Max Planck Institute for Biogeochemistry

Content

Biogeochemical Cycles in the Earth System
Mission and Structure

Scientific Units
Department Biogeochemical Processes
Molecular Biogeochemistry
Department Biogeochemical Systems
Department Biogeochemical Integration
Biospheric Theory and Modelling
Organic Paleobiogeochemistry
Carbon Balance and Ecosystems
International Max Planck Research School (IMPRS) for Global Biogeochemical Cycles

Research Service Facilities
Stable Isotopes
Gas Analytics
14C Analysis
Laboratory for Spectrometry
Routine Measurements and Analysis
Field Experiments & Instrumentation
General Services
Scientific Units

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Carbon, oxygen, hydrogen, and nitrogen: these four elements, essential for life on Earth, are continuously subject to biological, chemical and physical transformations. Bound in varying chemical combinations, they are released together with other organic compounds by the biosphere and are transported and distributed throughout the atmosphere, the hydrosphere and, on very long time scales, also the geosphere. Finally, they may find their way back to the biosphere to be converted again by various organisms. Since these transformations are interlinked and controlled by both the biology of the organisms as well as chemical and physical processes in the geo-, hydro- and atmosphere, they are known as the “biogeochemical cycles of the elements”.

Only rather recently has it become clear that the biogeochemical cycles are not just passive element flows subject to the physical environment, but have to be recognized as an interactive component of the Earth system. The atmospheric trace gases carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and water vapor (H₂O) exemplify such interactions. Although the air contains only low amounts of these gases, because of their properties as greenhouse gases, they have a decisive influence on the climate and, hence,

Parallel variations of atmospheric carbon dioxide (CO₂), methane (CH₄), and global temperature (relative to the mean for 1880-1899) over the last 400,000 years as determined from Antarctic ice cores by Petit et al. (Nature, 399, 429-436, 1999) and from in situ and other data for the past century. The dramatic increase of the atmospheric greenhouse gas concentrations during the last century, caused by direct human emissions, is clearly visible. (from Hansen, Clim. Change, 68, 269-279, 2005)

on the conditions of life on Earth. Conversely, the concentration and distribution of these gases is regulated by biological, chemical and physical processes occurring in the terrestrial biosphere, in the oceans and in the atmosphere. This opens up the possibilities for a multitude of feedbacks operating on various time scales between the physical climate system and the biogeochemical cycles, which have the potential to either stabilize or amplify perturbations of the coupled system. The most prominent demonstration of this interaction is the parallel variations of the atmospheric concentration of these gases and the temperature during the last glacial cycles as revealed from ice cores (Figure below).

These processes have not only been significant in the past, but are currently amplified by the intervention of human activities on a global scale through technological processes, without being
able yet to foresee the long-term consequences. Especially the worldwide burning of fossil fuels (oil, coal, gas) for energy production and the massive forest clearances for agriculture and other land use release carbon dioxide in substantial quantities and could re-establish an atmosphere and a climate comparable to earlier geological ages with enormous economic and societal consequences. In addition, the massive transition in land use and land management clearly has also huge impacts on ecosystems and biodiversity, which, however, are still largely unknown.

Analyzing the numerous biogeochemical interactions in the Earth system thus clearly represents an important and pressing scientific challenge. This has been recognized by the Max Planck Society by the founding of the Max Planck Institute for Biogeochemistry in Jena in 1997.

Global biogeochemistry cannot be researched in isolation but has to be seen as a new interdisciplinary field of study in the Earth sciences. Together, the different Earth sciences attempt to understand, quantify and ultimately predict the behavior of the very complex “Earth system” in response to natural and anthropogenic perturbations (Figure below).

Exemplary fundamental questions to be addressed are:
1. How is the Earth system organized? What processes control the flow of energy and matter between the different components? And how do the different components interact with each other?
2. What controls the distribution and availability of water?
3. How can the complexity of the Earth system be represented by theoretical and numerical models?
4. How can Earth system models and their components be evaluated and improved?
5. Which regions and components of the Earth system are particularly sensitive to climate change and human impacts?
6. Is it possible to “manage” the Earth system in the long term?

This demanding, fundamental research is performed jointly within the Earth System Research Partnership of the Max Planck Society, consisting of the MPI for Meteorology in Hamburg, which studies the physical climate system, i.e. the atmosphere, the ocean and the land surfaces, the MPI for Chemistry in Mainz, focusing on atmospheric chemistry and aerosols, and the MPI for Biogeochemistry in Jena.

Highly simplified, schematic diagram of the major components and interactions which constitute the “Earth system” (Earth System Research Partnership, MPI for Biogeochemistry, MPI for Meteorology, MPI for Chemistry, 2006).
A three-pronged approach is pursued to address this question:

1. Process studies and experiments are needed to identify and quantify key organisms and processes, together with their environmental drivers, which control the exchange fluxes of biogeochemical substances between the different ecosystem components and their surroundings.

2. Long-term comprehensive biogeochemical observations are needed to quantify and monitor the large-scale behavior of surface-atmosphere exchange fluxes.

3. Theory and modeling tools need to be developed to scale up and integrate a great quantity of point information for a consistent representation of biogeochemical processes in comprehensive Earth system models, in order to study biogeochemical-climate feedback on both a regional and global scale.

Our institute is structured in three departments, which loosely reflect these three research approaches:

1. The Department Biogeochemical Processes, directed by Susan Trumbore, investigates terrestrial ecosystem processes with a special emphasis on soils.

2. The Department Biogeochemical Systems, directed by Martin Heimann, looks at atmospheric biogeochemical trace gases, integrating regional surface exchanges.

3. The Department Biogeochemical Integration, directed by Markus Reichstein, studies the nature and the role of interactions between the biosphere and the atmosphere using a modeling approach, integrating observations from the organismic to the global scale.
In addition, independent research groups complement the departmental approaches:

- The W2 Group Molecular Biogeochemistry, headed by Gerd Gleixner, explores terrestrial organic matter cycling, metabolic isotope fractionation, and paleoclimate reconstruction at the molecular level.
- The Interdepartmental Max Planck Fellow Group Functional Biogeography, jointly headed by Christian Wirth (Fellow) and Jens Kattge, explores plant biodiversity and its role in biogeochemical cycles.
- The Emeritus Group of Ernst-Detlef Schulze is engaged in carbon balance and ecosystem research.
- The Max Planck Research Group Biospheric Theory and Modeling, headed by Axel Kleidon, develops and uses theoretical and numerical methods to investigate the role of the biota in driving global geochemical cycles within the Earth system.
- The Max Planck Research Group Organic Paleobiogeochemistry, headed by Christian Hallmann, investigates the evolution of life and environments on the early Earth using a combination of fieldwork and organic geochemistry.

Research in biogeochemistry is highly interdisciplinary and international. Success can only be achieved through a high degree of integration between scientific disciplines, and a strong link is necessary both between modeling and observation, and between theoretical and experimental research. Biologists, physicists, meteorologists, geologists, chemists, computer specialists, mathematicians, and statisticians work together closely in our research units, our Max Planck Research School for Global Biogeochemical Cycles, and the central service facilities (see below). Moreover, our staff maintains close co-operations with partner scientists in numerous research institutions around the world.

Our central service facilities support our scientists by providing the following state-of-the-art analytical and technical services:

- Stable isotope and gas analytics; ICOS lab
- Chemical analytics
- 14C-analyses
- Computing
- Field instrumentation and experiments
- Mechanic and electronic workshops
- Library

Facts & Figures: More than 200 people from 26 different nations are currently (2013) affiliated with the institute, including approximately 65 scientists and 45 PhD students. The annual budget turnover is about 10 Mio Euro, of which 15–20% comes from third-party funds. The MPI for Biogeochemistry, founded in September 1997, is part of the German Max Planck Society for the Advancement of Science, an independent, non-profit research organization that primarily promotes and supports basic research on natural, life, and social sciences at its 80 institutes. The Institute is located on the Beutenberg Campus, a science campus that is home to 12 different research institutions and start-up ventures.
Terrestrial ecosystems are undergoing rapid and unprecedented change. Humans have transformed more than half of the global land surface by direct activities such as deforestation and management of land for agriculture or pasture. All land areas experience effects of climate change, elevated carbon dioxide levels and air pollution. At the same time, the land surface is a key component of the global climate system and an important regulator of atmospheric trace gases. Our department seeks basic understanding of the biogeochemical functioning of ecosystems, and the consequences of current changes for climate and the sustainability of vegetation and soils.

Quantifying responses and feedbacks in complex, coupled systems requires a range of tools and approaches. Field studies determine fluxes of energy, water and gases between land and atmosphere in ecosystems ranging from tropical forests and savannahs to managed forests and grasslands in Germany. Laboratory and field experiments manipulate individual factors such as temperature, biodiversity or nutrient availability in order to document how different components of the ecosystem respond to changing environmental conditions. In both field and lab investigations, we develop new analytical tools using isotopes or other tracers that allow us to evaluate the importance of processes across a range of spatial and temporal scales.

We target our research on particular processes and ecosystems where significant uncertainties currently limit the predictive ability of global climate models, and where responses to climate change or direct human management might be expected in the coming century. Because we work at a variety of spatial scales, from organism to ecosystem to region to globe, we collaborate actively with the other departments of the Institute to integrate across these scales using isotopic tracers, models, and spatial analysis tools. Regions of

Portrait of the Director

Susan E. Trumbore has been the Director of the Department Biogeochemical Processes since 2009. Trumbore's research is in the role played by land vegetation and soils in the Earth’s carbon cycle. She has received a number of honors and awards, including election to the US National Academy of Sciences and Fellowship in the American Geophysical Union. The department was founded by E.-D. Schulze, who continues his scientific activities as an Emeritus member of the Institute.

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special emphasis include investigation of local land management and drought in Germany, documenting disturbance and carbon allocation in tropical forests of the Amazon Basin, and the vulnerability of carbon stored in high latitude soils to warming.

Focus 1. The origin, fate and vulnerability of organic matter stored in soils
Although soil organic matter is fundamental to human well-being and to a number of global biogeochemical cycles, we lack basic understanding of processes that store carbon in soils, and how factors such as climate, organisms, and mineral composition combine to determine how long it remains stabilized. Several groups of our department work on this topic, with goal of synthesizing information on soil carbon stocks, the chemistry and age of the organic matter, and how those are affected by changing vegetation, temperature, moisture, and land management.

Focus 2. Understanding plant allocation, respiration, defense and mortality
Plants use the products of photosynthesis for respiration, growth, defense, storage, and transfer to roots and soil. However, we do not have good theories to predict how allocation strategies among those pathways are determined, or how those allocation patterns will respond to changes in environmental conditions or the community composition. We have developed methods to use carbon isotopes to track allocation pathways and the residence time of carbon in plants. Experiments using drought to manipulate the supply and allocation of carbon in trees provide information on the links between carbon and water cycles and the causes of tree mortality. Measures of the age and use of plant storage and respiration allow improved understanding of how plants respond to stress.

Focus 3. The role of functional traits and biodiversity in biogeochemical cycles
The biota that inhabit ecosystems determine the role of biological systems in global element cycles. A major challenge lies in determining what aspects of the organisms present are required to adequately describe the response of ecosystems to change. Research ranges from experiments that manipulate biodiversity, to investigation of the long-term effects of land management. In tropical forest, we are studying the effects of disturbances, including fire and windthrow associated with downbursts, on species composition and carbon allocation patterns. We will use these field studies as tests of how well plant traits can represent function for analysis at larger spatial scales.

Focus 4. Reconstruction of Past Vegetation and Climate
Plants make compounds that, through their isotopic composition, record environmental variables. These relationships are defined using our ongoing studies and experiments, and can then be applied to reconstruct past variations recorded in tree rings, paleosols, or lake sediments. Ongoing research looks at the effects of past drought in German forests, and changes in monsoons on the Tibetan plateau.

A rain exclusion experiment to determine the causes of tree mortality caused by drought includes sensor monitoring of stressed trees and measurement of carbon fluxes.
Soil is an important site factor and its fertility determines plant and food production. It is also the habitat for a huge and diverse community of soil organisms which are responsible for the decomposition of dead organic material. Soil organic carbon content is a good indicator for site fertility, and soils are the biggest terrestrial reservoir for organic carbon on Earth. This reservoir is fed from carbon fluxes entering the soil (mainly as dead plant material), and reduced by carbon being mineralized (especially by microbes). As mineralization leads to the release of CO₂ into the atmosphere, soils can be a significant source of this greenhouse gas. Therefore it is important to understand soil carbon dynamics and the response of soil processes to global environmental changes and land use.

Soil processes determining carbon turnover are still largely unresolved due to their high complexity. Soil processes depend on interactions between vegetation composition and productivity, soil organisms abundance and activity, abiotic soil properties, and climate. They are additionally modified by land use and management, e.g. by vegetation changes, fertilization, or soil disturbance by plowing. The huge spatial variability of soils, their invisibility from the surface, and destructive sampling procedures so far hampered better characterization of soil carbon turnover and upscaling of point measurements to larger areas.

Focus 1. Soil carbon monitoring

Today it is assumed that European forests and grasslands are soil carbon sinks while croplands are minor sources. Evidence comes from gas exchange measurements and model results. Because of the large numbers of samples and long time periods required, direct observations of changes in soil carbon stocks are very difficult. Still they are necessary to verify the trends described above. In 2004, our group started a long term plot-based soil carbon monitoring at 12 European FLUXNET sites,
including forests, grasslands, and croplands (CarboEurope-IP). The first forest site, an old growth forest in central Germany, was resampled in 2009. The results indicate that the soil was a small net carbon sink during the last five years which is in line with gas exchange measurements. The resampling of other sites is ongoing.

**Focus 2. Mechanisms determining soil carbon storage**

Dead plants are the main source for new carbon entering the soil, but only a fraction of this carbon will form new soil organic matter. We follow the flow of carbon from plants into the soil using stable isotope labeling of living plants in greenhouses. This allows us to determine how much of the plant carbon is respired, integrated in the soil microbial biomass, or stored as soil organic matter under different environmental conditions (QUASOM-Project).

All organic material in soils is potentially degradable by microorganisms, provided the environmental conditions favor microbial growth. However a number of mechanisms reduce the bioavailability of organic material in soils. One of those mechanisms is the association of organic carbon with minerals. We want to characterize the factors driving the mobilization and immobilization of organic carbon adsorbed to the mineral phase, and the relevance of this protection mechanism for different soil types.

**Focus 3. Land use, biodiversity, and environmental changes**

Ecosystem processes are affected by different kinds of disturbances, such as land use change, climate change, or nitrogen deposition. Within the Biodiversity Exploratories (http://www.biodiversity-exploratories.de/) we are studying the effect of land use and management, and related changes in plant and microbial diversity, on soil carbon storage and turnover at the plot and landscape scale. As we found out, changes in plant species composition affect the amount and quality of organic matter entering the soil. Roots are frequently overlooked in ecosystem studies and we are especially interested in their role for soil carbon storage at different depths. We also address soil moisture and temperature effects on soil processes in laboratory and field experiments.

In greenhouses we study the fate of new plant-derived carbon in the soil, by continuous labeling of peppermint plants. We further determine how new plant carbon sources affect the decomposition of old soil organic matter (QUASOM field experiment).
Trees are exceptional organisms and form the most important terrestrial ecosystem – forests. These cover nearly 30% of the land surface and foster the majority of our planet’s terrestrial biodiversity. Forests also play a central role in the cycling of life-sustaining elements like carbon and nitrogen and control the global redistribution of water and solar energy. Their distribution is limited to regions where heat sums are sufficient for growth and reproduction and where precipitation is abundant.

Changes in precipitation pattern over the last decades have increased the frequency and severity of drought events with catastrophic consequences for forest ecosystems. Tree mortality rates have increased in many regions and widespread vegetation die-off events from heat and drought have been observed all over the globe – and this tendency is expected to increase during the upcoming decades.

