# WHITE PAPER CEPLAS - IPK

## Foundation of a virtual "Center for Translational Plant Biodiversity Research"

("TransCend")

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Plant research is of enormous strategic importance to enable the scientifically, socially, and politically demanded transformation of agricultural production. This systems transformation will require innovations to develop crops that meet the requirements in terms of sustainability, resilience, and yield performance. These goals are also recognized by international documents, such as the United Nations Sustainable Development Goals and the EU's Green Deal. There is only a narrow time horizon of a few decades available for meeting these challenges because it takes at least ten years to develop and approve a new crop variety for agricultural cultivation, using current procedures. Hence, there is barely enough time for three canonical breeding cycles until 2050. Thus, strengthening of plant and crop sciences is essential and without any alternative.

To adapt crops to future requirements, such as climate change and environmental sustainability, it is crucial to understand the functional consequences of biological diversity, which is defined by genetic and epigenetic variation in genomes, on trait performance and adaptation. IPK and CEPLAS will align their future strategic focus to strengthen translational biodiversity research, from fundamental discoveries to innovation.

# Agriculture in transition

Both, the United Nations' Sustainable Development Goals and the EU Commission's Green Deal aim at fundamental changes in the way we produce our food and live our lives. The key points are climate neutrality, increased environmental protection and restoration, conservation of resources, and the safeguarding of biodiversity as the foundation of human life on Earth. The ambitious initiatives include the EU-wide reduction of net greenhouse gas emissions to zero by 2050 (Germany aims to achieve this goal by 2045). At the same time, economic growth is to be decoupled from resource consumption, and the continuous use of limited resources has to be increasingly replaced by closed material cycles.

## The Green Deal also addresses agriculture and food production. Important requirements are:

- Sustainability in plant and animal production
- Reducing agrochemicals
- Reducing the agricultural carbon footprint
- Protecting biodiversity

The European Union's Farm to Fork strategy specifies the necessary contributions of agriculture. For the first time, the entire food system is considered, from production to consumption. Specific goals include the following:

» Pesticide use must be reduced by 50 percent and mineral fertilizer use by 20 percent, by 2030.

» The share of organic farming must be increased to a total of 25 percent (Germany aims at 30% by 2030). At the same time, yield reductions of up to 50 percent[1,2] must be compensated by innovations in organic and in conventional farming.

» Agriculture must reduce its greenhouse gas footprint and become a carbon sink. This should contribute to a net reduction of greenhouse gases in the atmosphere. Currently, agriculture still accounts for about nine percent of all greenhouse gas emissions in the EU.

» For long-term reduction of the carbon dioxide contents of the atmosphere, carbon dioxide must be moved from the atmosphere to the geosphere. (Crop) plants can contribute to the deposition of assimilated carbon to soil.

[1] Purnhagen KP, Clemens S, Eriksson D, Fresco LO, Tosun J, Qaim M, Visser RGF, Weber APM, Wesseler JHH, Zilberman D (2021) Europe's Farm to Fork Strategy and Its Commitment to Biotechnology and Organic Farming: Conflicting or Complementary Goals? Trends Plant Sci 26(6), 600-606.

[2] www.oekolandbau.de/handel/marktinformationen/der-biomarkt/marktberichte/ertraege-im-biologischen-und-konventionellen-landbau/

» Farmers should produce on less land sufficient high-quality plant-based food and feed for a healthy diet as well as plant-based raw materials for technical and medical use and for the production of bioenergy. Hence, the aim is to at least maintain yield performance despite fewer inputs.

» Domestic agriculture and food production should reduce the global ecological footprint. This can only be achieved by increasing yields on European production areas and refraining from net imports.

» To support further agricultural development, incentives are to be given to the end user (the consumer) to increase demand for sustainably produced food and to change eating habits.

» Farmers must adapt agricultural production to counter the impact of changing climatic conditions (changes in water and nutrient availability, pests, temperatures). It should be noted that the yield loss of the world's most important crops (wheat, rice, corn, soybean, potato) due to weeds, animal pests, and microbial pathogens is 20-40 percent without herbicides and pesticides.

To achieve these ambitious goals, innovations are needed along the entire agricultural value chain, in which crop plants form the foundation. These innovations must gain traction over the next decade, i.e., faster than is possible with classical cross-breeding and selection.

