Biogeochemical Cycles in the Earth System

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Carbon, oxygen, hydrogen, and nitrogen: these four elements are 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,

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 the 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. E.g. the world-wide 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?
2. What processes control the flow of energy and matter between the different components?
3. And how do the different components interact with each other?
4. What controls the distribution and availability of water?
5. How can the complexity of the Earth system be represented by theoretical and numerical models?
6. Which regions and components of the Earth system are particularly sensitive to climate change and human impacts?
7. 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, the MPI for Biogeochemistry in Jena, looking at the global biogeochemical cycles, the Potsdam Institute for Climate Impact Research (PIK) investigating the human dimension in the Earth system and several additional national and international partners.

**Figure 1.** The Earth system and its interactions.
We address this question using three complementary approaches:

1. Process studies and experiments identify and quantify the key organisms, processes, and environmental drivers that regulate the exchange of energy, water and elements between ecosystem components and their surroundings.

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

3. Theory and modeling tools are developed to scale up and integrate spatially distributed information for a consistent representation of biogeochemical processes in comprehensive Earth system models, in order to evaluate biogeochemistry-climate feedbacks on a regional and global scale.

The Institute is structured in three departments, reflecting these three research approaches:

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

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

3. The Department of Biogeochemical Synthesis is currently represented by two independent research groups:
   a) The Senior Research Group on Biogeochemical Model-Data Integration, headed by Markus Reichstein, analyzes linkages between biogeochemical element cycles (C, H, O, P) and plant-soil interactions by means of data assimilation, data mining and
dynamic global ecosystem models.

b) The Max Planck Research Group on Biospheric Theory and Modeling, headed by Axel Kleidon, develops and uses theoretical and numerical methods to investigate the role of the biota in driving the global geochemical cycles within the Earth system.

Research in biogeochemistry is highly interdisciplinary and international in scope. Success can only be achieved through a high degree of integration between scientific disciplines, and a strong link is necessary between modeling and observation, as well as between theoretical and experimental research. Biologists, physicists, meteorologists, geologists, ecologists, chemists, computer specialists, mathematicians, and statisticians work closely together in the two departments, the two independent research groups, our new International Max Planck Research School for Global Biogeochemical Cycles and in the central facilities. Moreover, our staff maintains collaborations with partner scientists in numerous research institutions located worldwide.

Our Central Service Facilities support the scientific departments by providing state-of-the-art analytical and technical support for the scientists:
- Stable isotope and gas analytics
- Chemical analytics (RoMA lab, Spectroscopy lab)
- ¹⁴C-analyses
- Scientific Computing
- Field instrumentation and experiments
- Mechanic and electronic workshops
- Library

Facts & Figures: Approximately 220 persons, recruited from 26 different nations, are currently (2011) affiliated with the institute, including 65 scientists and 60 PhD students. The annual budget turnover is about 10 Mio Euro of which about 20% are 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 comprised of 12 different research institutions and start-up centers.
The Department of Biogeochemical Processes explores key processes and organisms that regulate exchanges of energy, water and elements between ecosystems and their surroundings. We use observations, experiments and models to improve understanding of how human activities are altering ecosystem function, and the consequences for sustainability and regional and global climate.

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 Trumbore has been the Director of the Department of 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 CO$_2$ 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 organism 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.

**Portrait of the Principle Investigator**

Marion Schrumpf studied Geoecology at the University of Bayreuth where she also received her PhD. During that time her main research focus was on soils and nutrient fluxes in mountain rainforest ecosystems of Africa and South America. She came as a postdoc to MPI-BGC Jena in 2004, to study the soils part of the EU project "CarboEurope". Her current focus now lies in the determination of the temporal and spatial variability of carbon stocks in European soils, the processes underlying this variability, and sensitivities to environmental changes.

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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 materials in soils are potentially degradable by microorganisms, provided the environmental conditions favor microbial growth. However a number of mechanisms reduce the bioavailability of organic materials 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).
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 1000 different plant traits, ranging from leaf area, to fire tolerance, and nitrogen fixation capac-

Portrait of the Principle Investigator

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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ity. 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 rainforest, and provides empirical large-scale context for specific process studies, e.g. plant respiration, litter quality, or decomposition rates.