Surprisingly enough there are still large knowledge gaps on how drought kills trees. Current working hypotheses – carbon starvation, impeded carbon translocation from sources to sinks within the tree and hydraulic failure of cellular metabolism – are still not entirely supported by experimental evidence (Figure next page, bottom right).

A thorough understanding of the mechanisms underlying drought-induced mortality is key to understanding the impact of future drought events on vegetation dynamics and on the cycling of life-supporting elements through forest ecosystems. The Jena Drought Stress Experiment comprises a series of experiments specifically designed to investigate the underlying processes of drought-induced tree mortality. The experimental setup allows a detailed assessment of morphological, functional and physiological processes in trees under induced lethal drought and carbon starvation.

The simultaneous impact of drought on carbon assimilation (through stomatal closure) and carbon...
translocation (through reduced hydration of vascular tissue) hampers a clear identification of their individual contribution to tree death. This is why we are simulating drought effects on carbon assimilation by withholding CO2 from the atmosphere while simultaneously maintaining vascular tissue hydration at functional levels. This allows us to partition drought effects on carbon assimilation from (simulated) effects on carbon translocation. To do so we have designed and implemented a unique and complex facility at the MPI for Biogeochemistry in Jena (Figure at top of page).

Results obtained so far indicate that drought stress disrupts the physiological integrity of trees by separating individual tree compartments (leaves, branches, stem, roots) from each other. Above-ground tissues seemingly died from hydraulic failure (figure below) while roots were able to maintain functional levels of tissue hydration for longer and hence were capable of remobilizing stored carbon better than above-ground tissues. This didn’t prevent our trees from dying; roots died last and from carbon starvation.

The results of our experiments significantly contribute to the general understanding of drought-induced tree mortality. In doing so, they will also be useful for developing mitigation strategies against climate-change-type tree and forest mortality in a warmer and drier future world. However, we acknowledge the limitations of greenhouse and garden experiments with respect to their implication for natural forests. This is why we are currently planning to extend our research to similar manipulations in natural ecosystems. This will increase the general outreach and the applicability of the expected results.

Experimental trees (spruce) during the field trial. Droughted trees died after ~13 weeks (right) while control trees survived the experiment (left).

During drought trees have to reduce water consumption (stomatal closure) but also prevent carbon assimilation. This may cause carbon starvation on the long run but only if plant hydration is sufficient for cellular survival and allows the mobilization of stored carbon.
Landscape Processes

Scaling biogeochemical measurements from point locations (e.g., soil pits, flux towers, vegetation field-plots) to broader scales is confounded by the high degree of spatio-temporal heterogeneity inherent in ecological systems. We explore the processes that create, maintain and modify landscape heterogeneity, and assess the consequences of heterogeneity for biogeochemical functioning in the context of global change.

Landscapes are mosaics of different patches and gradients, varying in size, shape, composition and spatial configuration at multiple scales. This spatio-temporal heterogeneity has often been ignored in ecology, which traditionally focused on similarities rather than differences in ecological systems. We use remote sensing tools to explicitly quantify heterogeneity within landscapes and explore its underlying causes. We make extensive use of airborne LiDAR (laser altimetry) to map landscape and vegetation structures in three-dimensions (3-D) across a broad range of ecosystems including savannas, tropical forests, and temperate forests (Figure next page, top). We aim to improve understanding and modeling of ecosystem processes across scales and inform biodiversity conservation and land management.

**Focus 1. Topo-edaphic controls on ecosystem processes**

Ecological processes are seldom uniform or random in space, as landscapes contain spatial structures that mediate how energy, materials and organisms move through them. Underlying soil type and hillslope morphology are two primary controls that influence biogeochemical processes, but spatial heterogeneity of these factors is poorly accounted for in regional and global models. We aim to improve understanding of how ecological processes vary across landscapes and to facilitate integration with modeling efforts.

We are studying a range of hillslope catenas (topographically linked sequences of soil, water and vegetation) on different geologies across a rainfall gradient in South African savannas to better understand how climate and substrate influence biogeochemical processes (such as soil carbon storage and flux) at hillslope scales. We are currently expanding this research to sites in Australia and South America to gain a global perspective on hillslope-scale processes in savanna systems.

**Portrait of the Group Leader**

Shaun Levick studied landscape ecology at the University of the Witwatersrand, South Africa, where he obtained his PhD in 2008. He worked as a postdoc in the Carnegie Institution of Science, Stanford, CA, and as a remote sensing scientist at GNS Science, New Zealand, before joining the Max Planck Institute in 2012. He leads research on the heterogeneity of ecological systems and is particularly interested in savanna and tropical landscapes.

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Focus 2. Organisms as ecosystem engineers

“Ecosystem engineers” are organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in the abiotic or biotic environment. We are studying the ecosystem impacts of two such engineers in African savannas - termites and elephants.

Termites build their mounds from clays and are a major source of particle and nutrient redistribution in savannas. We are using LiDAR data collected by the Carnegie Airborne Observatory (CAO, http://cao.ciw.edu) to map the spatial location of termite mounds (Figure below) to gain better understanding of the spatial distribution and density of mounds on different soil types and under different rainfall regimes. We are also conducting a range of field studies to assess the scale of termite mound influence as a forage resource for other organisms.

At the larger end of the organism spectrum, elephants modify the physical environment by breaking branches and pushing over trees. Large trees form islands of biogeochemical activity within the landscape matrix, but are disappearing in many savannas through the interaction of increasing elephant densities and fire. We are using satellite imagery and airborne LiDAR (from the CAO) to understand the rate and spatial distribution of elephant impacts on large trees across different substrate, hillslope and rainfall settings. This research is conducted in close collaboration with South African National Parks (SANParks) scientists to understand the biogeochemical consequences of tree loss, and provide crucial information for the setting and evaluation of biodiversity conservation objectives.

Focus 3. Disturbance effects on ecosystem processes

The vegetation present at a given point in a landscape is a function not only of climate and environmental resources, but also of various disturbance agents acting across that landscape. In savannas, vegetation height and biomass is often much lower than what we would expect from climate potential alone, as fire, herbivores, wind and human land-use disturbance reduce standing biomass and are major determinants of vegetation structure and dynamics. We aim to understand how disturbance effects vary spatially across landscapes, and how the relative importance of different disturbances varies with spatial context.

Fire effects on carbon storage in savannas represent significant uncertainty in global carbon budgets, driving disparities between potential and realized biomass. We are using a network of long-term fire experiments in the savannas of southern Africa, northern Australia, and South America to improve understanding of how fire influences vegetation structure and carbon storage. This research is closely connected with land managers in these systems, who are interested in the biodiversity and carbon management implications of different fire policies.
Ecosystem ecology integrates processes occurring in both vegetation and soils, and focuses on understanding the mechanisms controlling stocks, fluxes, transfers, and transformations of carbon and other biogeochemically-relevant elements. Compared to the theory of population and community ecology, theoretical ecosystem ecology is still in a development phase, which offers opportunities to contribute to this branch of ecology.

An important aspect of ecosystem ecology is carbon cycle research and global change. Natural and anthropogenic ecosystems store large amounts of carbon and play a significant role in regulating the rates of cycling of other biologically-relevant elements. Advances in theoretical ecosystem ecology can lead to improved numerical models to predict the interactions between the carbon cycle and climate as well as the effects of human activities on ecosystem’s carbon and nutrient cycles.

Overarching research questions that guide our work include: What is the sensitivity of terrestrial ecosystems to simultaneous changes in climatic variables as well as in nutrient additions or removals? What controls and how can we characterize the residence and transit time of biogeochemically-relevant elements in ecosystems? Are there general mathematical models to represent biogeochemical cycling in terrestrial ecosystems? How can temporal variability, system heterogeneity, and perturbations be included in these general models?

Focus 1. Soil organic matter dynamics

Currently, one of the major challenges in Earth system science is to reduce the uncertainty related to a possible positive feedback between soil carbon stocks and global atmospheric temperatures. Soils store large quantities of carbon, and as temperature increases more carbon can be transferred from soils to the atmosphere by microbial respiration. In the atmosphere this extra carbon can cause more warming which in turn can promote more carbon

Portrait of the Group Leader

Carlos A. Sierra obtained a Bachelors degree in forestry at the National University of Colombia, and received his Master of Science and PhD in forest science from Oregon State University. He joined the Max Planck Institute for Biogeochemistry in 2010 as a postdoc and since then started building up the Theoretical Ecosystem Ecology and Modeling group within the Department of Biogeochemical Processes.

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release from soils.

This problem however, has been difficult to study due to limitations in observational data and the lack of a coherent theoretical framework. We are working on advancing the mathematical theory of soil organic matter decomposition; specifically, on how organic matter is stabilized and destabilized in soils, and how this processes responds to changes in multiple environmental variables such as climate.

To integrate our theoretical work, we are currently developing the SoilR modeling framework. This is an add-on software for the R programming language. SoilR integrates theoretical concepts we have developed and allows for the implementation of a large number of different soil organic matter decomposition models, with multiple choices for the temperature and moisture responses of decomposition. It is open source software freely available on the internet.

Focus 2. Ecosystem-level carbon allocation

When carbon enters a plant through photosynthesis it can be allocated to foliage, branches, stems, or roots, or it can also be respired during cell metabolism. There are a large number of observations, experiments, and models addressing this research problem, but there is a paucity of work on synthesis and development of mathematical theory.

Our work in this area focuses on ecosystem level carbon allocation rather than at the single-plant level. At the ecosystem level we study how the products of Gross Primary Production (GPP) and Net Primary Production (NPP) are assigned to different ecosystem compartments such as foliage, stems and roots as well as how much it is respired.

Currently we are studying the role of belowground resources (nutrients and water) on the allocation of the products of NPP. We are using as a model system an Amazon forest landscape that includes a series of forests growing under soils at different levels of development, but under similar climatic characteristics.

Additionally, we are developing a mathematical theory to integrate the theories of allometry and allocation under a common framework. We expect this work to help us to better understand global patterns of allometry and allocation, and to integrate these theories in new numerical models.

Focus 3. Forest carbon balance

Carbon cycling at the ecosystem level integrates above and belowground processes related to transfers of carbon among different pools and transformations to different compounds. We explore the temporal dynamics of forest carbon stores and investigate how they respond to natural and anthropogenic disturbances.

In this area we have developed models of ecosystem carbon accumulation in regrowing forests for the main carbon pools, and have studied the consequences for carbon accounting in continental-scale carbon budgets. We also have explored the effects of forest management on ecosystem carbon stores and their potential for carbon sequestration projects.
During the last centuries humans have increasingly modified the environment worldwide, with large consequences for biodiversity. Every day up to 130 biological species go extinct on our planet and human activity promotes the spread of alien species across the globe. How are ecosystems influenced by the loss or addition of species? How will the ecosystems interact with climate-driven shifts in disturbance regimes? How will these interactions modify species distribution - and vice versa? To address these questions we have to bridge the gap from species occurrence and richness to biodiversity in terms of variability of biogeochemical processes linked to ecosystem functioning. Here plant traits – the morphological and physiological properties of plants – determine how the primary producers respond to environmental factors. Traits provide a quantitative link from species occurrence to ecosystem functioning. However, so far data on plant traits have been dispersed over numerous databases, most of them not available to the scientific community. The functional biodiversity group has therefore initiated an international initiative, called TRY, to consolidate the data basis of plant traits at global scale and make these data available.

The TRY initiative (www.try-db.org) is an international network of vegetation scientists from more than 100 institutions, jointly headed with DIVERSITAS (International Programme of Biodiversity Science), IGBP (International Geosphere-Biosphere Programme), University of Leipzig, Multidisciplinary Institute of Plant Biology (IMBIV-CONICET, Córdoba, Argentina), Macquarie University (Sydney, Australia), CNRS and University of Paris-Sud (France). So far TRY has brought together 93 separate plant trait databases to produce a global database containing 3 million trait records for about 69,000 of the world’s ~300,000 plant species. This database covers more than 1,000 different plant traits, ranging from leaf area, to fire tolerance, and nitrogen fixation.

The Functional Diversity of Plants

The functional diversity of plants determines the response of the terrestrial biosphere to environmental changes - ranging from acclimation and adaptation to migration or extinction of single species or whole ecosystems. In the group Functional Biodiversity we therefore aim at consolidating empirical data bases to characterize plant functional diversity at global scale, understand links to ecosystem functioning, and improve its representation in Earth system models.

Portrait of the Group Leader

Jens Kattge studied biology and chemistry with major subjects plant ecology and soil sciences at the University of Gießen, where he also received his PhD. In 2002 he joined the Max Planck Institute for Biogeochemistry working as a postdoc on terrestrial biosphere modeling and data assimilation. He has been head of the group ‘Functional Diversity of Plants’ since 2010.

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capacity. The database was developed and is hosted at the Max Planck Institute for Biogeochemistry in Jena. Several groups worldwide use plant trait data via TRY. Within the Department of Biogeochemical Processes, the TRY database is used to study the impact of disturbances on species composition and ecosystem functioning in the Amazonian rain forest, and provides empirical large-scale context for specific process studies, e.g. plant respiration, litter quality, or decomposition rates.

In addition, research of our functional biodiversity group focuses on the following areas:

Focus 1. Quantifying and scaling plant trait variation at the global scale

We aim to use the rich compilation of data in the TRY database to quantify and understand patterns of plant trait variation at the global scale. For example, through projects such as ‘Plant Functional DIVersity of GRASSlands’ (DIVGRASS) and a funded collaboration with the our Department of Biogeochemical Integration and the University of Minnesota, we are characterizing plant trait variation in terms of statistical distributions and focusing on describing how plant traits vary spatially and in relationship to climate and soil characteristics. Other measures of variation allow us to identify phylogenetic constraints, explore the covariation of different traits, and disentangle variation within and between species and plant functional types, including those commonly used in global vegetation models.

Focus 2. Plant functional diversity and ecosystem functioning

The exchanges of carbon dioxide, water vapor, and energy are emergent properties of the ecosystem - the interplay of soil and vegetation. Plant trait data are required to link ecosystem functions and properties to plant function and diversity: Is there an effect of plant functional diversity on ecosystem functions and properties (a) between sites and (b) within? Here, eddy covariance measurements provide the opportunity of moving beyond “static” measures of ecosystem function like peak biomass towards using dynamic measurements, like evaluation of gross primary production (GPP), or drought sensitivity to determine the importance of functional diversity in controlling ecosystem function. In cooperation with our modellers this focus brings together plant traits and eddy covariance measurements.

Focus 3. Improving the representation of the terrestrial biosphere in Earth system models

Many Earth system models employ plant traits as parameters, but these models are still far from fully exploiting the wealth of available information. In cooperation with the Max Planck Institute for Meteorology and the IGBP initiative on Biome Boundary Shifts, we connect the respective scientific communities with the goal to channel plant ecological information into Earth system models. Getting from plant traits to model parameters and dealing with numerous covariates requires new statistical tools. We apply and develop inversion techniques and Hierarchical Bayesian models. Typical results that have also been applied in global models show that e.g. the nitrogen/phosphorus stoichiometry of plant leaves is dominated by phosphorous limitation on old soils in the tropics and southern hemisphere, with consequences for carbon sequestration.

Location of partner institutes (red) and sample sites (cyan) of the TRY network (status 03/2011).

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Biomarkers are molecules that contain information on the presence of individual organisms in the environment. They span a variety of molecules with different chemical characteristics and are read using the “omic” approaches. DNA and RNA, for example, contain the genetic information of organisms that can be read to identify individual organisms. Both molecules, however, are very easily decomposed in the environment and consequently provide only snapshots of actual organisms and communities. In contrast, lipids are compounds used to make cell membranes and cuticular waxes that can persist for a long time in the environment, and can even be isolated from Archaean rocks. Lipidomics is used to develop lipid profiles that allow identifying individuals or groups of organisms as well as profiles characteristic for environmental conditions including salinity, anoxia, and desiccation.

The key questions in molecular biogeochemistry are: Who is there, what are they doing, and why?

