The current debate over global change mostly emphasizes the role of the greenhouse effect, with its associated atmospheric warming and carbon cycle feedback. However, the Earth is much more complex; a comprehensive understanding of interactions between the carbon cycle and water, nutrient cycles, and the role of vegetation/soil feedback within the Earth system requires a more thorough investigation. Hence, our department is dedicated to developing new methods and models capable of better describing the state and dynamics of the terrestrial biosphere within the Earth system. This should allow for reconstructing as well as predicting ecosystem behaviour under different past and future environmental conditions. Within this context, we currently address five major, partly interconnected research themes using a range of methodologies spanning from data-driven to theory-driven approaches. These methodologies are largely represented by our respective research groups.

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

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

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

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

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

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

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

Focus 5. Lateral biogeosciences

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

Effects and feedbacks of the water cycle onto the carbon cycle and further biogeochemically relevant ecosystem processes using the example of dryness.
Terrestrial biogeochemical cycles are influenced by climate in many ways and on many time-scales. But they also affect climate because they control the atmospheric abundance of greenhouse gases such as carbon dioxide and nitrous oxide. The interactions between terrestrial biogeochemistry and climate are important components of observed past and present global environmental changes, and are essential to reliably project the consequences of anthropogenic greenhouse gas emissions on future climate studies. These interactions rely on numerical models of the terrestrial biosphere (terrestrial biosphere models), linking processes at the scale of a single leaf to processes at the scale of individual plants, ecosystems, biomes and continents. Being built on fundamental theories of plant, soil and ecosystem functioning, the predictive capacity of terrestrial biosphere models depends on i) a comprehensive representation of the key processes that affect biogeochemical cycles at larger scales and ii) ecosystem observations that constrain the terrestrial biogeochemical cycles, in particular carbon and nitrogen and their relationships with land-atmosphere energy and water exchanges. The research of our group within the Department of Biogeochemical Integration addresses these two domains, focusing on the following areas:

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

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

Earth system models (ESMs) increasingly incorporate state of the art terrestrial biosphere models as land model component to simulate the interactions between land, ocean, and atmosphere. These ESMs are emerging as the main tool with which to synthesise knowledge and predict the coupled behaviour of climate and biogeochemical cycles. Terrestrial interactions with the atmosphere operating through biophysical and biogeochemical processes are amongst the key uncertainties in the coupled behaviour of the Earth system. Within a European research network (Greencycles II), and as part of an international activity (International Land-Atmosphere Model Benchmarking Project, ILAMB), a comprehensive series of benchmarks and associated methodologies has been developed for the systematic and quantitative evaluation of ESMs and their terrestrial components. These model tests build on the latest understanding of the drivers of large-scale changes in vegetation greenness and atmospheric CO$_2$. We take this model evaluation a step further by integrating terrestrial biosphere models and Earth system observations systematically using an inverse modelling system. As part of the Max Planck Earth System Research Partnership, and in collaboration with the Max Planck Institute for Meteorology in Hamburg, such a system is developed for the Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (JSBACH), the land-surface model of the MPI-ESM. The data sources considered for inverse modelling range from vegetation characteristics, in situ flux observations, and vegetation activity from remote sensing to measurements of atmospheric carbon dioxide concentrations from a global network of atmospheric monitoring stations. The inverse system will be used to systematically constrain important model parameters in JSBACH at different spatial and temporal scales (Figure bottom). The aim of this work is to identify the need for improved representation of model ecosystem processes, but also to quantify and reduce model uncertainties, which will be directly useful for coupled climate-carbon cycle projections in the 21st century.

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**Figure top**: Carbon sequestration foregone because of lacking nitrogen availability in the current generation of coupled carbon-climate models.

**Figure bottom**: Effect of integrating half-hourly flux observations on the net land-atmosphere CO$_2$ exchange predicted by the JSBACH model.
Terrestrial ecosystems play a crucial role in biogeochemical cycles. The state of the atmosphere and human activities affects the rate at which plants and other living organisms produce and consume trace gases. In turn, there are profound influences of vegetation on the environment and climate at different temporal and spatial scales.

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

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

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

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

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

As recently shown in the literature, human induced carbon dioxide (CO$_2$) and nitrogen (N) fertilization leads to a stoichiometric imbalance which confers an important role to phosphorous availability and leads to shifts in C-N-P ratios and balances. As a consequence, potential significant impacts on the structures and functions of ecosystems are expected.

Portrait of the Group Leader

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

contact: mmiglia@bgc-jena.mpg.de
Manipulation experiments can be helpful to understand these interactions but ecosystem level manipulation is challenging. With our experimental activity we aim at understanding the role of nutrient availability and stoichiometry on ecosystem level carbon and water fluxes and their interannual variability. Finally we want to analyze the physiological response to changing N/P stoichiometry and water availability.

To explore these research questions we established a cluster of sites. At each site different measurements are performed and integrated: eddy covariance flux measurements, sap-flow measurements, lysimeter stations, collection of ancillary information, soil and biomass sampling, novel hyperspectral remote sensing measurements, and field spectroscopy.

