Research Article

Mofette Vegetation as an Indicator for Geogenic CO₂ Emission: A Case Study on the Banks of the Laacher See Volcano, Vulkaneifel, Germany

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A geogenic CO₂ emitting site (mofette U1) at the banks of the Laacher See, Eifel Mountains, was chosen to study the relationship between heavy postvolcanic soil degassing and vegetation during spring season. To test any interrelation between soil CO₂ degassing and vegetation, soil chemism (pH, water content, conductivity, and humus content) and vegetation studies (number of species, plant-soil coverage) were performed. Geogenic soil degassing patterns of carbon dioxide and oxygen were clearly inhomogeneous, resembling soil porosity and distinct permeation channels within the soil. CO₂ concentrations ranged from zero to 100%. Soil CO₂ increased, while soil oxygen decreased with increasing soil depth. There was a reasonable correlation between CO₂ degassing and soil pH as well as soil conductivity. Soil organic matter (SOM) resembled soil water distribution. The number of plant species (from a total of 69 species) as well as plant coverage strongly followed geogenic CO₂ degassing. The total number of growing species was highest in low CO₂ soils (max. 17 species per m²) and lowest at high CO₂-emitting sites (one species per m²). Plant coverage followed the same pattern. Total plant coverage reached values of up to 84% in slightly degassing soils and only 5–6% on heavy CO₂-venting sites. One plant species proved to be highly mofettophilic (marsh sedge, *Carex acutiformis*) and strictly grew on CO₂ degassing sites. Most other species like grove windflower, spring fumewort, fig buttercup, wood bluegrass, addersmeat, and common snowberry showed a mofettophobic behavior and strictly avoided degassing areas. Specific plant species can thus be used to detect and monitor pre- or postvolcanic CO₂ degassing.

1. Introduction

Mofettes are sites with dry CO₂ gas exhalations at ambient temperatures. The gaseous CO₂ originates from magma chambers or from Earth mantle degassing. It moves upward through fissures and cracks within the rocks [1–3]. Along its path, it reacts with wet and dry soil phases, finally exerting its influence on organisms living either within the subterranean soil or directly on the soil surface [4–10]. Depending on the local geological and hydrogeological conditions, the upward migration of CO₂ gas may appear at the surface either as dry CO₂ emanation (mofette) or as CO₂-rich mineral water. Several publications already described the effects of the potentially acidic gas of dry CO₂ emanations on the

soil phase [11–13], on soil insects, nematode worms, and spiders [14–16], on soil microbiota [for review see [5]], and on vegetation. Most authors describe the effects of enhanced geogenic CO₂ on physiological and ecophysiological processes, or anatomical and morphological adaptations of plants [6–8, 17–22]. Only a few references can be found on the special vegetation of these sites—the mofette vegetation [17, 23–26].

The present paper studies a natural, terrestrial mofette site at the Laacher See volcano, where CO₂ from the Laacher See volcano still reaches the surface, influencing ecosystems. The quiet volcano is part of the east Eifel Volcanic field belonging to the West European Rift System. The last eruptive phase of the Laacher See volcano is about 13,000 years

FIGURE 1: Photo from the U1 mofette as seen from north to south in June 2015. The dominating ground vegetation in the mofette is marsh sedge (*Carex acutiformis*). Several linden trees and oaks grow on the edge. The eastern bank of the Laacher See and the walking trail are located on the right side of the picture (a). Topography of the U1 mofette at the lower terrace of the eastern rim of the Laacher See caldera viewed from the Western side. North side is left and south right of the picture (b).

ago [27]. The aim of this work was to find out to which extent geogenic CO_2 concentrations within the soil influence soil chemism and allow or inhibit plant life. It was furthermore of great interest to figure out whether specific plant species can be used as biological indicators to detect and monitor otherwise nondetected volcanic CO_2 emissions.