Proteomic and metabolomic approaches bridge from the presence of organisms to their function in the environment. However, in order to explore the function of individual processes and in particular how the microbial fluxes link to the overall functioning of ecosystems, additional information is drawn from the isotopic information of biomarkers. Compound-specific isotopes (13C, 14C, 15N, 18O and 2H) of biomarkers trace the flow of matter through the element cycles. Our group combines approaches using the natural abundance of stable isotopes, isotope labeling, and stable isotope probing (SIP) to quantify key processes in the environment.

Focus 1. Understanding the origin, fate and stability of organic matter in soils

Soil organic matter (SOM) remains the largest single unknown in the terrestrial carbon cycle. We investigate in various projects how abiotic factors, like organic matter input, parent material, humid-
ity and temperature (see also QUASOM project) as well as biotic factors such as stand age, plant, and microbial diversity, influence SOM storage. The isotopic information of $^{13}$C, $^{14}$C, and $^{15}$N of biomarkers from individual compounds and fractions determine the molecular turnover of SOM and suggest high vulnerability of SOM stored in soils.

To understand the role of dissolved organic carbon (DOC) in the environment we determine its molecular and isotopic composition. The molecular fingerprint of DOC established by pyrolysis-GC/MS and LC/MS helps to identify sources of DOC. The isotopic content of DOC in soil depth profiles suggests that DOC from the surface is reactively transported in the soil and that DOC in deeper soil horizons is not related to the DOC in upper soil horizons.

Focus 2. Understanding carbon flow in plant metabolism
Carbohydrates are the central molecules in plant metabolism. In the daytime they transport energy and carbon fixed by photosynthesis to support respiration, storage, growth and defense. At night, they provide energy for the cellular metabolism using mitochondrial respiration. However, the regulation of carbohydrate metabolism and the role of different processes in plant metabolism are still not completely understood. Our group develops and applies molecular techniques to use the isotopic information of plant metabolites to trace the flow of carbon in plants and to understand its regulation.

Focus 3. Understanding the role of biodiversity in biogeochemical cycles
Plants react not only to abiotic factors like climate, but also to the presence of other plants and microorganisms in the soil. The interaction can be positive if, for example, resources are used complementarily but also negative if pathogens are infecting plants. At the community level, these interactions are difficult to investigate. Molecular tools can help to differentiate between the responses of individual species and communities. We focus on the effect of tree and grassland diversity on (1) the link between above- and below-ground diversity; and (2) the link between plant diversity, soil organic matter (SOM) dynamics and export of dissolved organic matter. In short term experiments we use isotopic labeling to trace the effect of diversity on how carbon is allocated from plants to soil microorganisms and SOM. In the long term we investigate if higher plant diversity assures a long term success of the community, even if some individual species of the community may fail in events like drought, late frost, and flooding (insurance hypothesis of biodiversity).

Focus 4. Understanding and reconstructing past climate and vegetation dynamics
Understanding the links between ecosystems, past, and present climate will improve our prediction for future climates and how they may affect biodiversity and ecosystem function. Reconstructions of the Holocene climate are strongly linked to information from polar ice cores, while climate reconstructions for larger areas that permit separation of the effects of local climate effects from large-scale circulation patterns are still very sparse. We explore the use of hydrogen isotopes in biomarkers as a proxy for palaeoclimate reconstructions. A major focus has been the construction of quantitative transfer functions linking hydrogen isotopes to the hydrologic cycle across humid, tropical, boreal, and mountain ecosystems. These methods are now being applied to the large-scale climate reconstructions of monsoon variation in the past 10,000 years on the Tibetan plateau.
Biogeochemical cycles are represented in the atmosphere by several important greenhouse gases, such as carbon dioxide, methane and nitrous oxide. In the Department of Biogeochemical Systems we develop methods to measure these gases in situ and by remote sensing, we expand the measurement network to remote hot-spot regions such as Siberia and Amazonia, and we develop and apply numerical models to quantify the large-scale sources and sinks of the greenhouse gases.

Many of the global biogeochemical cycles are reflected in the atmosphere by one or several trace gases such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), or also aerosols. Spatio-temporal variations of these tracers (and other quantities linked to them such as their isotopic composition) contain important information on location, magnitude, and temporal variability of the various source and sink processes of the species of interest. The atmosphere thereby is used as a natural “integrator” of the complex pattern of surface fluxes because of the rapid mixing of air. Atmospheric measurements may thus be used to observe surface processes on a range of spatial and temporal scales, from a small-scale regional ecosystem to entire continents and the globe. Thereby, atmospheric transport by winds and mixing has to be taken into account by using three-dimensional numerical meteorological models in an inversion or data assimilation mode. In the Department of Biogeochemical Systems we develop and apply this “top-down approach” in four focus areas:

Focus 1. Expansion of the atmospheric network of in situ measurements of high-accuracy biogeochemical trace species
The current global atmospheric network for biogeochemical trace gases contains many gaps in important areas. An effort therefore is directed at the establishment of new measuring stations in undersampled locations, which constitute “hot-spots” in the Earth system. Geographically we pursue this along three directions: (1) A string of tall towers from Europe into the Eurasian taiga at 60°N including the 300 m high measurement mast in central Siberia (ZOTTO, Figure next page, left). (2) A line of stations along the eastern Atlantic Ocean on remote islands and coasts (e.g., Shetland, Cape Verde, Namibia) for monitoring oceanic processes and air leaving the African continent. (3) Jointly with the MPI for Chemistry

Portraits of the Director

Martin Heimann is Director of the Department Biogeochemical Systems at the Max Planck Institute for Biogeochemistry since 2004. He is a member of the Max Planck Society, honorary professor at the Friedrich-Schiller-University of Jena, and elected member of the Academia Europaea. Over the last three decades Martin Heimann has worked on analyzing and modeling the global carbon cycle and its interaction with the physical climate system.

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in Mainz and partners in Brazil we will build and operate a 300 m tall measurement mast in central Amazonia (ATTO). A critical new development are quasi-continuous, concurrent observations of a whole suite of biogeochemical trace species, which allow us to discriminate between different source/sink processes.

**Focus 2. Development of new measuring techniques and observing systems**

The small spatial and temporal variability of long-lived biogeochemical atmospheric trace gases necessitates measurements with extreme accuracy. Ensuring this in remote areas under harsh environmental conditions poses a serious technical challenge. We explore new techniques, such as miniaturization of measurement devices for the deployment on routine civilian aircraft, application of ground-based Fourier Transformation Near-Infra-Red Spectroscopy of the sunlight, and, in collaboration with other partners, the development of new systems for space-based remote sensing of atmospheric biogeochemical trace gas concentrations.

**Focus 3. Linking atmospheric point measurements with regional model grid averages**

A critical “Achilles heel” in present regional and global inversion systems is the representation of point measurements in grid-based atmospheric models, especially if the measurements are taken over land covered by a heterogeneous mosaic of greenhouse gas sources and sinks. In order to bridge this gap, we conduct small and regional scale process studies by means of campaigns with a high density of observations using in situ stations, aircraft and remote sensing, together with high resolution regional meteorological modeling systems for the analysis.

**Focus 4. Development and application of atmospheric inverse modeling and data assimilation frameworks**

The determination of surface fluxes from atmospheric observations requires the use of realistic numerical models for the simulation of the atmospheric transport. Since in most cases observations from only a limited number of atmospheric stations are available, the underlying mathematical inversion problem is highly underdetermined. We attack this problem with a range of mathematical methods and by incorporating additional measurements: e.g. other atmospheric trace gas observations, surface properties such as the “greenness” of the vegetation seen from space, vegetation distributions and other geographical data. The ultimate goal is the development of a data assimilation framework consisting of land and ocean surface biogeochemical modules coupled to an atmospheric meteorological model. This is then being optimized in a consistent way by the wealth of available observations, similar to what is being done routinely in numerical weather forecasting. With these tools, we can quantify and monitor where and how biogeochemical trace gas budgets respond to climatic (e.g. heat, drought) and human (e.g. fossil fuel burning, fires, deforestation) impacts (Figure below). This provides important information for the improvement of modules of biogeochemical cycles in global comprehensive Earth system models.

![Zotino Tall Tower Observatory (ZOTTO): a 300 m tall mast for the long-term monitoring of biogeochemical trace gases, aerosols and atmospheric chemistry which we established in central Siberia together with the MPI for Chemistry and the Institute of Forest, Krasnojarsk; funded by the Max Planck Society.](image)

![Global distribution of carbon dioxide sources and sinks determined from atmospheric measurements (black triangles: monitoring stations) with the Jena inversion system averaged from 1996 to 2007 (Rödenbeck et al., 2003, ACP, updated). Units: gC m⁻² yr⁻¹, blue colors denote sinks, yellow and red colors denote sources. The imprint of the emissions from the highly industrialized regions in the northern hemisphere is clearly visible.](image)
Greenhouse gases like carbon dioxide, methane, or water vapor can be measured very accurately with in-situ instruments that sample the air around them. This becomes increasingly difficult for higher altitudes. However, the ability of greenhouse gases to absorb infrared radiation allows measuring them from a distance. When infrared radiation travels through the atmosphere, it is both absorbed and emitted by greenhouse gas molecules in a characteristic way. By detecting and analyzing this radiation, one can derive the abundance of many greenhouse gases. This can be done from above by a satellite as well as from the ground.

Remote sensing methods that observe natural electromagnetic radiation are called “passive” methods. Some constituents of the atmosphere like aerosols are better observed with “active” methods. For active remote sensing, an artificial light source, like a laser, is used to illuminate the part of the atmosphere to be sampled. The resulting scattered or absorbed light is then measured to derive, for example, the abundance of aerosols in the atmosphere.

Focus 1. Greenhouse gas measurements with Fourier-Transform Infrared Spectroscopy
The main project of the ARS group focuses on remote sensing of atmospheric greenhouse gases with a Fourier-Transform Infrared (FTIR) Spectrometer. This kind of instrument, which is also called FTS (Fourier-Transform Spectrometer), is able to observe a number of atmospheric trace gases at the same time. The main trace gases of interest are carbon dioxide (CO₂), methane (CH₄), water vapor (H₂O), carbon monoxide (CO) and nitrous oxide (N₂O). However, many more gas species as well as isotopes of these gases can be observed as well.

To measure these trace gases, the instrument uses a passive technique. When sunlight travels...
through the atmosphere, it is absorbed by the molecules of many trace gases, especially in the infrared region of the spectrum. When the molecules absorb light, they only do so at characteristic wavelengths. This way they produce spectral absorption lines that serve as a spectral fingerprint for each trace gas. The FTS analyzes the incoming sunlight and measures the strength of thousands of such spectral lines. From the position of the lines in the spectrum, one can identify the type of trace gas. The strength of the lines is a direct measure of the number of molecules between the sun and the FTS.

Because the light from the sun has crossed the whole atmosphere, the measurement provides information from the ground up to the top of the atmosphere. This is different from in-situ measurements which may be very accurate but only measure the air directly surrounding them. Ground-based FTIR measurements are therefore very valuable to validate satellite measurements of greenhouse gases. Satellite instruments typically also sample the whole atmosphere, e.g. when they look at reflected sunlight that has passed through the atmosphere twice.

The FTS is part of the Total Carbon Column Observation Network (TCCON), an international network of FTS instruments that have been set up in different parts of the world. In 2010, our FTS was transported to the University of Wollongong, Australia, to make side-by-side measurements with another FTS. Both instruments are part of TCCON, and the intercomparison of the data produced from both instruments is very valuable to improve the overall data quality of the network. Our instrument has now been set up on Ascension Island, a small British overseas territory in the South Atlantic. The location is unique as it allows sampling of tropical air that comes mostly from Africa and under certain conditions also from South America - two continents where such measurements have not yet been made.

**Focus 2. Remote sensing of atmospheric mixing layer height**

Besides direct greenhouse gas measurements, there are other important atmospheric parameters that can be measured with remote sensing methods. One of these parameters is the height of the atmospheric mixing layer. The mixing layer is located between the surface and the free troposphere. It is strongly influenced by surface processes: for example the emission or deposition of particles or the exchange of greenhouse gases between the biosphere and the atmosphere.

The thickness of the mixing layer can range from a few hundred to more than two thousand meters. It is a crucial parameter for computer models that calculate the transport of greenhouse gas emissions from the surface through the atmosphere. However, the mixing layer height used in these models is often very inaccurate and leads to errors in the model results. This may also affect the interpretation of the atmospheric measurements from the Integrated Carbon Observing System (ICOS), a network of European stations for monitoring greenhouse gases, which is currently being established.

To improve this situation, we are evaluating remote sensing methods that can be used to measure atmospheric mixing layer height at the future ICOS stations. One way to measure the mixing layer height is to illuminate the atmosphere with a laser and analyze the backscattered signal (LIDAR principle). Since LIDAR systems are usually very expensive, we are investigating the possibility of using simpler instruments like ceilometers. Ceilometers are meteorological instruments that measure the cloud base height. With improved data analysis techniques, ceilometers can also be used to derive mixing layer height. The project is carried out in cooperation with the German Weather Service (Deutscher Wetterdienst, DWD) and JENOPTIK.

*Overview of the methods used by the ARS group: passive measurements of greenhouse gases with an FTIR spectrometer (left), active measurements of mixing layer height with a ceilometer (right).*
Atmospheric measurements of biogeochemical trace gases are made by ground stations, by aircraft, and by remote sensing. In order to retrieve information about surface-atmosphere exchange from atmospheric measurements of trace gases, a combination of atmospheric transport and surface flux models is required. These models need to resolve the trace gas patterns in the atmosphere, so that individual measurements can be represented. Transport models are usually a by-product of operational weather forecasting, which means that specific adaptations to the models in order to simulate long-lived trace gases are needed. Airborne measurements can best capture the 3-dimensional atmospheric distribution, and are hence ideal for testing and optimizing these models. In addition, airborne measurements are the only means to validate remotely-sensed atmospheric concentration data. Thus the Airborne Trace Gas Measurements and Mesoscale Modeling Group (ATM) has a focus on several research areas:

Focus 1. Development of high-accuracy airborne in-situ measurement systems

An airborne in-situ measurement system requires special instruments suited for the aircraft environment, taking into account vibrations, weight limitations, strict safety regulations etc. Therefore, commercially available instruments usually need significant modifications before they can be operated onboard aircraft. Several instruments are under development for application onboard airplanes: (1) Together with industry partners, a greenhouse gas analyzer using the cavity ring-down spectroscopy technique is being modified for deployment onboard commercial airliners. As part of the EU infrastructure project IAGOS-ERI (In-service Aircraft for a Global Observing System) the system is scheduled to monitor CO₂ and CH₄ around the globe with a fleet of Airbus A340 aircraft. (2) ICON, the In-situ Capability for O₂/N₂ measurements, is designed to measure the oxygen to nitrogen ratio at very high precision.
onboard research aircraft. As oxygen is consumed/produced in processes that produce/consume CO$_2$ at a ratio specific for different processes, O$_2$/N$_2$ measurements provide information on sources and sinks of CO$_2$. (3) Within the EU infrastructure project ICOS (Integrated Carbon Observing System) an automated flask sampler suited for airborne and ground based collection of air samples for subsequent analysis of trace gases in the laboratory is under development in collaboration with other partners.

**Focus 2. Airborne measurement campaigns capturing atmospheric trace gas distributions for model validation and budgeting**

The atmospheric distribution of trace gases, derived from many vertical profile measurements during airborne campaigns, is an important constraint for regional budget studies and is used for validation of tracer transport models and remote sensing. Different types of airborne campaigns have been performed, including regional campaigns to study near-field effects on the CO$_2$ distribution in the vicinity of ground based stations, or the validation of ground-based Fourier-Transformation Near-Infrared Spectroscopy measurements such as those made within the Atmospheric Remote Sensing research group of our department. In addition, within the project BARCA (Balanço Atmosférico Regional de Carbono na Amazônia), the carbon balance of the Amazon basin has been investigated with partners from Brazil and the US using airborne campaigns during the dry and wet seasons (Figure below).

