2005
2020

Centre Report 2020

Genes to Energy | Energy to Yield

plant energy **biology**
ARC CENTRE OF EXCELLENCE

plantenergy.edu.au

CONTENTS

PEB PEOPLE HIGHLIGHTS

"I joined PEB because I believe in the work of PEB. If we are to feed 9 billion mouths by 2050, we are going to have to get a whole lot better at producing food. This starts with understanding how, why, when and where plants invest their energy."

Dr Nathan Tivendale

"The most exciting part of my work is to discover new clues as to how plants have evolved to cope with a challenging environment. I enjoy collaborating with people from across the globe and working with students and colleagues from diverse backgrounds."

Dr Ricarda Jost

"PEB is an excellent environment for scientific research. I am relishing the opportunity to develop my ideas, expand my knowledge and be part of a highly productive and innovative team of scientists."

Dr Caitlin Byrt

#PeopleofPEB

The Centre

CENTRE OVERVIEW

Since 2005, the Australian Research Council Centre of Excellence in Plant Energy Biology (PEB) has been focused on better understanding the way in which plants capture, convert and use energy in response to environmental change, with a view towards improving plant energy efficiency.

Vision

To enhance plant energy efficiency by simultaneously optimising energy capture, conversion and use in changing environments, in order to improve the sustainable productivity of plants.

Mission

- Define the complex system that determines overall energy efficiency in plants.
- Discover the key signals, 'gatekeeper' cells, and (epi)genetic controls that regulate this energy system.
- Manipulate these regulators in combination to optimise energy efficiency across the whole plant and enhance yield.

Strategic Priorities

- To elucidate the fundamental mechanisms of energy biology regulation in plants.
- To be a leading Centre for advanced training and education for plant and computational biologists, in Australia.
- To build strategic collaborations for Australia within the international science community.
- To enhance plant biotechnologies in order to build technological innovations and aid Australian agricultural innovation.

Plant Energy Biology Fast Facts 2005-2020

- 6 collaborating universities over time: The University of Western Australia (administrating organisation); Australian National University; The University of Adelaide (since 2011); La Trobe University (since 2014); The University of Sydney (2005-2009) and Flinders University (2009-2011).
- 14 Chief Investigators.
- 8 Partner Investigators in USA, Germany, Finland, Sweden and China.
- Partnerships with the Grain Research and Development Corporation, Agilent Technologies, Photon Systems Instruments and Groupe Limagrain.
- Over 470 internationally competitive staff, students and affiliated researchers.
- $58 million from the Australian Research Council and $28 million from partner universities and companies to fund the Centre through to 2020.
- Centre authors have contributed to over 1,000 publications.

Tapping into the potential of plants is what drives research at the ARC Centre of Excellence in Plant Energy Biology.

Addressing a critical problem

The world faces three interconnected threats to food security: limited agricultural resources (land, water and key nutrients); a rising human population and per capita food consumption; and a yield gap resulting from reduced productivity of crops due to mismatches between crop genetics and unpredictable environments.

Plant function is complex. Often research aims to optimise single-input processes, such as photosynthetic rate or nutrient uptake, in order to increase plant productivity. However, changing inputs alone can reduce the efficiency of downstream processes and thus limit their effectiveness.

PEB has been funded in two cycles by the Australian Research Council Centre of Excellence scheme. First from 2005-2013 to establish a Centre aimed to unite research on chloroplasts, mitochondria and peroxisomes as plant energy organelles and study them collectively as the plant energy system. Secondly, from 2013 till today, to use the established foundation to increase the efficiency of energy capture, conversion and use by plants by improving their ability to allocate resources and their tolerance to environmental challenges.

PEB's journey began with 7 Chief Investigators (CIs) and grew and changed with time to include 7 more CIs and 8 international research leaders who joined the ambitions of the Centre as partner investigators.

Adding efficiency gains together via molecular signalling and control will increase crop plant productivity. This approach to improving the sustainable productivity of plants will aid in future-proofing food production for Australia and the world.

An innovative research plan

In recent years, PEB's novel approach has been to improve sustainable plant yield by optimising their overall efficiency of energy capture, conversion and use. Rather than optimising single nutrient inputs or product outputs, targeting complex processes including plant metabolism, transport, and development for efficiency gains to will be more effective at enhancing overall plant productivity.

Improving multiple parameters simultaneously is a necessary solution to the increasing demand for more crop yield from finite land, water, and nutrient resources. Unpredictable environmental challenges adversely affect plant growth and further perturb plant energy balance, also limiting yield.

The genetic and epigenetic controls, gene variants and signals discovered by the Centre provide a new basis for creating sustainably productive crops that can weather changing and challenging climates.

The enhancement of plant energy efficiency is being approached by PEB through a number of major research themes which combine to translate molecular insights into whole plant performance. These five research themes are:

- Learning new signalling languages spoken in plant cells
- Balancing the energy budget in plant metabolism and biosynthesis
- Gatekeepers and other specialised cells for new gains in plant energy efficiency
- Genomes to phenomes and synthetic biology to build new phenotypes
- Better technology for hybrid cereal production

PEB recognises that increasing overall 'plant energy efficiency' - the efficiency not only of energy capture, but also of energy conversion and use by plants in order to produce yield - is key to long-term food security.

A collaborative effort

The Centre has been bringing together a collection of the world's best researchers from complementary disciplines and integrates scientific research across the range of scales required to truly address the different aspects of the energy efficiency challenge in plants.

Collaborations across Universities and with Industry Partners avoids "reinvention of the wheel" and draws on existing expertise. Sharing our research keeps it at the cutting edge and builds an international network for its application to real world solutions.

CHIEF INVESTIGATORS

PROFESSOR HARVEY MILLAR (2005-current)
(Director 2014-current)
(Deputy Director 2012-2013)

Harvey's research aims to understand the role of respiration in primary carbon and nitrogen metabolism in plants, plant response to oxidative stress and the dynamics of plant proteomes under limiting conditions. He is an ARC Laureate Fellow, was named Western Australia's 2017 Scientist of the Year and is a Fellow of the Australian Academy of Science.

PROFESSOR IAN SMALL (2005-current)
(Director 2006-2013)

Ian's research interests involve understanding how plants coordinate the expression of nuclear and organellar genes, and building computational models of plant metabolism. He was Western Australia's 2014 Scientist of the Year and an ARC Laureate Fellow and is a Fellow of the Australian Academy of Science.

PROFESSOR RYAN LISTER (2014-current)

Ryan's research aims to understand and manipulate cell identity, with a particular focus on the role of the epigenome. Ryan was the 2014 Australian Prime Minister's Awards Life Scientist of the Year, Western Australia's 2020 Scientist of the Year and is a Fellow of the Australian Academy of Science.

UWA

EMERITUS PROFESSOR RANA MUNNS (2014-current)

Rana's focus is on the mechanisms by which plants adapt to drought and salinity stress. Rana holds a joint position with the University of Western Australia and CSIRO Agriculture, Canberra. She is a Fellow of the Australian Academy of Science and The World Academy of Sciences. She is recognised internationally for her insights into the fundamental principles of crop adaptation to salinity, and for applications of these insights.

PROFESSOR STEVEN SMITH (2005-2013)

Steven's research focuses on discovering new enzymes and new metabolic pathways, forcing rethinking of energy metabolism in plant cells. He was an ARC Federation Fellow.

- UWA — **UNIVERSITY OF WESTERN AUSTRALIA**
- ANU — **AUSTRALIAN NATIONAL UNIVERSITY**
- UA — **UNIVERSITY OF ADELAIDE**
- LTU — **LA TROBE UNIVERSITY**
- FU — **FLINDERS UNIVERSITY**
- USYD — **UNIVERSITY OF SYDNEY**

PROFESSOR BARRY POGSON (2005-current)
(Deputy Director 2014-2020)

Barry's research looks into defining novel roles for carotenoids in plant developmental processes, with complementary research into organelle signalling to identify the mechanisms by which plants perceive and respond to drought and excess light. He is an ARC Laureate Fellow and a 2019 Australian Museum Eureka Prize winner. Barry was previously the Head of ANU's Division of Plant Sciences and is Chair of the Global Plant Council.

ANU

PROFESSOR JUSTIN BOREVITZ (2014-current)

Justin's research applies cutting edge genomics and phenomics approaches to the study of the genetic basis of climate adaptation in plants, and utilises model plants and foundation species in controlled and field environments.

PROFESSOR OWEN ATKIN (2014-current)

Owen's research focuses on assessing the impact of environmental gradients on plant physiological processes, particularly respiration. He is the Director of the Centre for Entrepreneurial Agri-Technology (CEAT) at ANU and was previously the Head of ANU's Division of Plant Sciences.

PROFESSOR MURRAY BADGER (2005-2013)
(Deputy Director 2005-2012)

Murray's wide-ranging research interests cover various aspects of photosynthesis research relating to plant biochemistry and plant physiology.

LTU

PROFESSOR JIM WHELAN (2005-current)

Jim's research combines physiological, phenotype, biochemical, genetic and 'omic' approaches to understand organelle biogenesis and signalling in plants. Jim is Research Director of the La Trobe Institute of Agriculture and Food (LIAF) and a Fellow of the Australian Academy of Science.

USYD FU

EMERITUS PROFESSOR DAVID DAY (2005-2011)

David's research focuses on plant biochemistry and molecular biology, particularly in relation to mitochondrial metabolism and biogenesis, whole plant respiration, ion transport and symbiotic nitrogen fixation. David is a Fellow of the Australian Academy of Science and serves on its Council as Secretary for Science Policy.

