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CARBON DIOXIDE IN THE SOILS AND ADJACENT CAVES OF THE MORAVIAN KARST

OGLJIKOVI DIOKSID V PRSTI IN JAMAH NA MORAVSKEM KRASU

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Abstract UDC 546.26:551.44(437.2)

Jiří Faimon & Monika Ličbinská: Carbon dioxide in the soils and adjacent caves of the Moravian Karst

Variations of soil/cave CO_2 concentrations and further variables such as temperature, humidity, and cave visitor attendance were studied in two sites of the Moravian Karst (Czech Republic). All the variables showed the same seasonality; they were strongly correlated with each other. The dependence of soil CO_2 levels on soil air temperature and absolute humidity was confirmed. Individual effects could not be distinguished because of multicollinearity. The effect of vegetation on soil CO_2 production was not recognized. Cave attendance was identified as the most significant predictor of cave CO_2 levels. Other variables, soil CO_2 and temperature gradients, were less significant. A spurious relationship was alternatively considered, in which external temperature was the universal predictor of cave CO_2 levels.

Keywords: carbon dioxide, cave, correlation, multiple regression analysis, soil, spurious relationship, Chech Republic.

Izvleček UDK 546.26:551.44(437.2)

Jiří Faimon & Monika Ličbinská: Ogljikovi dioksid v prsti in jamah na Moravskem krasu

Raziskovali smo spremembe koncentracije CO_2 in drugih spremenljivk, kot so temperatura, vlaga in prisotnost turistov v jamah Moravskega krasa (Republika Češka). Vse spremenljivke kažejo podobne letne trende in so med seboj korelirane. Dokazali smo povezavo med koncentracijo CO_2 ter temperaturo in vlago v prsti. Posamezne vplive zaradi multikolinearnosti nismo mogli izločiti. Vpliva vegetacije na produkcijo CO_2 v prsti nismo zaznali. Prisotnost ljudi v jami se je izkazal za najpomembnejši prediktor vrednosti CO_2. Druge spremenljivke, kot so CO_2 v prsti in temperaturni gradienti so se izkazale za manj pomembne. Raziskovali smo tudi neprave povezave, pri čemer smo vzeli zunanjo temperaturo kot prediktor koncentracij CO_2 v jamah.

Ključne besede: ogljikov dioksid, jama, korelacija, regresijska analiza, prst, lažne povezave, Češka republika.

INTRODUCTION

Carbon dioxide plays a key role in karst processes such as limestone dissolution and calcite speleothem growth (Dreybrodt 1999). In general, CO_2 levels correspond to a steady state, where CO_2 fluxes into the system are balanced by fluxes out of the system. Soil CO_2 concentrations vary between 0.1 and 10% vol. (Miotke 1974; Troester & White 1984). Soil input flux results from organic matter decomposition and root exhalation (Brovkin *et al.* 2008; Kuzyakov 2006). Output flux is composed from the flux into the outdoor atmosphere by diffusion (Longdoz *et al.* 2008) and the flux into percolating waters via dissolution (Kaufmann & Dreybrodt 2007). Soil CO_2 shows

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strong seasonal fluctuations (Spötl *et al.* 2005). Epikarst CO_2 as an alternative source seems to be relatively invariant (Fairchild *et al.* 2006).

Cave CO_2 shows seasonal variations similarly to soil (Troester & White 1984; Bourges *et al.* 2001; Spötl *et al.* 2005). Common cave CO_2 concentrations vary between 0.1 and 1.0% vol. (Tatár *et al.* 2004; Baldini *et al.* 2006). However, higher levels were also monitored in some caves (Atkinson 1977; Ek & Gewelt 1985). Cave input flux includes (1) natural fluxes, i.e. the fluxes derived from direct diffusion from soil/epikarst or dripwater degassing (Holland *et al.* 1964) and (2) anthropogenic flux, i.e. the flux stemming from a person exhaling (Faimon *et al.* 2006). Output flux is controlled by ventilation, which is given by the cave geometry and pressure/temperature gradients between the cave and the exterior (Spötl *et al.* 2005; Faimon *et al.* 2006). When input fluxes increase, cave P_{CO2} increases and the driving force of speleothem growth reduces. In contrast, increasing output flux induces a decrease in cave P_{CO2} and, thus, an increase in the driving forces. The main goal of the study was to test (1) CO_2 production in karst soil under different vegetation and (2) its impact on cave CO_2.

SITE OF STUDY

The Moravian Karst is the most extensive karstic area of the Czech Republic (Balák 1999). It covers an area of 94 km^2 as a belt 3-5 km wide and 25 km long. The altitude of the karst plateau varies between 250 m and 600 m asl. The granitoid rocks of the Brno Crystalline Massif (Proterozoic) form a crystalline basement. Limestones of the Macocha Formation of the Middle/Upper Devonian period are typical karst rocks (calcite content varies from 95 to 99% wt). Total rock thickness is 500–1000 m. Annual precipitation and temperatures are about 650 mm and 10°C, respectively. A sketch map of the monitoring sites is shown in Fig. 1.