**Focus 3. Mesoscale modeling to bridge the gap between observations and global models**

Trace gas fluxes at the Earth’s surface vary on small spatial scales, corresponding to patches of different land use and patterns of emissions from fossil fuel burning. The distribution of those gases in the atmosphere is variable on correspondingly small scales, albeit turbulence tends to remove some of this variability by mixing. In order to represent measurements made in the mixed layer (the lowest 1-2 km of the atmosphere) by stations such as tall towers, mesoscale models with resolution of 20 km or better are needed. Therefore there is a strong research focus on the following areas: (1) A high resolution modeling system that combines a mesoscale weather prediction model with flux models for CO$_2$ and other greenhouse gases has been developed and validated against campaign-based data. This system has been used to investigate the impact of the variability in atmospheric CO$_2$ on the interpretation of data from remote sensing and from mountain stations, and also to study the methane budget in the Amazon basin. (2) The Stochastic Time Inverted Lagrangian Transport model STILT was developed to study where and by how much measured air parcels are influenced by surface-atmosphere fluxes upstream. The model is implemented as a regional model within the Jena Inversion System to bridge the scale gap between observations and a global transport model. (3) Estimating surface fluxes from atmospheric observations requires accurate transport models. Thus an important research topic is the quantification and reduction of uncertainty in these models, especially in transport processes, such as turbulent mixing and moist convection through clouds that cannot be resolved but are described with parameterizations.
Inverse Data-driven Estimation

Quantification of the large-scale sources and sinks of CO$_2$ and other greenhouse gases is essential to understand the climate system and its feedbacks. Based on measurements of the atmospheric composition and various other data streams, inverse methods are used to obtain data-driven estimates of trace gas exchanges and their relation to climatic controls.

The major players of the global carbon cycle – the terrestrial biosphere, the oceans, human activity – exchange carbon dioxide (CO$_2$) and other greenhouse gases with the atmosphere, thereby influencing the climate through the greenhouse effect. The strength of the biospheric and oceanic exchanges strongly varies in space and time – from year to year, with season, from day to day, between day and night. This variability is, in turn, closely linked back to climatic influences. To comprehend the role of the carbon cycle in the climate system, we need to understand quantitatively how the carbon cycle processes on large spatial scales react to their climatic controls. As a prerequisite for such understanding, the temporal variability and spatial patterns of CO$_2$ exchange need to be quantified.

The research group “Inverse Data-driven Estimation (IDE)” focuses on such a quantification on the basis of measured data. Specifically, the following activities are currently pursued:

Focus 1. Quasi-operational CO$_2$ flux estimation (“Jena CO$_2$ inversion”)
Carbon dioxide is a direct tracer of the carbon cycle and its variability. Atmospheric CO$_2$ has been regularly measured by various institutions (including our MPI for Biogeochemistry in Jena) at more than 100 sites worldwide. Based on the gained data, CO$_2$ sources and sinks can be estimated quantitatively: CO$_2$ sources and sinks cause concentration gradients in the atmosphere, dependent on atmospheric transport processes. By measuring these gradients, the sources can be traced back using inverse methods in conjunction with a numerical transport model.

We perform such calculations with a focus on their interannual variations. By relating the year-to-year variations in the CO$_2$ sources or sinks to documented climate variations, we can reveal the driving mechanisms (Top figure, next page).

Portrait of the Group Leader

Christian Rödenbeck studied physics at Leipzig University, where he also got his PhD. As a postdoc at the Max Planck Institute for Complex Systems in Dresden he worked on dynamical systems theory. In 2000 he joined the Max Planck Institute for Biogeochemistry in Jena.

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The CO₂ flux estimates from the “Jena inversion” are regularly updated and made available to collaborating research groups (For documentation and download see http://www.bgc-jena.mpg.de/~christian.roedenbeck/download-CO2/).

Focus 2. Diagnostic data-driven models of the land biosphere

The information obtained by the atmospheric CO₂ measurements can also be combined with other sources of information, such as satellite-derived indices of vegetation state or meteorological data. This method has the advantage of exploiting both the small-scale structure in these data and the large-scale constraints from the atmospheric measurements. Through empirical models and again using inverse methods, the relation between surface CO₂ fluxes and climatic influences can be determined directly. The application of this method is currently being tested, with the aim of obtaining data-driven estimates of the climate sensitivity of the carbon cycle with respect to temperature, precipitation, or solar radiation.

Focus 3. Diagnostic data-driven models of the ocean carbon cycle

Carbon cycle processes do not only lead to gradients in atmospheric CO₂ but also to tiny variations in atmospheric oxygen. Oxygen measurements can thus provide additional information, in particular about ocean biogeochemistry (Figure right). At present, a diagnostic model is being developed that can incorporate further data streams, including carbon and oxygen measurements in the oceanic mixed layer, as well as sea surface temperature, sea-air heat fluxes, nutrient concentrations, and variables related to sea-air gas exchange and ocean-interior transport and chemistry. Estimates based on several independent data streams turn out to be mutually consistent, and thus corroborate each other. The diagnostic scheme can also be used to assess the information content of additional data, to help in the planning of new carbon cycle observations.

Focus 4. Regional inversions

Current-generation global models of atmospheric transport are much coarser in resolution than the actual variability of both atmospheric transport and carbon fluxes, particularly over continents. This leads to substantial errors in the inversion calculations. The problem can be tackled by focusing on a domain of interest over which fluxes and transport are more finely resolved. Strategies for such regional inversions are being developed and applied to various focus regions (Europe, Siberia).

Focus 5. Other tracers

The inverse methods developed for CO₂ are also applied to other atmospheric tracers, in particular the well-known greenhouse gases methane (CH₄) and nitrous oxide (N₂O). Another important tracer is carbonyl sulfate (COS), which is of interest both for its role in atmospheric chemistry and its link to the carbon cycle via photosynthetic uptake.

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Anomalies of the CO₂ exchange in summer 2003 (May–September, in g/m²/year). In red areas, more CO₂ was released than on average (1999–2008). In Europe, the response to the record heat and drought is clearly visible. Black triangles indicate the atmospheric measurement sites used. The coarse continent outlines correspond to the spatial resolution of the tracer transport model.

Interannual variations in the oxygen exchange between the tropical ocean and the atmosphere (black), compared with an El Niño index (red). In El Niño years (increased index) the oxygen outgassing tends to increase, too.
Tall Tower Atmospheric Gas Measurements

High precision, ground-based, and vertically resolved quasi-continuous atmospheric measurements of biogeochemical trace gases at coastal and continental sites are vital for the study of atmospheric transport, biogeochemical fluxes and human emissions. Our group develops and maintains atmospheric measurement sites and instrumentation with the objective of investigating global climate hot-spots and supporting the global atmospheric observational system.

High precision ground-based quasi-continuous atmospheric measurements and discrete (flask) samples are an important tool for the study of atmospheric transport, biogeochemical fluxes, and human emissions. They complement other types of atmospheric measurements such as ground- and space-based remote sensing and airborne measurements.

At our ground-based stations we measure alongside carbon dioxide (CO$_2$), the most frequently measured and most important anthropogenic greenhouse gas (GHG), also methane (CH$_4$), nitrous oxide (N$_2$O), and the synthetic GHG sulphur hexafluoride (SF$_6$). Additionally, the reactive non-GHG carbon monoxide (CO) is measured as it can serve as a tracer of human activity and has an influence on the concentrations of methane and ozone in the atmosphere. The isotopic composition of CO$_2$ (flask samples) and the O$_2$/N$_2$ ratio (continuous measurements and flasks) provide insight into the partitioning of the land and ocean portions of the carbon budget.

Despite substantial international efforts, the global GHG observational system is still far from adequately covering the entire globe. Particularly important are the critical gaps that still exist in so-called “hot-spot” areas, such as northern Eurasia, and the tropical regions of Africa and South America. These areas are considered as important climatic controls because of their large potential of carbon storage or loss in relation with land use and climate change (e.g., deforestation, permafrost thawing).

In contrast to atmospheric measurements close to the ground, a tall tower station offers the possibility to sample the atmosphere at different heights above the ground. This allows for measurement of vertical concentration gradients, local carbon flux estimation, and sampling of air masses above the

Portrait of the Group Leader

Jošt V. Lavrič studied geology in Ljubljana and holds a PhD in stable isotope inorganic and organic geochemistry from the University of Lausanne. During his post-doctoral stays at LGGE (Grenoble) and LSCE (Gif-sur-Yvette) his focus moved to paleoclimatology and atmospheric research. His expertise includes high-precision instruments for gas measurements, and facilities for molecular and isotopic compound analysis. He has been head of the research group for ‘Tall Tower Atmospheric Gas Measurements’ since 2009.

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nocturnal planetary boundary layer. The composition of these air masses is representative of a much larger region compared to locally-influenced air masses closer to the ground.

Technological advancements in instrumentation lower the need for maintenance and increase the number of gas species that we can measure continuously in the field with high precision. This is particularly important for stations at remote locations.

As part of a cooperative effort, the Tall Tower Atmospheric Gas Measurements group (TAG) is establishing measurement sites along a west-east transect at about 60°N from the North Atlantic to Siberia, and along a north-south transect in the Eastern Atlantic Ocean. In addition, TAG is dedicated to the development and improvement of instrumentation and measurement techniques (See figure above). Currently, four continuous and two flask-only sites are operative (See figure below).

The Ochsenkopf station is located on a mountain in northern Bavaria (Germany) and measures air primarily influenced by central-northern Germany and Benelux. The Bialystok station (Poland) is located east of densely populated Western Europe, which has important implications for the monitoring of its anthropogenic emissions.

The Zotino tall tower observatory (ZOTTO) is a joint German–Russian scientific platform in central Siberia for observing and understanding biogeochemical changes in Northern Eurasia (http://www.zottoproject.org/).

The Cape Verde atmospheric observatory (CVAO) is an international effort to observe and investigate the complex West African upwelling system and the underlying low oxygen zone (http://ncasweb.leeds.ac.uk/capeverde/). Our measurements will be used for an assessment of the biogeochemical trace gas budgets in this region.

The TAG group has two major forthcoming projects: new stations for continuous atmospheric measurements of biogeochemical trace gases at Gobabeb (Namibia) and in the Amazonian forest (Brazil; ATTO project).

The Benguela current system off the Namibian coast drives one of the four major eastern-boundary upwelling ecosystems. Oceanic upwelling creates zones of intensive primary production and influences the budgets of atmospheric gases via the air-sea exchange. At the Namibia atmospheric observatory (NAO), located close to the southern African Atlantic coast, we started to continuously measure the O₂/N₂ ratio and biogeochemical trace gases (CO₂, CH₄, N₂O, CO). The site is ideally located to study the air-sea gas fluxes of the nearby Benguela Current system, and the natural and anthropogenic greenhouse and other gas fluxes on the southern subtropical African continent.

The construction of the Amazonian Tall Tower Observatory (ATTO) in the Amazonian forest (Brazil) is the result of a joint Brazilian-German research project. Our multi-level continuous GHG measurements at the more than 300 m tall tower will bridge the gap between flux tower, remote sensing and airborne measurements in a key global hot-spot area.

At ZOTTO, the spherical buffer volumes (top left) allow a near-concurrent measurement of air from all six inlet heights with a single analyser.

The MPI-BGC-BSY-TAG atmospheric network consists of coastal and tall tower-based continuous and flask atmospheric measurement sites.
Complex feedback processes between terrestrial ecosystem functionality and climate change constitute a major source of uncertainty for forecasting future climate scenarios. In order to improve future climate predictions, we need to better understand the interactions between all components affecting ecosystem functionality, and their sensitivity towards changing environmental conditions. In this context, scale poses a considerable challenge. The ‘big questions’ are posed on large scales (e.g., ‘What are the trends in annual atmospheric carbon budgets?’, ‘How much methane will be released from Arctic ecosystems over the next decade under a warming climate?’), and appropriate monitoring and modeling tools survey these domains in relatively coarse resolution (e.g., monthly timestep, grid resolution of several tens of km). While these tools can detect changes and trends in surface-atmosphere exchange processes, they often cannot provide information on the underlying mechanisms since many of these mechanisms take place on smaller spatiotemporal scales. Finer-scale observation techniques (timesteps of seconds to hours, spatial scales ranging between meters to a few km) can target these mechanisms and their feedback with climate, but these datasets are only representative for (very) small domains, and their suitability to answer large-scale questions may be limited.

Our working group focuses on the design of networks of greenhouse gas observation systems covering multiple spatiotemporal scales, and the assimilation of these new datasets into flexible modeling frameworks. One major focus is placed on approaches to optimize a hierarchy of observation platforms across scales to constrain surface-atmosphere exchange fluxes of unknown, but presumably highly variable spatiotemporal distribution (e.g., methane fluxes in permafrost ecosystems). A second major focus, intimately related to the first, is to mine all information available on...
ecosystem feedbacks to climate variability, ranging from small scale soil chambers to large scale satellite data, from high-frequency eddy-covariance data to long-term biometric inventories, in order to improve the representation of underlying mechanisms in process models.

**Focus 1. Carbon fluxes in permafrost ecosystems**

As one of several collaborating institutes across Europe in the EU-funded project PAGE21, we coordinate a long-term experiment to monitor exchange fluxes of carbon dioxide and methane near Chersky, Northeast Siberia (68.7N, 161.4E). The new network, which will start operating in early summer 2013, comprises soil chamber measurements, eddy covariance towers, taller towers to produce highly accurate time series of atmospheric mixing ratios, and airborne sampling to integrate signals over very large areas. Data analysis will focus on the characterization of flux variability across multiple scales in both time and space, involving detailed studies on flux components on the microscale using isotope data. For macroscale analyses on the pan-Arctic scale, we will integrate our observations with datasets from collaborating research groups operating similar systems in Northwestern Siberia (Lena delta) and the Alaskan North slope (Barrow). Upscaling procedures will involve a framework of biosphere process models, source weight function modeling and atmospheric inverse modeling.

**Focus 2. Data assimilation based on high-resolution regional scale inverse modeling**

Atmospheric inverse modeling provides an approach to extract information on regional to global scales from atmospheric trace gas observations, while at the same time allowing to assimilate data from various other sources. A major challenge in this context is to find the most suitable setup for integration and weighing of different data sources. We are testing and evaluating conceptual strategies to handle the assimilation of various data sources into atmospheric inverse modeling frameworks, including geostatistical inverse modeling approaches that allow extracting information from atmospheric observations without placing constraints through prior assumptions, or rigid model structures. Part of this research will be carried out under focus 1; in addition, we are involved in an atmospheric inverse modeling study focusing on the state of Oregon in the Pacific Northwestern USA that is part of the North American Carbon Program. In this domain, a network of currently seven observation towers, the tallest of which reaches 283 m a.g.l., has been set up to monitor mixing ratio time series of CO₂ and CO in an effort to constrain biosphere and anthropogenic Carbon budgets.

**Focus 3. Carbon capture and storage monitoring**

Carbon capture and storage (CCS) is a growing industry that is supposed to provide an interim solution for dealing with growing greenhouse gas emissions by pumping exhausts as liquefied CO₂ into geological reservoirs. At present, monitoring, verification and accounting approaches are lacking behind advances in CCS technologies, with little rigorous research available that could guide CCS operators to set up the most suitable tools. We are involved in a pilot project focusing on two CCS sites in Canada where several surface based monitoring approaches will be tested, evaluated and finally integrated into a comprehensive network. This research aims at providing a tool to detect potential leaks, thus verifying how much of the injected greenhouse gas actually stays underground. Similar to the work focusing on permafrost carbon fluxes, we will use a suite of soil chambers, eddy covariance towers and mobile as well as stationary trace gas observation platforms to monitor the unknown, highly variable flux emission fields across different scales. Special attention will be paid here to the integration of a suite of different techniques into the framework, including multi-scale modeling approaches for biosphere flux activity, atmospheric transport, as well as observations of ancillary trace gases and isotope signals that characterize the injected gas mixture.
The current debate over global change mostly emphasizes the role of the greenhouse effect, with its associated atmospheric warming and carbon cycle feedback. However, the Earth is much more complex; a comprehensive understanding of interactions between the carbon cycle and water, nutrient cycles, and the role of vegetation/soil feedback within the Earth system requires a more thorough investigation. Hence, our department is dedicated to developing new methods and models capable of better describing the state and dynamics of the terrestrial biosphere within the Earth system. This should allow for reconstructing as well as predicting ecosystem behaviour under different past and future environmental conditions. Within this context, we currently address five major, partly interconnected research themes using a range of methodologies spanning from data-driven to theory-driven approaches. These methodologies are largely represented by our respective research groups.