UA

PROFESSOR MATTHEW GILLIHAM (2014-current)

Matt's research focuses on the physiological role of solute transport proteins in plant nutrition and in conferring tolerance to various stresses such as salinity, drought and extreme pH. He is Director of the Waite Research Institute, the University of Adelaide's Agricultural Research & Innovation flagship.

PROFESSOR RACHEL BURTON (2018-current)

Rachel's expertise lies in plant molecular biology and plant functional genomics particularly as it relates to polysaccharide biosynthesis, re-modelling and degradation and the impact these biological processes have on the end use quality of seeds. She has an interest in novel and emerging crops, with a focus on human health and nutrition, and biomass feedstocks. Rachel is a Science & Technology Australia (STA) STEM Ambassador.

EMERITUS PROFESSOR STEVE TYERMAN (2011-current)

Steve investigates the links between ion and water transport in plants and applies his research to grapevine physiology. Steve is a Fellow of the Australian Academy of Science.

PARTNERS

Max-Planck Institute for Molecular Plant Physiology
(Germany)

The MPI-MP is the elite European institute for research into central plant metabolic pathways, combined with analysis of gene function for development and implementation of phenotyping technologies and system approaches. Mark Stitt and Ralph Bock, two of MPI-MP's Directors, are partner investigators to PEB. MPI-MP has made a substantial commitment to collaborations within the Centre's programs, the provision of facilities for collaboration and to the support of PEB visitors.

Salk Institute for Biological Studies
(United States of America)

The Salk Institute focuses on discovery, and on mentoring future generations of researchers in genetics, cell and plant biology, and related disciplines. Two of its leading research professors, Joseph Ecker and Joanne Chory are partner investigators in PEB. Salk have made in-kind commitments to staff time for collaborations in all programs, to extensive access to facilities and new datasets for collaborations and to the support PEB visitors.

Umeå Plant Science Centre
(Sweden)

UPSC is one of the strongest research environments for basic plant research in Europe and covers a wide range of disciplines in plant biology. UPSC share a common goal to understand the mechanisms driving chloroplast biogenesis and plant adaptation to environments. Åsa Strand, from UPSC, is a partner investigator in PEB. UPSC has provided in-kind commitments in staff time for collaborations, and facilities for collaborations and PEB visits.

University of Turku
(Finland)

The University of Turku houses the Finnish Centre of Excellence in Molecular Biology of Primary Producers. Its Director, Eva-Mari Aro, is a partner investigator in PEB. The Centre participates through research on chloroplast biogenesis and signalling, and chloroplast function. In-kind commitment has been provided in staff time and facilities for collaborations.

University of Massachusetts
(United States of America)

Umass (Amhurst) is a major US research and teaching university with a strong reputation in plant science innovation. The UMass team, led by Elizabeth Vierling, research temperature responses in plants and collaborate with PEB to search for new gene networks for temperature tolerance in plants. Additional in-kind commitments involve follow up work at UMass and the hosting of visiting PEB staff.

Groupe Limagrain
(France)

Groupe Limagrain is an international agricultural cooperative group and the world's fourth-largest seed company. It has funded research on controlling male fertility through the manipulation of mitochondrial gene expression. Limagrain is providing wheat germplasm, testing candidate gene sequences proposed by the Centre, and evaluating lines for male fertility and the ability to produce hybrid wheat. Limagrain provide plant biotechnology development and licensing expertise to PEB.

Photon Systems Instruments
(Czech Republic)

PSI are a leading developer of new technology for imaging of plant growth and development. They have funded the development of instrumentation and new software for use in the Centre, and for deployment across Australia and bring imaging expertise to a number of Centre's projects.

Agilent Technologies
(Australia)

Agilent Technologies supports advances in life and agricultural sciences, and 'omic analysis and integration as an instrument manufacturer and product developer. The company work closely with PEB on analytical workflow solutions, automation and robotics in quality control for plant-sample QC analysis, and on refining laboratory management software and analysis. Agilent Technologies provide analytical product development expertise to PEB's Business Advisory Group.

Grain Research and Development Corporation
(Australia)

The GRDC invests in crop science for the Australian grains sector. GRDC have provided PhD scholarships and research costs to PEB and fund projects arising from CIs' discoveries for improving salinity tolerance and drought tolerance in wheat and barley. The GRDC give advice to the Centre, evaluate new PEB intellectual property for further funding by GRDC, and provide knowledge and links for PEB to Australia's grains industry.

Zhejiang University
(China)

ZJU is a major Chinese agricultural university and leads a large research program in increasing phosphate use efficiency in rice. ZJU's partnership role is in the collaborative development of rice varieties, with emphasis on use of its extensive field sites to facilitate translation from PEB's discoveries. The ZJU collaboration is led by Huixia Shou.

PEB PEOPLE HIGHLIGHTS

"Biology was always interesting to me, and plants were always a nice system to work with. Their importance cannot be overstated."

Dr Steve Eichten

"PEB provides an excellent environment for research mentoring and research facilities. While there are opportunities for plant biologists all around the world, there is no question to me that PEB is the place to be, particularly if one's goal is to develop crops for hostile climates."

Dr Sandra Tanz

"I love working for PEB. There are so many exciting multi-disciplinary things happening in the field of plant biology and new technology."

Dr Tim Brown

#PeopleofPEB

Our Research

What Is Plant Energy Biology?

Much of our food, feed, fibre and fuel is sourced directly or indirectly from plants in the form of energy-containing, nutrient-rich molecules. The synthesis, transport, storage and use of these molecules during plant growth and development is the plant energy system. The efficiency of a plant's energy system determines its final yield of plant products.

The efficiency of the plant energy system can be measured at different levels:

- In cells, as the proportion of energy used for cell maintenance versus growth.
- In whole plants, as the ratio of input resources versus harvestable product.
- In the environment, as the degree of adaptation within plant populations needed to grow successfully in variable conditions.

These measures serve as proxies for plant energy efficiency, an incredibly complex but essential plant trait.

The world urgently requires plants that can more efficiently attain the resources provided by nature and by farmers to generate more harvestable products. Furthermore, it needs plants that can to do so on agricultural soils that are decreasing in area and fertility, and that can maintain their performance in harsh and variable environments.

Energy efficiency, which sits at the centre of this requirement, can be gained or lost at multiple levels:

- At the molecular level, in the control of gene expression and metabolic processes.
- At the cellular level, through specialisation and signalling.
- At the developmental level, through physiological responses to the environment.

These gains and losses cumulatively impact across spatial scales, from tissues, to whole plants to plant populations.

The Problem

Presently, even under ideal conditions, elite crops only convert 10–15% of the carbon fixed by photosynthesis into harvestable yield, with even less efficiency seen under harsh environments.

Under suboptimal environments and in certain seasons, crop yields well below potential maxima are observed. In Australia, 60% yield gaps between potential and actual yield are now common.

Yields have varied more greatly since 2000 than in any period since 1950. Droughts of moderate severity lead to a 30–70% yield decrease.

The impact of saline soils and temperature extremes ranges from small losses up to complete crop failure, and nutrient-limitation can lead to an 80% decrease in yield.

The Solution

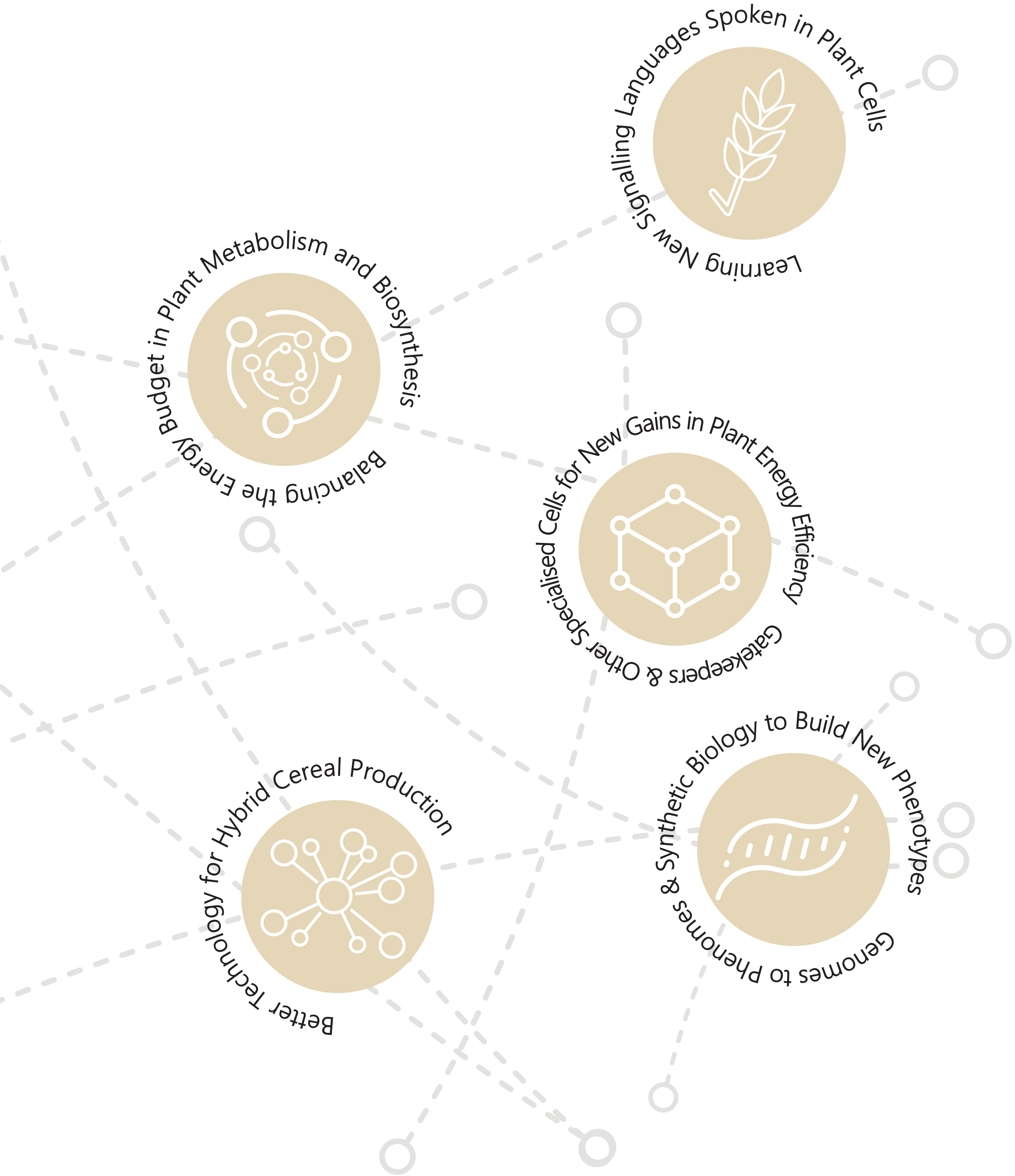
Many of these partial losses occur due to limitations and reduced efficiency in interconnected metabolic processes. Thus, small efficiency gains in the multitude of processes beyond carbon capture, but before harvest, can combine to have a magnified benefit on yield.