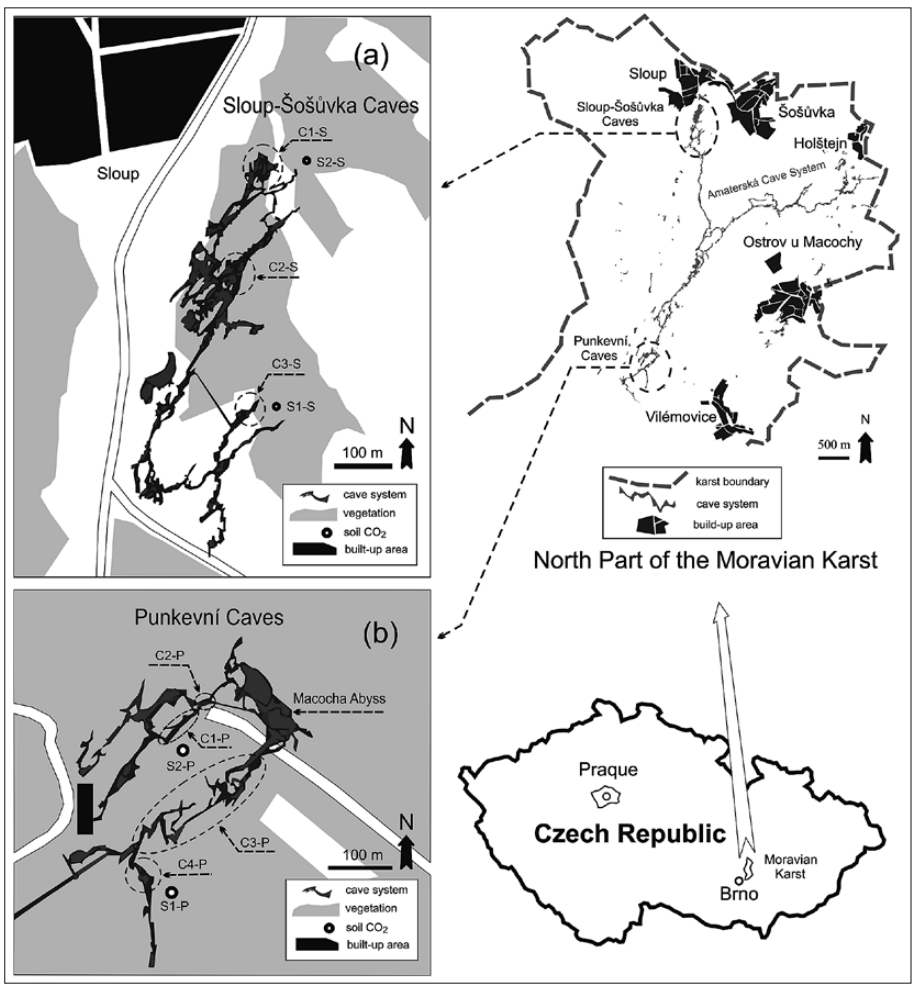

Fig. 1: Sketch map of the monitoring sites. a) Details of Sloup-Šošůvka Caves and b) Punkevní Caves. For explanation of the abbreviations, see Tab. 1 and Tab. 2.

SOILS

Grey rendzic Leptosols are typical for coniferous forests on the Macocha Plateau above the Punkevní Caves (S1-P) and the Sloup sites above the Sloup-Šošůvka Caves (S1-S). Brown rendzic Leptosols make up the decid-

Tab. 1: Soil monitoring sites.

code	site	detailed	soil type (IUSS Working Group WRB 2006)	PD[(a)] [m]	spatially associated with
S1-P	Macocha Plateau	coniferous forest soil	grey rendzic Leptosol	0.8	C3-P, C4-P
S2-P	Macocha Plateau	deciduous forest soil	mull rendzic Leptosol	0.3	C1-P, C2-P, C3-P
S1-S	Sloup-Šošůvka	coniferous forest soil	grey rendzic Leptosol	0.6	C3-S, C2-S
S2-S	Sloup-Šošůvka	deciduous forest soil	brown rendzic Leptosol	0.5	C1-S, C2-S

[(a)] soil profile mean depth

Tab. 2: Cave monitoring sites.

code	Cave	detailed site	projection area [m²]	volume [m³]	TO[(a)] [m]	spatially associated with
C1-P	Punkevní C.	Tunnel Corridor	545	3815	136	S2-P
C2-P	Punkevní C.	Anděl Chamber	140	1400	134	S2-P
C3-P	Punkevní C.	Punkva Sail	2640	10560	140	S1-P, S2-P
C4-P	Punkevní C.	Masaryk Hall	340	6120	140	S1-P
C1-S	Sloup-Šošůvka C.	Eliška Hall	915	18300	72	S2-S
C2-S	Sloup-Šošůvka C.	Chamber above Stupňovitá Abyss	3430	102900 48020*	51	S1-S, S2-S
C3-S	Sloup-Šošůvka C.	Chamber above Černá Abyss	550	33000 6600*	50	S1-S

[(a)] thickness of overburden
*chamber volume without abyss

uous forest soils above the Sloup-Šošůvka Caves (S2-S). Mull rendzic Leptosols are located in deciduous forest on the Macocha Plateau above the Punkevní Caves (S2-P). A summary of the soil monitoring sites is given in Tab. 1.

CAVES

The *Punkevní Caves* are open to tourists and consist of a complex of chambers, corridors, the Macocha Abyss, and the underground Punkva River. The sites for CO_2 monitoring were the Tunnel Corridor (C1-P), the Anděl Speleothem Chamber (C2-P), the Punkva Sail (C3-P) and the Masaryk Hall (C4-P). The *Sloup-Šošůvka Caves* are open to tourists and form a two-level complex of chambers, corridors and deep abysses. The monitoring sites were the Eliška Hall (C1-S), the Stupňovitá Abyss Chamber (C2-S) and the Černá Abyss Chamber (C3-S). A summary of the cave sites is given in Tab. 2.

METHODS

MONITORING

CO_2 concentrations, temperature and humidity were monitored at two-week intervals during the years 2006-2007. Soil monitoring was carried out in probe holes drilled into the soil A-horizon by a steel bar (cca 25 cm, 5 cm in diameter). The wall of each probe hole was reinforced with a cylinder of polyethylene netting and sealed with a plastic cover. Cave monitoring was accomplished in free atmosphere at a 1-m height above the cave floor.

CO_2 concentrations were measured with a hand-held device (2-channel A600-CO2H IR-detector FT linked with an ALMEMO 2290-4 V5, Ahlborn, Germany). All the measurements were performed between 10:00 and 16:00, close to the daily maximum.

Relative humidity and temperature were monitored by a digital GFTH 200 hydro/thermometer from Greisinger electronic GmbH, Germany.

External temperature data comes from two weather stations in Lhota u Rapotína and Protivanov. Along a straight line, the stations are about 16 and 18 km away

from the study area. The presented data are mean values from both the stations (standard deviation ~ 0.8°C; 3.4% relative deviation).

STATISTICAL ANALYSIS

All statistical calculations were performed in the Statistica code, Stat Soft. Inc. (Statistica 2010).

Variables

The monitored/derived variables are distinguished as **UVW–Z** abbreviations, where U stands for the physical entity/property (*O* for carbon dioxide, *T* for temperature, *dT* for temperature gradient, *RH* for relative humidity, *AH* for absolute humidity, and *AT* for attendance). The rest of the abbreviation, VW-Z, is consistent with Tabs. 1 and 2. The symbols VW are ignored for attendance, as they are associated with all cave sites. The temperature gradient was assumed either as an *absolute value* (e.g. $|dTC1–P| = |TC1–P - T(ext)|$) or as a *logical value* marked with index L (e.g. *dTC1–PL*) defined as follows: when $T(ext) < T(cave)$, then $dTCi–jL = T(cave) – T(ext)$; when $T(ext) \geq T(cave)$, then $dTCi–jL = 0$.