Focus 1. Interactions between biogeochemical cycles
The interactions between different biogeochemical cycles are not yet well understood. In particular, the water cycle plays a central role, governing a wide range of biogeochemical and biogeophysical feedback loops on both the regional and global level within the Earth system. The nitrogen cycle is also key, as it affects the carbon cycle through its effects on plants and soil microbes. For these reasons, the effects of climate change and rising CO₂ levels on ecosystems must be addressed in light of the role of water and nutrient cycles. We aim to better understand how the different biogeochemical cycles depend on each other and change over time, such as during ecosystem succession. This will allow us to explain phenomena like retrogressive ecosystem development and limitations of vegetation productivity in the tropics. Phosphorus, which exhibits a completely different cycling from the other elements (no gas phase), is an example of a key ele-
ment that cannot be understood without considering its interactions with the second focus.

**Focus 2. The role of soil in the global Earth system**

A major challenge has been the need for a comprehensive understanding of soil as an active agent in the biogeochemical system. Soil is a highly heterogeneous and dynamic system across many time scales. Biological transformation and transport processes involving roots, mycorrhiza, microbiota, and macro/mesofauna play important roles in shaping these dynamics, and concepts integrating these soil system properties are underdeveloped. For example, the theory dictating organic matter dynamics in soil is still largely based on simple chemical first-order reaction kinetics, whereby chemical properties determine stability. However, emerging evidence indicates that interactions between soil minerals and microbial agents, as well as spatial arrangements and accessibility are at least as important as chemical factors. Turning this “dead-soil” paradigm into a “living-soil” paradigm is a central endeavour in the Department of Biogeochemical Integration. Advances in this area will allow researchers to address the multiple sources of feedback within soil, as well as between the soil, vegetation, atmosphere, and hydrosphere.

**Focus 3. The impact of climate variability and extremes on the biosphere**

Prior research has focused on rising CO₂ levels and the associated gradual warming. However, the weather varies from year to year in an unpredictable manner. Extreme events such as droughts, hurricanes, ice-storms, and floods impose considerable stress on terrestrial biogeochemical cycles. For example, during the European heat wave event in 2003, the carbon uptake of five normal years was counteracted by the severe drought stress placed on European forest ecosystems. The relationship between year-to-year climate variability and net ecosystem carbon uptake remains one of the major puzzles for research in this area. Understanding this relationship should also improve knowledge regarding the response of ecosystems to longer-term climate variability and change. A worldwide network of continuous observations of biosphere-atmosphere exchange (FLUXNET) is one of the most important collaborative efforts and sources of scientific information in this area.

**Focus 4. The role of biological adaptation and biodiversity for shaping biogeochemical cycles**

It has been hypothesized that biodiversity and biological adaptation serve as a form of “insurance” against the stressors of environmental change. However, many aspects of the functioning of the global biosphere can be described using approaches which largely ignore biodiversity. This has been related to functional convergence, implying that, under similar environmental conditions, similar biological structures and functions may evolve. In strong collaboration with the plant trait database “TRY” (http://www.try-db.org/) hosted at our institute, we are currently asking the simple question of whether plant traits translate into functional properties of ecosystems. For example, we are currently examining how much between-site variability in ecosystem productivity can be explained by plant traits, as opposed to climatic and soil conditions. We are also studying how the vegetation-soil system adapts to imbalances in biogeochemical elements, such as increasing CO₂ levels, under conditions of nutrient limitation.

**Focus 5. Lateral biogeosciences**

Lateral processes, such as transport in air and water, are central to meteorology and hydrology. However, lateral transport processes also play important roles in biogeochemical cycles, albeit on very different time and space scales. Examples include the diffusion of nutrients to roots, soil erosion, fire spread, and vegetation dynamics. Key questions in this context include the search for unifying principles that are valid across different time and space scales. We want to know if new system properties emerge through the interaction between vertical and lateral processes, and whether we can detect spatial interactions using current Earth observation data.

Effects and feedbacks of the water cycle onto the carbon cycle and further biogeochemically relevant ecosystem processes using the example of dryness.
Terrestrial ecosystems play a crucial role in biogeochemical cycles. The state of the atmosphere and human activities affects the rate at which plants and other living organisms produce and consume trace gases. In turn, there are profound influences of vegetation on the environment and climate at different temporal and spatial scales.

The Biosphere-Atmosphere Interaction and Experimentation group (BAE) aims at improving the understanding of the interactions and feedbacks between climate, environmental changes, nutrient availability, and the biogeochemical cycles of carbon (C), nitrogen (N), and phosphorus (P).

To this end, we combine tools and approaches from biometeorology and biogeochemistry such as eddy covariance flux observations, field manipulation experiments, soil and plant analysis, and proximal and remote sensing techniques.

With a global focus, the group investigates the biosphere-atmosphere interactions by contributing to and analyzing globally distributed datasets (e.g. FLUXNET database, remote sensing products) using data-mining and model-data integration techniques.

Exploiting this generalized information, our final goal is to enhance the description of the response of biosphere’s element cycling to climate variability in state-of-the-art global terrestrial biosphere models (TBM) and up-scaling approaches.

Focus 1 Climatic, environmental, and biological controls on ecosystem-atmosphere fluxes from diurnal to decadal time-scales

As recently shown in the literature, human induced carbon dioxide (CO₂) and nitrogen (N) fertilization leads to a stoichiometric imbalance which confers an important role to phosphorous availability and leads to shifts in C-N-P ratios and balances. As a consequence, potential significant impacts on the structures and functions of ecosystems are expected.

Portrait of the Group Leader

Mirco Migliavacca studied environmental sciences at the University of Milano-Bicocca, Italy, where he obtained his PhD in 2008. He worked as a visiting PhD student at the Max Planck Institute for Biogeochemistry and as visiting PostDoc at the Harvard University. After his research activities as Grant Holder at the Climate Risk Management Unit of the Joint Research Centre of the European Commission, he joined the Department of Biogeochemical Integration in July 2013.

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through effects on growth rates and on the competitive abilities of different species.
Manipulation experiments can be helpful to understand these interactions but ecosystem level manipulation is challenging. With our experimental activity we aim at understanding the role of nutrient availability and stoichiometry on ecosystem level carbon and water fluxes and their interannual variability. Finally we want to analyze the physiological response to changing N/P stoichiometry and water availability.
To explore these research questions we established a cluster of sites. At each site different measurements are performed and integrated: eddy covariance flux measurements, sap-flow measurements, lysimeter stations, collection of ancillary information, soil and biomass sampling, novel hyperspectral remote sensing measurements, and field spectroscopy.

**Focus 2 Phenology and Ecosystem Processes**

Phenology, defined as the timing of biological events and its relationship with climate, is crucial as it mediates carbon, water, and energy fluxes, controlling many biosphere-atmosphere interactions and feedbacks. Understanding the drivers of phenological cycle of vegetation is critical for modeling the dynamics of terrestrial ecosystems. This is particularly relevant in structurally complex ecosystems such as tree-grass systems. In the past 20 years the development of Earth observation systems improved the temporal and spatial description of land surface phenology. However, the major efforts focused on temperate areas, while water limited ecosystems were largely ignored. The simplistic description of phenology of water-limited ecosystems in terrestrial biosphere models is one of the pivotal reasons of their poor performance in describing the seasonal and interannual variability of carbon and water fluxes.

The role of water availability and rain pulse in determining the land surface phenology of semi-arid systems and mixed herbaceous-tree ecosystems has been already discussed in the literature, but the underlying mechanisms and the causes of different responses are still not completely grasped. By using sites along rainfall precipitation gradients we aim at understanding the relationship and feedback between phenology and water cycle in semi-arid structurally complex ecosystems.

Finally, nutrients availability is suspected to be one relevant driver of plant phenology, both of leaf unfolding and senescence. Nevertheless, only few studies focused on this topic. Our aim is to evaluate with manipulation experiments the interactions and feedback between water availability, phosphorus, and land surface phenology, in order to improve our mechanistic understanding of the environmental and biological controls of plant phenology.

The development of tools for the measurements of land surface phenology in structurally complex ecosystems is a necessary step to better characterizing the spatial and temporal variability of phenological cycles.
Terrestrial biogeochemical cycles are influenced by climate in many ways and on many time-scales. But they also affect climate because they control the atmospheric abundance of greenhouse gases such as carbon dioxide and nitrous oxide. The interactions between terrestrial biogeochemistry and climate are important components of observed past and present global environmental changes, and are essential to reliably project the consequences of anthropogenic greenhouse gas emissions on future climate studies of these interactions rely on numerical models of the terrestrial biosphere (so called terrestrial biosphere models), linking processes at the scale of a single leaf to processes at the scale of individual plants, ecosystems, biomes and continents. Being built on fundamental theories of plant, soil and ecosystem functioning, the predicative capacity of terrestrial biosphere models depends on i) a comprehensive representation of the key processes that affect biogeochemical cycles at larger scales and ii) ecosystem observations that constrain the terrestrial biogeochemical cycles, in particular carbon and nitrogen and their relationships with land-atmosphere energy and water exchanges. The research of our group within the Department of Biogeochemical Integration addresses these two domains, focusing on the following areas:

Focus 1. Interactions between terrestrial carbon and nutrient cycles
The growth of plants and the decay of organic matter are limited by the availability of nutrients such as nitrogen and phosphorus. The availability and dynamics of these nutrients and the flexibility of the stoichiometric ratios of carbon, nitrogen and phosphorus in biological systems affect the responses of the biosphere to changes in climate, atmospheric composition and disturbance. We develop models of the coupled terrestrial carbon and nitrogen cycles that can be used to better quantify large-scale effects of air pollution (such as...
tropospheric ozone), climate change and increasing atmospheric CO$_2$. An important outcome of this research is a better understanding of the role of nutrient availability on long-term terrestrial carbon storage and ecosystem composition (e.g. Figure top). These studies also help to better understand the effect of historic (and future) changes in land use, climate, as well as atmospheric composition and pollution on recent trends in vegetation greenness, and their controls on net land-atmosphere exchanges of energy, water and greenhouse gases such as carbon dioxide. A key component of this work is to investigate uncertainties that result from incomplete process understanding or ambiguities in the parameterisation of processes such as biological nitrogen fixation or nutrient losses. Ecosystem manipulation experiments such as the elevation of atmospheric CO$_2$ levels, soil warming, and the addition of nutrient through atmospheric pollution, give information about how nutrient dynamics shape ecosystem responses to likely future environmental changes. As part of an international working group of observational and modelling scientists, we use the results of Free Air CO$_2$ Enrichment (FACE) experiments to decipher key processes that control carbon and nutrient cycles, and to evaluate existing and to derive novel model formulations.

**Focus 2. Integrating carbon-cycle observations into terrestrial biosphere and Earth system models**

Earth system models (ESMs) increasingly incorporate state of the art terrestrial biosphere models as land model component to simulate the interactions between land, ocean, and atmosphere. These ESMs are emerging as the main tool with which to synthesise knowledge and predict the coupled behaviour of climate and biogeochemical cycles. Terrestrial interactions with the atmosphere operating through biophysical and biogeochemical processes are amongst the key uncertainties in the coupled behaviour of the Earth system. Within a European research network (Greencycles II), and as part of an international activity (International Land-Atmosphere Model Benchmarking Project, ILAMB), a comprehensive series of benchmarks and associated methodologies has been developed for the systematic and quantitative evaluation of ESMs and their terrestrial components. These model tests build on the latest understanding of the drivers of large-scale changes in vegetation greenness and atmospheric CO$_2$. We take this model evaluation a step further by integrating terrestrial biosphere models and Earth system observations systematically using an inverse modelling system. As part of the Max Planck Earth System Research Partnership, and in collaboration with the Max Planck Institute for Meteorology in Hamburg, such a system is developed for the Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (JSBACH), the land-surface model of the MPI-ESM. The data sources considered for inverse modelling range from vegetation characteristics, in situ flux observations, and vegetation activity from remote sensing to measurements of atmospheric carbon dioxide concentrations from a global network of atmospheric monitoring stations. The inverse system will be used to systematically constrain important model parameters in JSBACH at different spatial and temporal scales (Figure bottom). The aim of this work is to identify the need for improved representation of model ecosystem processes, but also to quantify and reduce model uncertainties, which will be directly useful for coupled climate-carbon cycle projections in the 21st century.
The Department Biogeochemical Integration embraces various methodological approaches to study the terrestrial biosphere and its interaction with the climate system. Our global empirical inference group was set up to put an emphasis on the empirical exploration of site-level and Earth observations as well as modelling results. The incitation of this group was motivated by the insight that conventional hypothesis-driven research can be complemented by purely data-driven, through directed exploration of complex phenomena. Our aim is to foster novelty detection through methods developed for or adapted to ecological data. Currently, our research agenda revolves around the following topics:

Focus 1. Extreme anomalies in ecosystem functioning: from global detection to local attribution

“Global change” is not only manifested in changing global mean temperatures. We also experience more subtle changes, for instance in the reoccurrences and intensities of climate extremes. Hence, a plethora of studies investigated to what degree climate extremes can modify the terrestrial carbon cycle. In our group we are very much interested in this question, however, we address this issue by reversing the burden of proof: We develop methods to detect globally relevant extremes in data that monitor the state and functioning of the terrestrial biosphere directly. In a second step we seek to attribute these globally identified extremes experienced by the biosphere to the locally anomalous trajectories in the climate system. In this way we gain an overview on which ecosystems are most sensitive to climate anomalies, and we understand why specific ecosystems are highly sensitive to climate fluctuations ("responders") and hence more vulnerable to changing climate extremes compared to other more inert ecosystems ("non-responders"). Naturally, follow-up questions will address the question if unprecedented ("record breaking") climate extremes
are necessarily accompanied by extraordinary responses in the biogeochemical functioning of the ecosystems under scrutiny.

Focus 2. The role of interannual variability for land-atmosphere exchanges

The relevance of extreme events in the terrestrial biosphere can only be properly understood in relation to other “expected” modes of variability. Hence, we work towards a profound understanding of land-surface-atmosphere fluxes on multiple time scales. In this context we also aim to identify which processes trigger year-to-year differences in land-atmosphere fluxes. Here, we don’t exclusively rely on Earth observations and rather also profit from the evaluation of model scenarios (e.g. the CMIP5 experiments).

Focus 3. Intrinsic responses of ecosystems to climate drivers

The exchanges of CO₂ and other trace gases between the terrestrial biosphere and atmosphere are precise feelers for within-ecosystem transformations and their sensitivities to climate variability. The basic principles controlling key processes, for instance photosynthesis, are well known. For certain processes, however, we don’t yet have a fully consistent picture of how different driving variables are interacting in detail. An example is the entire respiratory complex of terrestrial ecosystems and its response to various external and ecosystem internal drivers. To shed light on this aspect, we apply novel nonlinear methods that can identify response pathways, quantify process interactions, and distinguish functional responses on multiple time scales. We work with a wide set of methods, from improved semi-empirical models where we account for confounding factors, to non-parametric response functions where we don’t make any assumption about the underlying functionality. Our latest work is exploring how reverse engineering approaches help us to unravel the basic functionalities of biogeochemical processes in terrestrial ecosystems.

Focus 4. Does biodiversity have an effect in the biogeochemical functioning of our ecosystems?