Discovering the interconnected signalling processes that dictate and limit how plants perform in variable environments is critical to gaining the sustainable increases in actual plant yields that are needed for our future.

Major targets for efficiency gains include the energy spent on: translocation of carbohydrates and nutrients from leaves to roots and seeds; uptake and storage of nutrients from soils; assimilation and allocation of phosphate, nitrogen and sulphur into proteins, lipids and organics; protein synthesis and turnover and maintenance of cellular ion-gradients.

Tackling plant energy research requires a team with expertise ranging from genes and proteins through to plant physiology. Through our combined expertise and using technological innovation the Centre is enhancing the energy efficiency of plants.

PEB RESEARCH THEMES



Learning new signalling languages spoken in plant cells

Cellular communication is critical to all life on Earth, animals and plants alike, and like the evolution of languages for humans, the evolution of communications systems within plants has given rise to multiple 'languages' that vary across space and time. In order to successfully complete the lifecycle from seed germination to seed production to plants needed to integrate internal signalling pathways associated with development and external stimuli from the environment.

Our Centre has made a series of fundamental discoveries about the languages that relate to energy production and metabolism. These discoveries have revealed that organelle signalling pathways are crucial hubs for sensing, integration and initiation of a variety of signals to optimise plant growth and performance under limiting conditions.

The focus of the Centre has been on retrograde signalling pathways, those that are initiated in organelles, i.e. mitochondria **(Box 1)** and chloroplasts **(Box 2)**, and relayed to the nucleus to control gene expression. The Centre has also discovered a new plant signal, gamma aminobutyric acid (GABA) **(Box 3).**

Researchers in the Centre have uncovered and dissected the mechanism of some of these pathways to establish the centre and its researchers as world leaders in the area of organelle and GABA signalling. In doing so we have revealed how the energy organelles regulate plant development and acclimation to environmental stimuli, such as drought, temperature and excess light.

[BOX 1]

Sensing and responding to changes in energy metabolism - in mitochondria

While the machinery that drives energy production and metabolism in mitochondria has been elucidated, the mechanisms of regulation of expression of nuclear genes encoding mitochondrial proteins (NGEMP) was not known in terms of molecular components, the signals involved and how these interacted with other anterograde and retrograde signalling pathways. Key discoveries by centre researchers revealed that ABI4, ANAC017 and TCP transcription factors play central roles in regulating and integrating expression of NGEMP with cell, organ and whole plant processes.

These defining studies revealed that a previously uncharacterised set of NAC transcription factors played key roles in regulating the mitochondrial stress response (Ng et al. 2013), and that the master regulator ANAC017, is a strong negative regulator of growth via interaction with auxin, is involved in senescence and also links mitochondrial and chloroplast signalling.

Interaction of organelle signalling with ABA was demonstrated via the role of ABI4 in regulating alternative oxidase (Giraud et al. 2009). The role of TCP transcription factors in regulating NGEMP and interacting with the circadian clock also links the regulation of mitochondrial and chloroplast function (Giraud et al 2010).

[BOX 2]

Sensing and responding to changes in energy production – in chloroplasts

The Centre's research has also revealed key pathways by which chloroplasts communicate their status to the cell to regulate how plants respond to environments. We achieved this by dissecting communication networks that regulate chloroplast development, photosynthesis and abiotic stress. The suite of responses included functional changes within chloroplasts and re-programming of the expression of genes (Estavillo et al. 2011).

We identified PAP as the first signal that can move between the chloroplast and nucleus; its chloroplast regulator; and mode of action, thereby assembling a retrograde signaling pathway (Chan et al. 2016). We have also showed how PAP regulates stomata across plant taxonomic groupings (Zhao et al. 2019). The utility of this mechanism in modulating crop responses to drought is part of our Centre's commercialisation strategy.

[BOX 3]

The discovery of a new signalling compound in plants

The finding that GABA production is invoked by stress turned into subject matter itself during the life of the Centre. We were first to identify that GABA was more than a metabolic shunt to maintain energy generation through respiration when it is inhibited by stress by discovering GABA receptors in plants (Ramesh et al. 2015).

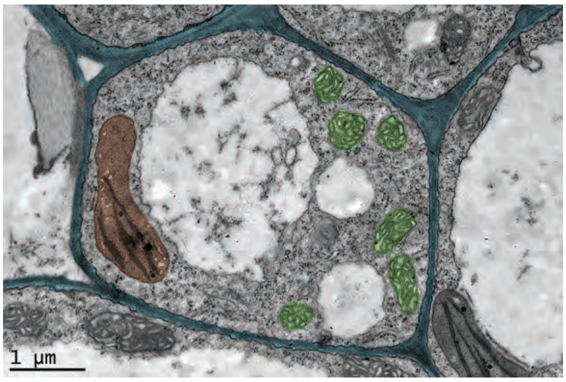
There had been speculation for more than 20 years that GABA may be a signal – but the mechanism by which it acts in plants was unknown, including its physiological role. Our data suggests GABA encodes a plant signal that links primary metabolism to physiological status and stomatal opening to fine tune plant responses to the environment (Xu et al. 2021).

The industry impact of these findings are currently being explored. As they are linked to major stress tolerances, this opens alternative avenues for improving plant stress resilience.

Outcomes and impact

Our research on new stress signals and retrograde signals continues to delineate new functions for energy organelles. For example, we have shown that memory of oxidative, drought and high light stress is not mediated by DNA methylation or noncoding RNAs. Rather, we showed that rapid recovery-specific gene expression networks are controlled by RNA stability which are regulated by chloroplast signals.

Our discoveries are leading to insights into the genes and metabolites involved in epigenetics, RNA metabolism, retrograde signaling, vitamin and pigment biosynthesis, photosynthesis and respiration and drought resistance.



Highlighted papers:

Chan KX et al (2016) Sensing and signaling of oxidative stress in chloroplasts by inactivation of the SAL1 phosphoadenosine phosphatase. **Proc. Natl Acad. Sci.** 113, E4567-E4576.

Estavillo GM (2011) Evidence for a SAL1-PAP Chloroplast Retrograde Pathway That Functions in Drought and High Light Signaling in Arabidopsis. **Plant Cell** 23, 3992-4012.

Giraud E et al (2009) The Transcription Factor ABI4 Is a Regulator of Mitochondrial Retrograde Expression of ALTERNATIVE OXIDASE1a. **Plant Physiol.** 150, 1286-1296.

Giraud E et al (2010) TCP Transcription Factors Link the Regulation of Genes Encoding Mitochondrial Proteins with the Circadian Clock in Arabidopsis thaliana. **Plant Cell** 22, 3921-3934.

Ng S et al (2013) A Membrane-Bound NAC Transcription Factor, ANAC017, Mediates Mitochondrial Retrograde Signaling in Arabidopsis. **Plant Cell** 25, 3450-3471.

Ramesh SR et al (2015) GABA signalling modulates plant growth by directly regulating the activity of plant-specific anion transporters. **Nat Commun** 6: 7879.

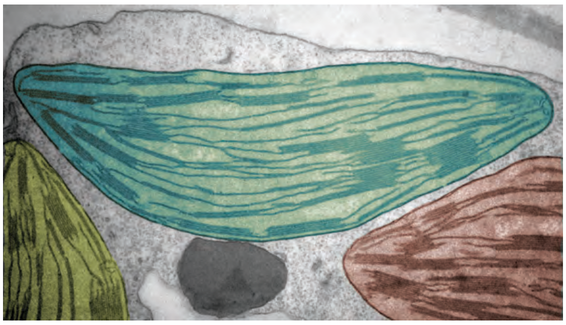
Xu B et al (2021) GABA signalling modulates stomatal opening to enhance plant water use efficiency and drought resilience. **Nat Commun** 12:1952.

Zhao C et al (2019) Evolution of chloroplast retrograde signaling facilitates green plant adaptation to land. **Proc. Natl Acad. Sci.** 116 (11), 5015-5020.