Outliers

To detect outliers, Grubbs' test of raw data was conducted at the $\alpha = 0.05$ significance level. Only a few outliers were identified, always singly in individual populations (*RHS2-P*, *RHC1-P*, *RHC2-S*, *OC3-P*, and *TC2-S*). The outliers were not rejected, as they did not change the results of the data analysis significantly.

Correlation Analysis

Correlation between the raw data allowed appropriate variables to be selected for subsequent analysis. Based on cross-correlation, the selected variables were tested for a time lag. The weekly data were transformed by linear interpolation into equidistant data with a 15-day step. Data on cave attendance, available as monthly integral attendance, were recalculated into mean daily data and then transformed by linear interpolation into equidistant data consistent with the former data (with a 15-day step). Based on the found lag, the relevant data were transformed into new data without a lag.

Multicollinearity

A strong correlation between predictors (multicollinearity) produces redundancy of independent variables in regression analysis. Multicollinearity was assessed using the Variance Inflation Factor (VIF). VIF>5 was taken to indicate multicollinearity (Neter *et al.* 1989; Mayers 1990).

Multiple Linear Regression Analysis

Multiple Linear Regression Analysis (MLRA) was chosen to find the most significant predictors of the soil/cave CO_2-levels. *Stepwise Ridge Regression* with *Backward Elimination* was applied (Schmidt & Muller 1978; Rozeboom 1979).

RESULTS

SOIL DATA

The progress of carbon dioxide, humidity, and temperature of the soil atmosphere over one year of monitoring is given in Fig. 2. All the variables were seasonally dependent; the trends in evolution of CO_2 and temperature are mutually similar; the trend in relative humidity evolution is opposite (Fig. 2b).

Temperature

Soil atmosphere temperatures roughly copied outdoor temperatures. They exceeded 30°C in some sites in July 2006 and approached 30°C in June 2007. The temperature drops below zero at the end of January 2007 (Fig. 2a).

Humidity

The relative humidity of the soil atmosphere varied between 40 and 85%. Minima were registered in the summer months (July 2006 and August 2007). An extensive maximum is obvious during the monitoring period, from August 2006 to May 2007. A shallow local minimum is presented in January 2007 (Fig. 2b).

Carbon dioxide

Maxima of carbon dioxide concentrations (between 0.4 and 0.5% vol.) were registered during the late summer/early fall months (September and October). The highest carbon dioxide concentrations were systematically monitored during summer/early fall (June to September). Minima (about 0.1 to 0.2% vol.) were recorded during the winter/early spring months (December to March). The

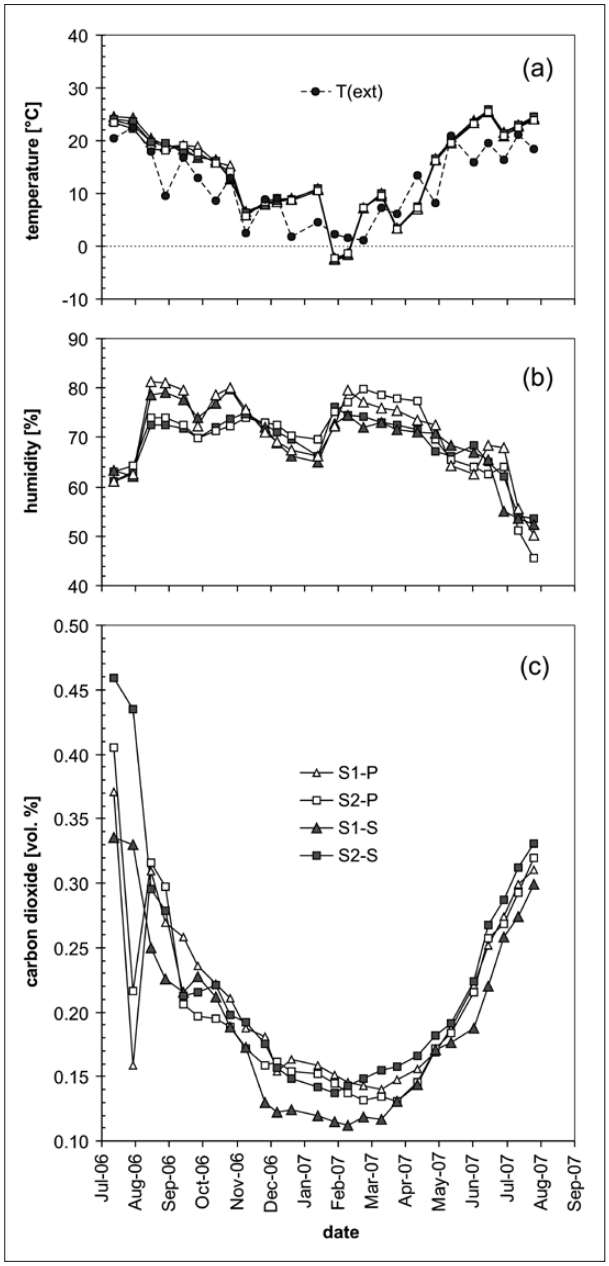

Fig. 2: Soil atmosphere: the progress of a) temperature, b) humidity, and c) carbon dioxide concentration during one year of monitoring. For explanation of the abbreviations, see Tab. 1 and Tab. 2.

