to >10% (Geisler, 1973), depending on soil texture, depth, temperature, compaction and water saturation. However, the soil atmosphere in mofette fields may be almost completely composed of (geogenic) CO_2. This is partially considered in the classification system of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014) by the 'reductic' qualifier, which is on the second level of categorical detail. The 'reductic' qualifier applies for soils "having reducing conditions, in ≥25% of the volume of the fine earth within 100 cm of the soil surface, caused by gaseous emissions, e.g. methane or carbon dioxide, or caused by liquid intrusions, e.g. gasoline" (IUSS Working Group WRB, 2014). Thus, the qualifier is not exclusive for soils with a CO_2 atmosphere. In the definition of the qualifier, no differentiation is made between the chemically rather passive geogenic CO_2, which displaces O_2 in the soil atmosphere, and substances actively involved in redox reactions such as CH_4, H_2S and hydrocarbons.

The reductic qualifier can be combined with only 4 of 32 reference soil groups, Andosols (as supplementary qualifier), Gleysols, Stagnosols and Technosols (as principal qualifier). While there is no consideration of the influence of CO_2 or other gases on soil development in the US Soil Taxonomy, the German soil classification (Ad-hoc Arbeitsgruppe Boden, 2005) defines the soil type 'Reduktosol' similar to the 'reductic' qualifier. Again, the soil type comprises soils characterized by gases such as CH_4, H_2S and CO_2 without considering the differing effects of the respective gases. The 'Reduktosol' has a diagnostic Y horizon, which may feature an oxidized Yo horizon, coloured by secondary Fe oxides and with temporary CH_4 and CO_2 in the soil atmosphere (≥10%), and/or a reduced Yr horizon with an O_2-free, CH_4- or CO_2-rich soil atmosphere and white, grey, grey-green, blue-green and black colours.

Soils on mofette fields are a natural laboratory to study the effects of high CO_2 concentrations in the soil atmosphere on the dynamics of SOM, weathering and mineral formation, which might be transferrable to soil development at increased biogenic and/or atmospheric CO_2 concentrations in soil. The aim of this review is to summarize the recently growing knowledge on soil formation and properties on mofette fields and to identify gaps in knowledge, especially regarding the role of CO_2 as a soil-forming factor.

2. Composition and fluxes of gases in mofette fields

At mofettes sites, gases from deep magma chambers in the earth mantle or from seismic fraction zones reach the soil surface. Depending on the local characteristics of the lithosphere, CO_2, after being dissolved out, diffuses upward to the soil surface. Unevenly distributed cracks and fissures within the lithosphere and soil, permeable and impermeable soil zones and the presence of soil water strongly influence the upward penetration of geogenic gases. Less permeable to impermeable (loamy, clayey) soil zones block the way of the permeating gas, while highly permeable (sandy) zones facilitate upward diffusion. This leads to a very inhomogeneous degassing pattern that is observed in nearly all mofette areas. At highly degassing sites, soil CO_2 concentrations ($[CO_2]$) in the upper 0.8 m of soil can reach very high values. Several authors already published soil $[CO_2]$ and CO_2 efflux rates (e.g., Kämpf et al., 2013; Pfanz et al., 2004; Saßmannshausen, 2010; Thomalla, 2015; Vodnik et al., 2006, 2009). Despite the relatively large heterogeneity of the degassing regime in different areas, the obvious degassing patterns have been found to be fairly stable over longer time periods (Thomalla, 2015; Vodnik et al., 2006).

Data on CO_2 concentration and flux (Figs. 1 and 2) were collected on a mofette field in the Czech Plesná valley (Saßmannshausen, 2010; Thomalla, 2015) along lengthwise (15 m) and crosswise (9 m) transects.

The spatial heterogeneity of geogenic $[CO_2]$ at different soil depths is demonstrated in Fig. 1. Fig. 1a shows $[CO_2]$ at 10 cm soil depth that is at control levels at the upper part of the mofette field, whereas the lower right part of Fig. 1a already shows high $[CO_2]$ in a very shallow soil horizon. From 10 to 60 cm soil depth, $[CO_2]$ increases, although the surface concentrations are still mirrored at 20 cm (Fig. 1b). At 60 cm soil depth, >30% of the area shows $[CO_2]$ >70% (Fig. 1d). As CO_2 displaces O_2 in the soil atmosphere of mofette fields, the concentrations of these gases are commonly strongly negatively correlated ($r^2 > 0.8$; e.g., Saßmannshausen, 2010; Thomalla, 2015).

Soil CO_2 fluxes mirror the measured CO_2 concentrations (Fig. 2). As gas fluxes were measured in chambers attached to the soil surface, the best accordance is between CO_2 flux and CO_2 concentrations of the upper soil layers (Figs. 1, 2). In control plots, CO_2 fluxes ranged from 0.2 to 10 mol m^{-2} d^{-1}, while at highly degassing spots, fluxes reach values of 250 to 750 mol m^{-2} d^{-1}. At one single spot, even 10,320 mol CO_2 m^{-2} d^{-1} were determined. These data are in accordance with fluxes published by Chiodini (2008) and Mörner and Etiope (2002). Soil CO_2 diffuse degassing from non-volcanic sites ranged from 0.1 to 5 kg CO_2 m^{-2} a^{-1} (Fort Sulphurdale, USA; Klusman et al., 2000) via 208 kg CO_2 m^{-2} a^{-1} (Dixie Valley; Bergfeld et al., 2001) and 3285 kg CO_2 m^{-2} a^{-1} (Selvana, Italy; Rogie et al., 2000) to 11,900 kg CO_2 m^{-2} a^{-1} at a mud volcano in the Yellowstone National Park (Werner et al., 2000).

3. Vegetation on mofette fields

In mofette fields, plants adapt physiologically or anatomically to the very special mofette situation. Aside from this morpho-physiological adaption, there is also a kind of floristic adaptation: the occurrence of a very typical mofette vegetation. According to Pfanz (2008), plants in mofette fields can be grouped into three categories. Plants that strictly avoid geogenic CO_2 at concentrations above 2–3% are called *mofettophobic* (Fig. 3a), whereas those that grow directly above strong CO_2 emanations are *mofettophilic* (Fig. 3b). Plants that occur in degassing as well as in control areas are named *mofettovague* (see also Saßmannshausen, 2010; Thomalla, 2015). At sites, where both the soil CO_2 concentration and the CO_2 flux are large, plants do not grow at all (Fig. 4). There seems to be no adaptation mechanism in plants able to cope the excess of CO_2, which was similarly found for collembolans and nematodes in CO_2 high-flux areas of the Italian mofette Il Bossoleto (Pfanz, Hohberg, Schulz, unpublished results).