Balancing the energy budget in plant metabolism and biosynthesis

Plants capture light energy from the sun, convert it to chemical energy and use it to drive biosynthetic processes essential for plant growth and development. In the process they undertake a global shaping of atmospheric composition through CO_2 consumption and O_2 evolution that influence climate and are impacted by changing precipitation patterns and temperatures.

The Centre focuses on understanding the regulation and use of this plant energy system by molecular analysis of mechanisms that undertake and control plant metabolism (Box 1); by quantifying and modifying energy use by plants for biosynthesis processes (Box 2); and modelling the impact of plant energy generation and use at the plant, field and global scales (Box 3).



[BOX 1]

Controlling plant respiration rate

While a considerable amount is known about the control of photosynthesis, what determines the two-fold intra-species and 10-fold inter-species variation in respiration rate has been little researched and has been a focus in the Centre (Atkin et al. 2015).

Our researchers have uncovered mechanisms of temperature responses in respiration (Rashid et al. 2020), the role of kinase signalling in respiration responding to amino acid levels (O'Leary et al 2020), and how malate is exchanged for citate to drive respiration and supply carbon skeletons for amino acid production in plants (Lee et al 2021).

[BOX 2]

The costs of biosynthesis

Biosynthesis of macromolecular polymers such as proteins and complex carbohydrates collectively represent a major proportion of the cost of plant growth and maintenance.

The amount of energy available to invest in growth will determine plant fitness in the face of increasingly prevalent climate stresses. It also impacts reproductive success, important to humans as yield and seed or grain quality; both essential elements of food security.

Proteins: Protein turnover consumes 20-30% of the chemical energy generated in plant cells. The Centre has developed approaches to breakdown this number to the specific cost of maintaining individual proteins, cell structures and organelles (Li et al 2017) and in the process has discovered new rapidly degrading proteins, tissue specific differences and the impact of the diurnal cycle and high light on protein turnover processes.

Cell wall polysaccharides: In barley grain the relatively unexplored polysaccharide class of fructans has been targeted, devising better ways to measure them and define their place in the starch:mixed-linkage glucan: fructan nexus (Lim et al 2020).

Seed quality of a range of hemp cultivars has been reported and the Centre has been making great progress in unravelling the drivers and mechanisms of mucilage polysaccharide production by Plantago seed which determine psyllium yield (Cowley & Burton 2021).

[BOX 3]

Modelling of global impacts

Most model frameworks that predict rates of plant respiratory energy production assume simple relationships linking respiratory rates with photosynthesis and tissue nitrogen concentrations, and simple assumptions on how respiration varies with temperature.

The Centre has shown that relationships between respiration, photosynthesis and nitrogen differ systematically among contrasting types of plants and environments (Atkin et al. 2015), including how seasonal changes in environmental energy metabolism in natural (Zhu et al. 2021) and managed ecosystems (Coast et al. 2021).

Outcomes and impact

The Centre has led efforts to develop methods that enable high-throughput screening of respiratory energy use efficiency in wheat breeding programs using robotic measurements of gas exchange and light-reflectance approaches (Coast et al. 2019).

Our models of dynamic responses of plant respiration to short and long-term changes in temperature (e.g. Heskel et al. 2016) are enabling prediction of respiratory energy production through time across the Earth's surface by leading international climate modeling consortia (Huntingford et al. 2017).

Fructans are a neglected class of polysaccharides with influence on both dietary value and grain metabolism in cereals but they are also the key storage carbohydrate in the emerging crop agave. Traditionally used to make alcoholic beverages, agave have much broader potential in the production of foodstuffs, nutraceuticals, stock feed and renewable energy, particularly hydrogen.

The establishment of this crop in Australia, by exploring its fundamental biology and genetics, is an ongoing research focus with industry partners.

Highlighted papers:

Atkin OK (2015) Global variability in leaf respiration in relation to climate, plant functional types and leaf traits **New Phyt.** 206, 614-636.

Coast O et al (2021) Acclimation of leaf photosynthesis and respiration to warming in field-grown wheat. **Plant, Cell & Environ.** 44, 2331-2346.

Coast, O., et al. (2019). Predicting dark respiration rates of wheat leaves from hyperspectral reflectance. **Plant Cell & Environ** 42, 2133-2150.

Cowley JM, Burton RA (2021) The good stuff: Plantago as a myxospermous model with modern utility. **New Phyt** 229, 1917-1923.

Heskel MA et al (2016) Convergence in the temperature response of leaf respiration across biomes and plant functional types. **Proc. Natl Acad. Sci.** 113, 3832-3837.

Huntingford C et al (2017) Implications of improved representations of plant respiration in a changing climate. **Nature Comms.** 8, 1-11.

Lee CP et al (2021) The versatility of plant organic acid metabolism in leaves is underpinned by mitochondrial malate–citrate exchange. **Plant Cell** 33, 3700–3720.

Li L et al. (2017) Protein Degradation Rate in Arabidopsis thaliana Leaf Growth and Development. **Plant Cell** 29:207-228.

Lim WL et al (2020) Overexpression of HvCslF6 in barley grain alters carbohydrate partitioning plus transfer tissue and endosperm development. **J Exp Bot** 71, 138-153.

O'Leary BM et al (2020) Metabolite Regulatory Interactions Control Plant Respiratory Metabolism via Target of Rapamycin (TOR) Kinase Activation. **Plant Cell** 32:666-682.

Rashid FAA et al (2020) Diel-and temperature-driven variation of leaf dark respiration rates and metabolite levels in rice **New Phyt.** 228, 56-69.

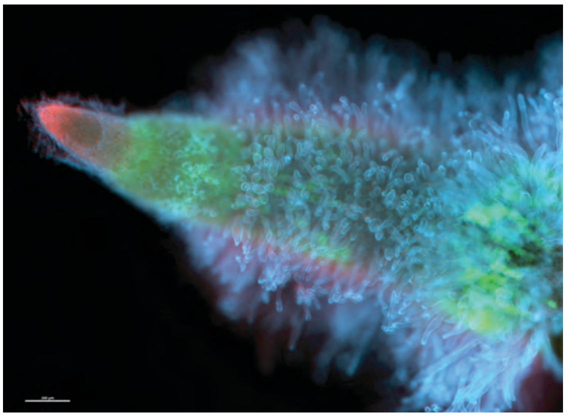
Zhu L et al (2021) Acclimation of leaf respiration temperature responses across thermally contrasting biomes. **New Phyt.** 229, 1312-1325.

Gatekeepers and other specialised cells for new gains in energy efficiency

Acquisition of necessary nutrients and the exclusion of soil toxins are essential for agricultural production. The acquisition of nutrients and the control of resource transport through plants are energy-intensive processes for plants, as are the exclusion and cellular detoxification of toxic substances. Australian soils are generally phosphorus-deficient, and many areas are highly saline.

Global supplies of phosphate fertilizer are diminishing, and soil salinity is limiting food production world-wide because of climate change and a scarcity of good agricultural land. Low-grade plant fertilizers also come with heavy metal contamination. All these nutrients and toxins travel with water in plants.

Uptake of nutrients and their transport within the plant are controlled by key cell types. These often form a rate-limiting step within the transport pathway of nutrients, metabolites and toxins– we call these strategically located cells "gatekeepers". The Centre's work has aimed to improve the efficiency of plant energy use during the acquisition and partitioning of key resources by manipulating the transport properties of the gatekeeper cells for water **(Box 1)**, phosphate **(Box 2)**, and salt **(Box 3)**.



[BOX 1]

Aquaporins

Water is the major limitation to crop yields in Australia, and this influence is only expected to increase in the face of further climate change. Water use in plants is closely associated with carbon capture, nutrient acquisition, and drought and salinity tolerance. Proteinaceous water channels embedded in all plant membranes also called aquaporins (AQPs) are primarily responsible for water transport across membranes in gatekeeper cells.

These AQPs play a significant role in how plants respond to stress. The Centre's research (Tyerman et al 2021) has shown that some plant AQPs also play a role in transporting ions e.g. Na^+, K^+, NH_4^+, NO_3-. These multifunctional AQPs have been referred to as ion conducting icAQPs. They are candidates for important, but molecularly unidentified, cation and anion channels in plant membranes. They are potentially the missing links explaining sodium leaks in root gatekeeper cells which are so important for the energetics of salinity tolerance.

[BOX 2]

Altering phosphate uptake, storage and use as keys to boost the energy currency of cells

Phosphate is essential to all life on earth. Phosphate predominantly enters the food chain via plants – as they take it up from the soil solution via their root systems. Too little soil phosphate dramatically decreases plant growth, flower production and yield.

The Centre has used a variety of forward and reverse genetic approaches to identify new regulators of phosphate uptake in plants, the mechanism of how they functioned and how this is regulated in a cell specific manner. We have developed predictive tools to identify root-cell type enriched transcripts associated with the plant's phosphate starvation response (Linn et al 2017).

We have expanded our understanding of how phosphorus status is sensed and how phosphate uptake is coordinated with plant development. We have assessed plant adaptation to low and high phosphate environments and exploited natural genetic variation in key molecular controls (Osorio et al 2019). We have also identified a role of epigenetic regulation in Pi uptake in plants (Secco et al 2015).

[BOX 3]

New insights into salt tolerance in plants

Salinity (NaCl in soils) reduces the growth and yield of plants by imposing ionic and osmotic stress on their constituent tissues.

Our Centre has advanced the molecular and physiological understanding of the key proteins within gatekeeper cells involved in the exclusion of sodium ions from the shoots of wheat, barley, tomato, grapevine and soybean (e.g. Byrt et al. 2014, Guan et al. 2014, Henderson et al. 2018). We characterised an important membrane transporter responsible for chloride exclusion from plants.