The rapid expansion of Earth observations triggered by modern satellites, higher data acquisition rates and higher sampling resolutions is accompanied by comparable developments in related fields. Most notably, biodiversity research is experiencing unprecedented transformation as more and more observations are being made available to the public. For instance, we see that regional floristic inventories are concatenated to large continental databases, or the TRY initiative (www.try-db.org, our group “Functional Diversity of Plants”) has managed to come up with a first global collation of plant traits across plant kingdoms and ecosystems. Our group aims to support ongoing research in exploring this high-dimensional and intrinsically nonlinear data spaces. Ardent questions are, for instance, how to quantify the encoded functional diversity such that we account for nonlinearities, but are not confounded by species richness or the number of traits for specific geographical areas. Moreover, we support the objectives to link plant traits to ecosystem functional properties.

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**Empirical response functions of GPP (CO₂-Uptake) und Reco (ecosystem respiration) to temperature (from the ongoing work by Jannis von Buttlar)***

*Global map of 100 largest extremes in fAPAR (fraction of absorbed photosynthetically active radiation) with an occurrence probability of 1% or less, averaged over the years 1982-2011. Decrease in carbon uptake is given in kg/year per grid cell (doctoral thesis: Jakob Zscheischler).*
The responses of terrestrial ecosystems to changes in climate and environmental conditions vary in space and time. Exchanges of water and carbon fluxes between the terrestrial ecosystems and the atmosphere, resulting from biological activity, are modulated by – and in turn influence – the climate system. To diagnose the temporal and spatial patterns of ecosystem-atmosphere interactions is a key element for monitoring purposes and prognostics of the carbon and water cycles.

Observations are the basis upon which we generate hypotheses and formulate models about ecosystem function and against which we improve and evaluate our models, that are eventually applied, and generate new hypotheses. Observations span from leaf level measurements of instantaneous light response curves, through hourly to decadal eddy covariance measurements of ecosystem fluxes, to global observations of vegetation dynamics by satellite remote sensing. These observations embed ecosystem responses to climate and other environmental drivers resulting from different processes operating at different temporal and spatial scales. On the other hand, models rely on more or less simple descriptions of processes such as photosynthesis and respiration, allocation, litterfall, mortality and decomposition, to simulate the carbon and water cycles.

We explore formal methods to integrate data and models in order to challenge model structures, evaluate and improve parameterizations and test hypothesis on ecosystem functioning. Inverse parameter optimization allows transferring information from data to models through changes in the parameter vectors and propagation of model uncertainties. The selection of multiple observational streams and of metrics to compare models and data becomes utterly important to maximize this information transfer. Ultimately, these exercises will enable us to assess the uncertainties and improve the current and future temporal and spatial patterns of simulated terrestrial carbon and water cycles.

**Model-Data Integration**

The Model-Data Integration group is strongly motivated by the challenge in Earth system research to represent terrestrial ecosystem fluxes of carbon and water in space and time. We explore strategies and develop methods to extract and transfer information from data to models towards improving our understanding of ecosystem functioning.

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**Portrait of the Group Leader**

Nuno Carvalhais studied environmental sciences in the New University of Lisbon, where he also holds a PhD from. During the PhD his research activities at NASA Goddard Space Flight Center and Boston University stimulated bringing together terrestrial biogeochemical models and remote sensing observations of vegetation properties. It is the interest in improving the description of ecosystem fluxes and testing hypothesis about ecosystem dynamics with data and models that bring him to the Max Planck Institute for Biogeochemistry. He leads the ‘Model-Data Integration Group’ since 2013. Contact: ncarval@bgc-jena.mpg.de
Focus 1. Improving interannual variability with multiple constraints approaches

Currently, we are still short on realizing the mechanisms behind interannual variability of ecosystem carbon and water fluxes. Notwithstanding, many models are able to simulate the fast and seasonal ecosystem dynamics. Addressing ecosystem dynamics at annual and larger scales gains especial importance when global simulations of the carbon cycle into the future show that the role of the land component significantly diverges between different models. Bringing together long-term observations of carbon and water fluxes and pools at ecosystem scales are a unique opportunity to investigate model behavior. By inverse optimization approaches we explore the extent until which optimal parameterizations enable us to explain the observations. Further, considering multiple observations as model constraints leads to higher confidence in parameters. Limits in simulations at annual or longer scales may translate misrepresentation of conceptual carbon pools and/or internal circulation processes (e.g., plant allocation, root exudation, soil decomposition). In long-term datasets we can look for synchronous cause-effect of extreme environmental conditions (e.g., droughts), but also investigate carry-over effects (e.g., damage from a drought year can influence the next year’s dynamics). Ultimately, comprehensive improvements in diagnostics of interannual variability should contribute to reducing the between-model spread observed for prognostic estimates.

Focus 2. Data constraints in global diagnostics of carbon and water cycles

Global observations of land surface properties from satellite remote sensing span for three decades already. These global records show the spatial and temporal patterns of the effects of climate variability and disturbance mechanisms on plant physiology and vegetation dynamics. The identification of regions with pronounced trends or significant changes in behavior generate hypotheses about which mechanisms lead to particular dynamics. To understand the climate-vegetation interactions it is relevant to distinguish the role of climate variability or other biotic and abiotic disturbance mechanisms behind positive or negative trends in vegetation activity. We compare regional observations of vegetation biophysical properties with alternative model formulations to test hypothesis about the likely mechanisms behind spatial and temporal variations, which consequently reflect changes in regional to global biogeochemical cycles. Eddy covariance measurements are a strong constraint for simple modeling approaches that rely on climate and remote sensing observations of vegetation activity to simulate carbon and water fluxes at ecosystem level. However, the high spatial variability of factors controlling the responses of ecosystem fluxes to environmental conditions hampers our global diagnostic ability. Here we explore simultaneously the information content of site level measurements of carbon and water fluxes with satellite observations of vegetation activity and soil water stocks (e.g., soil moisture or total water storage) for coherent descriptions of the carbon and water cycle across scales. This approach poses significant challenges regarding data and model representativeness, characterizing data uncertainties and bringing together particular data streams into common cost functions. Ultimately, the complementarity between simple semi-mechanistic models and comprehensive observations of ecosystem states provides a coherent diagnostic of carbon and water cycles in terrestrial ecosystems.
Observation data are crucial to study, and test our process-based models of how ecosystems respond to climate variability at global scale. However, in-situ measurements are local in nature and scattered across the globe, which makes it difficult to quantify global land fluxes and to generalize process knowledge gained at individual sites. Satellite remote sensing provides repeated global coverage of a few relevant land surface properties but cannot deliver directly the biosphere-atmosphere fluxes or ecosystem properties of interest. By combining in-situ measurements with satellite remote sensing and meteorological data, we estimate the global spatial and temporal distribution of relevant quantities. We use machine learning tools to identify which remote sensing and climate variables are informative, and train regression algorithms that predict the quantity of interest based on these variables. Rather than specifying response functions a priori, we use machine learning algorithms to find the associations and mappings from the explanatory variables and the response variable. Methodological development is an important aspect of our work.

In the past few years we have developed such an approach and applied it to the FLUXNET data set. FLUXNET compiles global eddy covariance measurements of biosphere-atmosphere fluxes of carbon, water, and energy in a global data base. The resulting global fields are independent from, and complementary to simulations from global Land Surface Models, and are therefore increasingly used for cross-consistency checks. Our products provide insights on global patterns of biosphere-atmosphere exchange related to climate which highlight the importance of water availability for ecosystem functioning. For example, we found that the spatial distribution of gross primary production is primarily related to rainfall patterns, and we found a decline of the global evapotranspiration trend due to increasing soil moisture limitations (1998-2008).
with respect to 1982-1997). We could show that hot-spot regions of large interannual variability occur in transitional semi-arid/semi-humid regions. We are currently leading the FLUXCOM initiative where about 10 international groups aim at generating global data-driven flux products using harmonized data sets and protocols to understand various aspects of uncertainty and to foster science in this direction.

In the context of FLUXCOM we further develop our upscaling approaches and capitalize on improved methods and enlarged data sets. We are increasingly interested in applying our approaches to derived ecosystem properties as well as to better understand their variability, and to contribute to improving the representation of ecosystem functional groups in more process-oriented models.

The significance of the close link between the water and other biogeochemical cycles enlarged our interest in global ecohydrological research. We are contributing to a departmental effort that aims at developing a global data-driven carbon and water cycle modelling approach which integrates various in-situ measured and remotely sensed data streams. We are keen on exploring the potential of recent and upcoming data sets from remote sensing such as land surface fluorescence.

As a regional focus we concentrate on Africa, where water scarcity is a key factor for ecosystems as well as for humanity. We are synthesizing data on past variations of moisture conditions in Africa using various remotely sensed products sets but also in-situ measurements. We aim at inferring regions of large interannual variability of moisture conditions that are particularly vulnerable, and aim at assessing historical and future moisture trends using data-oriented modelling. We want to understand which ecohydrological factors control the between watershed variability of rainfall partitioning into runoff and evapotranspiration. We investigate which factors control vegetation dynamics, and build empirical models that predict the vegetation response to environmental variations. These data-driven models can contribute to early warning systems by assessing the anticipated vegetation response using seasonal and decadal meteorological forecasts.

Derived mean annual global gross primary production (gC/m²/yr) from FLUXNET observations (black dots).
Matter mixes, water flows downhill and wood burns into ashes. In the absence of other processes, sooner or later all matter would be uniformly mixed. Water would collect in the world's oceans, mountains would be eroded down to the seafloor, and wood would be burnt to ashes. These processes would transform the distribution of geochemical elements into a „dead“ Earth state, with no gradients present to drive fluxes that result in global cycles of geochemical elements and no free energy would be available to “run” life.

These seemingly trivial observations highlight an underlying general direction into which any process in the Earth system evolves in time. The examples describe processes that cannot be undone, or, technically speaking, they are irreversible. This direction is understood and quantified in general terms using the fundamental physical theory of thermodynamics, and applies to all geochemical processes and global cycles of Earth as well as life itself.

What is it about the planet Earth which allows it to be maintained so far away from the final, „dead“ state of thermodynamic equilibrium? Which processes perform the physical and chemical work that separates matter, moves water uphill, forms mountains, and produces wood out of ashes? What role does life and its inherent diversity play in driving the Earth's state far from equilibrium? And when we consider human activities and associated global change, do these bring the Earth system closer to or further away from the „dead“ state of thermodynamic equilibrium?

The research of the “Biospheric Theory and Modelling” group addresses these questions based on a holistic perspective of how the thermodynamic Earth system works. The research...
Focuses primarily on (i) developing the thermodynamic foundation of Earth system processes, their couplings and interactions, (ii) a detailed understanding of the processes that exchange, transform and transport energy and geochemical elements on land and (iii) explaining the functioning of a diverse, terrestrial biosphere and how it interacts with the prevailing geochemical conditions.

Focus 1. Thermodynamics of the Earth System
We describe Earth system processes in purely thermodynamic terms and implement these formulations into analytical and numerical models. Processes related to biogeochemical cycles are formulated as functions of thermodynamic gradients that result in fluxes depleting those gradients. These models are used to quantify the thermodynamic nature of geochemical processes and their sensitivity to alterations, for example by various biotic effects, inter alia human modifications such as deforestation and the extraction of wind power to generate electricity. We test the applicability of the proposed principle of Maximum Entropy Production to a variety of complex Earth system processes. This principle states that sufficiently complex processes generate and dissipate as much free energy as possible. We use these approaches to improve model formulations and to evaluate how the reconstructed patterns of Earth-life co-evolution relate to thermodynamic trends. This research focus contributes to the Helmholtz Alliance on “Planetary Evolution and Life”.

Focus 2. Land Surface Dynamics
We develop numerical models to simulate the dynamics of the land surface, continental transport processes, geochemical cycling on land, and the sensitivity of the processes involved to biotic activity. Processes such as the weathering of rocks, soil formation, and erosion of soils impose constraints on biotic activity, biogeochemical cycling, and feedbacks to the Earth system on a variety of time scales. The intensity of the weathering of silicate rocks, for instance, strongly shapes the geologic carbon cycle, which in turn determines atmospheric carbon dioxide concentrations at time scales of millions of years. Closely linked to the weathering of primary material is the availability of phosphorus, which is believed to be a primary limiting nutrient in tropical ecosystems. Hence, processes operating at time scales of millions of years can play a critical role in shaping the short-term response of the biota and land surface fluxes to global change. Our simulation models allow us to quantify this highly relevant aspect for the interpretation of Earth system history as well as the impacts of anticipated future global changes.

Focus 3. The Diverse Biosphere
We work on and apply novel approaches to explain patterns and function of the diverse biosphere. Our simulation model allows us to analyze current patterns of the terrestrial biosphere, such as the distribution of vegetation biodiversity, relative abundance distributions of species within communities, functional traits of vegetation and the extent to which climate is reflected in these. By explicitly modelling population and diversity dynamics of the vegetative cover, we are able to evaluate the effect of diversity on land surface fluxes and the extent to which the vegetative cover can adapt to a changing climate. We evaluate different hypotheses that formulate causes, consequences and patterns of biodiversity and relate emergent biogeochemical fluxes and vegetation structure to complex systems theories and optimization approaches.
The Phanerozoic Eon, which spans the last 541 million years, contains most of the commonly studied geological and paleontological events, yet covers only 15% of Earth history. Despite its variation in environmental conditions, the Phanerozoic Earth can be largely designated as a ‘modern’ system. This was very different during the preceding 4 billion years. The Precambrian witnessed not only the origin of life, but Earth also went through a number of transitions in terms of atmospheric oxygen budget, marine redox chemistry, nutrient cycling and climatic extremes, before reaching its Phanerozoic state that is habitable by complex organisms. This progression was mediated by - and reciprocally steered - a continuously evolving microbiosphere.

We aim to understand the details of Precambrian Earth system evolution by analyzing molecular fossils, or biomarkers, in sediments. These molecules are the preserved hydrocarbon remnants of lipids once produced in the ancient water column and/or sediment. Taxonomic specificity of select compounds allows the reconstruction of past organismic diversity, while their stable carbon isotopic composition can point towards certain metabolisms.

Our methodological approach starts with geological fieldwork and drilling campaigns to obtain the freshest possible sample material, whereafter we use organic and carbonate carbon isotope stratigraphy for intraregional stratigraphic correlations. The principal work component consists of wet chemical methods to extract and separate trace abundances of hydrocarbons and to analyze these using superbly sensitive gas chromatography and tandem mass spectrometry.

While asking questions pertaining to the co-evolution of life and environments throughout geological history, our lab focuses on three key areas of research.

Portrait of the Group Leader

Christian Hallmann leads the Max Planck Research Group “Organic Paleobiogeochemistry” since 2012 and holds a secondary appointment as a staff scientist at the University of Bremen, where he and his team are located. Christian received a Diploma in geology and palaeontology from the University of Cologne in 2005 and a PhD in applied chemistry from Curtin University in 2009. Before joining the Max Planck Society, he worked as an Agouron Geobiology Fellow and post-doctoral associate at the Massachusetts Institute of Technology.

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Focus 1. Earth’s oldest sedimentary hydrocarbons

The late Archean and Paleoproterozoic sedimentary sequence records (most likely) the biological invention of oxygenic photosynthesis and the initial rise of oxygen in Earth's atmosphere, termed the Great Oxidation Event. Our knowledge of biological diversity around this time, as well as the effect that rising O₂ levels had on existing biota is scant. Sedimentary biomarkers can carry such information but most sedimentary basins of this age have experienced a metamorphic overprint beyond the theoretical thermal stability of polycyclic terpenoid molecules. Furthermore, indigenous hydrocarbon concentrations can be expected to be very low, making any sample material highly vulnerable to contamination during sampling, handling and storage. We use advanced sampling (ultra-clean drilling) and work-up protocols (slicing experiments and sequential extraction-digestion techniques) to distinguish contaminants from indigenous biomarkers and determine the oldest sedimentary hydrocarbons that can provide clues to the nature of life on the early Earth. In this context we also aim to determine biomarker breakdown products that still carry diagnostic value.