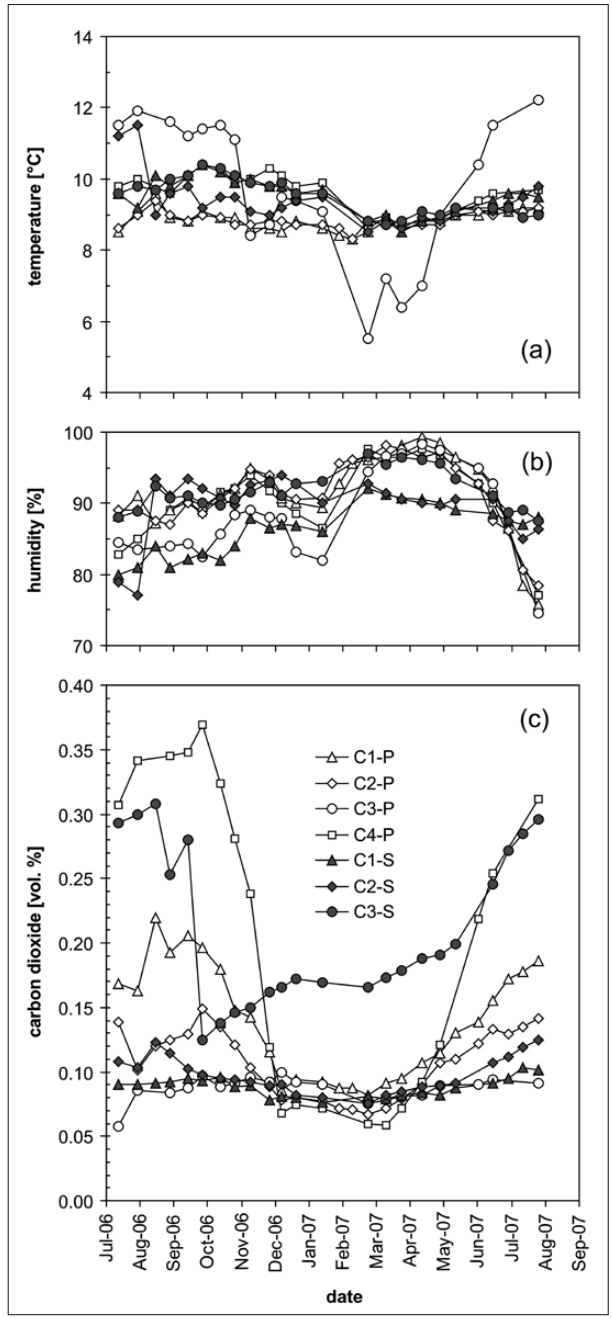

Fig. 3: Cave atmosphere: the progress of a) temperature, b) humidity, and c) carbon dioxide concentration during one year of monitoring. For explanation of the abbreviations, see Tab. 1 and Tab. 2.

lowest carbon dioxide concentrations were registered in coniferous forest soils (S1-P) during winter (Fig. 2c).

CAVE DATA

Cave CO_2 data are highly seasonally dependent. In contrast, cave humidity is less dependent, and temperature is almost conserved in most of the caves (Fig. 3).

Temperature

Cave temperatures remained almost constant during the year. Depending on locality, temperatures were between 8 and 14°C. Only the Punkva Sail site (C3-P) showed larger seasonal variations, from 5 to 13°C (Fig. 3a).

Humidity

Cave humidity shows similar seasonal trends as soil humidity, however, less obvious. Minima were registered in the summer months (July), maxima are in the winter/spring months (February 2007 to May 2007). A local minimum is visible in January 2007 similarly to soils (Fig. 3b).

Carbon dioxide

Maxima of carbon dioxide concentrations (between 0.3 and 0.4% vol.) were recorded during late summer/early fall (August to September). Minima (about 0.1% vol.) were recorded during winter/early spring (December to April). During the period, somewhat enhanced concentrations (up to 0.19% vol.) were achieved in the Černá Abyss (C3-S). The largest seasonal variations were registered in the Masaryk Dóm Chamber (C4-P). In contrast, only slight variations were found in the Punkva Sail (C3-P), Anděl Dóm Chamber (C2-P), Stupňovitá Abyss (C2-S), and the Eliška Dóm Chamber (C1-S) (Fig. 3c).

DATA ANALYSIS

RAW DATA CORRELATIONS

Soils

Positive correlations were found between all the soil variables except for relative humidity. For individual soils, strong correlations are found between absolute humidity and temperature ($r > 0.9$), CO_2 concentrations and temperature, and CO_2 concentrations and absolute humidity ($r \sim 0.74$ to 0.83).

Punkevní Caves

In the C1-P, C2-P, and C4-P sites, CO_2 levels are positively correlated with the soil CO_2 concentrations ($r \sim 0.74$ to 0.85), attendance ($r \sim 0.74$ to 0.77), and external temperature ($r \sim 0.68$ to 0.72). The correlations with absolute value of temperature gradient are insignificant ($r \sim 0.22$ to 0.31). In turn, the correlations with logical temperature gradients are stronger and negative ($r \sim -0.59$ to -0.67). The cave CO_2 levels are strongly correlated with each other between different sites ($r \sim 0.90$ to 0.97), except for site 3. In site 3, the correlations of all variables are quite insignificant ($r \sim -0.24$ to 0.15). Important correlations ($r \sim 0.66$ to 0.86). Important correlations are given in Tab. 3. All correlations are significant at $\alpha < 0.05$.

Tab. 3: Correlation matrix: Macocha Plateau and Sloup-Šošůvka soils.

	OS1-P	*TS1-P*	*AHS1-P*	*OS2-P*	*TS2-P*	*AHS2-P*	*OS1-S*	*TS1-S*	*AHS1-S*	*OS2-S*	*TS2-S*	*AHS2-S*	*T(ext)*
OS1-P	1.00												
TS1-P	0.74	1.00											
AHS1-P	0.74	0.95	1.00										
OS2-P	0.95	0.76	0.74	1.00									
TS2-P	0.74	1.00	0.96	0.76	1.00								
AHS2-P	0.71	0.95	0.99	0.74	0.96	1.00							
OS1-S	0.81	0.82	0.78	0.87	0.83	0.79	1.00						
TS1-S	0.74	1.00	0.95	0.77	1.00	0.95	0.83	1.00					
AHS1-S	0.73	0.95	0.98	0.76	0.96	0.99	0.79	0.96	1.00				
OS2-S	0.74	0.75	0.71	0.87	0.75	0.74	0.96	0.77	0.74	1.00			
TS2-S	0.74	1.00	0.95	0.77	1.00	0.96	0.84	1.00	0.96	0.78	1.00		
AHS2-S	0.72	0.96	0.98	0.76	0.97	0.98	0.81	0.97	0.99	0.77	0.97	1.00	
T(ext)	0.66	0.86	0.82	0.70	0.86	0.83	0.81	0.86	0.83	0.76	0.86	0.85	1.00

In addition, strong correlations are found between the same quantities in different soils and even different sites (the Macocha Plateau and Sloup-Šošůvka sites). This is the case for CO_2 concentrations ($r \sim 0.74$ to 0.95), temperature ($r \sim 1$), and absolute humidity ($r \sim 0.98$ to 0.99). All variables correlate with external temperature

Tab. 4: Correlation matrix: Punkevní Caves.