# Requirements for future crops, plant breeding, and plant protection

Future crops must exhibit high yield quantity, quality, and stability. Under changing and more extreme weather conditions, it is important to maintain yields, despite a significantly lower input of pesticides, mineral fertilizers, and water. There will also be a need to introduce new or hitherto disregarded crop species into agricultural practice, if they provide new products or product qualities and a better adaptation to low-input agricultural practices and climate change. In particular, the increased cultivation of legumes adapted to regional conditions as a source of vegetable protein holds high potential. New agricultural practices, including various mixed crops or cultivation of perennial species will need to be implemented to protect and enhance soil quality and agricultural ecosystems. Breeding methods must be significantly advanced to allow the efficient use of natural genetic diversity and the targeted generation of traits based on the understanding of causal reasons for biological functions. With the existing methods of classical cross-breeding, this is either not possible, or only in very time-consuming ways. Finally, in plant protection and plant nutrition, agrochemicals must increasingly be replaced through biological agents and/or novel cultivation practices, such as beneficial microbiota and allelopathic mechanisms.

# Transition of plant research to systems science

Modern plant sciences must create the knowledge base for the development of crops, cultivation practices, and plant protection measures that contribute to reaching the goals set for future agriculture. Future improvement of crop plants will require a deep understanding of the genetic, biochemical, and physiological basis of trait development, which, in combination with heuristic approaches, will facilitate prediction of plant performance based on intrinsic (e.g., DNA sequence diversity) and extrinsic variables (e.g., environmental conditions).

To further the goal of predicting plant performance in given environments, the largely discipline-based plant sciences must converge to enable the systemic, multidisciplinary analysis of complex biological processes and functions, addressing complex biological questions from different angles and bringing together expertise from a broad spectrum of scientific fields. This will also require the IT-based structuring, analysis, and interpretation of large volumes of data (“big data”), to deduce biological knowledge from such data. Such a task requires the creation and coordinated bundling of capacities and know-how at existing research institutions into networks, as well as their close cooperation with practitioners in plant breeding, plant protection, and plant production.

# Research and teaching

## in the „Cluster of Excellence on Plant Sciences“ (CEPLAS) and at the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK)

# CEPLAS

The „Cluster of Excellence on Plant Sciences“ (CEPLAS) is a collaborative research program of the Heinrich-Heine-University Düsseldorf, the University of Cologne, the Max-Planck-Institute for Plant Breeding Research Cologne, and the Forschungszentrum Jülich. CEPLAS research focuses on elucidating fundamental mechanisms of plant interaction with their environment in terms of development, metabolism, nutrition, and plant-microbiota interactions. Data science and modeling of biological processes play a crucial role in this process, ultimately enabling the development of modules for the design and control of plant traits through synthetic biology. The overall goal of CEPLAS researchers is to develop the knowledge base for innovative strategies related to sustainable crop production. Along with research, training and career development of the next generation of researchers is the second central pillar of the CEPLAS program. An active dialog on the social importance of plant sciences with the general public as well as political decision makers and the advancement of the transfer of research results into economic use (cooperation with commercial enterprises, start-ups) is integral to all these research and teaching activities.

# IPK

The Leibniz Institute ranks among the international leaders in plant research and is home to two research infrastructures of international importance: the Federal Ex situ Gene Bank and the plant phenotyping center. Research at the Institute is aimed at elucidating fundamental principles of evolution and plant development to enable the adaptation of major crops to changing environmental and climatic conditions. The starting point is the development of innovative approaches to knowledge-based conservation, exploration, and exploitation of crop diversity and the underlying genetic, biochemical, and physiological pathways. IPK‘s research goals are focused on the efficient and sustainable provision of food, energy and raw materials, and thus on meeting global challenges.

# Future cooperation of IPK and CEPLAS

The overarching goal of closer cooperation between IPK and CEPLAS is to strengthen plant sciences in Germany and Europe in terms of personnel, finance, structure and support, with a strategic view on long-term research and development, and the transfer of results to economy and general society. In this way, translational research will contribute to achieving the targets for agricultural production formulated by the United Nations and the EU. Specifically, the collaboration between IPK and CEPLAS aims to:

» Integrate the competences, capacities and infrastructures available in the two institutions, in a transdisciplinary way, to enable scientific breakthroughs that benefit future agriculture.