Focus 2. The Emergence of complex life

Most of the Precambrian was dominated by simple unicellular and later multicellular organisms. But it was the advent of the metazoan kingdom with their differentiated multicellularity that would lead to today’s organismic diversity. After more than a billion years of apparent evolutionary stasis, the Cambrian (~541 to 485 Ma) witnessed a period of accelerated evolutionary pace and diversification, mainly within the metazoa (i.e. the ’Cambrian explosion’). We are interested in the first appearance of this complex life. Demospongiae are the most basal representatives of the metazoan kingdom. While the oldest sponge spicules are found in Cambrian strata, molecular clocks place the appearance of demosponges deep in the Neoproterozoic Era, which was characterized by strong perturbations of the marine carbon cycle, varying ocean redox chemistry and severe climatic events. We trace the appearance and radiation of metazoa using a characteristic steroid (24-isopropylcholestane) and try to gain an integrated understanding of this evolutionary innovation in light of changing environmental conditions and its spatiotemporal distribution.

Focus 3. Nutrient cycling and redox structure in Precambrian oceans

While currently a rare environmental condition, stratified and sulfidic marine waters were much more common during the Proterozoic Eon. Initially fuelled by the onset of oxic continental weathering and a consequently growing marine sulfate pool, such euxinic conditions not only stripped the Proterozoic ocean of its vast Fe (II) reservoir but likely also depleted redox-sensitive bioessential elements such as molybdenum (Mo). Debilitation of Mo nitrogenase enzymes could have led to nitrogen-limiting conditions, allowing reduced productivity and prokaryote-dominated marine ecosystems. We are interested in the interplay between marine redox structure, nitrogen cycling, and the strength of the biological pump. Our approach to these questions involves studying the structure and stable isotopic composition of tetrapyrrole-pigment degradation products, the comparison of intrabasinal distal and littoral facies, and the identification of different sedimentary carbon pools that were sourced at varying palaeo-water depths.

Paleoproterozoic stromatolites. Elsewhere such lithified bacteriogenic structures represent the oldest traces of life on our planet.

One of our field sites on the Belcher Islands, Nunavut, Canada.

Organic geochemistry in the field – 1500 km to the nearest lab.
Emeritus Group
Carbon Balance, Ecosystems and Land Management

Ernst-Detlef Schulze, the founding director of the Max Planck Institute for Biogeochemistry, retired in September 2009. The former head of the department Biogeochemical Processes successfully continues his research activities exploring ecosystem processes, biodiversity, and land management with emphasis on forests.

In the past, my research focused on establishing a trace gas balance of Europe. This research developed like a “tree” with a “primary root” in plant ecophysiology, aiming to understand the physiological basis of plant growth under various environmental conditions, and a “secondary root” focusing on soil organic carbon, soil respiration and soil carbon turnover. Also, “aboveground” carbon cycle research developed two major branches, namely the role of biodiversity in plant communities, and the investigation of land management, including the economics of land use emphasizing forests. There is a major gap, which we may call the “management gap”, between the visions of climate and ecosystem researchers of how to capture more carbon and the objectives and limitations of land owners to make a living or profit of their land. Unless we close this gap, even the best theories and models about climate change mitigation may fail. Based on this “tree” of carbon cycle research the following research activities are presently in my focus:

Focus 1. Ecophysiology of trees and soils
Carbon isotope and nitrogen ratios were initially studied in Australia along a transect reaching from Darwin to Alice Springs. Carbon isotope ratios remain constant along a steep rainfall gradient (2000 mm to 350 mm) due to the change in species composition and associated changes in specific leaf area. This observation was confirmed along a transect running from Perth to Alice Springs. It remained unclear, however, how seasonality in rainfall would alter these patterns. Thus, plants were sampled from winter- to summer-rain in West Australia in 2010 including legumes (Acacia trees). It becomes apparent that the dominance of Acacia in the un-seasonal rain fall region is not based on nitrogen fixation.

Based on a meta-analysis we hypothesized that old growth forests remain a carbon sink. We showed that soils are the major carbon sink for continuous carbon storage. Also, we quantified the intensity of

Portrait

Ernst–Detlef Schulze is member of the Max Planck Society, honorary professor at the University of Jena, elected member of the German National Academy, the American Academy of Arts and Sciences, and the Portuguese Academy of Science. In 2010 Prof Schulze was appointed leading scientist at the Siberian Federal University of Krasnoyarsk. For his merits in ecology and ecosystem research, Ernst–Detlef Schulze received the ‘Deutsche Umweltpreis’ and the Ernst Haeckel Award of the European Ecological Society. He manages his own forest enterprise.

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forest management by comparing the existing stand density and age with the natural self-thinning line of undisturbed forests. This research led to investigations of forest history and its effects on present carbon storage. To our surprise, forest management has much less effects on the ecosystem carbon balance than previously assumed. The extraction of wood apparently does not change the soil carbon balance and the present rate of storage.

Based on a meta-analysis of existing information, a carbon balance of Siberia has been established using the top-down and the bottom up approach of the CarboEurope project: Siberia is a weak carbon sink.

In 2010 I was appointed as “leading scientist” at the Siberian University of Krasnoyarsk, an honor connected with the obligation to encourage cooperation between international researchers and Russian Universities (Russian mega grants). Even though Russia was financing this project, it turned out to be impossible to be carried out as planned. However, a forest inventory along the 69° longitude reaching from the Mongolian boarder to the Arctic Ocean could be carried out, and we presently study the interaction between soils and forest cover.

Focus 2. Biodiversity and Nature Conservation

As treasurer of the International Union of Biological Sciences, I once upon a time initiate the international Diversitas project. Also, I started a number of long-term biodiversity experiments, such as the Jena Experiment in 2002 and the BioTree experiment in 2004. I remain tightly connected to these experiments and to Nature Conservation in Thuringia. With respect to forests, it emerges that 60 to 80% of the tree species are going to be lost in the regeneration, not due to forestry nor to climate change but to excessive deer populations and inadequate hunting.

We published the “Atlas of stem anatomy of herbs, shrubs and trees” describing the stem anatomy of about 3000 species in relation to plant structure, climate, and stem evolution (Schweingruber et al., 2010, 2012). A third volume on grasses is in progress.

Focus 3. Land Management

Within the project Exploratories, funded by the German Research Foundation, I had been responsible for establishing forest inventories and the connected databases. I am particularly interested in the “management gap”: getting to know the rules and limitations governing land management decisions, and to study the effects of demands by the society on land management. Managing my own coniferous and deciduous forest, the experiences in forest management go along with my own research. I investigate different management types such as selective cutting, or the ecological consequences of bioenergy production, and the priorities needed in land management with respect to climate mitigation.

Besides the economics of forestry, there are, however, increasing demands on forests by the society ranging from recreation to protection and from water supply to tourism. The demands get increasingly contradictory. The society wants firewood beyond the level of growth in German forests, but discards emissions of GHGs from their stoves. The society wants construction wood, mainly using Douglas fir, and the society pays extra for green energy. At the same time, the society condemns the growth of Douglas fir as neophytic species. 10% of the state forest should to move out of management being protected, and more space for recreation and tourism is requested because agricultural land is being used for biogas. Thus, Germany has moved outside any level of sustainability with each of the demands. I think that these demands on land use needs further investigation if we want to achieve climate mitigation.
The key elements to life such as carbon, oxygen, and nitrogen are continuously exchanged among land, ocean and atmosphere through processes known as global biogeochemical cycles. Research activities in the IMPRS aim at a fundamental understanding of these cycles, how they are interconnected, and how they can change with an altering climate and with human activities. Students participate in ongoing research comprising field observations, method development, experiments, and modeling. The school is thus an excellent starting platform for a successful career in a field related to global biogeochemical cycles and Earth system science.

Structure of the PhD program
The three-year IMPRS-gBGC program is focused on original and independent research leading to a PhD thesis. An additional PhD curriculum provides a valuable complement to the research work. Students have a primary affiliation with a research group of either the university or our institute and are enrolled as graduate students at the FSU. Besides Max Planck scientists, the faculty of the research school includes professors from the Faculty of Chemical and Earth Sciences, the Faculty of Biology and Pharmacy, and the Faculty of Mathematics and Computer Science at the FSU.

At the end of the PhD program a written thesis (ideally cumulative, i.e. based on at least three publications) and its successful defense qualify for a doctoral degree at the Friedrich Schiller University. The degree certificate mentions that the PhD was obtained within the IMPRS.

Supervision
Besides the guidance from their direct advisor, students are also supervised and mentored by a PhD advisory committee (PAC). A PAC is com-

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### The IMPRS-gBGC team

**Friedrich Schiller Univ. Jena:**
- Stephan Halle (ecology)
- Kirsten Küsel (geomicrobiology)
- Erika Kothe (microbial phytopathology)
- Kai-Uwe Tötsche (hydrogeology)
- Reinhard Gaupp (general geology)
- Georg Büchel (geology, palaeontology)
- Peter Frenzel (geology, palaeontology)
- Michael Pirrung (palaeontology)

**MPI for Biogeochemistry:**
- Martin Heimann
- Christoph Gerbig
- Christiane Schmullius
- Beate Mihalzlik
- Jurgen Popp
- Georg Pohnert
- Michael Neumann
- Peter Dittrich
- Anke Hildebrandt

**MPI for Biogeochemistry:**
- Roland Mäusbacher (phys. geography)
- Christiane Schmullius (remote sensing)
- Beate Mihalzlik (soil science)
- Jurgen Popp (physical chemistry)
- Georg Pohnert (analytical chemistry)
- Michael Neumann (stochastics)
- Peter Dittrich (bio systems analysis)
- Anke Hildebrandt (ecological modeling)

**Speaker:** Martin Heimann
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**URL:** [www.imprs-gbgc.de](http://www.imprs-gbgc.de)
posed of the direct supervisor, another IMPRS-gBGC faculty member (from FSU if the direct advisor is from MPI-BGC and vice versa) and at least one other senior scientist.

Curriculum
Besides their own scientific research culminating in the PhD thesis, the students complete an additional training program to develop a broad understanding of Earth system science.

The additional curriculum comprises several partially elective elements:

- **Courses** offered by faculty members of the school (in English):
  - An overview course on global biogeochemical cycles and core courses that introduce the students to scientific fields relevant to global biogeochemical cycles in which they have no deep knowledge yet. This will facilitate interdisciplinary communication and collaboration.
  - Specific skills courses on techniques that are relevant for research in global biogeochemical cycles.

- **Participation in summer schools and workshops** related to the PhD project

- **Training in collaborative research through short-term research visits** at foreign top level research groups. These exchange visits give the opportunity to specialize and further qualify in a field of interest. This will give unique contacts to top experts in the field and increase visibility of the students’ research projects. The foreign research visit lasts 3 months in total.

- **Workshops on any personal skills** which will improve the students’ employment opportunities and future career performance in academia and elsewhere.

- **Outreach activities** such as presentations of results at international conferences, publications in international journals, and explanation of one’s own scientific work to the general public (either in Germany or in the student’s home country).

- Other activities that are relevant for a scientific career (e.g. organization of scientific events) are also encouraged.

Network
This doctoral program provides young researchers with numerous opportunities to establish their personal networks for scientific exchange and career advancement. Apart from the elements of the curriculum, the extensive international cooperations of each supervisor serve that purpose.

We are part of an effort of the Max Planck Society to promote PhD students. There are close ties to other IMPRSs, especially within the Earth System Research Partnership (ESRP), an interdisciplinary initiative that aims to understand how the Earth functions as a complex system and to improve the predictability of the effects of human actions.

We are also part of an active local network of graduate schools.

Getting involved
The IMPRS currently accepts applications for PhD fellowships and associated memberships twice a year.

Applications from well-motivated and highly-qualified students from all countries will be considered; prerequisite is a diploma or Master of Science degree in geosciences, environmental sciences, biological sciences, physics, chemistry, computer sciences or related fields, including a corresponding thesis.

For more information on the program and open positions please refer to: http://www.imprs-gbgc.de.

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*Example teaching modules of the IMPRS-gBGC*
There is no science of global change without good measurements. The changes in the atmosphere apply to all gases comprising air, not only CO$_2$, and only few of these are abundant enough to expect an easy job for quantifying. To follow the fate of the trace gases therefore requires excellent measurement capabilities and a dedication to the long term accuracy of the measurements, now spanning several decades of direct atmospheric measurements.

Not only is it necessary to know how much change occurs for the relevant trace gases, it is almost equally important to infer from where these changes arise. However, this information is very difficult to obtain. One of the tools we can use to answer these questions is the analysis of stable isotopes ($^{13}$C, $^{12}$C, $^2$H, $^{18}$O, $^{16}$O) in the trace gases, which can be done routinely for CH$_4$ and CO$_2$. However, the corresponding alterations are very small making such measurements a challenge, which few laboratories have developed the skills to perform.

The general technique for analyzing stable isotope ratios is by mass spectrometry. Original samples need to be converted into pure, simple measurement gases like CO$_2$, N$_2$, H$_2$, or O$_2$, requiring a careful chemical conversion step with a reaction yield of 100%. In the mass spectrometer these sample gases are ionized, and the different isotopic species (‘isotopologues’) are separated by a magnet. At the end of their flight path, the ions are collected in their respective home detectors and the ratio of the different ion currents is recorded. The same procedure is applied to a reference gas with known isotopic composition. On this basis, a very precise comparison is made, allowing for accurate isotopic characterization of the sample gases.

The Stable Isotope Laboratory (‘BGC IsoLab’) is one of these highly specialized mass spectrometric laboratories analyzing stable isotope ratio variations in atmospheric samples, but also in soils, water, or plant materials with a maximum of precision and accuracy. Such variations are indicative of processes that have left their mark this way. A key example is photosynthesis. Using sunlight, this process combines CO$_2$ and water to glucose, from which all other organic matter is derived. Photosynthesis is catalyzed by RubisCO, a plant enzyme, which prefers the light isotope $^{12}$C to its

Portrait of the Leader

Willi A. Brand has headed the BGC IsoLab since its founding in 1998 and has made this facility one of the largest in Europe. Before joining the new MPI-BGC in Jena, he was responsible for the stable isotope development group at Thermo-Finnigan in Bremen. He has represented the stable isotope section on the board of the German Mass Spectrometry Society. At present, he is the chair of CIAAW, the IUPAC Commission of Isotope Abundances and Atomic Weights.

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heavier sibling 13C. Hence, plant matter produced via photosynthesis has less 13C than the air-CO2 which is left with a higher content of 13C during this process. The resulting variations are often extremely small. At the same time, they are highly significant and robust over time. All fossil fuel has been generated by photosynthesis in the distant past. Therefore, combustion of oil, coal, or natural gas leads to an addition of isotopically ‘light’ CO2 to the atmosphere, which we can measure and relate to human activities over time.

Other stable isotopes under investigation at the BGC IsoLab include deuterium and the 18O/16O ratio in water samples, deuterium in fossil molecules, 15N/14N ratios from plants and soils, or the variation of 13C/12C in tree rings. The fine variations in these isotopic abundances allow one to trace the signal back to processes that have altered these isotopic signatures in the past. Glaciers in Greenland or Antarctica have been formed from snow, covering a time span of up to 1 million years before present. The snow converts into ice in layers, which can be resolved as annual layers at least for the more recent history (~ 10 000 years). The isotopic content of these layers preserve the temperature history. This is how we learn about details in the history of the ice ages.

In addition to these direct stable isotope observations, we use the same technology to measure the O2 concentration in present-day air with very high precision. The well known increase in CO2 is accompanied by a (less well publicized) decline of O2 in the atmosphere in a complementary fashion. For every fossil fuel carbon atom, which is combusted to CO2, one molecule of O2 is removed from the atmosphere. Hence, there is a stoichiometric relation. But: The O2 changes happen on a much larger background (O2 has ~21 % abundance in air, CO2 ‘only’ ~ 0.04 %). Making these measurements at the required levels of precision and accuracy is a challenge, which we have mastered successfully by developing our own equipment and design our own sample handling and calibration protocols. By studying the records of both gases together, we get an insight into the carbon cycle, which we would not be able to get by studying CO2 alone.