	OS1-P	*OS2-P*	*OC1-P*	*|dTC1-P|*	*dTC1-PL*	*OC2-P*	*|dTC2-P|*	*dTC2-PL*	*OC3-P*	*|dTC3-P|*	*dTC3-PL*	*OC4-P*	*|dTC4-P|*	*dTC4-PL*	*T(ext)*	*AT-P*
OS1-P	1.00															
OS2-P	**0.95**	1.00														
OC1-P	**0.83**	**0.76**	1.00													
|dTC1-P|	**0.41**	**0.48**	0.31	1.00												
dTC1-PL	**-0.52**	**-0.51**	**-0.60**	0.00	1.00											
OC2-P	**0.85**	**0.76**	**0.90**	0.29	**-0.67**	1.00										
|dTC2-P|	**0.40**	**0.47**	0.31	**1.00**	0.01	0.29	1.00									
dTC2-PL	**-0.52**	**-0.51**	**-0.60**	0.00	**1.00**	**-0.67**	0.01	1.00								
OC3-P	-0.15	-0.24	0.10	-0.20	-0.14	0.15	-0.21	-0.15	1.00							
|dTC3-P|	0.31	**0.40**	0.24	**0.92**	0.05	0.23	**0.92**	0.04	-0.15	1.00						
dTC3-PL	**-0.42**	**-0.41**	**-0.45**	-0.08	**0.92**	**-0.51**	-0.08	**0.91**	0.00	0.07	1.00					
OC4-P	**0.78**	**0.74**	**0.97**	0.34	**-0.58**	**0.90**	0.34	**-0.58**	0.10	0.27	**-0.42**	1.00				
|dTC4-P|	0.31	0.39	0.20	**0.98**	0.14	0.17	**0.98**	0.14	-0.17	**0.94**	0.07	0.22	1.00			
dTC4-PL	**-0.54**	**-0.54**	**-0.62**	-0.08	**0.99**	**-0.68**	-0.07	**0.99**	-0.08	0.00	**0.94**	**-0.59**	0.07	1.00		
T(ext)	**0.66**	**0.70**	**0.68**	**0.59**	**-0.80**	**0.72**	**0.59**	**-0.80**	0.01	**0.51**	**-0.78**	**0.68**	**0.47**	**-0.84**	1.00	
AT-P	**0.78**	**0.84**	**0.76**	**0.59**	**-0.66**	**0.77**	**0.58**	**-0.66**	-0.09	**0.52**	**-0.61**	**0.74**	**0.48**	**-0.72**	**0.89**	1.00

are summarized in Tab. 4. The correlations significant at $\alpha < 0.05$ are highlighted.

Sloup-Šošůvka Caves

The CO_2 concentrations in the Sloup-Šošůvka Cave sites are positively correlated with the soil concentrations (r ~ 0.66 to 0.85), external temperature (r ~ 0.69 to 0.77), and attendance (r ~ 0.76 to 0.91). Insignificant or weak correlations are found between CO_2 levels and absolute temperature gradients (r ~ 0.33 to 0.59). Negative correlations are found between the CO_2 levels and logical temperature gradients (r ~ -0.49 to –0.66). Similarly to the Punkevní Caves, CO_2 concentrations themselves strongly correlate between adjacent parts of the cave system (r ~ 0.80 to 0.86), but less strongly between non-adjacent sites (r ~ 0.59). Important correlations are given in Tab. 5. The correlations significant at $\alpha < 0.05$ are highlighted.

CROSS-CORRELATION OF EQUIDISTANT DATA

The equidistant data on soil CO_2 levels were cross-correlated with those on soil temperature (*T*), relative/absolute humidity (*RH/AH*), and external temperature ($T_{(ext)}$).

Tab. 5: Correlation matrix: Sloup-Šošůvka Caves.

	OS1-S	*OS2-S*	*OC1-S*	*|dTC1-S|*	*dTC1-SL*	*OC2-S*	*|dTC2-S|*	*dTC2-SL*	*OC3-S*	*|dTC3-S|*	*dTC3-SL*	*T(ext)*	*AT-S*
OS1-S	1.00												
OS2-S	**0.96**	1.00											
OC1-S	**0.82**	**0.66**	1.00										
|dTC1-S|	**0.49**	**0.52**	0.33	1.00									
dTC1-SL	**-0.60**	**-0.53**	**-0.56**	0.08	1.00								
OC2-S	**0.85**	**0.78**	**0.86**	0.30	**-0.67**	1.00							
|dTC2-S|	**0.47**	**0.47**	0.37	**0.98**	0.05	0.34	1.00						
dTC2-SL	**-0.58**	**-0.52**	**-0.55**	0.11	**1.00**	**-0.66**	0.09	1.00					
OC3-S	**0.77**	**0.80**	**0.59**	**0.57**	**-0.49**	**0.80**	**0.56**	**-0.46**	1.00				
|dTC3-S|	**0.50**	**0.53**	0.37	**1.00**	0.06	0.34	**0.99**	0.10	**0.59**	1.00			
dTC3-SL	**-0.60**	**-0.53**	**-0.55**	0.07	**1.00**	**-0.67**	0.04	**1.00**	**-0.49**	0.05	1.00		
T(ext)	**0.81**	**0.76**	**0.69**	**0.48**	**-0.83**	**0.77**	**0.50**	**-0.81**	**0.74**	**0.49**	**-0.84**	1.00	
AT-S	**0.91**	**0.89**	**0.76**	**0.51**	**-0.63**	**0.91**	**0.52**	**-0.61**	**0.91**	**0.54**	**-0.63**	**0.84**	1.00

The results are presented in Tab. 6. All time lags are zero, except for OS1-P, which lags after soil absolute humidity and external temperature (both lags ~ 2).

The cave CO_2 concentrations were cross-correlated with attendance, logical temperature gradients, and soil CO_2 levels. The results are given in Tab. 7. Time lags vary from –1 (where the lagging variable follows the first variable) to an extreme of 5 (where the lagged variables precede the first variable). Whereas cave CO_2 levels do not significantly lag behind soil levels (except for the pair *OC1-P*/*OS2-P*), the logical temperature gradient precedes the cave CO_2 levels (except for the pair *OC3-S*/*dTC3-S*). The CO_2 levels in the Punkevní Cave sites lag after attendance by lag ~ 2, except for the extreme lag ~ 5 at site 3. In the Sloup-Šošůvka Cave sites, the attendance is without any lag.

