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Carbon dioxide fluxes and carbon balance after the 2004 stand replacing wind throw in the Tatra National Park

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Abstract

Since 2007 CO2 soil fluxes have been measured by chamber method in the larch-spruce ecosystem heavily disturbed by the 2004 windstorm. In 2012 measurement of photosynthesis started and allowed calculation of carbon balance. The instant CO2 fluxes were measured during growing on 14 day cycle on fixed points and the values were extrapolated both spatially and temporally according to the microhabitat types, soil moisture and temperature, PAR and LAI. Carbon balance in 2012 was negative. The affected ecosystem emitted 1.8 t C ha-1 y^{-1}.

Key words: CO2 sequestration**,** carbon balance, forest disturbances, Tatra National Park, spruce forest

Introduction

Carbon dioxide (CO_2) is an important greenhouse gas and its increasing concentration in the atmosphere is often interpreted as a main reason for global climate change. Accumulation of carbon (C) in plant biomass is one of the most effective ways to reduce CO2 in the atmosphere. Forest ecosystems play an important role in global carbon sequestration. Without forest current global CO_2 concentration would be roughly 510 ppm. Almost 46 % of terrestrial C is stored in forest biomass and forest soils. In recent years forest potential sequestration has been reduced due to increasing disturbances. According to the projected changes destructive storms, floods, drought and insect outbreaks probably would cause even more significant changes of carbon fluxes in both, ecosystem and global cycles (Hasenauer et al., 2012).

Forest of Tatra National Park was strongly affected by an extreme wind throw in November 2004. Wind reaching 230 km/h laid down more than 12 000 ha (2.3 mil m^3) of natural and seminatural larch-spruce forest. This event has initiated international ecological research with special emphasis on energy, water and nutrient fluxes (Fleischer, 2008). In this paper we present data on C efflux (soil and ecosystem respiration) which has been monitored since 2007. We also present amount of C assimilated by vegetation in 2012 and calculate C balance as difference between these two major C fluxes.

Materials and methods

Research site

Our study was conducted on research sites established for long-term monitoring of ecological processes after the 2004 windfall in the Tatra National Park To understand the impact of different disturbance levels and different management on larch-spruce ecosystems the research sites were established on almost identical site conditions (granit moraines, dystric cambisoils, slope 10-25%, altitude 1100/1200 m a.s.l., south oriented, acidophilus vegetation, etc.); EXT – windtrow site, timber removed, FIR – windhrow and fire site, timber remowed, NEX – windthrow site, no management. The fourth site REF represented reference, undisturbed stands (Fleischer, 2008).

Sampling design

CO2 fluxes were measures on fixed points established along transects shaped in 6-arm starr. Meteorological tower formed the cross points of transects on each site. Distance between measuring points along transects was 10 m. Number of measuring points on each site ranged from 8 up to 22 according to the site specific variability. Average frequency of measuring each point was 14 days during growing season (May-September), and monthly during autumn – early spring.

Microsite conditions

The 2004 windthrow, but also previous wind disturbances, formed very dynamic soil surface represented by pit and mound micro topography. Early stage succession vegetation differs according to the soil physical properties (moisture, depth, particle size) and humus content. According to presence of dominant vegetation so far four key rmicrosites with distinct vegetation were identified: 1. Deeper, loamy and moist soil (cambisoil) in terrain depressions with Rubus *ideaus* and *Salix caprea*; 2. Shalow, sandy/rocky soil (ranker) on elevations with *Calluna vulgaris* and *Vaccinium vitis ideae*; 3. Sites with fast decomposing organic material and dominated by *Chamerion angustifolium*, 4. Sites dominated by *Calamagrostis villosa* mostly on Podsolic cambisoils. Site conditions and vegetation types were mapped in the field using fine scale IR aerial photographs and GIS tools. Species specific and seasonal changes of leaf area index (LAI) were estimated by destructive opto-gravimetric method using ImageJ© software and by non-destructive optical method (Licor 2200, Licor, USA).