BGC-Isolab: a visionary view into the early Isotope lab on the Zeiss premises. Since November 2002, the laboratory is located in the institute’s building on the Beutenberg Campus in Jena.
Measurements of the atmospheric air composition provide key information on changes of greenhouse gas budgets and help to understand the underlying natural and anthropogenic driving forces. One fundamental aspect is the long-term perspective: many of the relevant biogeochemical changes in the climate system evolve slowly, implying that the air composition has to be recorded over decades in order to detect these changes. Equally important is the global coverage of the monitoring network that must represent all geographic areas that significantly contribute to the global carbon cycle. This global monitoring network is operated by many institutions; some of the important continuous long-term observatories (e.g., at Cape Verde, in Siberia and in Namibia) are run by our institute. On the European level the currently existing observational network is being expanded within the course of the construction of the Integrated Carbon Observing System (ICOS). This new European research infrastructure for studies on the European carbon budget has evolved from the CarboEurope project that had been coordinated at our institute. ICOS has been designed with major input from MPI scientists.

The time horizon and geographic dimension entail high requirements in detecting small systematic differences in the trace gas concentrations. The reliability of scientific findings crucially depends on data quality. The major task therefore is to ensure that atmospheric observations performed by us yield long-term consistent data that are compatible with those supplied by other laboratories involved in the global monitoring network.

Specific tasks of GasLab
1. Production of reference gases
Analyzers at observatories have to be calibrated for atmospheric monitoring using reference gases. These reference gases are produced at the institute using dried, natural ambient air, and are targe-
added in their composition by spiking or scrubbing specific trace gases. The traceability to the international accepted calibration scales is achieved by thorough analysis using precise instruments that are themselves calibrated with standard gases from the global Central Calibration Laboratory. GasLab has served as calibration laboratory within the framework of European research projects also for partner institutions in recent years. Presently, the ICOS Flask- and Calibration Laboratory is being set-up in Jena with funds from the German Ministry for Research and Education. This laboratory will then take over the role as the central service laboratory for greenhouse gas measurements in the European observation network.

As part of a research project on atmospheric hydrogen GasLab has developed a procedure for precise mixing of hydrogen in air in order to obtain reference mixtures. Reference gases produced by this method have been accepted by the World Meteorological Organization (WMO) as international calibration scale and GasLab has been assigned the role of the WMO Central Calibration Laboratory (CCL) for molecular hydrogen in air.

For these measurements we run several different analytical instruments. Many analyzers operate based on spectral photometric techniques like non-dispersive infrared absorption spectroscopy (NDIR), cavity ringdown spectroscopy or vacuum UV fluorescence resonance spectroscopy.

2. Trace gas analysis of grab air samples

Some 3000–4000 discrete air samples collected in glass flasks are analyzed for greenhouse gas mole fractions and supplement tracers (including their isotopic composition), that provide ancillary information on the fate of the air mass that has been sampled. Parameters that are analyzed in GasLab are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), carbon monoxide (CO), hydrogen (H₂), and sulfur hexafluoride (SF₆).

Some of these samples originate from monitoring stations contributing to the long-term observations of the background atmosphere. Others are collected as part of measurement campaigns and also serve various research questions. Examples are soil air analysis regularly taken at different ecosystem sites as well as air samples from chamber experiments that allow the investigation of plant or soil respiration. These process studies help understanding the mechanisms that control greenhouse gas fluxes in natural ecosystems.

Analysis of flask air samples are performed using gas-chromatographic techniques as these only consume small amounts of sample. The employed detecting principles are flame ionization detection (CH₄, CO₂), electron capture detection (N₂O, SF₆), HgO-reduction detection (CO, H₂), and pulsed discharge detection (H₂O).

Gas chromatographic system for trace gas analysis of air samples
In 2005, the Laboratory for Spectrometry (SpecLab) was launched as an offshoot of “ChemLab”, the former central service facility for inorganic chemical analyses. SpecLab now focuses on spectroscopic and chromatographic analyses of water, plant, and soil samples, as well as soil extracts. Routine analyses implement methods ensuring the sensitive and reliable determination of carbohydrates in plant extracts and water samples. The methods implemented by SpecLab were successfully presented at national and international conferences in locations ranging from Israel and Japan to the US, and have been published in high-impact scientific journals.

Spectroscopy

Spectroscopic analyses base upon the interactions of electromagnetic radiation with atoms, ions, or molecules to identify chemical compounds. The liquid sample is pumped via capillary tubing to a nebulizer, where an aerosol is produced using pneumatic force. This aerosol is then transported to argon plasma, where the solvent is removed. The aerosol is then vaporized, atomized, and ionized at temperatures of about 6000 – 8000 K. The light emitted by the excited atoms and ions in the plasma is measured to obtain information about the sample. As the excited material in the plasma emits light at several different wavelengths, the emissions from the plasma are polychromatic. This polychromatic radiation is then separated into individual wavelengths. The emissions from each excited compound can thus be identified, and the intensity can be measured without interference from emissions of other wavelengths. Finally, the separated emission lines of each element present in the sample reach the detector. Quantification of the analyte in the sample is based upon the intensity of the measured emission after appropriate calibration.

Portrait of the Leader

Michael Raessler studied chemistry in Munich and Kiel. After completing his undergraduate work he joined the GSF Research Centre for Environment and Health, Institute of Ecological Chemistry, at Neuberberg, and obtained his PhD in analytical chemistry and environmental analytics from Technical University of Munich (TUM). In 1997, he built up the service facility of Inorganic Analytics at MPI-BGC, serving as its head until 2005. Since 2006 he has served as the head of the SpecLab service facility; he also teaches at the FSU Jena.

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Spectroscopic Instrumentation
The following equipment is used for spectroscopic measurements and analyses:

- ICP atomic emission spectrometer, ‘Optima 3300 DV’, Perkin-Elmer
- GF atomic absorption spectrometer, ‘Zeman 3030’, Perkin-Elmer
- UV/VIS spectrometer, ‘Lambda2’, Perkin Elmer
- Microwave-assisted high pressure digestion unit, ‘Multiwave’, Perkin-Elmer

Spectroscopic Measurement Record
In 2010 and 2011, approximately 3,000 spectroscopic analyses were carried out, including about 1,900 water samples. These analyses detected the following elements: aluminium (Al), boron (B), calcium (Ca), cadmium (Cd), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), phosphorus (P), sulphur (S), silicon (Si), strontium (Sr), and zinc (Zn). Of the approximately 1,000 soil extracts that were analysed, roughly 200 extracted ammonium chloride, 500 extracted dithionite, 230 extracted oxalate, and 72 extracted ammonium acetate. Elements detected in the ammonium chloride and ammonium acetate extracts were Al, Ca, Fe, K, Mg, Mn, Na, and P. Elements detected in the dithionite and oxalate extracts were Al and Fe. Additionally, about 40 plant samples were digested and analysed for phosphorus, as well as an additional 20 coal/lignite samples that were analysed for heavy metals in accordance with the German sewage directive (‘Klärschlammverordnung’, DIN EN ISO 11885). To guarantee high-quality analytical data, SpecLab has a rigid quality control protocol; wherever possible, analyses employ standard reference materials issued by the National Institute of Standards and Technology (NIST).

Chromatography
Carbohydrates are one of the major components of plants; the composition of these carbohydrates varies with season, light availability, and vegetative stage. Additionally, the composition of non-structural carbohydrates (NSC) reflects growth and variations in photosynthesis, as well as abiotic stress phenomena such as hyperosmosis. In addition to studying the biological properties of carbohydrates, their exact identification and quantification in plant material is also of vital importance to establishing more precise and reliable carbon balances to more accurately understand biogeochemical cycles and create more realistic models.

SpecLab’s method for analysing these carbohydrates is based on High Performance Anion Exchange Chromatography coupled with Pulsed Amperometric Detection (HPAEC-PAD). A Dionex ICS 3000 ion chromatographic system equipped with a SP gradient pump, a column oven, an AS 40 autosampler, and an ED amperometric detector with a gold working electrode are used for this process. Analyses are carried out using a CarboPac PA 10 column with 18 mMol NaOH as the eluent, at a flow rate of 1 mL/min. Overall analysis time, including column regeneration, is 30 min.

More than 1,000 plant samples of different origin (e.g., perennial rye grass, deciduous trees such as ash, oak, and wild cherry; and evergreens such as larch and pine) have been analysed for compounds such as sugar alcohols, glucose, sucrose, fructose, arabinose, galactose, raffinose salicin, polyfructans, inulin, and starch.
The “Routine Measurements & Analysis (RoMA)” laboratory as one of the institute’s service facilities provides analytical primary data for scientists and young researchers, with main focus on carbon and nitrogen determination in environmental samples. Depending on the details in specific studies and ongoing research projects, RoMA customizes its analytical methods and applications.

Elemental analysis, for instance, is one of the common procedures done in RoMA. Much of our work involves the determination of carbon and nitrogen contents in a large variety of samples: soils, sediments, plant litter, plants, carbonates, chars, and other solid materials, as well as the analysis of dissolved organic compounds and soluble inorganic ions in different matrices. The exact quantification of organic and inorganic carbon is important for studying the effects of land use, land management, and biodiversity on soil organic carbon (SOC) and dissolved organic carbon (DOC). Such investigations provide an insight into the variability of SOC stocks and how these stocks may affect regional and global carbon sources and sinks.

In addition to routine analyses, RoMA also develops and thoroughly tests new analytical methods. One example is the quantitative separation of organic and inorganic carbon in soils, a particularly difficult procedure due to the chemical characteristics of organic matter and mineralogical composition of the carbonates. The measurement includes an initial total carbon analysis integrating both fractions. Subsequently, a subsample of the soil is pretreated either chemically with a non-oxidizing acid to destroy the carbonates, or thermally with temperature-controlled heating to decompose the soil organic matter. The accuracy of organic carbon determination in soil samples using the thermal pretreatment method

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**Portrait of the Leader**

Ines Hilke studied Chemistry at the Martin-Luther-University in Halle and at the Dresden Technical University, where she specialized in water chemistry. She worked at the Faculty of Forest, Geo and Hydro Sciences at the TU Dresden. In 1998 she joined the Max Planck Institute for Biogeochemistry in Jena. Since 2006 she is leading the service facility „Routine Measurements & Analysis“. Her professional interests and activities comprise limnology, soil science as well as instrumental analytics. 

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is outlined in a study of soil carbon storage in experimental grasslands (Steinbeiss et al., Global Change Biology (2008) 14, 2937–2949).

Additional measurements performed in the RoMA lab include:

- Analysis of hydrogen and sulfur contents in sediments, soils, and organics, providing information on the family of chemical compounds in the sample and the biological availability of these elements.

- Analysis of soluble ions using ion chromatography and flow injection analysis. Anions and cations in solution can be measured, including fluoride, chloride, bromide, phosphate, sulphate, nitrate, nitrite, ammonium, sodium, potassium, magnesium, calcium, and manganese.

- Isolation of mobile, easily available, or microbial fractions of carbon and nitrogen in water samples and in individual soil fractions. Unique fractions are obtained using various extracting agents such as cold water, hot water, salt solutions, or acids.

- Analysis of soluble carbon and nitrogen in dissolved organic and inorganic form.

The quality of our analytical data is continuously monitored. RoMA participates in the annual inter-laboratory comparison of VDLUFA (Federation of German Agricultural Investigation and Research Institutes) and is certified for carbon and nitrogen quantification in soil samples.

The RoMA team ensures careful management of samples, timely analyses, application of optimized analytical methods, and highly accurate measurements to produce reliable data of excellent quality for large sample numbers.

In addition to the laboratory tasks, RoMA offers training courses for various age groups and people with different levels of expertise, cooperating closely with the nearby vocational training centre, the Jena University of Applied Sciences, and the Friedrich Schiller University. Thus, trainees and students can learn about the research commonly done in the institute and in particular in the scientific departments, supported by the central facilities.

Young academics are very welcome to contact our lab for an introduction to chemical analysis.

Excellent primary data need a careful sample preparation and the profound knowledge of the analytical methods as well as the skilful handling and maintenance of the instruments. For elemental analysis the exact weighing (pictures left) of the homogenized sample material is important for subsequent measurements as well as the careful maintenance of the auto-analyzer (picture right).

Furthermore, chemical standards and certified reference materials are permanently applied for monitoring the daily performance and the long-term precision of the measurement devices.
Successful research depends upon a sophisticated and continually upgraded IT and communication infrastructure. The mission of the central computing / IT facility, headed by Bertram Smolny, is to provide a thoroughly planned and maintained, robust computing infrastructure which is capable of responding to ever changing and increasing computational demands.

The IT staff provides support and solutions for all technological matters, ranging from network infrastructure to telephone IP communication, including provisions for IT security, hardware procurement, and software licensing, training, and support. Of particular importance for scientists are support for visiting guests, seminar programs, and online experiments, as well as in-house high-performance computing with sophisticated data handling. A specially trained scientific database developer helps to support data management for lab and field experiments. With seven current staff members, the IT group also contributes to developing the local community by offering apprenticeships and internships to interested individuals.

Research Coordination involves a web of connections between different institutional and external bodies. The coordinator, Eberhard Fritz, assists the Managing Director in any and all aspects of institute management, as per the requirements of the Max Planck headquarters. He takes care of institutional organization and reporting and is responsible for internal communication and public relations outreach activities.

The public relations (PR) and communications office, run by Susanne Hermsmeier and headed by the research coordinator, is concerned with activities pertaining to the media and the general public. To communicate scientific results to a broader audience, research findings must not only often be translated into other languages, but also need to be presented in a lay-accessible fashion; this information is predominantly published on the institute’s web page, but also in print media. Press releases and media kits - the traditional tools used to inform the journalistic community - are complemented by brochures, newsletters, fact sheets, and reports.

The PR and communications office also organizes the institute’s participation in larger public events, such as the “Long Night of Sciences” and the “Noble Talks” on the Beutenberg Campus, as well as public lectures and similar activities for

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scholars and interested groups. Finally, this office manages internal communications, including the coordination of internal events and activities.

Operated in conjunction with our next-door neighbor, the Max Planck Institute for Chemical Ecology, the **library** is an indispensable partner in research, learning, and teaching. The library, run by Linda Maack, provides scientists, students, and staff with professional information resources, access to collections, bibliographic information systems, and reference services. Library services include retrieving all kinds of requested media, delivering electronic resources, and managing an online catalog in addition to the Institutes’ in-house publications.

The library provides access to about 100 full-text electronic journals covering diverse aspects of biogeochemistry. In addition, another 30,000 international scientific journals are available online through the Max Planck Society. Librarians assist with use of the library infrastructure and equipment, perform in-house trainings on the use of bibliographic databases and literature management systems, and organize academic courses.

With its 24-hour accessibility and the professional support of our librarians, the library has evolved to a pleasant and effective information and communication center for members of both Max Planck Institutes.

The main tasks of the **administration** unit, led by Petra Bauer, include the organization of personnel, as well as financial, travel, and purchasing issues. The administration unit supports the growing demand for international travel to cooperation partners and field sites by Institute scientists, in addition to the shipping of scientific equipment. Standard accounting of institutional revenues and expenditures is complemented by the financial management of third-party projects supported by external national (e.g., DFG, BMBF) and international (e.g., EC) funds.

As an internationally recognized research organization, the institute puts particular emphasis on the effective recruitment of and assistance to our national and international staff. The institute provides full, usually bilingual, support on all administrative issues and organizes internal language classes to improve communication skills. For newcomers and guests, short-term housing is offered in our on-site guest apartments. The institute complies with standards of equal opportunity.

**Building services**, headed by René Schwalbe, is responsible for the maintenance of institute buildings and grounds, as well as the functioning of its technical infrastructure. The **electronics and mechanics workshops**, headed by Harald Schmalsasser and Frank Voigt, respectively, are active in developing new instrumentation, as well as in repairing and improving commercially available scientific instruments. Staff from all three units are specifically trained in electrical, mechanical, and building-related techniques. They also participate in the planning, set-up, and maintenance of measurement containers, stations, and towers in support of field measurement campaigns both in Germany and abroad.