2. Material and Methods

2.1. Site Description. The study area “U1 mofette” (Figure 1(a)) is located on the first terrace on the eastern inner flanks of the Laacher See Volcano, Eifel Mountains, Germany (see also [28]), just 5 m from the southern wall of the ruins of the so-called Jesuiten-Villa (a two-stored stone house used by the monks to celebrate their free days). It belongs to the cadastral district “Bei der rechten Erde” and extents parallel to the banks of the Laacher See. The terrace is the result of the second drainage phase of the lake performed in 1844 (first drainage in 1164; [29]). As the area is located within a forest, mostly half-light and only rarely full-light conditions prevail, with some heavily shaded parts at the upper left part of the area. Topographically, the U1 area is flat with the highest part in the SE corner (Figure 1(b)). The first 54 m of the 80-90 m long area was

under investigation. In the lake close to the mofette area, CO_2 bubbles indicate visible geogenic gas emission [30].

2.1.1. Sampling and Measurements. The area was chosen to study the relationship between geogenic soil degassing of carbon dioxide and the prevailing vegetation and between soil gas and selected geochemical and soil biological parameters. Seven transects with 2 m spacing and a total length of 54 m were laid out parallel to the lakeshore line. The hiking trail marked the western (lower) end of the study area (Figures 1(a) and 1(b)). All measurements were made at each 2 m intersection of the transect lines, resulting in 224 individual sample spots. Soil gas concentrations (CO_2 and O_2) were measured at all 224 spots at four different soil depths (10, 20, 40, and 60 cm), by coring holes into the soil and inserting gas tight tubing. During the measurements, the holes were closed with a lid to avoid air mixing during the actual measurements. The gas measurements were carried out with a portable landfill gas analyser GA2000 (Geotechnical Instruments, England) equipped with water and dust filters. Problems occurred when the ground was wet or waterlogged, as liquid water would damage the sensitive cells of the analyser. Polyethylene and Teflon tubing (1 cm diameter) was used to enlarge the measuring radius. Readings were recorded after several seconds to one minute.

Gas flux was performed at each grid intersection using a portable diffuse carbon dioxide flux meter system (West Systems Portable diffuse flux meter carbon dioxide high-flux, Pisa, Italy). The device consists of an accumulation chamber (type B), a CO₂ IR detector (Polytron, Dräger), and a PDA palmtop (Brand, Acer n300) for data communication, evaluation, and storage.

The CO₂ flux measurement method is based on the measurement of rising CO₂ concentration versus time in terms of ppm s⁻¹. If the gas concentration inside the chamber is constant, linear regression is used to calculate the gas flux F [moles·m⁻²·day⁻¹] by the following equation:

$$F = K * s \quad (1)$$

where K is the accumulation chamber factor and s is the slope of the flux curve, determined by linear regression.

K is calculated by the following equation:

$$K = \frac{86400 * P}{106 * R * T} * \frac{V}{A} \quad (2)$$

where P is the barometric pressure (hPa), R is the gas constant 0.08314510 (L·bar·K⁻¹·mol⁻¹), T is the air temperature (K), V is the chamber net volume (6.186*10⁻³ m³), and A is the chamber inlet net area (3.140*10⁻² m²). P was measured with the GA2000 and T with a thermocouple thermometer.

2.2. Soil Analysis. After determination of the soil gas, soil cores were taken very close to the points of the gas measurements. A standard soil borer (Pürkhauer; Thomas Müller, Germany) was used, and samples were taken between soil depths of 7 to 13 cm. This depth range was thought to reflect the main rooting horizon of herbaceous plants [31]; this soil depth is also the approximate range of the aerated surface soil [32]. The fresh samples were placed in small airtight plastic cylinders and stored cool until analysis.

Soil water content was determined by drying the soil samples of known fresh weight at 75°C for three days in an oven and reweighing after cooling to room temperature in a desiccator. Dry soil samples were ground, and soil pH was measured with a pH electrode (WTW, Germany) in bi-distilled water (750 mg dry soil in 15 ml water). After pH determination, soil conductivity was determined in the same solution using a conductivity meter (inoLab Multi 9420 IDS, WTW, Germany).

To determine soil organic matter (SOM), 1 g of ground, dry soil was heated (450°C for 18 hours) in an oven (muffle furnace; Heraeus, Germany), cooled to room temperature in a desiccator, and reweighed (for details see [33]).