Soil/ecosystem respiration

Soil/ecosystem efflux of CO_2 was detected by infra-red gas analyzers (Vaisala GMP 343, Vaisala Finland and EGM4, PP Systems USA) applying closed chamber methods. Vaisala sensors were installed inside custom built non- transparent PVC chamber (16 dm^3) equipped with small fan for mixing sampling air. Before each measurement the CO2 probe was adjusted to instant air humidity, temperature and pressure. The CPY4 chamber (2.2 dm^3) was used with the EGM4 instrument. For respiration measurement non transparent cap was placed on the chamber. The chambers were firmly but carefully placed on fixed collars (diameter 30 cm, 10 cm tall and 2-3 cm inserted into the soil) to avoid gas leaking. Measuring interval was 120 s for PP Systems (small chamber), 300 s for Vaisala and sampling frequency 5 s in both instruments. Vegetation from some collars was systematically clipped out, efflux data represented soil respiration (Rs). The other collars and EGM readings represented ecosystem (Re) respiration.

Photosynthesis (GPP)

Both of the instruments have been used also for estimation of photosynthesis. Measured CO2 concentration indicated net ecosystem exchange (NEE), which resulted from instant difference between photosynthesis (or gross primary productivity, GPP) and total (or ecosystem) respiration:

$$NEE= GPP-Re \quad (1)$$

Applied Plexiglas transparent chambers had different size (from 16 up to 80 dm3) according to the type and height of measured vegetation. Photosyntetically active radiation (PAR) and air temperature were measured during CO_2 sampling. On each point the NEE measurements repeated consequently under modified light conditions. Intensity of solar light entering the chamber was modified by shading the chamber with plastic nets with different transparency.

Microclimate measurement

During CO_2 measurement instant microclimate data near the sampling point were recorded. Soil temperature was measured in 2 and 10 cm by soil thermometer (Ahlborn, Germany) and soil moisture in 0-6 cm by ML2x (Delta theta, UK). Air humidity was measured by Ahlborn (Germany), PAR by Skye Quantum (Ireland), wind speed by Met (Germany). On each research site fixed automatic meteorological stations (AMS) recorded microclimate data (profile soil temperature and moisture, profile air temperature and humidity, wind speed and direction, global and PAR radiation, soil heat flux, precipitation) in 60 min intervals. The CPY4 chamber was equipped with the PAR, air temperature and humidity sensors.

Calculation of fluxes

Data recorded by the Vaisala instruments represented temporal (5 s) CO_2 concentration changes. Values of each measurement were plotted and linear trend was tested (MS Office Excell). Only data showing R^2>0.96 were used for flux calculation confirming proper measurement (well sample mixing, no leaking, etc.). According to Drewit et al. (2002) we applied ideal gas law to calculate CO_2 flux (umol.m^{-2}.s^{-1}):

$$F_{CO2} = (P*V*{}_{\Delta}CO_2)/(R*T*A) \quad (2)$$

P-air pressure (Pa)
V – chamber volume
A – chamber surface
${}_{\Delta}CO_2$ - concentration increment (ppm/min)
T – air temperature in chamber (^{o} K)
R – gas constant

Data recorded by the EGM4 were calculated by the instrument software and presented in g $CO2.m^{-2}.h^{-1}$. The CO_2 fluxes measured in the chambers represented the difference between assimilation (GPP) and respiration (Re) *(1)*. Under dark conditions GPP=0, so NEE=Re (Tagesson, 2006).

Temporal extrapolation of CO_2 fluxes from snap to seasonal scale was based on the regression models (Tuomi et al., 2008; Chen et al., 2010; DelGrosso et al., 2005; Byrne et al., 2005). Soil respiration was extrapolated for the entire year according to the soil temperature and humidity. Photosynthesis was extrapolated across the growing season according to the PAR and LAI using the Michaelis-Menten regression. Nonlinear regression parameters were estimated by Satistica 7. For comparison of different models we used MSE, AIC and ME criteria as proposed by Bauer (2009).

Annual C balance (NEE) was calculated as difference between annual Re and seasonal photosynthesis (GPP). Positive NEE (GPP>Re) means that ecosystem is C sink. Negative balance (GPP<Re) indicates ecosystem as C source.

Results

During field work we interpreted IR ortophotomap from the windthrown area using GIS instruments. Fine scale (20 cm per pixel) allowed reasonable classification of dominant vegetation (Erdas Imagine©). Fig. 1 shows part of the classified area where distinct colors represent different vegetation and land use types. Verification was done on sites 20x20 m (red squares).