Tab. 6: Time lag of selected variables against soil CO_2 concentrations.

	first (dependent) variable			
lagged independent variable	**OS1-P**	**OS2-P**	**OS1-S**	**OS2-S**
soil temperature	0	0	0	0
soil relative humidity	0	0	0	0
soil absolute humidity	2	0	0	0
external temperature	2	0	0	0

j stands for relevant environment P or S; i stands for relevant sites 1 to 2
lag ~ 1 corresponds to 15-day step

Soils

Both soil air temperature (sites OS1-P, OS2-P, and OS1-S) and absolute humidity (sites OS1-P, OS2-S) appear to be the best predictors of soil CO_2 concentrations. For site OS1-P, the effect of both lag-transformed predictors were distinguished. In this case, temperature and humidity explain the soil CO_2 by 38 and 60%, respectively. Alternatively, linear models with external temperature as an alternative predictor were derived (Tab. 9). All models are statistically significant.

Caves

Almost all models indicate visitor attendance as the most significant predictor of cave CO_2 levels. This is the case for the Punkevní Caves except for site C2–P, where the untransformed soil CO_2 and temperature gradient are predictors. For site C1–P, soil CO_2 is an additional predictor to attendance. The attendance is the sole predictor at sites C3-P and C4-P, although the former model is less significant.

In the case of the Sloup-Šošůvka Caves, attendance is the sole predictor in all the models in which untransformed data were used. In the case of lag-transformed data, both temperature gradient and soil CO_2 are significant variables for site C1-S. The soil CO_2 is an additional predictor together with attendance for site C2-S.

LINEAR REGRESSION

Linear models of soil/cave CO_2 levels with the external temperature as a unique predictor were derived (Tab. 9).

Tab. 7: Time lag of selected variables against cave CO_2 concentrations.

	first (dependent) variable						
lagged independent variable	**OC1–P**	**OC2–P**	**OC3–P**	**OC4–P**	**OC1–S**	**OC2–S**	**OC3–S**
cave attendance	2	2	5	2	0	0	0
temperature gradient (logical)	2	2	5	2	2	1	-1
soil CO_2 (coniferous)	0	0	0	0	0	0	0
soil CO_2 (deciduous)	1	0	0	0	0	0	0

i stands for relevant sites 1 to 4
j stands for relevant environment P or S
lag ~ 1 corresponds to 15-day step

REGRESSION ANALYSIS

The Multiple Linear Regression Analysis (MLRA) was conducted separately for the data for which the time lag was accepted (transformed data) versus unaccepted (raw data without any transformation). All significant models are presented in Tab. 8. The terms in regression equations with *p*-values exceeding 0.05 are mentioned in the notes. The models that were physically inappropriate, e.g. those including a term with an illogical sign, were rejected.

Except for *OC3–P*, all models are significant at $\alpha < 0.05$ and show that external temperature explains the CO_2 levels by 68 to 77%.

ESTIMATION OF ANTHROPOGENIC CO_2 CONTENT IN CAVE CO_2

Based on (1) monthly attendance, (2) visiting period at individual sites, (3) cave site volumes, and (4) exhaled CO_2 (15 L of exhaled air per minute per person; 5% vol.

Tab. 8: Multiple linear regression analysis (stepwise ridge regression).

dependent variable	model: equation	df	F-value	R^2	p-value	beta coefficients: I. variable	beta coefficients: II. variable	notes
	cave CO_2							
OC1–P	*OC1–P* = 0.0681 + 0.000036 *AT–P*[(a)] + 0.2294 *OS2–P*[(b)]	2/**23**	16.**8**	0.59	<**0.001**	0.41	0.38	nLa
	OC1–P = 0.0841 + 0.000086 *AT–P*	1/22	137.9	0.86	<0.001	0.89	n	La
OC2–P	*OC2–P* = 0.0727 + 0.1929 *OS2–P* - 0.00348 *dTC2–PL*	2/**23**	20.7	0.64	<**0.001**	0.52	-0.36	nLa
	OC2–P = 0.0758 + 0.000048 *AT–P*	1/22	74.3	0.77	<0.001	0.84	n	La
OC3–P	No model	n	n	n	n	n	n	nLa
	OC3–P = 0.0838 + 0.000008 *AT–P*	1/19	11.9	0.38	0.003	0.59	n	La
OC4–P	*OC4–P* = 0.0953 + 0.000162 *AT–P*	1/**24**	23.9	0.50	<**0.001**	0.67	n	nLa
	OC4–P = 0.0561 + 0.000219 *AT–P*	1/22	110.1	0.83	<0.001	0.87	n	La
OC1–S	*OC1–S* = 0.0820 + 0.000029 *AT–S*	1/**24**	26.8	0.53	<**0.001**	0.69	n	nLa
	OC1–S = 0.0701 - 0.000548 *dTC1–SL* + 0.0890 *OS2–S*	2/21	39.1	0.79	<0.001	-0.25	0.69	La
OC2–S	*OC2–S* = 0.0837 + 0.000068 *AT–S*	1/**24**	75.7	0.75	<**0.001**	0.83	n	nLa
	OC2–S = 0.0723 + 0.000044 *AT–S* + 0.0827 *OS1–S*	2/22	52.8	0.83	<0.001	0.54	0.36	La
OC3–S	*OC3–S* = 0.1581 + 0.002750 *AT–S*	1/**24**	74.9	0.75	<**0.001**	O.83	n	nLa
	OC3–S = 0.1574 + 0.000275 *AT–S*	1/23	70.8	0.75	<0.001	0.83	n	La
	soil CO_2							
OS1–P	*OS1-P* = 0.1003 + 0.01203 *AHS1-P*	1/24	23,6	0,50	<0.001	0.67	n	nLa
	OS1–P = 0.0831 + 0.00279 *TS1–P* + 0.00943 *AHS1–P*	2/21	59.1	0.85	<0.001	0.38	0.60	La
OS2–P	*OS2-P* = 0.1180 + 0.00611 *TS2-P*	1/24	27.0	0.53	<0.001	0.69	n	nL
OS1–S	*OS1-S* = 0.1017 + 0.00627 *TS1-S*	1/24	40.3	0.63	<0.001	0.75	n	nL
OS2–S	*OS2-S* = 0.0733 + 0.01656 *AHS2-S*	1/24	28.1	0.54	<0.001	0.70	n	nL