2.3. Vegetation Analysis. Vegetation cover was estimated according to [34]. Londo's decimal scale has some advantages over the most commonly used scale of [35]. The decimal scale is a pure dominance scale that uses smaller steps of maximal 10%. The more precise information about the plots' vegetation cover leads to better correlations with the abiotic factors. On the other hand, a transformation into

the Braun-Blanquet scale can be arranged without great difficulty [36].

All measurements were carried out at stable weather conditions during a one-week period in February 2013. Vegetation analysis was done in May 2013.

2.4. Statistical Analysis. Statistical analysis was carried out using MS Excel (Microsoft, USA), SigmaPlot 11.0 (Systat Software, USA), and SPSS (SPSS, USA). Multivariable statistical analysis was done using multiattribute analysis based on canonical correspondence analysis (CCA; CANOCO 4.5 program). Probable correlations between plant habitat parameters, plant species composition, and plant distribution can thus be detected [37].

3. Results and Discussion

3.1. Degassing Patterns

3.1.1. Soil Gas Concentrations. Geogenic CO₂ degassing was clearly heterogeneous within the selected area. At 10 cm soil depth, high [CO₂] were found in a line running nearly diagonal from the left upper corner to the area close to the lower right part (Figure 2(a)). At this depth, CO₂ extremes evolved as isolated islands surrounded by lower values.

Soil gas concentrations clearly changed with soil depth. Carbon dioxide increased with increasing soil depth whereas oxygen values decreased at deeper soil horizons (Figures 2(a)–(d) and 3(a)–(d)). Yet the principal “diagonal” degassing pattern was still visible although at a soil depth of 60 cm the whole area showed highly increased CO₂ values. Thus, at deeper soil horizons, a clear broadening of the degassing pattern occurs which narrows when the gas moves upward to the soil surface. Sometimes, the narrowing of CO₂ concentrations at lower soil depths is evident as small channels are formed showing the vertical gas-transducing chimneys. The transect illustration shows the modification of gas permeation pathways with soil depth.

There are two selected transects of the U1 mofette (Figure 4). The upper panel nicely shows two CO₂ gas chimneys (at 12 m and 42 m) emerging at a soil depth of ca. 30 cm further narrowing to a diameter of less than 50 cm finishing at the very soil surface. Gas concentration at the surface thus reaches 80–100% CO₂. Another CO₂ channel (at 36 m) does not reach the actual soil surface but ends at 10 cm soil depth (Figure 4). A less permeable or impermeable soil layer transiently or permanently locks the permeating gas in pockets.

The same is true for oxygen, although in this case a narrowing of oxygen channels with increasing soil depths is visible (Figure 4(b)). Between 8 and 14 m and at point 48 m and 54 m, high O₂ concentrations can be measured even at a soil depth of 40–50 cm. At 54 m, oxygen concentrations are high at even deeper soil levels (Figure 4). At these locations, control plants (mofettophobes) could easily grow.

Also for oxygen, a more or less diagonal concentration pattern from the left upper corner to the right lower corner of the area is seen (Figures 3(a)–3(d)). Yet in contrast to the [CO₂], an inverse pattern is found for [O₂] (Figures 2 and 3). At spots with high [CO₂], low [O₂] is found and vice

FIGURE 2: (a–d) Soil CO₂ concentrations within the U1 mofette (14 × 54 m). Measurements were done at each intersection of the 1 × 2 m grid. CO₂ concentrations at four different soil depths are given: (a) 10 cm, (b) 20 cm, (c) 40 cm, and (d) 60 cm. The colour bar indicates the gas concentration ranges. Orientation of the site as in Figure 1(b). CO₂ concentrations are given in %.

FIGURE 3: (a–d) Soil O₂ concentrations within the U1 mofette. Measurements were performed at each intersection of the 1 × 2 m grid. O₂ concentrations at four different soil depths are given: (a) 10 cm, (b) 20 cm, (c) 40 cm, and (d) 60 cm. The colour bar indicates the gas concentration ranges. Orientation of the site as in Figure 1(b). CO₂ concentrations are given in %.

versa. If CO₂ migrates towards the surface, mainly by diffusion and advective processes, it leads to a dilution of the in situ soil gas composition. Vodnik et al. [10] have already published the inverse proportionality between carbon dioxide and oxygen concentrations at mofette sites.