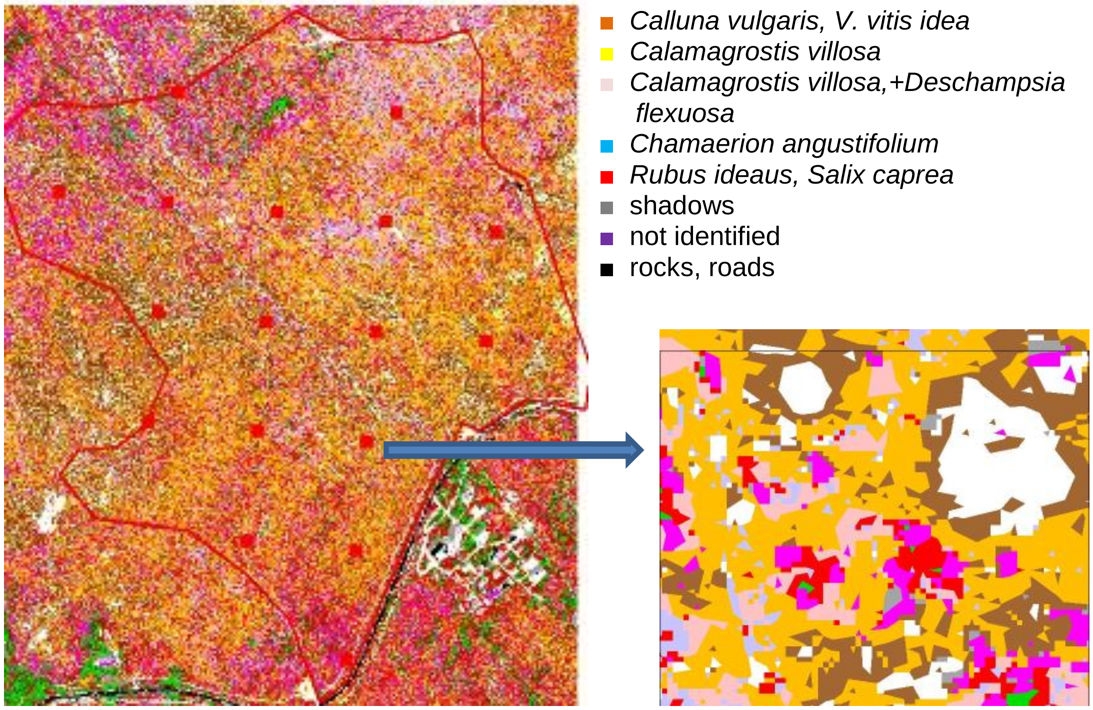

Fig. 1 Vegetation and land use map and detail (20x20m), study site FIR

Soil respiration

Between 2010 and 2012 we did more than 1100 soil/ecosystem respiration measurements on the FIR and EXT sites. Less intensive was measurement on the NEX site due to repeated damage on sampling sites by game. So far we did not find any significant difference among sites with soil versus ecosystem respiration. Basic statistics of measured data are presented in Tab.1

In 2012 we noted strong reduction in difference between the FIR and EXT sites. Statistical analysis (Two Sample t test) confirmed no difference between the sites on 0.05 sig level. In previous years soil respiration on the FIR site was much higher than on the EXT.

As in previous years we have observed close relation between microsite conditions (represented by specific vegetation) and soil efflux. For each microsite/vegetation type (*Rubus ideus, Calamagrostis villosa, Chamerion angustifolium, Calluna vulgaris)* we applied available models (Tab. 2).