In addition, the research of the 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 Model-Data-Integration group of the institute 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 the Model-Data-Integration group 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).

Latitudinal gradient of the phosphorus/nitrogen ratio in plant leaves. The colors indicate P content per dry mass (blue: low; red: high; mg/g; TRY database, 12651 observations).
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 present and active organisms. This genomic information can be read and individual organisms can be identified. Both molecules, however, are very easily decomposed in the environment and consequently provide only snapshots of actual 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 profiles that can identify individuals or groups of organisms as well as lipid 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 approach bridges from the presence of organisms to their function in the environment. However, in order to explore the function of individual processes and how the microbial fluxes link to the overall functioning of ecosystems, additional information is drawn from the isotopic information of biomarkers. Compound specific isotopes ($^{13}$C, $^{14}$C, $^{15}$N, $^{18}$O and $^2$H) of biomarkers trace the flow of matter through the element cycles. The group of molecular biogeochemistry 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. The group investigates in various projects how abiotic...
factors like organic matter input, parent material, humidity 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 $^{13}\text{C}$, $^{14}\text{C}$ and $^{15}\text{N}$ of biomarkers from individual compounds and fractions determines the molecular turnover of SOM and suggests high vulnerability of SOM stored in soils.

We determine the molecular and isotopic composition of dissolved organic matter (DOC) in order to understand the role of DOC in the environment. We use the molecular fingerprint of DOC using pyrolysis-GC/MS and LC/MS 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. During the day, 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, so far the regulation of carbohydrate metabolism and the role of different processes in plant metabolism is still not completely understood. The 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. Our work is focused 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 gives the insurance for a long term success of the community, even if some individual species of the community may fail.

**Focus 4. Understanding and reconstructing past climate and vegetation dynamics**

Understanding of the links between ecosystems and 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. The group explores the use of hydrogen isotopes of biomarkers as a proxy for palaeoclimate reconstructions. A major focus has been the construction of quantitative transfer functions that link 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.
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 new 300 m high measurement mast in central Siberia (ZOTTO, Figure next page). (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...
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 is 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.
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 ($\text{CO}_2$), methane ($\text{CH}_4$), water vapor ($\text{H}_2\text{O}$), carbon monoxide (CO) and nitrous oxide ($\text{N}_2\text{O}$). 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, the 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. Eventually, the instrument will be 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 CO$_2$ and CH$_4$ around the globe with a fleet of Airbus A340 aircraft. (2) ICON, the In-situ Capability for O$_2$/N$_2$ 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 CO₂ at a ratio specific for different processes, O₂/N₂ measurements provide information on sources and sinks of CO₂. (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 CO₂ 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.

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 CO₂ 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 CO₂ 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.

Enhanced CH₄ in the lower atmosphere shown in the altitude-distance cross-section measured during BARCA on 21st May 2009 (right: flight track).
Terrestrial biogeochemical cycles are influenced by climate in many ways and on many timescales. They affect in turn the climate system through their control on atmospheric greenhouse gas concentrations. These interactions are essential for understanding observed past and present atmospheric and climatic changes, and for projecting future climate change as the consequence of anthropogenic greenhouse gas emissions. Studies of these interactions rely heavily 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 ecosystems, biomes and continents. Terrestrial biosphere models can be driven with observed changes in land use, climate, and atmospheric composition to simulate recent trends in vegetation activity, and their controls on net land-atmosphere exchanges of energy, water and greenhouse gases such as carbon dioxide, to attribute these trends to their causes (Figure next page), and to project likely future developments. Being built on fundamental theories of plant 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 such as carbon and nitrogen and their relationships with land-atmosphere energy and water exchanges. The research of the Terrestrial Biosphere Modelling and Data Assimilation (TBM) group within the Department of Biogeochemical Systems focuses 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 phosphorous. The flexibility of the stoichiometry of biological systems and the dynamics of these nutrients influence