Oxygen concentrations < 2% were only apparent at soil depths below 40 cm. Nevertheless, even at a soil depth of 20 cm, the main rooting zone of many plants, [O₂] below 15% (slightly hypoxic conditions) can be found in many spots.

3.1.2. CO₂ Fluxes. Additional to the CO₂ concentrations, soil CO₂ fluxes within the U1 mofette were determined directly on the soil surface (Figure 5). Care was taken to avoid the

inclusion of vegetation inside the accumulation chamber. As measurements were performed in February, also, biotic CO₂ evolution by the soil edaphon is expected to be reduced due to the cooler winter temperatures. Postvolcanic soil CO₂ fluxes nicely paralleled soil CO₂ concentrations. Again, CO₂ fluxes were clearly inhomogeneous within the area and a diagonal degassing pattern of enhanced CO₂ flux is seen through the mofette area with the highest CO₂ emission rates in the upper left corner of the area. Rates of 600 moles CO₂ m⁻² soil surface day⁻¹ were seen in two heavily degassing islands (Figure 5). As with the [CO₂], the upper right corner and the lower left part of the mofette still act as control sites (2–8 moles CO₂ m⁻² soil surface day⁻¹).

FIGURE 4: Vertical sections of CO₂ (a) and O₂ (b) concentrations showing the prevailing gas channels. Two different transects for the two different gases were chosen. (a) CO₂ concentrations are shown in linear transect 4. Up to five CO₂ channels can be seen from which four are reaching the soil surface. (b) Transect 6 is used to illustrate oxygen channels through the soil. CO₂ concentrations are given in %.

FIGURE 5: CO₂ soil fluxes in moles m⁻² d⁻¹ as measured at each intersection of the 1 × 2 m grid within the U1 mofette. Orientation of the site as in Figure 1(b).

3.1.3. Gas Permeation Barriers. Interestingly, soil penetration data underline the gas permeation pathways established by gas concentration measurements. Soil rigidity data obtained with a penetrometer clearly mark the microsities of low and high gas permeability (Figure 6(b)). Higher soil density or compactness occurs in loamy or otherwise clogged soil parts or in soil with a high skeleton content (stones, stone fragments). These soil characteristics reduce or even do not permit at all the upward migration of the CO₂ gas toward the surface.

Following the data from the soil surface down to a soil depth of 80 cm, it becomes clear that the higher the soil resistance, the lower the actual CO₂ penetration or concentration. Soil hardness is extremely heterogeneous within the area but increases with soil depth. Due to the inhomogeneity of this parameter, a three-dimensional network of vertical and horizontal soil channels is formed allowing gas penetration only in distinct directions. A three-dimensional pattern of easy penetration and prohibited sites is thus formed. The picture

of soil gas concentrations nicely mirrors this diffusional barrier pattern (Figures 2 and 6(b)).

Even the extractable skeleton content in the soil somehow reflects the gas emission pattern (Figure 6(a)). The topsoil has a low content of stones and fragments in high gas emission zones (diagonal line from top left to bottom right), whereas in the upper right corner of the mofette, 50% of dry matter belongs to the soil skeleton. Naturally, the stone fragments are not a perfect hindrance to gas permeation per se. Penetrating gas could easily circumvent isolated stone fragments within the soil. The concentration of stones just reflects the presence of larger blocks and a solid lithosphere in the lower ground.

3.2. Physicochemical Soil Parameters

3.2.1. Soil Water. Figure 6(c) shows values for the soil water content within the mofette area. At the time of our measurements, the water content of the area ranged between 10 and

FIGURE 6: (a–f) Soil skeleton content (a) and soil rigidity (b) of the U1 mofette as measured by stone extraction and weight and by soil penetration using a penetrometer. Water content (c), soil pH (d), soil conductivity (e), and soil organic matter (SOM) (f) are also given. Orientation of the site as in Figure 1(b).