Tab.1 Basic characteristic of the soil respiration on EXT and FIR sites (CO_2 in umol m^{-2} s^{-1})

Year	*Site*	*No Of measurement*	*Average Soil respiration*	*Standard Deviation*	*Coeficient Of variation (%)*
2012	EXT	263	5,50	2,94	53,53
	FIR	124	6,23	3,09	49,63
	sum	387	5,74	3,01	52,45
2011	EXT	138	4,36	2,22	50,97
	FIR	129	5,39	3,05	56,52
	sum	267	4,86	2,70	55,53
2010	EXT	198	5,08	2,40	47,37
	FIR	231	6,86	3,55	51,70
	sum	429	6,04	3,19	52,93

Tab. 2 Overview of equitations used to model soil respiration on EXT and FIR sites, T– temperature, SM – soil moisture, a-e - parameters

Model	Equitation
Linear	$Y=a+bT$
Quadratic (T)	$Y= aT^2$
Kucera, Kirkham	$Y=a(T+10)^b$
Fang, Moncrief	$Y=a(T-T_{min})^2$
Exponential	$Y=ae^{b*T}$
Arrhenius	$Y= ae^{bT^{-1}}$
Quadratic (SM)	$Y= a +b*sm + c*sm^2$
Boltzman S courve	$Y= b +\frac{a-b}{1+e^{\frac{sm-c}{d}}}$
Empirical (T, SM)	$Y=(asme^{bT})$
Mielnick, Dugas	$Y=(a*s_m)e^{bT}2{,}12(SM-SM_{min})(SM_{max}-SM)^c$
Combined Botzman .	$Y= \left(b + \frac{a-b}{1+e^{\frac{sm-c}{d}}}\right)*e^{eT}$
Del Grosso	Y=(a*(0,56+(1,46*(arctan(π*0,0309)*(T-15,7))/ π))*(5*(0,287+(arctan(π*0,009*SM-17,74)))/ π))

On the example of *Rubus ideaus* we present tested models, fitted parameters and calculated statistical criteria (MSE, AICc, ME). The results are presented in the Tab. 3 and Fig. 4. Red numbers in Tab. 3 indicate statistical significance (<0.05). The order of parameters is the same as in the equitations in Tab. 2.

Tab. 3 Models, parameters and criteria for estimation of soil respiration for *R. ideaus* community

Model	MSE	ME	AICc	parameters
Linear	6.4	0.40	141.3	0.43;0.58
Quadratic (T)				No significant
Kucera, Kirkham	6.43	0.40	-8.67	0.04;1.55
Fang, Moncrief				No significant
Exponential	6.71	0.38	146.94	2.8;0.05
Arrhenius	6.4	0.43	141.4	17.75;-13.24
Quadratic (SM)	8.58	0.26	167.1	-14.26;1.02; -0.01
Boltzman S courve	8.64	0.25	169.598	9.32;1.51;0.28;0.04
Empirical (T, SM)	3.9	0.65	106.72	0.07;0.06
Mielnick, Dugas				No significant
Combined Botzman	3.63	0,67	107.48	4.64;.0.34;0.33;0.08;0.06
Del Grosso	4.24	0.61	111.83	6.73

MSE – mean squared error, AICc – Akaike information criterion, ME – Model effectivity

To compare soil respiration in different microhabitat types we chose the best fit models. Annual course of CO_2 efflux is presented in Fig. 4. Annual respiration for distinct vegetation type was as follow*:* *Rubus ideaus* 13.2 t C ha^{-1}, *Calluna vulgaris* 6.9, Chamerion angustifolium 10.1, and Calamagrostis villosa 8.9 t C ha^{-1}.

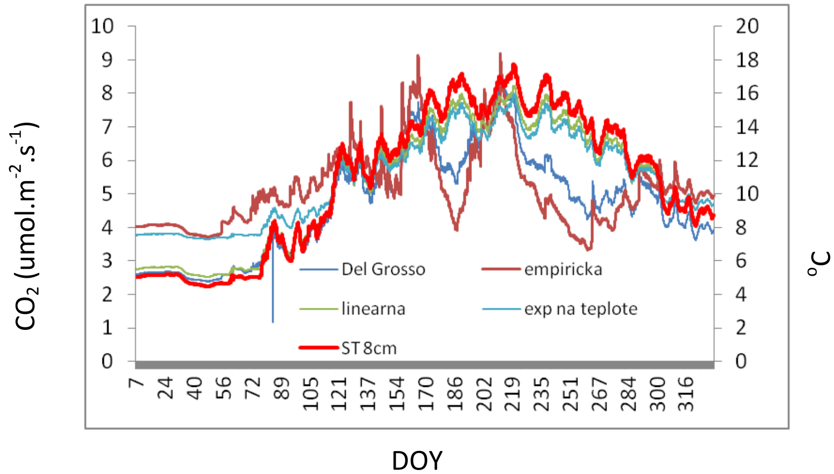

Fig. 3 Annual courses of soil CO_2 efflux in *R. ideaus* type calculated by the best fit models, soil temperature in 8 cm is also shown