Portrait of the Principle Investigator

Sönke Zaehle studied geo-ecology and environmental sciences in Braunschweig and Norwich, and holds a PhD from the University of Potsdam and the Potsdam Institute for Climate Impact Research. During his PostDoc at the Laboratoire des Sciences du Climat et de l’Environnement in Gif-sur-Yvette he became interested in studying the interactions between the terrestrial biosphere and the climate system using comprehensive numerical models. He has been head of the research group terrestrial biosphere modelling and data assimilation since 2009. contact: szaehle@bge-jena.mpg.de
the responses of biosphere processes to changes in climate, atmospheric composition (such as the CO₂ concentration of the atmosphere) and disturbance. Ecosystem manipulation experiments, such as the elevation of atmospheric CO₂ levels, soil warming, and the addition of nutrients through atmospheric pollution, give information about how nutrient dynamics shape ecosystem responses to likely future environmental changes. As part of an international working group at the National Center for Ecosystem Analysis and Synthesis (NCEAS), TBM uses the results of Free Air CO₂ Enrichment (FACE) experiments to decipher key processes that control carbon and nutrient cycles, and to evaluate existing and derive novel model formulations. Together with supplementary information, for example provided by global databases on plant physiological characteristics, the aim of this work is to better represent ecological processes in the modeling of interactions between terrestrial biogeochemistry and climate.

**Focus 2. Evaluation of state-of-the-art terrestrial biosphere models**

State of the art terrestrial biosphere models are increasingly incorporated in Earth System Models (ESMs) as land model components to simulate the interactions between land, ocean, and atmosphere. These ESMs are emerging as the main tool with which to synthesize knowledge and predict the coupled behavior of climate and biogeochemical cycles. Terrestrial interactions with the atmosphere operating through biophysical and biogeochemical processes are amongst the key uncertainties in the coupled behavior 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 is being developed for the systematic and quantitative evaluation of ESMs and their terrestrial components. These projects emphasize the need to better quantify the links between current trends in regional and global biogeochemical cycles and climatic variability and changes. Foci are the compilation and harmonization of existing in situ measurements, inventories, atmospheric observations, and remote sensing datasets, and the development of evaluation techniques that provide rigorous constraints on future projections.

**Focus 3. Development of a carbon cycle data assimilation system**

The third pillar of the group's work is to bring the model evaluation a step further by integrating terrestrial biosphere models and Earth system observations systematically using an inverse modeling system. As part of the Max Planck Initiative on Earth System Modelling (ENIGMA), and in collaboration with the Max Planck Institute for Meteorology in Hamburg, such a system is being developed for the Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (JSBACH), the landsurface model of the COSMOS Earth System Model. 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. 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.

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Simulated and observed concentrations of atmospheric CO₂ and N₂O using a terrestrial biosphere model (O-CN)
Inverse Data-driven Estimation

Quantification of the large-scale sources and sinks of CO₂ 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 (CO₂) 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 CO₂ 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:

Quasi-operational CO₂ flux estimation (“Jena CO₂ inversion”)

Carbon dioxide is a direct tracer of the carbon cycle and its variability. Atmospheric CO₂ has been regularly measured by various institutions (including our MPI for Biogeochemistry Jena) at more than 100 sites worldwide. Based on the gained data, CO₂ sources and sinks can be estimated quantitatively: CO₂ 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 CO₂ sources or sinks to documented climate variations, we can reveal the driving mechanisms (top figure, next page).

Portrait of the Principle Investigator

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.rodenbeck/download-CO2/).

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.

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.

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).

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 sulfide (COS), which is of interest both for its role in atmospheric chemistry and its link to the carbon cycle via photosynthetic uptake.
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 \(\text{CO}_2\), the most frequently measured and most important anthropogenic greenhouse gas (GHG), also methane \(\text{CH}_4\), nitrous oxide \(\text{N}_2\text{O}\), and the synthetic GHG sulphur hexafluoride \(\text{SF}_6\). Additionally, the reactive non-GHG carbon monoxide \(\text{CO}\) 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 \(\text{CO}_2\) (flask samples) and the \(\text{O}_2/\text{N}_2\) 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 Principle Investigator**

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 above). Currently, four continuous and two flask-only sites are operative (see 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 will continuously measure the O\textsubscript{2}/N\textsubscript{2} ratio and biogeochemical trace gases (CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O, 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.