30%, with an average between 20 and 30%. Dry sites with a water content less than 10% occurred in larger islands on the upper border and a site in the upper right corner. Also, around the lower margin (14–16 m), a drier island was seen. Only three very small islands in the upper left corner contained more water and reached values of up to 60%. The position of these islands corresponds to the position of the three main vents, characterized by high CO_2 fluxes and high soil CO_2 concentrations at 10 cm depth and thereunder (Figures 2 and 5).

3.2.2. Soil pH. Ascending geogenic carbon dioxide permeates through different soil phases, and due to its high solubility in water, it dissolves in soil water according to temperature, atmospheric pressure, and actual gas concentration and/or flux. Dissolved CO_2 rapidly dissociates in water producing protons thus acidifying the aqueous soil phases as long as buffering capacities are below a certain limit [38–40]. To check whether the CO_2 -permeated mofette soil already shows acidification, soil pH was determined within the U1 mofette at each grid intersection (Figure 6(d)). It can be said *cum grano salis* that there is a reasonable correlation between soil pH and the prevailing CO_2 concentrations. The measured values ranged between pH 3.6 and pH 6.4 with a clear diagonal pattern where slightly more acidic soils prevail. Higher pH values (around 5.5 to 6) occur at microsites with lower CO_2 concentrations/fluxes. Yet two regions clearly differ. At the right end of the area and between 10 and 20 m (lowest transect) in front of the area, pH values are quite

low (pH ca. 4.4–4.0) although $[\text{CO}_2]$ concentrations are not enhanced. [10, 41] already described this pH-lowering effect with accordant results from mofette fields in Slovenia whereas [42] found no effects for three Japanese CO_2 springs [see also [12, 13]]. Our findings are in line with a recent study of [43] which showed that persistent CO_2 leakage affects the soil chemical composition, altering soil from slight alkaline to acidic over a period of 38 treatment days. [44] laid a transect through a gas vent in Italy and found that across the transition zone, between vent core and background, soil pH values dropped quickly from 4.5 to 3.8, which resulted in a clear influence on the chemical composition of the soil. Most oxide concentrations decreased, while parameters such as cation exchange capacity, loss on ignition, and total organic carbon began to increase. These chemical soil conditions will certainly affect nutrient availability or uptake [7], root functioning [45, 46], and the above ground processes of photosynthesis [7, 19].

3.2.3. Soil Organic Matter. Stagnant soil water and hypoxic soil conditions should also affect the formation of soil organic matter [SOM; [11, 47, 48]]. Therefore, the total SOM content was analysed in all soil samples (Figure 6(f)). Positive relationships between SOM and soil water have been published several times [49–51]. The accumulation of dead biomass in wet soils is thought to be the consequence of a disturbed mineralisation. It may be explained by the oxygen requirement of most litter-decomposing animals, fungi, and bacteria. A sufficient oxygen supply cannot be maintained when

the soil pores are filled with water because the diffusion rate of oxygen in water is 10,000 times lower than that in a gaseous medium [52]. In mephitic soils, oxygen is deprived by the pure presence of enhanced CO₂. The SOM pattern of the mofette (Figure 6(f)) largely reflects the distribution of soil water (Figure 6(c)) with the highest SOM contents in the upper left and right corner of the mofette area.

3.3. Vegetation

3.3.1. Number of Plant Species. In the present study, 69 different plant species were counted within the mofette area during a quantitative species survey in May 2013 (Table 1). Most species could be determined to the species level. In four juvenile and pathogenically affected specimens, only the genus could be determined (*Cirsium*, *Chaerophyllum*, *Dryopteris*, and *Epilobium*). The plants found are in good agreement with those found by others in that area [53–55]. As the total number of species as well as the soil coverage of each single species was estimated in each 2 m² square, occurrence and soil coverage of each species could well be correlated with the degassing pattern of CO₂ and O₂ in the soil.

Comparing the pattern of the number of species per area within the U1 mofette with the prevailing CO₂ degassing pattern, it becomes evident that high species numbers (up to 17 per 2 m²) only occur at sites of diminished CO₂ presence (Figures 2 and 7). Two locations with a high number of species become apparent. On the left upper corner, a diagonal pattern (from 7/16 to 2/2) and a spot on the lower middle (3/30 to 3/44) are evident. Both areas are defined by very low [CO₂]. In contrast, the species number is small at sites of higher CO₂ emission (CO₂ diagonal emission). One to four different species are found at CO₂ extremes.