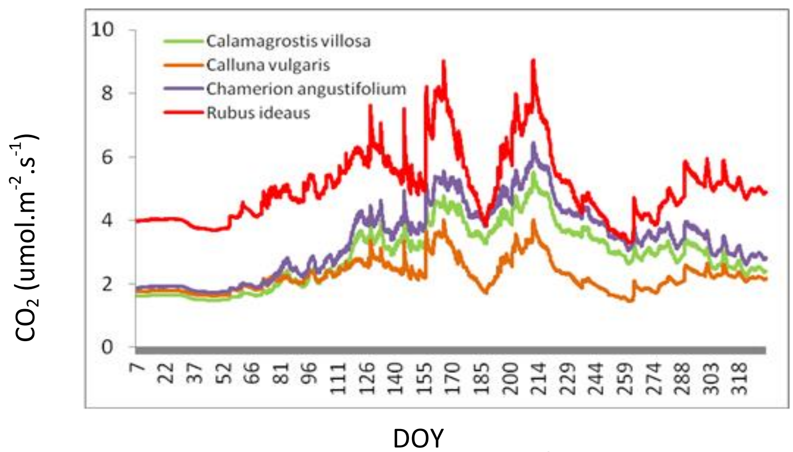

Fig. 4 Annual course of the soil CO_2 efflux (umol m^{-2} s^{-1}) for the most spread vegetation types

Total annual respiration for the windthrow site was calculated as area weighted CO_2 efflux for each micohabitat type. According to the proportion of vegetation types (Fleischer et al. 2013) the average CO_2 efflux in 2012 was 8.7 t C ha^{-1}.

Photosynthesis

Estimated instant GPP values were fitted with Michaelis-Menten type of regression:

$$GPP = a_1 \left(\frac{PAR}{a_2 + PAR} \right) \left(\frac{LAI}{a_3 + LAI} \right) \quad (3)$$

Calculated parameters for selected species (*Calamagrostis villosa, Calluna vulgaris*) are presented in Tab. 6. The parameters for other key species were not significant.

Tab. 6 Correlation, parameters and LAI for Michaelis-Menten regression (3), (sig of parameters <0.05)

Vegetation	R^2	a_1	a_2	a_3	LAI
Calluna vulgaris	0,73	2,1	693,78	-0,46	0,9
Callamagrostis vilosa	0,76	3,91	650,21	-0,54	1,1

Continuously measured PAR values were used for extrapolation of instant GPP values across growing season. Diurnal GPP for *C. villosa* is shown in Fig. 5. GPP for *Chamerion angustifolium* and *Rubus ideaus,* which were difficult to measure directly due to their size, was calculated by biometric method (Marek et al., 2011). Total annual sum of GPP reached 6.9 t C ha^{-1}.

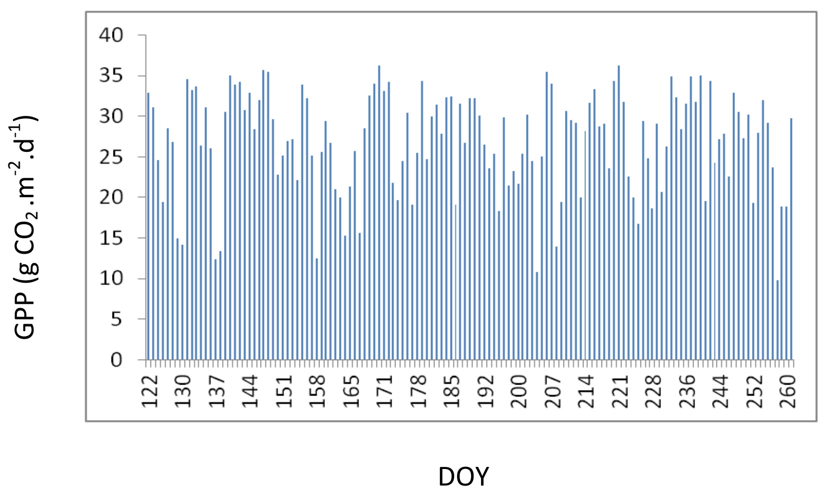

Fig. 5. Diurnal sum of GPP (g CO_2 m^{-2} d^{-1}) for *Calamagrostis villosa* during growing season