» Generate synergy effects through the complementation of know-how, capacities and infrastructure, to increase research efficiency and output.

» Increase awareness of the importance and achievements of plant sciences in the public and political spheres.

» Increase the attractiveness for partners, customers and investors regarding the transfer of research results into practical use (incl. promotion of a "start-up culture").

» Stimulate and initiate new research funding programs that address the scientific challenges relating to transformation in the sense described above.

The key scientific question to be addressed in this cooperation is: How can the yield of agricultural and horticultural plant production be maintained at current levels or even increased, using fewer resources and taking into account environmental protection and biodiversity conservation?

As a contribution to answering this question, the mechanisms underpinning the evolution of plant diversity will be explored, and the know-how generated by this research will be made accessible and applicable to plant breeding and agricultural/horticultural plant production. The strength of a close cooperation between IPK and CEPLAS is in the unique opportunity for implementation of a number of multidisciplinary approaches. These include the exploitation of a huge and well characterized collection of genetic resources, sophisticated phenotyping capacities and know-how, state-of-the-art molecular and metabolic analyses, tailor-made data sciences and mathematical modelling, as well as know-how in breeding methods, theory, and practice.

# Developing a common research framework for IPK and CEPLAS

By combining existing expertise, methods, concepts, and infrastructures, IPK and CEPLAS will create an internationally recognized core for strategic orientation of plant research in Germany. This will be leveraged to attract further partners, so that Germany can maintain and further strengthen its strong position in the strategic field of "plant research", as well as in the knowledge transfer of the results and the recruitment of young scientists, which has been achieved over the past three decades.

# Research focus

The central and unifying theme of the research collaboration between IPK and CEPLAS is the causal understanding of the mechanisms of plant trait evolution and the relationships between natural and induced variation of nucleotide sequences and trait expression.

A fundamental mechanistic understanding of evolutionary processes and causal effects of nucleotide sequence variations will allow the prediction and targeted control of how plants adapt to changing environmental conditions in their respective ecosystems and how they comply with the agricultural production requirements. However, the available time period for the practical implementation of the findings is several orders of magnitude shorter than is typically the case for natural evolutionary processes. Here, we are not only interested in the genetically encoded properties of individual plants, but also in the genetic mechanisms of plant interaction with their living and non-living environment. Research questions include understanding trade-offs (e.g., immunity to pests vs. maximizing yield, yield formation vs. nutrient requirements) and elucidating the theoretical limits of plant performance (e.g., harvest index but also yield quality and stability).

The strategic vision of our common research approaches is to make the process of crop breeding more precise and time-efficient, to develop environmentally friendly biological concepts for plant protection and plant nutrition, and to be able to predict and specifically control the resilience of (agro-) ecosystems.

# Research program

The major aim of the research program is to use the accumulated knowledge in a structured form. The life sciences increasingly transition to data-driven discoveries. Hence, a basis and core competence for our common research program will be data sciences, including model and theory formation. The program will build on past and current research programs such as GABI, PLANT2030, and will employ a systems biology approach. Through recent developments in artificial intelligence and machine learning, as well as mathematical modeling, the large-scale data sets provided by omics technologies will be linked to other data sources and reinterpreted. This will enable the development of predictive models for complex biological processes at different levels of aggregation. In addition to looking at individual cells, tissues, organs, and whole organisms, the latter will also integrate interactions with other systems (microbiome, harmful organisms) and plants in their ecosystems. Detailed knowledge of genetic factors and their mechanisms of action in the expression of plant traits in diverse environments will be utilized for prediction and knowledge-based crop improvement.

The research collaboration will address four focal areas, which are considered as crucial to advance crop plant research.

## 1. Identifying and describing diversity

The complete cataloging of the biological diversity of plants is to be advanced. Basis for that are intelligent collections that are created in the course of the transformation process from ex situ gene banks into so-called „bio-digital resource centers." For instance, the entire diversity of the first crop plant species has already been decoded in the so-called pan-genome and is now available in digital form. One example of this is the BRIDGE[3] project. Approaches such as the Tree of Life Web Project[4] also provide a basis for recording overall biodiversity and link data sciences with diversity research. In addition, more ecological approaches to research are laying the groundwork for recording complex populations and the interactions of plants with different environments.