We have improved our understanding of how carbohydrate metabolism and energy production is affected by salinity in cereal tissues, and that a blockage of energy production can be bypassed by the GABA shunt (Che-Othman et al. 2020). We introduced a new framework for modelling the energy costs of the various cellular mechanisms that underpin salt tolerance, and developed the concept of an energy deficit as being the primary driver of poor crop performance under salt (Munns et al 2020).

Outcomes and impact

The impact of our work on membrane transporters that control sodium uptake has led to yield increases of wheat and soybean in saline soils, and quality improvements in grapevine. New germplasm and molecular markers have been taken up by wheat and barley breeding programs.

The fundamental knowledge on genes controlling water uptake and phosphate uptake provides new approaches to breed for greater crop yields in dry or P-deficient soils.

Highlighted papers:

Byrt CS et al. (2014) Accumulation of Na+ in bread wheat is controlled by the Na+ transporter TaHKT1;5-D **Plant J.** 8:516–526.

Che-Othman M et al. (2020) Wheat mitochondrial respiration shifts from the tricarboxylic acid cycle to the GABA shunt under salt stress. **New Phyt.** 225: 1166-1180.

Guan R et al. (2014) Salinity tolerance in soybean is modulated by natural variation in GmSALT3. **Plant J.** 8: 937–950.

Henderson SW et al. (2018) Functional differences in transport properties of natural HKT1;1 variants influence shoot Na+ exclusion in grapevine rootstocks. **New Phyt**. 217: 113-1127.

Munns R, et al. (2020) Energy costs of salt tolerance in crop plants. **New Phyt.** 225:1072-1090.

Linn, J et al. (2017). Root Cell-Specific Regulators of Phosphate-Dependent Growth. **Plant Physiol.** 174, 1969-1989.

Osorio, MB et al. (2019). SPX4 Acts on PHR1-Dependent and -Independent Regulation of Shoot Phosphorus Status in Arabidopsis. **Plant Physiol.** 181, 332-352.

Secco D et al. (2015). Stress induced gene expression drives transient DNA methylation changes at adjacent repetitive elements. **eLife** 4:e09343.

Tyerman SD et al. 2021. Adaptable and multifunctional ion-conducting aquaporins. **Annu. Rev. Plant Biol.** 72:703-736.

Genomes to phenomes and synthetic biology to build new phenotypes

As plants radiate into diverse habitats, populations adapt by fine-tuning their energy systems to withstand and exploit changing environmental conditions. Natural genetic diversity controls many potentially adaptive traits, the molecular basis of which can be mined from plant genomes by unifying modern genomics technologies with precision phenotyping and sensitive environmental observation, at both the individual and population levels (Box 1).

In addition to determining the adapted genetic loci of adapted plants, it is critical to understand the gene expression patterns and epigenetic codes that govern where and when the genetic information is used (Box 2). Knowledge of this variation underlying complex plant functions is allowing us to engineer plants with far more precision for future, more variable environments (Box 3).

[BOX 1]

Phenotyping with precision

The Centre has extended Arabidopsis resources to look at climate adaptation and photosynthesis in 2nd generation growth chambers and chlorophyll fluorescence phenotyping (Brown et al 2014, Namin et al 2018). We established the Brachypodium model plant system for GWAS of Energy Traits including biomass, yield and photosynthetic potential (Wilson et al 2019). The methods and resources are available to the research community to study adaptation, invasion and polyploidization in this model cereal.

We developed new methods and genomic resources to dissect the adaptive radiation among Eucalyptus foundation species (Supple et al, 2018). We are extending our capabilities to characterize plant performance by 3rd generation Growth Capsules that make up the 'Grain Phenomics Climate Facility'.

These stand alone capsules contain climate control rooms and a ventilated light loft. They can simulate high light, spectral quality, temperature and humidity cycles to replicate local diurnal and seasonal conditions. This allows laboratory studies of local adaptation under field like conditions.

High resolution field environmental monitoring with panoramic, camera tower, time lapse imaging is providing leaf level phenotyping to bridge the gap between lab and field.

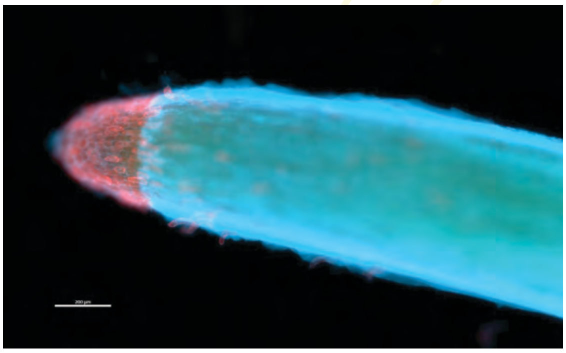
[BOX 2]

Transcriptional landscapes

The Centre also made significant advances in our understanding of epigenome landscapes, dynamics, and functions in plant populations, growth, development, and stress response.

These include the first comprehensive characterization of cell-type specific DNA methylation patterns in single cell types in somatic plant tissues (Kawakatsu et al 2016), characterization of stress-induced changes in DNA methylation in multiple plant species and the extent to which such epigenetic changes can be maintained through plant growth and into subsequent generations (Secco et al 2015, Crisp et al 2017), comprehensive mapping of transposable element mobilization in plant populations and their impact upon the (epi)genome and transcriptional variation (Stuart et al 2016, Eichten et al 2016), and analysis of epigenome dynamics during development and abiotic stress (Narsai et al 2017a,b).

Collectively, this research has produced many important insights into the plant epigenome and its role in the control of plant cell activity in normal and challenging environments.

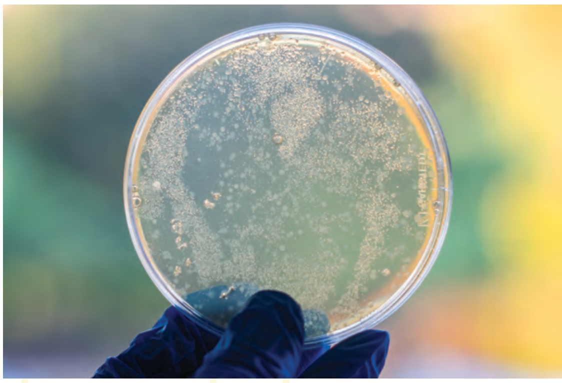


[BOX 3]

Programmable gene expression

We have optimized and applied new single cell genomics technologies to deeply characterize plant cellular identity and activity, developmental processes and their regulators, and cell type specific responses to the environment at the single cell level, contributing to an unprecedented atlas of cellular identity and function in plant tissues.

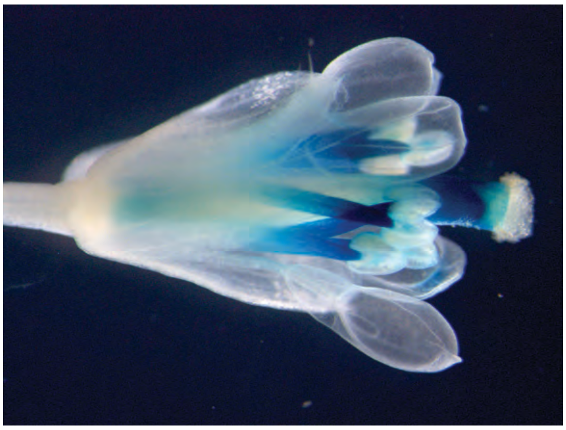
We have also developed new molecular tools for manipulating plant gene expression, consisting of a suite of programmable transcriptional regulators. This provides new capabilities in controlling gene expression to improve plant performance, and new tools for wider application in plant biotechnology.

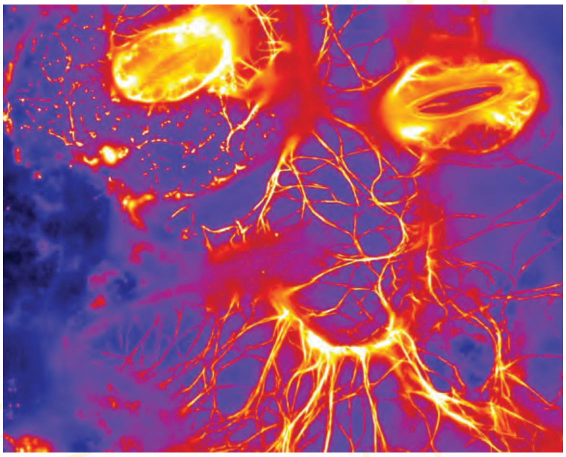


Outcomes and impact

Collectively, the Centre's advances in the development and application of phenomics, genomics, and synthetic biology technologies provide important new insights into how plants grow and cope with challenging environments.

Both the knowledge and tools will be critical for research and development spanning basic plant sciences to advanced plant biotechnology and agricultural industries.





Highlighted papers:

Brown TB et al. (2014) TraitCapture: genomic and environment modelling of plant phenomic data. **Curr. Op. Plant Biol.** 18, 73-79.

Crisp PA et al (2017) Rapid recovery gene downregulation during excess-light stress and recovery in Arabidopsis. **Plant Cell** 29, 1836-1863.

Eichten SR (2016) DNA methylation profiles of diverse Brachypodium distachyon align with underlying genetic diversity. **Genome Res.** 26, 1520-1531.

Kawakatsu T et al (2016) Unique cell-type-specific patterns of DNA methylation in the root meristem **Nature Plants** 2,16058.

Namin ST et al (2018) Deep phenotyping: deep learning for temporal phenotype/genotype classification. **Plant Methods** 14, 1-14.

