



Preface

“Stable Isotopes and Biogeochemical Cycles in Terrestrial Ecosystems”

M. Bahn¹, N. Buchmann², and A. Knohl³

¹University of Innsbruck, Institute of Ecology, Sternwartestraße 15, 6020 Innsbruck, Austria

²ETH Zurich, Institute of Agricultural Sciences, Universitätsstrasse 2, 8092 Zurich, Switzerland

³Georg-August-University Göttingen, Büsingen Institute, Büsingenweg 2, 37077 Göttingen, Germany

Correspondence to: M. Bahn (michael.bahn@uibk.ac.at)

In view of a rapidly changing environment there is the need to better understand the response of ecosystems to global changes of climate and land use. While there are substantial ongoing efforts in monitoring fluxes of carbon (C), water and nitrogen (N) between ecosystems and their environment (e.g. Baldocchi, 2008; Sutton et al., 2012), there is still an insufficient understanding of the processes underpinning biogeochemical cycles at the interfaces between atmosphere, plant, soil and microbes. One important field that deserves increasing attention concerns plant – soil interactions (see also recent special issue, Subke et al., 2012), whose study has so far been limited by considerable methodological problems, in particular in terms of the soil compartment.

Stable isotopes are a powerful tool for tracing elements and for unravelling plant and soil processes as well as their coupling to the atmosphere at various temporal and spatial scales. Stable isotopes have yielded significant breakthroughs, such as identifying the imprint of biospheric CO₂ fluxes from terrestrial ecosystems on the atmosphere (using ¹³C and ¹⁸O), separating autotrophic and heterotrophic respiration in soils (¹³C) and quantifying atmospheric N₂ inputs to ecosystems (¹⁵N) and their impact on ecosystem functions (Ciais et al., 1995; Yakir and Sternberg, 2000; Robinson, 2001; Flanagan et al., 2005; Dawson and Siegwolf, 2007; Bowling et al., 2008). Over the last decade, advances in measurement techniques, e.g. laser spectrometry and compound specific analysis, have enabled scientists to apply stable isotopes to study processes in environmental research in so far unprecedented resolution and detail.

International efforts to network scientists applying stable isotopes in different earth system science disciplines, such as COST Action ES0806 Stable Isotopes in Biosphere-

Atmosphere-Earth System Research (SIBAE), resulted in further advancements of our mechanistic understanding. This special issue on “Stable Isotopes and Biogeochemical Cycles in Terrestrial Ecosystems” highlights some of these recent advances and presents reviews and case studies addressing the following topics: (1) tracing C from photosynthetic assimilation to respired CO₂, soil organic matter and soil biota, (2) unraveling and upscaling nitrogen dynamics, (3) analyzing linkages between carbon and water cycles, and (4) applying isotopes for constraining global biogeochemical models.

C allocation is a key process in terrestrial ecosystems, whose dynamics are still poorly understood but can now be studied in some detail using isotopic tracers combined with compound-specific analysis and/or isotope laser spectroscopy (Brüggemann et al., 2011; Epron et al., 2012). The natural stable carbon and oxygen isotope composition of respiratory substrates and of plant- and soil-respired CO₂ follows pronounced diel variations, which typically decrease from leaves to trunks and roots (Gavrishkova et al., 2011; Werner and Gessler, 2011). These are most likely determined by post-photosynthetic fractionation processes as related to changes in C allocation to different metabolic pathways, and by a mixing of substrates and of component fluxes (Werner and Gessler, 2011). In situ pulse labeling experiments on mature trees indicate that the patterns of C allocation to below-ground respiration are species-specific and change seasonally depending on the phenology of species (Epron et al., 2011). Stress, e.g. induced by chronic ozone exposure, can reduce the allocation of recent photosynthates to stem and root respiration (Ritter et al., 2011; cf. also Brüggemann et al., 2011). Long-term tracer application of ¹³CO₂ by free air CO₂ enrichment (FACE) permits identifying the diurnal

and seasonal variability of components of soil respiration, including root/rhizosphere respiration and the decomposition of litter and soil organic matter of two age classes (Taneva and Gonzalez-Meier, 2011). CO₂ emissions from soils not only reflect biological activity, but also physical processes related to the transport and the dissolution of CO₂. Combining a tracer experiment with modeling, Gamnitzer et al. (2011) demonstrate that due to isotopic disequilibria in the soil–atmosphere system, as caused by modifications of the C isotope composition of the atmosphere or of soil respiration and as altered by dissolution effects, $\delta^{13}\text{C}$ of CO₂ derived from respiration may strongly differ from that of the CO₂ actually emitted from the soil at a given point of time. This calls for great care when interpreting $\delta^{13}\text{C}$ from soil CO₂ efflux under nonequilibrium conditions.