3.3.2. Plant Coverage. The same observation is made when plant coverage is correlated with the CO₂ degassing pattern (Figure 7(b)). The plant coverage of 41 to 84% is found only at sites of low CO₂ emission. A linear transect from the upper left corner to the upper right corner of the area shows high plant coverages at low CO₂ concentrations. A larger island in the middle of the area also shows high plant coverage and low CO₂ concentrations at lower soil levels (Figure 7). At high CO₂ concentrations (and fluxes), plant coverage can be as low as 4–10%. These results are in line with findings of [44] who reported on a naturally occurring gas vent located within a Mediterranean pasture ecosystem (Latera geothermal field, central Italy). They found no vegetation within the 6 m wide center of the vent where CO₂ concentrations > 95% were determined; an approximately 20 m wide halo surrounding the core formed a transition zone, over which a gradual decrease in [CO₂] and a rapid decrease in CO₂ fluxes could be observed. In the transition zone, grasses dominated near the vent core. They were progressively replaced by clover and a greater plant diversity distant from the vent center. However, this study had not provided a full characterization of the botanical taxa.

3.3.3. Mofettophilic and Mofettophobic Plants. Correlating the growth patterns of selected plants and the degassing pattern within the designated mofette area, it turns out that just

TABLE 1: List of species of the U1 mofette found during a quantitative survey in May 2013.

	<i>Alliaria petiolata</i>	<i>Anemone nemorosa</i>
	<i>Carex acutiformis</i>	<i>Carex hirsutella</i>
	<i>Cardamine hirsuta</i>	<i>Cerastium holosteoides</i>
	<i>Chaerophyllum</i> spec.	<i>Cirsium</i> spec.
	<i>Corydalis solida</i>	<i>Dactylis glomerata</i>
	<i>Dentaria bulbifera</i>	<i>Deschampsia cespitosa</i>
	<i>Dianthus carthusianorum</i>	<i>Dryopteris filix-mas</i>
	<i>Dryopteris</i> spec.	<i>Epilobium</i> spec.
	<i>Equisetum</i> spec.	<i>Galeopsis tetrahit</i>
	<i>Galium aparine</i>	<i>Galium odoratum</i>
	<i>Geranium robertianum</i>	<i>Geum urbanum</i>
Herbaceous plants/ferns	<i>Hieracium murorum</i>	<i>Hypericum perforatum</i>
	<i>Lapsana communis</i>	<i>Melica mutica</i>
	<i>Mercurialis perennis</i>	<i>Moehringia trinervia</i>
	<i>Mycelis muralis</i>	<i>Poa annua</i>
	<i>Poa nemoralis</i>	<i>Polygonatum multiflorum</i>
	<i>Potentilla sterilis</i>	<i>Polygonum</i> spec.
	<i>Senecio sylvaticus</i>	<i>Ranunculus ficaria</i>
	<i>Stellaria media</i>	<i>Stellaria holostea</i>
	<i>Teucrium scordium</i>	<i>Taraxacum officinale</i>
	<i>Veronica chamaedrys</i>	<i>Veronica hederifolia</i>
	<i>Veronica officinale</i>	<i>Vinca minor</i>
	<i>Cornus sanguinea</i>	<i>Crataegus monogyna</i>
	<i>Crataegus oxyacantha</i>	<i>Euonymus europaeus</i>
	<i>Lonicera periclymenum</i>	<i>Hedera helix</i>
Shrubs and subshrubs	<i>Ribes petraeum</i>	<i>Rosa</i> spec.
	<i>Rubus fruticosus</i> agg.	<i>Sambucus nigra</i>
	<i>Symphoricarpos albus</i>	<i>Syringa vulgaris</i>
	<i>Acer platanoides</i>	<i>Acer pseudoplatanus</i>
	<i>Carpinus betulus</i>	<i>Fagus sylvatica</i>
Trees	<i>Fraxinus excelsior</i>	<i>Malus domestica</i>
	<i>Prunus avium</i>	<i>Quercus petraea</i>
	<i>Tilia platyphyllos</i>	
	<i>Atrichum undulatum</i>	<i>Plagiomnium affine</i>
Mosses	<i>Polytrichum commune</i>	

one single plant species clearly follows the degassing pattern of CO₂. Marsh sedge (*Carex acutiformis* Ehrh.) grows in great densities directly above strongly degassing areas within