Carbon balance

Measurement of the both fluxes in 2012 allowed us to calculate annual C balance on the windthrow site. Assording to the formula *(1)* carbon balance (NEE) as difference between GPP (6.9 t C ha y^{-1}) and Re (8.7 t C ha y^{-1}) was negative (-1.8 t C). It means that the windthrow site was C source.

Discussion

Based on sampling size (number of sampling points per site) and estimated variability of soil efflux we could calculate the accuracy of our sampling. According to the formula:

$$n = \frac{s^2 t_\alpha^2}{D^2} \quad (4)$$

s – standard deviation, t_α – critical value of Students distribution if α=0.05, n – number of sampling points

The accuracy of C efflux estimation was ± 0.75 umol m^{-2} s^{-1}. In previous years the differences among the sites and individual years were much bigger. Recently, due to progressive homogenization of microclimate and vegetation, the differences are less pronounced. Average soil temperature (in 8 cm) during growing season 2012 was 13.4 ^{o}C on EXT and 13.2 on FIR site. In 2011 the difference was 0.7 ^{o}C. Soil moisture in 2012 on both the sites was even identical (28 %), a year before the difference was 7%. The source of CO_2 efflux variability raised mostly from the heterogeneity of microhabitat structures. Variation was partly reduces by grouping sampling points into relatively homogenous types identified by dominant vegetation.

We have applied vast range of soil respiration models for estimation of CO_2 efflux. The best fit between modeled and measured values showed models based on both soil temperature and soil moisture, esp. model by DelGrosso and our own,named Empirical model. The largest differences were found during non-growing season (modeled value 4 umol, real value 0.5 umol m^{-2} s^{-1}).

Photosynthetic production (GPP) derived from PAR and LAI yield comparable results than gravimetric method. The difference in C uptake between chamber and biomass methods ranged from 3 (for *C. villosa*) up to 13 % (for *Ch. angustifolium*) (Fleischer et al., 2013). GPP measurement was problematic under intensive PAR and thus elevated temperature in Plexiglass chambers. Measurement was often disturbed when vapour pressure deficit exceeded 2 kPa. At such a level stomata close and CO_2 uptake stops (Marek et al., 2011).

Conclusion

Carbon dioxide fluxes, respiration and photosynthesis, were measured by the chamber method on the site heavily disturbed in 2004 by an extreme windstorm. Large differences among sites representing different disturbance agents (wind, fire) gradually declined. Site CO_2 efflux heterogeneity depended mostly on microhabitat variability. Repeated windfalls have formed pit and mound microtopography with contrast soil and hydric conditions reflected by specific vegetation cover. Instant soil respiration values were extrapolated both spatially and temporally. Spatial extrapolation was based on the actual vegetation map derived from fine scale aerial ortophotomaps. Temporal extrapolation of CO2 fluxes was based on soil temperature, soil moisture, PAR and LAI. Difference between carbon efflux and uptake, net ecosystem exchange, showed that balance up to 2012 was negative (the windtrow in 2012 produced 1.8 t C per ha). It is expected that increasing vegetation cover, biomass and LAI under warm and moist conditions might increase carbon sequestration and change the balance to positive (carbon sink). Further research needs to solve GPP measurement of oversized vegetation and overheating inside transparent chambers.

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Summary

V porastoch postihnutých vetrovou kalamitou v r. 2004 sme komorovou metódou merali okamžité toky CO_2 (pôdnu, resp. ekosystémovú respiráciu a asimiláciu). Aj po 8 rokoch boli poškodené ekosystémy zdrojom uhlíka, keď ročne emitovali 1.8 t C ha^{-1}. Napriek pokračujúcej regenerácii vegetačných a homogenizácii mikroklimatických podmienok, sú rozdiely v emisii CO_2 medzi mikrostanovištnými typmi na postihnutom území stale výrazné.

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