The MPI-BGC-BSY-TAG atmospheric network consists of coastal and tall tower-based continuous and flask atmospheric measurement sites.
The current debate about “global change” mostly emphasises the greenhouse effect, the associated warming of the atmosphere and the feedback through the carbon cycle. However, the Earth is much more complex. For a comprehensive understanding of the Earth system the interaction of the carbon cycle with water and nutrient cycles and the role of vegetation-soil feedbacks have to be addressed much more thoroughly. Hence the Biogeochemical Model-Data Integration Group (BGC-MDI) is dedicated to develop new methods and models capable of better diagnosing the state and dynamics of the terrestrial biosphere. This should allow to better reconstruct as well as predict the Ecosystems’ behaviour under different past and future environmental conditions.

The BGC-MDI group is conceptually divided into three strongly interacting and complementary focus groups:

**Focus 1. Empirical inference and global modelling of biosphere-atmosphere interactions**

The goal is to extract relevant empirical information on biosphere-atmosphere interactions from the vast and highly multivariate global Earth Observation data sources. A very challenging task is already to quantify regional to global spatial patterns of carbon and water balances. Typical research questions of this focus group include:

- What is the impact of climate variability and weather extremes as well as the response of soil carbon to increasing temperature on global warming (www.carbo-extreme.eu).

**Focus 2. Model-development and Earth system simulation**

The goal is to develop new modelling and model-data integration approaches, allowing the representation of terrestrial biosphere-atmosphere interactions on global scale. This will be achieved by applying different vegetation, carbon, and nitrogen cycles implemented in the Earth system model CLM4-MPI, as well as the development of a globally distributed process-based soil carbon and nitrogen cycle model in order to improve the representation of processes at regional to global scale.

**Focus 3. Model-data integration**

This focus group is dedicated to close the gap between process-based models and Earth system models, and to reduce the uncertainties of Earth system models. This will be achieved by applying various methods of model-data integration including empirical upscaling and downscaling of process-based models, symbolic model-data fusion, and machine learning approaches.
How do ecosystems react/adapt to environmental stresses?

How does the water cycle influence the carbon cycle and vice versa?

As one major source of information this focus group co-builds the global FLUXNET- network database: A comprehensive summary of ecosystem CO₂ and water flux observations with more than 250 sites worldwide and measurements up to 18 years now (www.fluxdata.org). The combination with global satellite remote sensing fields and weather forecasts leads to better global maps of carbon and water fluxes (Figure bottom). Thus, we are able to evaluate whether climate model components represent realistic global conditions. Exemplary, we were able to quantify the impact of the 2003 summer heatwave on the European carbon balance, and to infer that contrary to public perception, this “heatwave” was felt by the European terrestrial biosphere rather as a dry spell, i.e. the water deficit was a more important factor than the high temperatures.

Focus 2. Process-based modelling of the soil in the Earth system.

Soil functions and structure are still very crudely represented in current Earth system models. For instance, vertical differentiation of the soil is largely ignored and also is the role of soil biota. This leads us to the notion of a “dead-soil paradigm” in current global models. We have gained strong evidence that such models are not able to describe several phenomena of carbon and nutrient dynamics, such as the varying temperature dependence of soil respiration. Our ERC-funded QUASOM project (www.bgc-jena.mpg.de/quasom) aims at overcoming this “dead-soil paradigm” by explicitly describing the role of the soil biota in a heterogeneous, vertically differentiated soil environment (Figure right). The challenge is to develop models which are consistent with theoretical considerations as well as the mentioned empirical evidence, but still simple enough for global applications, e.g. as part of climate models.

Focus 3. Development of model-data integration methodologies.