FIGURE 7: Species number per area (a) and total plant coverage (b) within the U1 mofette. The number of different plant species per 2 m² area is given. Plant/soil coverage is given in percent plant surface area per given soil surface. Orientation of the site as in Figure 1(b).

the mofette (Figure 1(a); Figure 8). There is no growth of *Carex* on the top right and lower left corner with less or nearly no CO₂ emission. Being a highlight to half-light loving species, marsh sedge is absent on the top left corner of the area, although CO₂ emission is maximal. The dense canopy formed by beech and limewood trees strongly prevents its growth. Mirroring the CO₂ degassing pattern, *Carex acutiformis* is thought to be the only *eu-mofettophilic* (CO₂-indicating) species in the study area. It is worth mentioning that on other sites also *Carex* species have a high affinity for CO₂ and act as geogas bioindicators. In NW-Czech mofette areas, *Carex nigra* is strictly mofettophilic, whereas in a Yellowstone NP site, *Carex aquatica* plays that part (Pfan, Tercek, King, unpubl).

Quite in contrast to the growth pattern of *Carex acutiformis* are those of grove windflower (*Anemone nemorosa*), spring fumewort (*Corydalis solida*), fig buttercup (*Ranunculus ficaria*), wood bluegrass (*Poa nemoralis*), two-flower melic grass (*Melica mutica*), and addersmeat (*Stellaria holostea*) (Figure 9).

These species clearly avoid growing on degassing sites and occur only on control plots. The growth pattern of some species marks a linear or half-moon-like structure in the upper left corner of the site (running from 7/10-16 to 2/2). This is true for *A. nemorosa*, *P. nemoralis*, *S. holostea*, and *R. ficaria* (Figure 9). To a certain extent, it is also true for *Carpinus betulus*, *Melica mutica*, and *Corydalis solida* (not shown). The upper right part of the area and the lower part in front are also covered.

Two other species like common snowberry (*Symphoricarpos albus*) and Robert geranium (*Geranium robertianum*) cover the lower part of the nongassing area (Figure 10), while common periwinkle (*Vinca minor*), bulbiferous coralwort (*Dentaria bulbifera*), and common honeysuckle (*Lonicera periclymenum*) occupy the nongassing locations at the right rim of the area. Depending on the species, specific mofettophobic plants overgrew either the whole control site or just the light degassing sites. In some cases, mofettophobes grew only at certain low-gas locations. This observation may be explained by the differences in soil permeability, soil water, soil pH, nutrient availability, and shading by tree canopy.

3.3.4. CCA. Canonical correspondence analyses (CCA) were carried out on all environmental and individual species abundance data [37]. In order to exclude random results, plant species were used only if soil coverage of individuals

FIGURE 8: Exact growth sites of *Carex acutiformis* within the study site in % coverage. The colour bar decodes the coverage of the plant. Orientation of the site as in Figure 1(b).

was higher than 5% per area. Species response curves were performed on plant species, with at least one representative from each of the species groups distinguished in CCA. The category “mofettophilic and mofettophobic” [according to [17]] was assessed from CCA diagrams and species response curves for those species, which had their optimum (higher densities) in patches with >2-3% CO₂ concentrations.

The canonical correspondence analyses CCA (Figures 11(a)–11(b)) revealed strong correlations between environmental measures and plant species.

The strongest environmental vectors separated the plant species into two to three species groups (Figure 11). Group 1 corresponded to high CO₂ concentration and consisted of one single species, namely, marsh sedge (*Carex acutiformis*; Figure 8). In some analyses, also, *Tilia platyphyllos* was added to that group. In contrast, group 2 was grouped clearly at the lowest CO₂ emission sites and consisted of more species (*Vinca minor*, *Symphoricarpos albus*, *Stellaria holostea*, *Poa nemoralis*, and *Melica mutica*). Group 3 consisted of varying plant species and was grouped around either slightly acidic soil pH values, soil moisture, SOM, or soil density. Depending on analysis, several species stayed near the plot origin of the diagram, revealing neither positive nor negative correlations to any of the respective environmental measures.