[(a)]p = 0.051; [(b)]p = 0.069

df – degree of freedom; n - not relevant

Beta–coefficient indicates relative weight of single independent variable for prediction of dependent variable

notes: nL – no lag; nLa – no lag accepted; La – lag accepted

Tab. 9: Linear regression analysis: soil/cave CO_2 vs. external temperature.

	model: df	F-value	R^2	p-value	regression coefficient: b_0	p-value	b_1	p-value	beta
OS1-P	1/24	19.0	0.44	<0.001	0.1392	<0.001	0.00142	<0.001	0.66
OS2-P	1/24	23.0	0.49	<0.001	0.1224	<0.001	0.00722	<0.001	0.70
OS1-S	1/24	45.1	0.65	<0.001	0.0989	<0.001	0.00799	<0.001	0.81
OS2-S	1/24	35.6	0.60	<0.001	0.0776	<0.001	0.00160	<0.001	0.77
OC1-P	1/24	20.6	0.46	<0.001	0.0900	<0.001	0.00427	<0.001	0.68
OC2-P	1/24	25.5	0.52	<0.001	0.0752	<0.001	0.00272	<0.001	0.72
OC3-P	1/24	0.0	0.00	0.980	0.0870	<0.001	0.00007	0.980	0.01
OC4-P	1/24	20.2	0.46	<0.001	0.0711	0.048	0.01140	<0.001	0.68
OC1-S	1/24	22.4	0.48	<0.001	0.0021	<0.001	0.00074	<0.001	0.69
OC2-S	1/24	35.6	0.60	<0.001	0.0776	<0.001	0.00160	<0.001	0.77
OC3-S	1/24	29.4	0.55	<0.001	0.1360	<0.001	0.00626	<0.001	0.74

of CO_2), contents of anthropogenic CO_2 were estimated for individual cave sites under the assumption that the sites were not ventilated. The results are presented in Fig. 4. as the ratio of hypothetical anthropogenic CO_2 concentrations to the actual CO_2 concentration. In the Punkevní Caves, the levels of exhaled CO_2 should exceed by many times the actual CO_2 levels. In contrast, the anthropogenic CO_2 levels in the Sloup-Šošůvka Caves show a much lower proportion relative to the actual CO_2 concentrations: at sites C2-S and C3-S, the anthropogenic CO_2 would not cover the actual levels.

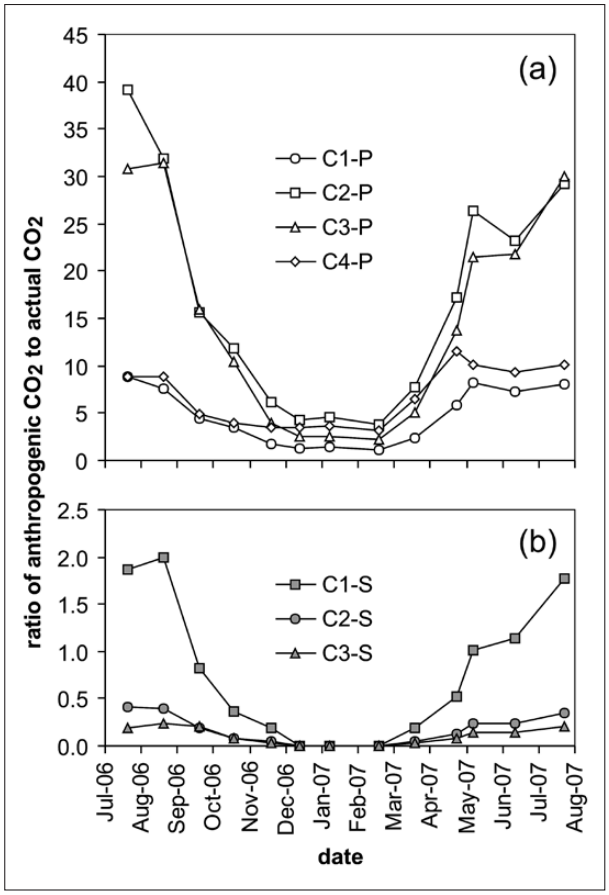

Fig. 4: The ratio of hypothetical anthropogenic CO_2 concentrations to the actual CO_2 concentration in a) the Punkevní Caves and b) Sloup-Šošůvka Caves. For explanation of the abbreviations, see Tab. 1 and Tab. 2.

DISCUSSION

Soil CO_2

The observed soil CO_2 levels up to 1% vol. are in the range found by others (Zhang *et al.* 2005). The data analysis confirmed that soil CO_2 concentrations are controlled by soil temperature and humidity. This is consistent with the findings of other authors (Jassal *et al.* 2004; Iqbal *et al.* 2008). Both quantities are strongly interrelated, which makes it difficult to separate individual effects (Li *et al.* 2008). MLRA allowed the distinguishing of lag-transformed soil temperature and absolute humidity (the site S1-P), but this distinguishing is based purely on the significance of individual variables.

For a convenient prediction of soil CO_2 concentrations, linear models with external temperature as the predictor were designed. Beta coefficients showed that external temperature could explain the soil CO_2 levels by 66 to 81%.

The strong correlations of the CO_2 concentrations found between different soil types and even between different sites did not confirm the influence of vegetation on soil CO_2 production and did moderate the concern about the impact of vegetation on karst processes (e.g. Balák *et al.* 1999; Bárány-Kevei 1999).

Cave CO_2

The monitored cave CO_2 levels are consistent with the values up to 1% vol. found by many researchers (Baldini *et al.* 2006, 2008). In comparison to soils, the cave CO_2 levels showed greater variability.

One problem with cave CO_2 modelling is the time lag of variables. It is obvious that soil CO_2 requires a certain period of time in order to reach a given cave. Similarly, cave ventilation associated with the temperature gradient needs some period to exchange the cave atmosphere. Although anthropogenic CO_2 appears in the cave immediately, a certain period is needed for CO_2 levels to return to their natural state. Faimon *et al.* (2006) showed that the relaxation time of a well-ventilated cave is about 24 hours. However, this period could be much higher in the case of poorly ventilated caves. The lag ~ 2 (corresponding to 30 days) of the attendance in the Punkevní Cave sites C1-P, C2-P, C4-P against cave CO_2 is long but perhaps acceptable. In contrast, the lag ~ 5 at site C3-P is clearly inconceivable. A data transformation into new data without the lag is a possible approach to identifying the driving variable. Because the resulting regression equations with differently lagged variables are hardly applicable for a convenient cave CO_2 level prediction, alternative models based on the original data were derived.