The major question here is how information from biogeochemical observations can be used to improve biogeochemical models. This focus group develops statistical approaches which are robust enough to deal with inevitable deficiencies of data and models for complex systems. The two major challenges are the identification of plausible model structures, and the transformation of data properties (‘patterns’) into model properties (‘parameters’). This is achieved by a so-called ‘multiple-constraints’ approach: using a multitude of data streams containing complementary information regarding processes and time-scales – for example data on carbon and water exchange, plant growth, tree rings and soil and vegetation carbon and nitrogen pools. Combining classical inverse parameter estimation techniques with machine learning approaches and modern time-series analysis has already proven a valuable approach for improving models. The computationally intensive methods are ideally supported by the compute cluster infrastructure at the MPI for Biogeochemistry.

Global map of gross ecosystem productivity (CO₂ uptake as gC m⁻² year⁻¹, red colors indicate high uptake, blue colors low) estimated from FLUXNET eddy covariance towers (black dots) global meteorology and remote sensing data. [M. Jung]

Soil profile with one of our conceptual modelling approaches. [M. Braakhekke]
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.
International Max Planck Research School for Global Biogeochemical Cycles

The International Max Planck Research School for Global Biogeochemical Cycles (IMPRS-gBGC) is a close cooperation between the Max Planck Institute for Biogeochemistry and the Friedrich Schiller University of Jena (FSU). It aims at providing first class training and education for outstanding doctoral students from all over the world in a stimulating research environment.

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.

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

<table>
<thead>
<tr>
<th>Overview module</th>
<th>Choice core courses</th>
<th>Choice skill courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogeochemical cycles in the earth system</td>
<td>Atmosphere &amp; ocean</td>
<td>Applied statistics &amp; data analysis</td>
</tr>
<tr>
<td></td>
<td>Ecosystems &amp; biosphere</td>
<td>Earth observation</td>
</tr>
<tr>
<td></td>
<td>Soils, soil microbiology and soil hydrology</td>
<td>Modeling and numerical techniques</td>
</tr>
<tr>
<td></td>
<td>Paleoclimate</td>
<td>Analytical techniques</td>
</tr>
</tbody>
</table>

*Example teaching modules of the IMPRS-gBGC*
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 (\(^{13}\text{C}, ^{12}\text{C}, ^{2}\text{H}, ^{18}\text{O}, ^{16}\text{O}\)) in the trace gases, which can be done routinely for \(\text{CH}_4\) and \(\text{CO}_2\). 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 \(\text{CO}_2\), \(\text{N}_2\), \(\text{H}_2\), or \(\text{O}_2\), 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 \(\text{CO}_2\) 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 \(^{12}\text{C}\) to its counterpart.

**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 $^{13}$C. Hence, plant matter produced via photosynthesis has less $^{13}$C than the air-$\text{CO}_2$ which is left with a higher content of $^{13}$C 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’ CO$_2$ 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 $^{18}$O/$^{16}$O ratio in water samples, deuterium in fossil molecules, $^{15}$N/$^{14}$N ratios from plants and soils, or the variation of $^{13}$C/$^{12}$C 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 O$_2$ concentration in present-day air with very high precision. The well known increase in CO$_2$ is accompanied by a (less well publicized) decline of O$_2$ in the atmosphere in a complementary fashion. For every fossil fuel carbon atom, which is combusted to CO$_2$, one molecule of O$_2$ is removed from the atmosphere. Hence, there is a stoichiometric relation. But: The O$_2$ changes happen on a much larger background (O$_2$ has ~21% abundance in air, CO$_2$ ‘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 CO$_2$ alone.

BGC-Isolab: a visionary view into the early Isotope lab on the Zeiss premises. Since November 2002, the laboratory is located in the new building on the Beutenberg Campus in Jena.
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 with a non-oxidizing acid to destroy the carbonates, or with temperature-controlled heating to decompose the soil organic matter. The accuracy and precision of organic carbon determination in soil samples using the thermal pre-treatment method

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**Research Service Facility**

**Routine Measurements & Analyses**

Research in biogeochemical cycles and processes involves the investigation of chemical elements and their compounds as well as the calculation of elemental budgets in different ecosystem compartments. To quantify fractions of carbon, nitrogen, hydrogen, sulfur, phosphorus and other elements in liquid and solid materials, scientists cooperate closely with the analytical chemistry laboratory called “Routine Measurements & Analyses (RoMA)”.