Narsai R et al (2017) Dynamic and rapid changes in the transcriptome and epigenome during germination and in developing rice (Oryza sativa) coleoptiles under anoxia and reoxygenation. **Plant J.** 89, 805-824.

Narsai R et al (2017) Extensive transcriptomic and epigenomic remodelling occurs during Arabidopsis thaliana germination. **Genome Biol.** 18 (1), 1-18.

Secco D et al (2015) Stress induced gene expression drives transient DNA methylation changes at adjacent repetitive elements. **eLife** 4, e09343.

Stuart T et al (2016) Population scale mapping of transposable element diversity reveals links to gene regulation and epigenomic variation. **Elife** 5, e20777.

Supple MA et al (2018) Landscape genomic prediction for restoration of a Eucalyptus foundation species under climate change. **eLife** 7, e31835.

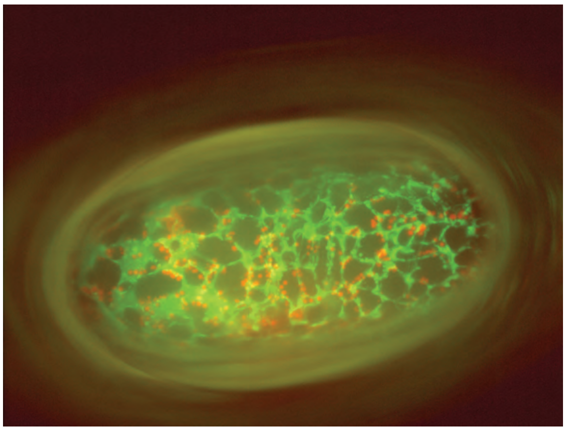
Wilson PB et al (2019) Global diversity of the Brachypodium species complex as a resource for genome-wide association studies demonstrated for agronomic traits in response to climate. **Genetics** 211, 317-331.

Better technology for hybrid cereal production

The use of hybrid crop varieties is increasing because of their attractive agronomic traits. Hybrid crops tend towards faster growth and better yields (hybrid vigour). Gains in productivity commonly exceed 15-20%. They are generally more resilient to biotic and abiotic challenges also.

Most field-grown crops are self-pollinators, and development of hybrid breeding systems for these crops requires a means to control this - the female (seed) parent must be prevented from self-pollinating. One genetic method that can be exploited employs a mitochondrial gene that induces cytoplasmic male sterility (CMS).

However, to ensure the hybrids are fertile, breeders use a male parent that carries a nuclear Restorer-of-fertility (Rf) gene to prevent expression of the CMS gene in the hybrid by binding the CMS transcript and preventing its translation.



The high value of hybrid crops makes effective Rf genes highly desired. Building on the Centre's investigation of gene expression in energy organelles (Box 1), we have developed world-class expertise in the study of pentatricopeptide repeat (PPR) proteins (Box 2). Almost all known Rf proteins are PPR proteins.

In recent years we have focused on PPR genes in rice, sorghum, barley, rye, wheat (e.g. IWGSC, 2018, Walkowiak, et al. 2020), culminating in the identification of two wheat Rf genes and their mitochondrial RNA targets (Melonek et al 2021) , in collaboration with the multinational seed company, Groupe Limagrain.

Our understanding of the structure and function of PPR proteins is leading to their use in synthetic biology as programmable RNA binding and editing factors (Box 3).

[BOX 1]

Organelle gene expression through plant development

Centre researchers helped to discover the important roles of energy organelles in plant development, and particularly how the expression patterns of energy organelle genes contribute to these processes.

The critical period for chloroplast gene expression is in early vegetative development as the plant transitions from energy supplied by the reserves in the seed to energy supplied by photosynthesis (eg. Baerenfaller et al 2012, Dubreuil et al 2018).

There are two critical periods for mitochondrial gene expression: the early stages of seed germination and reproductive development, particularly pollen development. Producing pollen requires a great deal of energy provided by mitochondria in the tapetal cell layer of the anther (Hu et al 2016).

[BOX 2]

Pentatricopeptide repeat (PPR) proteins

PPR proteins are sequence-specific RNA binding proteins present in huge numbers in plants, and a particular focus of the Centre because of their important role in controlling energy organelle gene expression (Barken & Small 2014)

PEB has been one of the leaders in PPR research for the last decade, making key contributions to understanding the structure (Cheng et al. 2016), function, and diversity (Gutmann et al 2020) of PPR proteins in plants.

Understanding how these proteins recognise their RNA targets was a massive breakthrough, leading to exciting applications (Barken et al 2012). A second important breakthrough was the identification of a clade of PPR proteins specifically implicated in suppressing cytoplasmic male sterility (Fujii et al 2011). It was this discovery that led directly to our research on hybrid cereals.

[BOX 3]

Designing RNA-binding proteins for synthetic biology

The modular structure of PPR proteins and the knowledge of the basic recognition code between the PPR protein and the RNA it binds makes it possible to modify existing PPR proteins to alter their specificity and, consequently, the expression of mitochondrial or plastid genes.

PEB researchers have achieved this outcome using both modified PPR proteins (e.g. Kindgren et al 2016), and fully synthetic proteins (e.g. Royan et al 2021). These approaches open possibilities to deliberately alter the expression of organelle genomes and design tools for biotechnological applications.

Outcomes and impact

PEB research in this area has led to three patent applications and long-lasting collaborations with multiple partners including agricultural research institutes such as the IPK in Gatersleben, Germany, the USDA in the USA, INRAE in France, as well as CSIRO and QAAFI in Australia.

Industry partners have included Syngenta, NuSeed, Australian Grain Technologies, and most notably, Groupe Limagrain, who have supported this research for the last 7 years and are continuing to do so.

We have identified Rf genes usable for hybrid breeding in wheat, rye, sorghum and barley and expect these discoveries to lead to substantial accelerations in the commercialisation of hybrid varieties in these crops.

Highlighted papers:

Baerenfaller, K. et al. (2012) Systems-based analysis of Arabidopsis leaf growth reveals adaptation to water deficit. **Mol. Syst. Biol.** 8, 606.

Barkan, A. & Small, I. (2014) Pentatricopeptide repeat proteins in plants. **Annu. Rev. Plant Biol.** 65, 415442.

Barkan, A. et al. (2012) A combinatorial amino acid code for RNA recognition by pentatricopeptide repeat proteins. **PLoS Genet.** 8, e1002910.

Cheng, S. et al. (2016) Redefining the structural motifs that determine RNA binding and RNA editing by pentatricopeptide repeat proteins in land plants. **Plant J.** 85, 532547.

Dubreuil, C. et al. (2018) Establishment of photosynthesis is controlled by two distinct regulatory phases. **Plant Physiol.** 176:11991214.

Fujii, S. et al. (2011) Selection patterns on restorer-like genes reveal a conflict between nuclear and mitochondrial genomes throughout angiosperm evolution. **Proc. Natl. Acad. Sci.** 108, 1723–1728.

Gutmann, B. et al. (2020) The expansion and diversification of pentatricopeptide repeat RNA-editing factors in plants. **Mol. Plant** 13, 215230.

Hu, Z. et al. (2016) Mitochondrial defects confer tolerance against cellulose deficiency. **Plant Cell** 28, 22762290.

International Wheat Genome Sequencing Consortium (IWGSC) et al. (2018) Shifting the limits in wheat research and breeding using a fully annotated reference genome. **Science** 361, eaar7191.

Kindgren, P et al (2015) Predictable alteration of sequence recognition by RNA editing factors from Arabidopsis. **Plant Cell** 27, 403–416.

Melonek, J. et al. (2021) The genetic basis of cytoplasmic male sterility and fertility restoration in wheat. **Nat. Commun.** 12, 1036.

Royan, S. et al. (2021) A synthetic RNA editing factor edits its target site in chloroplasts and bacteria. **Commun Biol** 4, 545.

Walkowiak, S. et al. (2020) Multiple wheat genomes reveal global variation in modern breeding. **Nature** 588, 277–283.

Our ability to answer scientific questions can be expanded with innovative technologies. PEB research has given rise to a number of new technologies that have enhanced the breadth and outcomes of research not only for the Centre but for scientists around the globe.

cropPAL
PROTEINS WITH ANNOTATED LOCATIONS

cropPAL: Crop Proteins with Annotated Locations

Barley, wheat, rice and maize provide the bulk of human nutrition and have extensive industrial use as agricultural products. Each of the genomes of these crop plants contain more than 40,000 genes, each in turn encoding proteins. However, the major genome databases for these species lack annotation information about the subcellular location of greater than 80% of these proteins.

To address this gap, PEB created a compendium of crop protein subcellular locations called cropPAL; *crop Proteins with Annotated Locations* with the support of the Australian National Data Service (ANDS). CropPAL collates more than 550 data sets from previously published fluorescent tagging or mass spectrometry studies around the world, and ten pre-computed subcellular predictions for barley, wheat, rice and maize proteomes.

The data collection, including metadata for proteins, has been made publically available and studies can be interrogated through a search portal (www.crop-pal.org). As an open access research tool, cropPAL is a valuable asset to assist plant researchers, biotechnology companies and the crop breeding industry.

Protein subcellular location is an important clue to protein function, and to how proteins interact within the metabolic household. The subcellular localisation information housed in cropPAL helps to depict plant cells as compartmentalised protein networks that can be investigated for improving crop yield and quality and for developing new biotechnological solutions to agricultural challenges.

Epimodification Tools

Epigenetic systems play critical roles in the genomic functions of plants. Epigenetic modifications such as DNA methylation can influence gene expression without modifying the underlying DNA sequence.