**Focus 2 Phenology and Ecosystem Processes**

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

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

Finally, nutrients availability is suspected to be one relevant driver of plant phenology, both of leaf unfolding and senescence. Nevertheless, only few studies focused on this topic. Our aim is to evaluate with manipulation experiments the interactions and feedback between water availability, phosphorus, and land surface phenology, in order to improve our mechanistic understanding of the environmental and biological controls of plant phenology. The development of tools for the measurements of land surface phenology in structurally complex ecosystems is a necessary step to better characterizing the spatial and temporal variability of phenological cycles.
Global Empirical Inference

The exploration of big data is increasingly becoming a key element in Earth system sciences. It’s the long-term observations that encode our knowledge on how land-surface processes respond to climatic conditions or help elucidating the role of biodiversity for biogeochemical functioning. Our group develops methods to decode the precious information in these data: we explore big data to enhance our understanding of land ecosystems in the Earth system around specific aspects such as climate extremes.

The Department Biogeochemical Integration embraces various methodological approaches to study the terrestrial biosphere and its interaction with the climate system. Our global empirical inference group was set up to put an emphasis on the empirical exploration of site-level and Earth observations as well as modelling results. The incitation of this group was motivated by the insight that conventional hypothesis-driven research can be complemented by purely data-driven, through directed exploration of complex phenomena. Our aim is to foster novelty detection through methods developed for or adapted to ecological data. Currently, our research agenda revolves around the following topics:

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

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

Focus 2. The role of interannual variability for land-atmosphere exchanges
The relevance of extreme events in the terrestrial biosphere can only be properly understood in relation to other “expected” modes of variability. Hence, we work towards a profound understanding of land-surface-atmosphere fluxes on multiple time scales. In this context we also aim to identify which processes trigger year-to-year differences in land-atmosphere fluxes. Here, we don’t exclusively rely on Earth observations and rather also profit from the evaluation of model scenarios (e.g. the CMIP5 experiments).

Focus 3. Intrinsic responses of ecosystems to climate drivers
The exchanges of CO₂ and other trace gases between the terrestrial biosphere and atmosphere are precise feelers for within-ecosystem transformations and their sensitivities to climate variability. The basic principles controlling key processes, for instance photosynthesis, are well known. For certain processes, however, we don’t yet have a fully consistent picture of how different driving variables are interacting in detail. An example is the entire respiratory complex of terrestrial ecosystems and its response to various external and ecosystem internal drivers. To shed light on this aspect, we apply novel nonlinear methods that can identify response pathways, quantify process interactions, and distinguish functional responses on multiple time scales. We work with a wide set of methods, from improved semi-empirical models where we account for confounding factors, to non-parametric response functions where we don’t make any assumption about the underlying functionality. Our latest work is exploring how reverse engineering approaches help us to unravel the basic functionalities of biogeochemical processes in terrestrial ecosystems.

Focus 4. Does biodiversity have an effect in the biogeochemical functioning of our ecosystems?
The rapid expansion of Earth observations triggered by modern satellites, higher data acquisition rates and higher sampling resolutions is accompanied by comparable developments in related fields. Most notably, biodiversity research is experiencing unprecedented transformation as more and more observations are being made available to the public. For instance, we see that regional floristic inventories are concatenated to large continental databases, or the TRY initiative (www.try-db.org, our group “Functional Diversity of Plants”) has managed to come up with a first global collocation of plant traits across plant kingdoms and ecosystems. Our group aims to support ongoing research in exploring this high-dimensional and intrinsically nonlinear data spaces. Ardent questions are, for instance, how to quantify the encoded functional diversity such that we account for nonlinearities, but are not confounded by species richness or the number of traits for specific geographical areas. Moreover, we support the objectives to link plant traits to ecosystem functional properties.

Global map of 100 largest extremes in fAPAR (fration of absorbed photosynthetically active radiation) with an occurrence probability of 1% or less, averaged over the years 1982-2011. Decrease in carbon uptake is given in kg/year per grid cell (doctoral thesis: Jakob Zscheischler).

Empirical response functions of GPP (CO₂-Uptake) und Reco (ecosystem respiration) to temperature (from the ongoing work by Jannis von Buttlar)
The responses of terrestrial ecosystems to changes in climate and environmental conditions vary in space and time. Exchanges of water and carbon fluxes between the terrestrial ecosystems and the atmosphere, resulting from biological activity, are modulated by – and in turn influence – the climate system. To diagnose the temporal and spatial patterns of ecosystem-atmosphere interactions is a key element for monitoring purposes and prognostics of the carbon and water cycles.

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

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

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

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Focus 1. Improving interannual variability with multiple constraints approaches

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

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

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

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

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

The significance of the close link between the water and other biogeochemical cycles enlarged our interest in global ecohydrological research. We are contributing to a departmental effort that aims at developing a global data-driven carbon and water cycle modelling approach which integrates various in-situ measured and remotely sensed data streams.

We are keen on exploring the potential of recent and upcoming data sets from remote sensing such as land surface fluorescence.

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