¹³C labeled litter was successfully applied to study microbial food web dynamics and pathways of litter C losses. Along a soil chronosequence at a glacier forefield, Esper-schütz et al. (2011) found that while incorporation of ¹³C from litter in microbial biomass was pronounced irrespective of the age of sites, the relative contribution of different microbial groups changed from archaea, fungi and protozoa to bacteria as primary succession progressed. Using labeled litter in a beech forest it was observed, surprisingly, that twig litter was decomposed at almost the same rate as leaf litter and released less DOC to the mineral soil, thus potentially contributing less to soil C storage than leaf litter (Kammer and Hagedorn, 2011).

Long-term C storage depends not only on C inputs from photosynthates and litter, but also on carbon stabilization in soils, whose mechanisms are not easily identified. Kayler et al. (2011) combined analyzes of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from soil organic matter fractions along with soil mineral proxies for soils with different land-use histories. They found that forest soils contained a higher proportion of stabilized C than arable soils, and that in both soils occluded organo-mineral complexes were highly protected from microbial processing. Analyzing the response of C and N isotope composition of soil organic matter fractions of a tallgrass prairie to experimental warming, Cheng et al. (2011) observed an accelerated loss of soil N, while soil C remained largely unaffected by warming.

N isotopes have since long been used to quantify key processes in ecosystem N turnover, such as gross nitrogen mineralization and nitrification (Davidson et al., 1991). Concerning another important aspect of the N cycle, Rütting et al. (2011) demonstrate that denitrification need not be the only relevant process for dissimilatory nitrate reduction, but that dissimilatory nitrate reduction to ammonium may be important as well. At larger scales, Bai et al. (2012) used natural variations in N isotopes, coupled with two models, to trace global pathways of N loss from land to water and atmosphere and to identify global nitrogen hotspots across natural terrestrial ecosystems. They highlight that tropical regions

are the major hotspot of nitrogen export from the terrestrial biosphere.

Finally, the water cycle is an important determinant influencing both C and nutrient cycles. “Water use efficiency” (i.e. the ratio of C gained versus water lost by a plant or an ecosystem) is a parameter frequently used for linking C and water cycles across scales (Werner et al., 2012). It is reflected both in the C and the O isotope composition of plant tissues (Scheidegger et al., 2000; Seibt et al., 2008). At the plant scale, Maguas et al. (2011) suggest for coastal sand dune systems that the variability of predawn water potential, a proxy of access of plant roots to soil water, and of bulk leaf $\delta^{13}\text{C}$, a proxy of water use efficiency integrated over leaf lifetime, was related to ground water level for deep-rooted species and phraeatophyte species, but was decoupled for a drought-adapted shrub, highlighting a diverse and species-specific interplay of morphology and physiology for plant responses to water availability.

Based on a global analysis, Ballantyne et al. (2011) demonstrate that seasonal values of C isotope composition of source CO₂ to the atmosphere are correlated to vapor pressure deficit rather than atmospheric relative humidity, which they suggest to be a useful finding for global models and for choosing an appropriate stomatal conductance model. Finally, Werner et al. (2012) showcase current progress and opportunities but also emerging challenges in the field of plant water and carbon relations at different spatio-temporal scales. In addition, they also discuss pros and cons of recent technological advancements and their applications in biogeochemical studies.

Thus, highlighting recent studies on carbon, nitrogen and water cycles in terrestrial ecosystems, this special issue clearly demonstrates that stable isotopes not only permit an integration across scales, but also a separation of processes whose knowledge is essential for understanding and predicting effects of global changes on the biogeochemical cycles in terrestrial ecosystems.

Acknowledgements. This Special Issue emerged from a Conference on “Stable Isotopes and Biogeochemical Cycles in Terrestrial Ecosystems” held at the Centro Stefano Franscini, Ascona (Switzerland) in March 2010, which was financially supported by ETH Zurich, the Swiss National Science Foundation (SNF), a Marie Curie Excellence Grant of the European Commission (Project No.: MEXT-CT-2006-042268), BASIN (funded by the National Science Foundation, USA) and the COST Action ES0806 Stable Isotopes in Biosphere-Atmosphere-Earth System Research (SIBAE). We would like to thank Todd Dawson for his initial support, and Albrecht Neftel for his editorial handling of one of the manuscripts submitted to this special issue of Biogeosciences.