Techniques to accurately map DNA methylation throughout the entire genome at unprecedented resolution are now being used in the Centre to study plant epigenomes and look at the involvement of the epigenome in plant growth, cellular identity and function, in maintaining energy systems and in response to challenging environments.

The next step along this research path is to develop novel molecular tools to deliberately and precisely engineer the epigenome, something which has not previously been possible.

Work in the Centre is looking at combined application of customizable DNA binding proteins - that allow targeting of a specific DNA sequence - with the capacity to induce DNA methylation in order to generate a novel tool that enables the artificial induction of changes in DNA methylation at specific target loci in the genome. This tool will be used to both explore the functions of cell-type specific DNA methylation, and to engineer plants with conditional epigenetic responses to stressful environments.

Measuring Protein Turnover

Proteins are constantly being synthesised and degraded as plants grow, develop and adapt. A thorough understanding of protein turnover is essential to appreciate and understand the responses of plants to environmental and developmental cues. Technology currently exists for determining relative amounts of proteins from tissues of interest and between conditions of interest.

What is lacking is the ability to determine whether abundance changes are due to alterations in protein synthesis, degradation, or both.

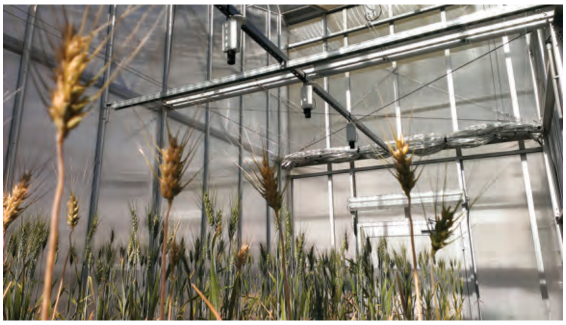
Work at PEB is addressing this through a technology that allows the tracking of specific protein abundance and the attribution of changes in abundance to shifts in synthesis and/or degradation. This work is also taking into consideration the existence of different forms of a protein, multiple localisations of proteins within a cell, and variable protein populations within the many cell types that make up a tissue by characterising protein turnover characteristics for different subcellular protein populations and cell-type specific proteomics.

When we can address all of these layers of complexity we can develop a more thorough understanding of all the various types of plant cells steady state as well as its response to non-steady scenarios e.g. biotic and abiotic stress. With this more complete understanding more informed decisions for intelligent engineering of crops for a changing world can be made.

Phenomic Monitoring Pipelines

Plant physiology research is progressing from the detailed study of a few different genotypes at a time, to high throughput, quantitative, phenomic studies on populations with fully sequenced genomes. The current challenge, however, is integrating these new techniques into a package that can be implemented across phenomics platforms, on different plant species, and that can be applied to field data.

The Centre uses climate-mimicking growth environments with sophisticated LEB lighting and cameras to build monitor-able climate scenarios, and is now coupling this with software pipelines to comprehensively measure and record plant responses and integrate different data sources. One group in the Centre is actively developing software tools to integrate new cameras with advanced image analysis, genetic dissection, and plant models - pieces that each interact to enhance one other.



Online data visualisation and analysis tools are core components in the approach. Web-based visualisation will allow real-time graphing of environment data with associated time-lapse movies.

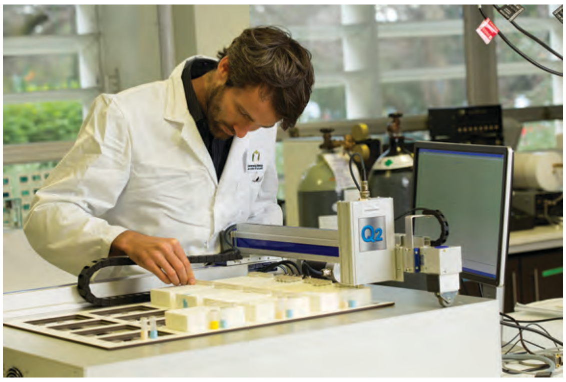
Employing open-source and web-based software integration approaches will allow phenomic data to be remotely processed and easily shared facilitate widespread use and collaboration between researchers, both locally and internationally.

Re-purposing Q2 Technology for Leaf respiration measurements

Astec Global's Q2 Technology was created for the high-throughput measurement of oxygen consumption by single seeds by measuring fluorescence that is proportional to the oxygen concentration in a hermetically sealed sample tube. The instrument's ability to record oxygen levels over time can offer the oxygen depletion rate caused by seed respiration and the unit's design allows measurements to be made at four different temperatures simultaneously.

PEB researchers, driven by an interest in increasing capacity to perform leaf respiration measurements *en masse*, re-purposed the Q2 Technology to take oxygen readings from leaf and other plant tissues.

A protocol for leaf tissue measurements, taking into consideration variables such as tissue handling and preparation, optimal sample amount and appropriate instrument settings was successfully optimized and development of light sources to illuminate leaf tissue during Q2 measurements is being pursued.



Illuminating leaf tissue allows for oxygen evolution through photosynthesis to be measured. Hence, this technology can provide high-throughput screening of both respiration and photosynthesis.

The re-purposed Q2 Technology has proven valuable for a number of the Centre's studies, allowing high-throughput screening of leaf, root and stem tissues at varying temperatures, dramatically increasing the scope of numerous research projects.

The Centre is now in possession of three Q2 instruments with plans to make the methodology available so that other plant researchers can take advantage of this high-throughput research approach.

PUBLICATIONS

Core to a research Centre's activities is the publication of its findings. In 2020 PEB hit a milestone 1,000 publications. These papers represent over 1,000 significant contributions to plant and related sciences.

PEB's publications have, collectively, clocked over 60,000 citations by other researchers from around the world, having far reaching impact in the research and general community alike.

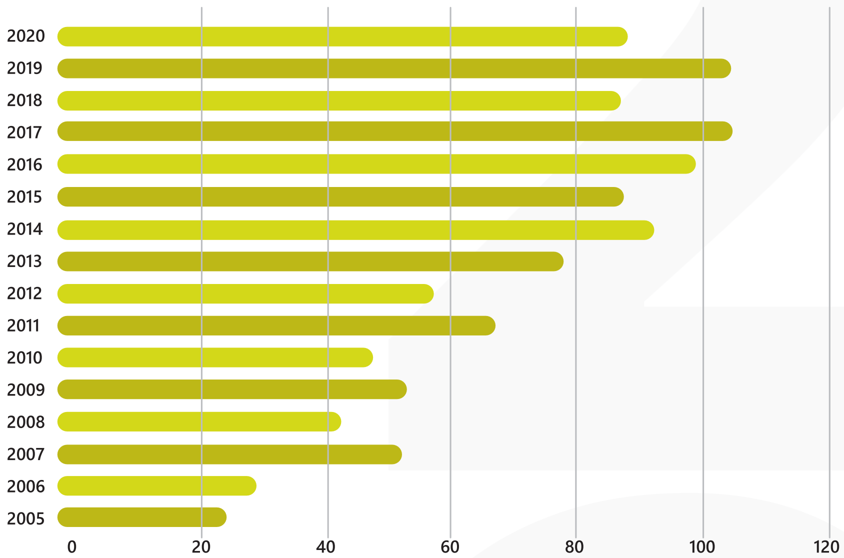
"From top publications in leading journals such as Cell and Science, to quirky findings that captured people's imagination, each paper marks a unique and significant step in our quest to understand more about the world around us." Prof. Harvey Millar, PEB Director.

PEB Publication Fast Facts, 2005-2020

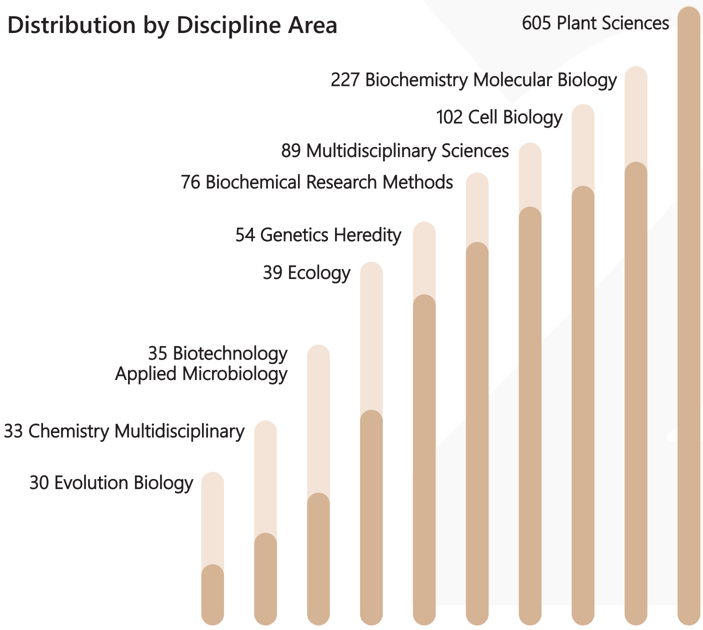
- Total number of publications by Centre staff: 1078
- Average impact factor: 6.9
- Publications in top journals (impact factor 10 and above): 173
- Top journals include: Nature (12), Science (4), Nature Plants (4), Genome Research (8), Nature Communications (12), Trends in Plant Science (22), Nucleic Acids Research (14), The Plant Cell (59) and PNAS (23).