To assess genetic diversity within and across species, pan-genomes will be assembled, and „absence/presence" patterns, genome structure variations, the epigenome, and microbial diversity will be recorded. In addition, there are quantitative considerations of diversity: cultivars vs. native breeds vs. wild species.

## 2. Assignment of functions to diversity

The goal is to elucidate the functional biological impact of diversity. Both, hypothesis-driven and hypothesis-free research approaches will be pursued to demonstrate causal functional relationships in the expression of complex plant traits. The focus is on yield formation, carbon dioxide sequestration in the form of soil organic matter or biomass, expression of resistance and tolerance to biotic and abiotic stresses and their interplay, efficiency of nutrient uptake and utilization, developmental processes that determine plant architecture and their temporal and spatial control. Causal relationships between genetic variation will be investigated at the levels of nucleotide sequence and genome structure, and the expression of biological functions, i.e., ultimately traits in defined environments.

[3] https://bridge.ipk-gatersleben.de
[4] http://tolweb.org

## 3. Elucidation of mechanisms for adaptation of different functions to different environments

Based on the growing knowledge of the mechanisms of evolution of plant genomes at the structural and functional levels, the goal is to understand, interpret, and exploit the fundamental mechanisms for adapting biological functions to changes in environmental conditions: weather extremes, climate changes, changes in water and nutrient supply, new pathogens and pests, as well as ecosystem changes. Understanding evolutionary developments that have become established over geological time scales at the molecular level is a prerequisite for developing innovative approaches in which these evolutionary blueprints are harnessed for crop adaptation over the short period dictated by current climate changes. Thus, contributions will also be made to the protection of the environment and biodiversity, in order to at least avoid exceeding stress limits (tipping points). A systemic view will be taken by simultaneously investigating the interaction between exogenous factors and the complex networks of the expression of traits and their effect on ecosystems. In this context, the effective and efficient use of large and complex data sets, modeling, and theory building are essential tools and foundations.

## 4. Deduction of innovations for plant breeding and crop production/plant protection

Data sciences and model formation, in-depth diversity mapping, understanding the biological functionalities of diversity as well as its adaptation to changing environmental conditions should eventually lead to innovations in plant breeding, plant protection, plant nutrition, agricultural cultivation practices, and biodiversity conservation approaches. In plant breeding, for example, predictions of trait characteristics, which have so far been based exclusively on statistical probabilities, are to be supplemented or replaced by predictions from the modeling of biological processes. The expectation is that this will make breeding processes more rapid and precise. This, in turn, is essential for developing crop varieties in the time available that meet the requirements for sustainability in agricultural production as well as for performance and quality traits.

The research cooperation between IPK and CEPLAS will focus on programs and projects that are clearly aligned with the objectives of the United Nations Sustainable Development Goals and the European Union's Green Deal. The envisaged research priorities and their interactions (see Figure 1) are underpinned by specific project proposals from researchers at IPK and in CEPLAS gathered in two workshops involving more than 60 scientists. These project proposals can be assigned to the four research and development focal points, as outlined in the Addendum. To further support this spirit of cooperation, and to create a solid foundation for the envisaged strategic cooperation, projects from this list of proposals will be selected for short-term seed funding (funded by existing internal resources at IPK and CEPLAS), in a competitive process.