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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. She is leading the service facility "Routine Measurements & Analysis" since 2006. 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 continuous flow analysis. Anions and cations in solution can be measured, including fluoride, chloride, bromide, phosphate, sulphate, nitrate, nitrite, ammonium, sodium, potassium, magnesium, calcium, 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 precise and 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, which are supported by the central facilities.

Young academics are very welcome to contact our lab for an introduction to instrumental 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. In case of elemental analysis, the exact weighing (pictures left) of the homogenized sample material is important for subsequent measurements, just as the preventive maintenance of the auto-analyzer (picture right).

Furthermore, chemical standards and certified reference materials are constantly used to ensure the accuracy and the long-term precision of the measurement results.
The main tasks of the **Administration** unit, led by Petra Bauer, include organization of personnel, financial, travel and purchasing issues. The administration supports the scientists in their growing demand for international travels to cooperation partners or field sites, including shipping of scientific equipment. Standard accounting of institutional revenues and expenditures is complemented by the financial management of third-party projects which are supported by national (e.g. DFG, BMBF) and international (e.g. EC) external 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 administration 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.

Successful research depends upon a sophisticated and continually upgraded IT and communications infrastructure. The mission of the **Scientific Computing / IT Facility**, headed by Bertram Smolny provides a thoroughly planned and maintained, robust computing infrastructure which is capable of responding to the 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 is the support for visiting guests, seminar programs, and online experiments, and for 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 7 current staff members, the IT group also contributes to developing the local community by offering apprenticeships and internships to interested individuals.

Located in the building of our next-door neighbor, the Max Planck Institute for Chemical Ecology, the conjointly operated **Library** is an indispensable partner in research, learning, and
teaching. The library, run by Linda Maack, provides the scientists, students and staff with professional information resources, access to collections, bibliographic information systems, and reference services. Library attendance includes retrieving all kinds of enquired media, delivering electronic resources, and managing an online catalog as well as the institutes’ own publications.

The library maintains a collection of over 13,000 volumes and provides access to about 100 full-text electronic journals covering diverse aspects of biogeochemistry. In addition, another 30,000 international scientific journals are directly online accessible for the researchers through the Max Planck Society. The librarians assist with using the library infrastructure and equipment, they perform in-house training in the use of bibliographic data bases and literature management systems, and they organize academic courses. With its all-day accessibility and the professional support by our librarians, the library has evolved to a pleasant and effective information and communication center for members of both Max-Planck institutes.

The Public Relations and communication office, run by Susanne Hermsmeier and headed by the Research Coordinator, is concerned with activities directed to the media and the general public. To spread scientific results to a broader audience, the research findings need to be translated into a more generally understandable language as well as sometimes between languages. The accordingly prepared information is predominantly published on the web page but also as print media. Press releases and media kits as a traditional tool to inform the journalist 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, like the “Long Night of Science” and the “Nobel Talks” at the Beutenberg Campus, as well as public lectures and similar activities for scholars and interested groups. Managing communication also includes internal communication, e.g. coordination of internal events and institute activities.

Research Coordination covers a broad spectrum of cross-connections between several institutional and external units. The coordinator Eberhard Fritz thus assists the Managing Director in any aspects of institute management, e.g. by considering the requirements from the Max-Planck headquarters. He takes care of the central service facilities and is responsible for internal communication and outreach activities in conjunction with public relations.

The Technical Service Facility, headed by Harald Schmalwasser, is responsible for the maintenance of the buildings and grounds of the institute and the functioning of its technical infrastructure. For this, the staff is specifically trained in electrical, mechanical and building-related techniques. On the scientific side, the workshops are active in developing new instrumentation as well as repairing and improving commercially available scientific instruments. Moreover, staff of the Technical Service Facility also participates in the planning, set-up and maintenance of measurement containers, stations and towers in support of field measurement campaigns, both in Germany and abroad.