CCA thus corroborate the findings of the distribution of species according to the geogenic soil gas emission. Marsh sedge proved to be the only real “*eu-mofettophilic*” plant species within the measured area.

4. Conclusion

Postvolcanic CO₂ gas leakage still occurs around the Laacher See resulting in distinct, dry CO₂ emanations sites (mofettes). Our results indicate that this CO₂ degassing significantly

FIGURE 9: Growth sites (in % coverage) of selected mofettophobic plants within the study site. From top left to bottom right: *Anemone nemorosa*, *Corydalis solida*, *Ranunculus ficaria*, *Poa nemoralis*, *Melica mutica*, and *Stellaria holostea*. The colour bar decodes the coverage of the plant. Orientation of the site as in Figure 1(b).

FIGURE 10: Growth sites (in % coverage) of selected mofettophobic to mofettovague plants within the study site. From top left to bottom right: *Symphoricarpos albus*, *Geranium robertianum*, *Vinca minor*, *Lonicera periclymenum*, and *Dentaria bulbifera*. The colour bar decodes the coverage of the plant. Orientation of the site as in Figure 1(b).

affects the terrestrial soil ecosystem. The living organisms within this ecosystem appear to have adapted to the locally high CO_2 concentrations through species substitution or

adaption, with a shift towards hypoxic and acidophilic adaptations. In the case of plants, an azonally growing helophyte, namely, marsh sedge (*C. acutiformis*), is able to grow on

FIGURE 11: (a–b) CCA (CANOCO 4.5) of selected soil parameters, CO₂ concentrations in (a) 20 cm and (b) 40 cm soil depths (arrows), and plant species (triangles) in the U1 mofette. AnemNemo: *Anemone nemorosa*; CareAcut: *Carex acutiformis*; LoniPeri: *Lonicera periclymenum*; MeliMuti: *Melica mutica*; PoaNemo: *Poa nemoralis*; RanuFica: *Ranunculus ficaria*; StelHolo: *Stellaria holostea*; SymphAlb: *Symphoricarpos albus*; TiliPlat: *Tilia platyphyllos*; VincMino: *Vinca minor*. Eigenvalues for (a): 0.529, 0.425, 0.267, and 0.066, and (b): 0.460, 0.341, 0.210, and 0.046 (data sampling in February and May 2013).

highly gas-emitting soils. Its ability to supply oxygen to its roots enables the sedge to establish at hypoxic and concomitantly acidic soils. In this area, *C. acutiformis* is the only really eu-mofettophilic plant species which can be used to biologically indicate geogenic CO₂ emissions. Yet in other mofettic places, there are different *Carex* species showing a high affinity for CO₂; they act as geogas bioindicators. In NW Czech mofette areas, *Carex nigra* is strictly mofettophilic, whereas in a Yellowstone NP site, *Carex aquatica* plays that part (Pfan, Tercek, King, unpubl).

The competent, botanical characterization of mofette sites and the identification of eu-mofettophilic (CO₂ indicating) and mofettophobic (CO₂-avoiding) plant species may help to map gas-emitting tectonic structures with a combination of vegetation data, supported by [CO₂] measurements, and may provide easily detectable plant indicators for geogenic (pre- or postvolcanic) CO₂ emission.

Whether knowledge on CO₂ gas indicator plants will also help to identify gas leaks in artificial CO₂ storage fields (CCS) is still a matter of debate.

Data Availability

We cannot share the data with other colleagues at present on a public scale as we are producing more scientific papers with these data. In this case, we have a time series over several years where these data are included. After publishing the follow-up papers, we may allow public access to the data.

Additional Points

Highlights. Indicative plants can hint geogenic carbon dioxide exhalations—mofettophilic plants. Most plants avoid

growth on high degassing sites—mofettophobic plants. Gas diffusion clearly follows cracks and soil fissures and is not homogeneous within the area. Geogenic soil CO₂ gas flux clearly follows gas concentration patterns.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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