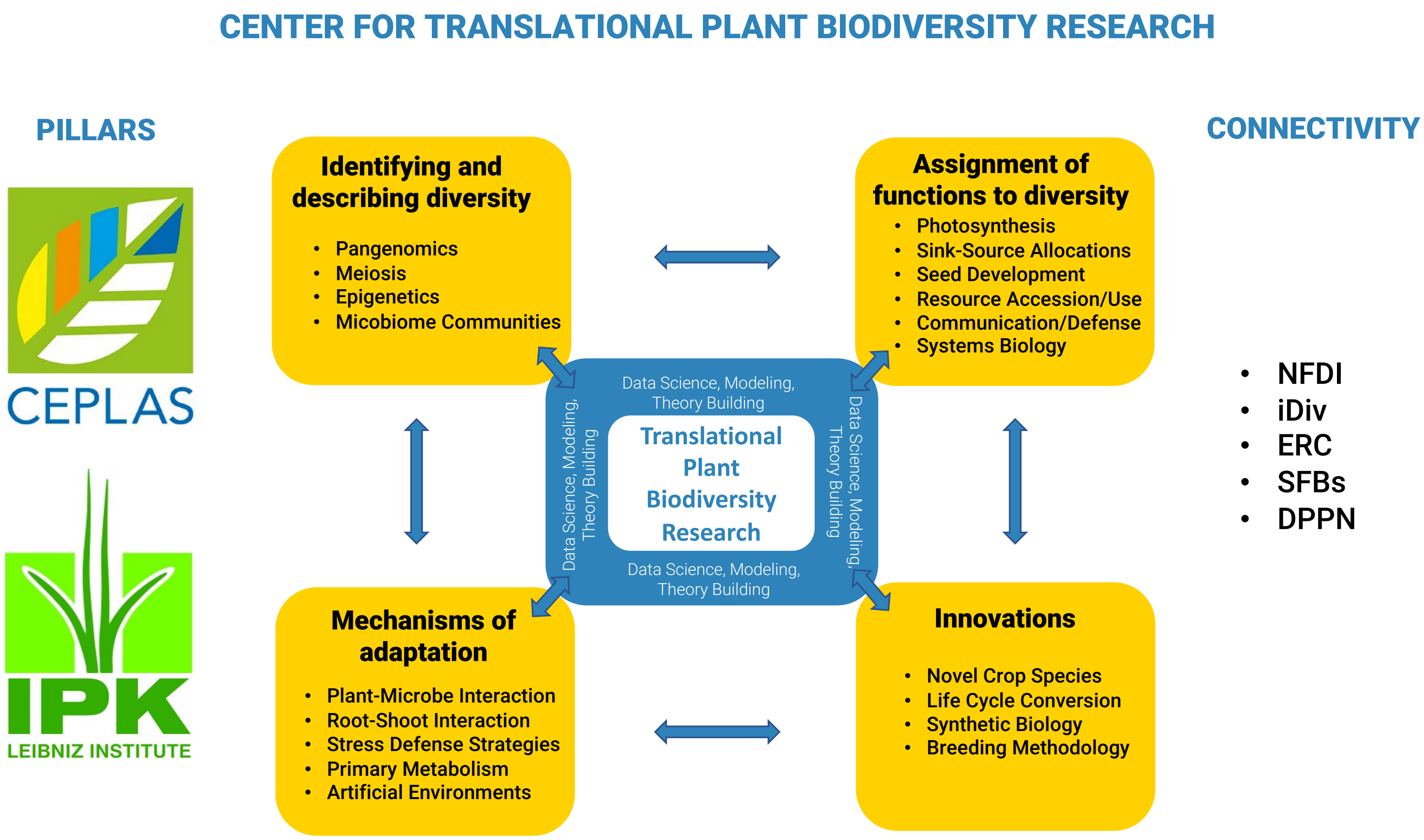


Figure 1. Focal research topics in the Center for Translational Plant Biodiversity Research (TransCend)

# Research structures and early-career researchers

The collaboration will be organized under the auspices of a virtual Center for Translational Plant Biodiversity Research (TransCend). Joint research projects, regular project meetings and workshops will form the basis of cooperation, ensure the exchange of know-how, and serve to evaluate project progress. By reciprocal opening up the training programs already offered by the two institutions, and by jointly organizing new teaching and training courses, we will be expanding the training of young scientists and their familiarity with research networking. Established graduate schools will receive additional stimuli, which will increase the attractiveness of plant research, and support the development of promising research. The virtual center will be formed by IPK and CEPLAS.  Moreover, the center will become a hub for extensive research and development collaborations with research institutions at the national and international level.

# Research transfer

Technology transfer is the nexus between knowledge acquisition and utilization. The first structural and content-related prerequisites for this have been created at IPK and CEPLAS. Both IPK and CEPLAS are committed to supporting the translation of research results into practical use more intensively than in the past and to further developing the structures and programs required for this purpose.

Transfer into practical use can generally be achieved by out-licensing IPR-protected research results to commercial enterprises and/or by cooperating with commercial enterprises in research and development. At the same time, the founding of startup-companies by scientists from both institutions is to be promoted over the long term.