References

- Bai, E., Houlton, B. Z., and Wang, Y. P.: Isotopic identification of nitrogen hotspots across natural terrestrial ecosystems, *Biogeosciences*, 9, 3287–3304, doi:10.5194/bg-9-3287-2012, 2012.

- Baldocchi, D. D.: “Breathing” of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurements systems, *Turner Review, Aust. J. Bot.*, 56, 1–26, 2008.
- Ballantyne, A. P., Miller, J. B., Baker, I. T., Tans, P. P., and White, J. W. C.: Novel applications of carbon isotopes in atmospheric CO₂: what can atmospheric measurements teach us about processes in the biosphere?, *Biogeosciences*, 8, 3093–3106, doi:10.5194/bg-8-3093-2011, 2011.
- Bowling, D. R., Pataki, D. E., and Randerson, J. T.: Carbon isotopes in terrestrial ecosystem pools and CO₂ fluxes, *New Phytol.*, 178, 24–40, 2008.
- Brüggemann, N., Gessler, A., Kayler, Z., Keel, S. G., Badeck, F., Barthel, M., Boeckx, P., Buchmann, N., Brugnoli, E., Esperschütz, J., Gavrichkova, O., Ghashghaie, J., Gomez-Casanovas, N., Keitel, C., Knohl, A., Kuptz, D., Palacio, S., Salmon, Y., Uchida, Y., and Bahn, M.: Carbon allocation and carbon isotope fluxes in the plant-soil-atmosphere continuum: a review, *Biogeosciences*, 8, 3457–3489, doi:10.5194/bg-8-3457-2011, 2011.
- Ciais, P., Tans, P. P., Trolier, M., White, J. W. C., and Francey, R.: A large Northern Hemisphere terrestrial CO₂ sink indicated by the ¹³C/¹²C ratio of atmospheric CO₂, *Science*, 269, 1098–1102, 1995.
- Cheng, X., Luo, Y., Xu, X., Sherry, R., and Zhang, Q.: Soil organic matter dynamics in a North America tallgrass prairie after 9 yr of experimental warming, *Biogeosciences*, 8, 1487–1498, doi:10.5194/bg-8-1487-2011, 2011.
- Davidson, E. A., Hart, S. C., Shanks, C. H., and Firestone, M. K.: Measuring gross nitrogen mineralization, immobilization and nitrification by ¹⁵N pool dilution in intact soil cores, *Eur. J. Soil Sci.*, 42, 335–349, 1991.
- Dawson, T. E. and Siegwolf, R. T. W. (Eds.): *Stable Isotopes as Indicators of Ecological Change*, Academic Press-Elsevier, San Diego, 2007.
- Epron, D., Ngao, J., Dannoura, M., Bakker, M. R., Zeller, B., Bazot, S., Bosc, A., Plain, C., Lata, J. C., Priault, P., Barthes, L., and Loustau, D.: Seasonal variations of belowground carbon transfer assessed by in situ ¹³CO₂ pulse labelling of trees, *Biogeosciences*, 8, 1153–1168, doi:10.5194/bg-8-1153-2011, 2011.
- Epron, D., Bahn, M., Derrien, D., Lattanzi, F., Pumpanen, J., Gessler, A., Högberg, P., Dannoura, M., Gerant, D., Maillard, P., and Buchmann, N.: Pulse-labelling trees to study carbon allocation dynamics: a review of methods, current knowledge and future prospects, *Tree Phys.*, 32, 776–798, 2012.
- Esperschütz, J., Pérez-de-Mora, A., Schreiner, K., Welzl, G., Buegger, F., Zeyer, J., Hagedorn, F., Munch, J. C., and Schloter, M.: Microbial food web dynamics along a soil chronosequence of a glacier forefield, *Biogeosciences*, 8, 3283–3294, doi:10.5194/bg-8-3283-2011, 2011.
- Flanagan, L. B., Ehleringer, J. R., and Pataki D. E. (Eds.): *Stable isotopes and biosphere-atmosphere interactions*, Elsevier Academic Press, San Diego, US, 318 pp., 2005.
- Gammitzer, U., Moyes, A. B., Bowling, D. R., and Schnyder, H.: Measuring and modelling the isotopic composition of soil respiration: insights from a grassland tracer experiment, *Biogeosciences*, 8, 1333–1350, doi:10.5194/bg-8-1333-2011, 2011.