Cave CO_2 sources

Data analysis suggests that the generally accepted belief that soils are the main source of cave CO_2 could be questioned. MLRA showed that the soil CO_2 levels appeared as predictors in only four models (of thirteen in total) and always combined with another predictor. In these models, the share of soil CO_2 in cave CO_2 levels varied between 38 and 69%. Doubts about the dominant role of soils in cave CO_2 resonate with some authors (Miotke 1974; Bárány-Kevei 1999; Tatár *et al.* 2004; Baldini *et al.* 2005). Even if the soil CO_2 effect was superimposed by anthropogenic CO_2 in this study, alternative sources (e.g. epikarstic sediments) should be considered in future studies.

Attendance was identified as a main predictor of cave CO_2 levels in both the caves, which indicates a broad anthropogenic impact. An exception is site C3-P, where no model was found for untransformed data and

the model for lagged data is physically unacceptable. In this site, the CO_2 values are probably controlled by distinct factors despite the MLRA results (see the discussion later). The attendance impact is most obvious in the Sloup-Šošůvka Caves, especially in sites C2-S and C3-S, where the lag of variables is near zero. Paradoxically, based on the estimations of exhaled CO_2, the contributions of anthropogenic CO_2 levels in these sites should be lowest. The reason for this contradiction may be an overestimation of cave site volumes. Both the sites are linked to abysses lying below the visitor route with a disputable contribution to total site volumes. If the abyss volumes are omitted, the share of anthropogenic CO_2 rises to 87% (C2-S) or above 100% (C3-S) of actual cave CO_2. Despite the clear influence of anthropogenic CO_2 on the cave environment, long-term monitoring of dripwaters (in the Punkevní Caves especially) shows permanent water supersaturation (Faimon & Ličbinská, unpublished data), which indicates that the impact is not destructive. This conclusion is consistent with the study of the anthropogenic CO_2 impact in the Císařská Cave (Faimon *et al.* 2006).

Factors suppressing cave CO_2 levels

It is well known that cave air circulation depends on temperature gradients between the interior and exterior (de Freitas *et al.* 1982; Russell & McLean 2008). Dynamic caves (see Geiger *et al.* 2003; Spötl *et al.* 2005; Liñán *et al.* 2008) are ventilated year-round, although the ventilation is more intensive at external temperatures below the cave temperature (Faimon, unpublished work). In static/semi-dynamic caves, such effects are emphasized under the same conditions.

MLRA only sporadically identified the temperature gradient as a significant predictor of cave CO_2 levels (only at sites C2–P and C1–S). This indicates the minor role of cave ventilation. However, this is contradictory to the estimations of the anthropogenic CO_2 share of actual CO_2 levels at individual cave sites. Therefore, we guess that the ventilation effect is undervalued. This is especially the case at site C3–P, with its extremely low CO_2 levels at low variance. Because the site is unique due to its large free water table surface, the possibility of CO_2 dissolution was considered. Based on the analyses of 13 water samples, however, partial pressures of CO_2 in the water ($\log P_{CO2}$ = -2.20±0.26) exceeded those in the air ($\log P_{CO2}$ = -2.98±0.35). Therefore, degassing must be expected instead of dissolution. Based on these facts, the hypothesis about CO_2 dissolution was rejected and ventilation remained the sole factor explaining the cave CO_2 levels. This is consistent with enhanced temperature variations (Fig. 3). Temperature gradients seem to be an unsuitable proxy for ventilation in case the cave atmosphere is totally exchanged with the external atmosphere, and CO_2 levels are nearly constant.

The strong correlation of the CO_2 concentrations between different sites (except for site C3-P) indicates the strong mutual dependency of cave sites. The dependence diminishes with site distance.

Spurious relationship problem

It is well known that statistically related variables (correlated) need not show a causal connection and that the correlation can be the result of a spurious relationship (see, e.g., Ben-Zeev & Star 2001; Pearl 2009). Therefore, we considered the possibility that between cave CO_2 concentrations and other tested variables there is no causal interrelation and that all correlations are the result of external temperature as a confounding factor. A set of linear models was derived, in which external temperature is a unique cave CO_2 level predictor. All the models are significant at $\alpha = 0.05$ and valid for all the cave sites except for C3-P. These models explain cave CO_2 levels by 68 to 77%. We believe that further studying of more sophisticated data (equidistant data with a short distance in the range of hours or minutes) could contribute to a better understanding of the problem.

CONCLUSIONS

Spatial and temporal variations of carbon dioxide were studied in two sites of the Moravian Karst: (1) soils in the Macocha Plateau with the adjacent Punkevní Caves, and (2) soils in the Sloup-Šošůvka field with the adjacent Sloup-Šošůvka Caves. The soil air CO_2 levels, cave air CO_2 levels, cave attendance, and external temperatures showed similar seasonality. It was confirmed that soil CO_2 production is controlled by temperature/humidity. Both effects are indistinguishable because of multicollinearity. The impact of vegetation was not proven. Based on multiple linear regression analyses, cave attendance seems to be the most significant variable controlling cave CO_2 levels and, subsequently, calcite deposition in the given sites. Temperature gradients and soil CO_2 levels were identified as further controlling variables. Because statistical analysis is not able to reveal a causal relation-

ship, a spurious relationship was considered with external temperature as a lurking variable. To demonstrate such possibility, alternative linear models were derived in which external temperature operates as unique universal predictor of cave CO_2 levels.

Two general conclusions may be derived from the study: (1) soils need not necessarily control cave CO_2 levels, and (2) the anthropogenic impact may easily superimpose upon natural processes in caves. From the former conclusion, it follows that the speleothem growth rate does not need to be directly related to soil/surface conditions. This is important for palaeoenvironmental reconstructions based on the study of terrestrial speleothems. The latter conclusion is important for karst/cave environment conservation and protection: it shows that the anthropogenic impact in caves is not negligible even if its consequences are not evident or destructive.

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