For each of these forms of research transfer, the cooperation between IPK and CEPLAS provides a comprehensive support program. A pronounced common focus is put on increasing the number of start-up-foundations on the basis of research results originating from IPK and CEPLAS. By providing joint training programs, professional advice and the required infrastructure to scientists interested in the foundation of start-up-companies, a lively “start-up-culture” is expected to develop at the two institutions.

## Intensive cooperation between IPK and CEPLAS in the area of research transfer is expected

» To generate synergy effects, which will also lead to an increase in cost efficiency and the efficient use of existing structures.

» To enhance the negotiating position ("clout") and attractiveness of the two institutions vis-à-vis potential licensees, cooperation partners from industry and investors.

# Science communication

Dialogue with the interested public and all other stakeholders from society, culture, politics, and industry is an integral aspect of our work at IPK and all research institutions involved in CEPLAS. The variety of our established channels, formats and methods of communication are characterized by efforts to elucidate, classify, substantiate, discuss, and inspire. Analogously to research, we believe that it is important to establish synergies and a creative competition for ideas and concepts in the realm of communication. In addition, we aim to motivate and involve our young scientists in these communication processes at an early stage. Our aim is to create more opportunities and to impart know-how in order to report on one's own work and personal motivation and also to be able to stand up competently in discussions and critical scrutiny.  The Center for Translational Plant Biodiversity Research ("TransCend") also aims to increase the effectiveness of IPK and CEPLAS in scientific communication, both on mainstream social media platforms and in policy discussions.

# Governance of cooperation

The progress and success of the cooperation program will be controlled by a Steering Committee composed of an equal number of members from IPK and CEPLAS, representing research, on the one hand, and also the complementary fields, such as training, science communication, equal opportunity, and technology transfer. A Coordination Team of members from IPK and CEPLAS, reporting to the Steering Committee, will be responsible for the operational management of the cooperation. In addition, a Scientific Advisory Board will be installed to regularly evaluate the development of the cooperation, from an external point of view, and suggest ways for improvement to the Steering Committee.

# Addendum

Allocation of cooperative project proposals made by IPK and CEPLAS scientists to the research topics of "TranSCend"

## Identification and structural description of diversity

Reasons and consequences for within-accession diversity in (predominantly) selfing species

- How genetic variation is generated - Understanding natural variation in meiotic recombination
- Reconstructing complex genomes and pan-genomes

## Functional consequences of diversity – molecular mechanisms of trait emergence and variation

- Genome functional annotation:
  - Gene-less functional annotation of crop genomes
  - FIND-CIS: Genome-wide, in vivo, high-resolution mapping of functional cis-elements in plants
  - Barley transcription factor cis-trome and its application
- Using Pan-genome data to understand mechanisms: adaptive control of chloroplast development and maturation and photosynthesis in crop plants – focus barley

# Mechanisms underpinning adaptation to varying environments

- » The role of microbial diversity in the rhizosphere on biotic and abiotic stress tolerance and in plant nutrition (monocot barley and the dicot Arabidopsis)
- » Nutrients and plant performance: Genetic variability in barley accessions representing worldwide diversity to mycorrhizal colonization and the genotypic response to low phosphate
- » Genetic basis of diversity in photosynthetic primary metabolism
- » Impact of diversity in primary metabolism on plant performance in changing environments
- » Adapting barley phenology and shoot (root?) architecture to changing environments
- » Source/sink:
  - » Genetic diversity of source-sink allocation and root/shoot structure in controlled and field conditions (including high $CO_2$ in the field)
  - » Modulating source-sink activities: Assimilate allocation between plant generations: inside-out view on living seeds
  - » Seed performance – bridging metabolite composition and seed vigor
- » The key to the holy grail: Sequence variation-based prediction and systems biological investigation of plant performance-trait expression in specifically designed controlled environments

# Innovations for plant breeding, plant protection and agricultural plant production

- Exploiting natural meiotic recombination rate variation in barley to develop highly recombining genotypes
- Toolkit for accelerated (de novo) domestication (protein crops as a possible example)
- Wild species as a valuable base for potato hybrid breeding
- Modeling photosynthetic spectral optimum for diverse forms of cultivation
- Automated plant phenotyping using multimodal image analysis