- Gavrichkova, O., Proietti, S., Moscatello, S., Portarena, S., Battistelli, A., Matteucci, G., and Brugnoli, E.: Short-term natural ¹³C and ¹⁸O variations in pools and fluxes in a beech forest: the transfer of isotopic signal from recent photosynthates to soil respired CO₂, *Biogeosciences*, 8, 2833–2846, doi:10.5194/bg-8-2833-2011, 2011.
- Kammer, A. and Hagedorn, F.: Mineralisation, leaching and stabilisation of ¹³C-labelled leaf and twig litter in a beech forest soil, *Biogeosciences*, 8, 2195–2208, doi:10.5194/bg-8-2195-2011, 2011.
- Kayler, Z. E., Kaiser, M., Gessler, A., Ellerbrock, R. H., and Sommer, M.: Application of ¹³C and ¹⁵N isotopic signatures of organic matter fractions sequentially separated from adjacent arable and forest soils to identify carbon stabilization mechanisms, *Biogeosciences*, 8, 2895–2906, doi:10.5194/bg-8-2895-2011, 2011.
- Máguas, C., Rascher, K. G., Martins-Loução, A., Carvalho, P., Pinho, P., Ramos, M., Correia, O., and Werner, C.: Responses of woody species to spatial and temporal ground water changes in coastal sand dune systems, *Biogeosciences*, 8, 3823–3832, doi:10.5194/bg-8-3823-2011, 2011.
- Ritter, W., Andersen, C. P., Matyssek, R., and Grams, T. E. E.: Carbon flux to woody tissues in a beech/spruce forest during summer and in response to chronic O₃ exposure, *Biogeosciences*, 8, 3127–3138, doi:10.5194/bg-8-3127-2011, 2011.
- Robinson, D.: ¹⁵N as an integrator of the nitrogen cycle, *Trends Ecol. Evol.*, 16, 153–162, 2001.
- Rütting, T., Boeckx, P., Müller, C., and Klemetsson, L.: Assessment of the importance of dissimilatory nitrate reduction to ammonium for the terrestrial nitrogen cycle, *Biogeosciences*, 8, 1779–1791, doi:10.5194/bg-8-1779-2011, 2011.
- Scheidegger, Y., Saurer, M., Bahn, M., Siegwolf, R.: Linking stable oxygen and carbon isotopes with stomatal conductance and photosynthetic capacity: a conceptual model, *Oecologia*, 125, 350–357, 2000.
- Seibt, U., Rajabi, A., Griffiths, H., Berry, J. A.: Carbon isotopes and water use efficiency: sense and sensitivity, *Oecologia*, 155, 441–454, 2008.
- Subke, J.-A., Carbone, M. S., Khomik, M., Stoy, P., and Bahn M.: Preface “Biotic interactions and biogeochemical processes in the soil environment”, *Biogeosciences*, 9, 1823–1825, 2012.
- Sutton, M. A. , Reis, S. , Billen, G. , Cellier, P. , Erismann, J. W. , Mosier, A. R. , Nemitz, E. , Sprent, J. , van Grinsven, H. , Voss, M. , Beier, C. , and Skiba U. : Preface “Nitrogen & Global Change”, *Biogeosciences*, 9, 1691–1693, 2012.
- Taneva, L. and Gonzalez-Meler, M. A.: Distinct patterns in the diurnal and seasonal variability in four components of soil respiration in a temperate forest under free-air CO₂ enrichment, *Biogeosciences*, 8, 3077–3092, doi:10.5194/bg-8-3077-2011, 2011.
- Werner, C. and Gessler, A.: Diel variations in the carbon isotope composition of respired CO₂ and associated carbon sources: a review of dynamics and mechanisms, *Biogeosciences*, 8, 2437–2459, 2011.
- Werner, C., Schnyder, H., Cuntz, M., Keitel, C., Zeeman, M. J., Dawson, T. E., Badeck, F.-W., Brugnoli, E., Ghashghaie, J., Grams, T. E. E., Kayler, Z. E., Lakatos, M., Lee, X., Máguas, C., Og J., Rascher, K. G., Siegwolf, R. T. W., Unger, S., Welker, J., Wingate, L., and Gessler, A.: Progress and challenges in using stable isotopes to trace plant carbon and water relations across scales, *Biogeosciences*, 9, 3083–3111, doi:10.5194/bg-9-3083-2012, 2012.
- Yakir, D. and Sternberg, L.: The use of stable isotopes to study ecosystem gas exchange, *Oecologia*, 123, 297–311, 2000.