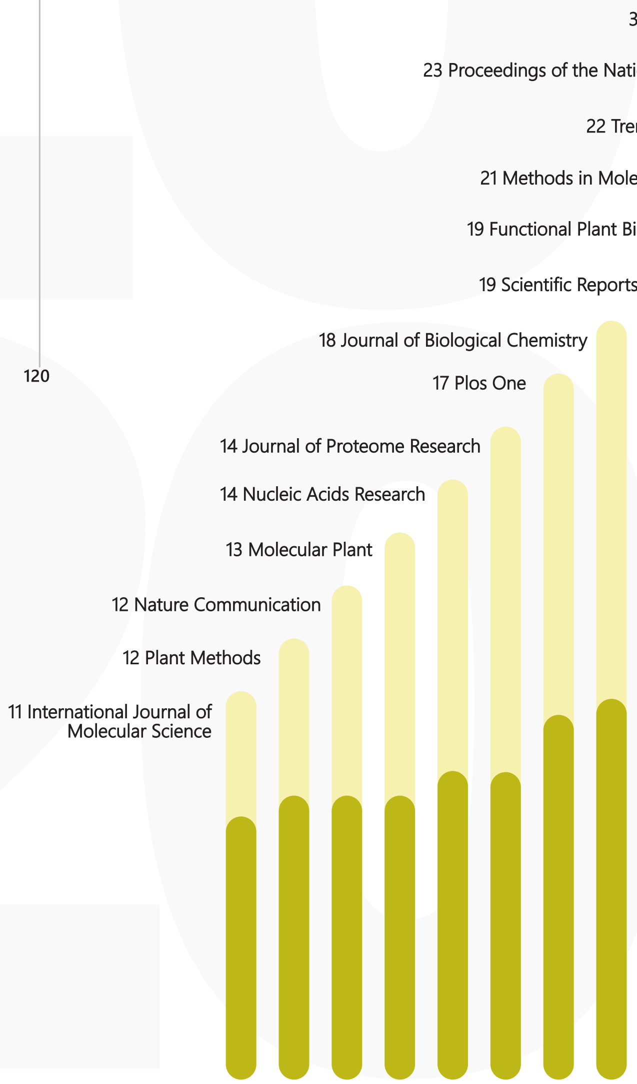
A full list of PEB publications can be found at www.plantenergy.edu.au

Publications by year



Distribution by Discipline Area

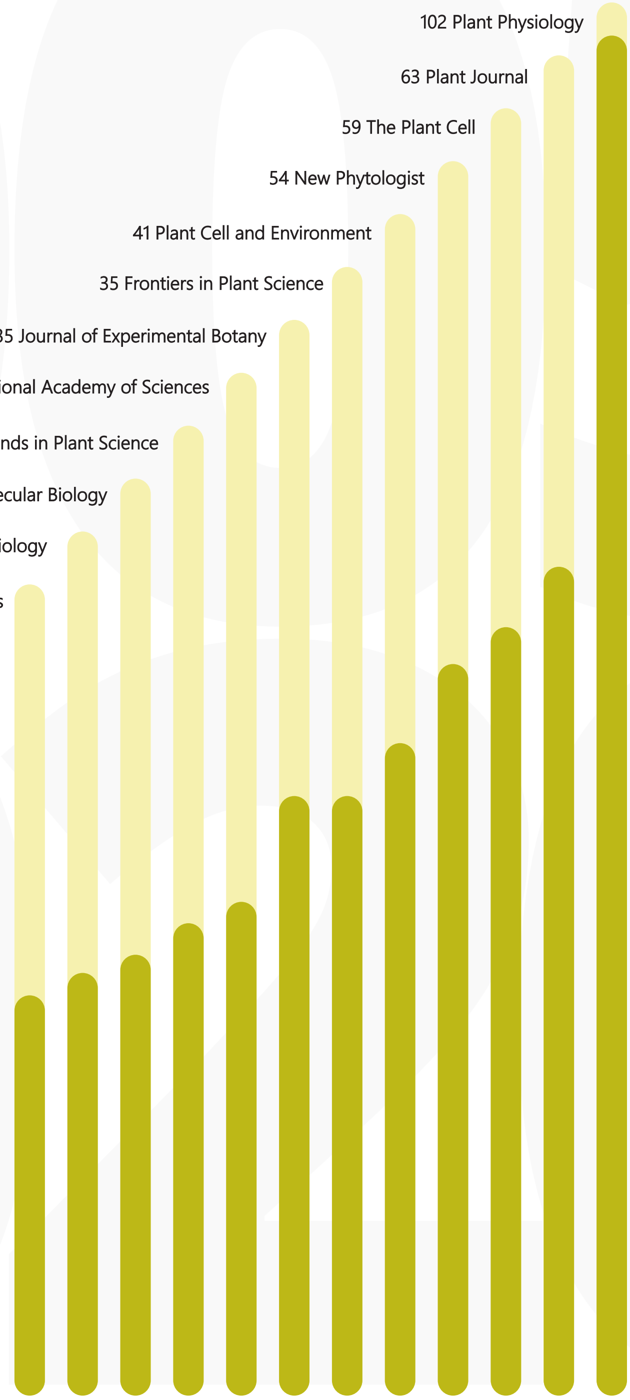




1000 Discoveries

To celebrate the 1,000 publications milestone, PEB ran a #1000Discoveries campaign in November 2020. The online and social media campaign recounted some of the Centre's biggest, weirdest, most impactful and most surprising discoveries of the last 15 years.

Distribution by Journal



Collaborating Author Organisation

740 UNIVERSITY OF WESTERN AUSTRALIA
222 AUSTRALIAN NATIONAL UNIVERSITY
168 UNIVERSITY OF ADELAIDE
103 LA TROBE UNIVERSITY
61 CSIRO AUSTRALIA
41 HARRY PERKINS INST OF MEDICAL RESEARCH
39 UNIVERSITY OF QUEENSLAND
38 ZHEJIANG UNIVERSITY
31 FLINDERS UNIVERSITY
29 UNIVERSITY OF SYDNEY
27 UNIVERSITY OF TASMANIA
26 UNIVERSITY OF MELBOURNE
25 CHINESE ACADEMY OF SCIENCES
24 UNIVERSITY OF COPENHAGEN
24 GHENT UNIVERSITY
24 UNIVERSITY OF MINNESOTA
19 SALK INSTITUTE OF BIOLOGICAL STUDIES
18 STOCKHOLM UNIVERSITY
18 UMEA UNIVERSITY
17 INRA FRANCE

PEB PEOPLE HIGHLIGHTS

"A better understanding of how plants deal with stress will open up new opportunities to develop stronger plants for agriculture in the future."
Dr Katharina Belt

"Soil salinity is a major threat to agriculture throughout the world. Given the narrow nature of genetic diversity for salt tolerance within crops, the introduction of salt-tolerant genes from naturally salt-loving plants has real potential in tackling this issue."
Dr Jayakumar Bose

"Being a part of a farming family I hope that the research we do will make a difference, so the prosperity of Australian farming can continue."
Dr Allison Pearson

#PeopleofPEB

Impact

Growing more for less – energy use efficiency for wheat yield

To address the need for dramatic global crop yield increases in order to meet future food security needs, the Agriculture Ministers of the G20 nations established the International Wheat Yield Partnership (IWYP) - a unique, multi-national funding initiative to co-ordinate wheat research efforts globally.

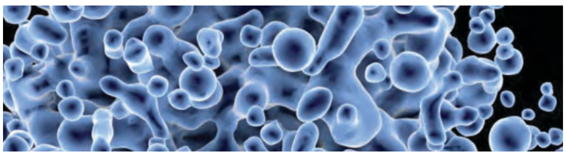
The PEB-led IWYP project Improving Wheat Yield By Optimising Energy Use Efficiency comprised of teams at UWA, UA and ANU that examined the relationship between photosynthesis, respiration, growth and yield in order to exploit the energy systems of wheat plants and dramatically increase their productivity.

Along with partners at the ARC Centre of Excellence in Translational Photosynthesis and the International Maize and Wheat Improvement Centre (CIMMYT), the team used hyperspectral measurements of photosynthesis, high-throughput measures of respiration, biochemistry and genetics, along with field-based physiological measurements in a novel approach to screen wheat populations and identify new yield-related traits.

Field and controlled environment trials using inbred and diverse panels of wheat lines generated a unique, valuable dataset of physiology, -omics and genetic information which has been interrogated using machine learning methods.

Novel protein relationships with respiration and yield were uncovered, and the importance of factors surrounding the pyruvate pool as essential to understanding Energy Use Efficiency (EUE) was highlighted.

New quantitative trait loci (QTL) influencing these traits and deployment of findings in hyperspectral models will assist future breeding programs to enhance wheat yield potential.



Genomic approaches for phosphate use efficiency improvement

Phosphate is a key limiting factor to agricultural production and incurs major costs as a fertiliser. Fundamental knowledge of how plants balance their phosphate requirements and how to make modern crop varieties more efficient in their nutrient use is urgently needed to improve modern cropping systems that use targeted fertiliser placement and automated plant health monitoring.

Three "genomic" approaches were undertaken by PEB to discover key determinants of phosphate relations in plants. Root cell-specific regulators of phosphate uptake and translocation were identified that perceive how much phosphate is available to plant roots and alter the expression of phosphate-responsive genes.

Genome Wide Association Studies allowed identification of genes that drive survival in phosphate poor environments and an understanding of population dynamics driven by changes in soil phosphate.

Finally, the role of SPX DOMAIN PROTEIN4 (SPX4), a sensor of leaf organic phosphorus status, in conveying phosphorus status information to the nucleus and altering gene expression related to nutrient uptake and plant development was studied.

Taken together these projects have identified 11 novel root cell-enriched and 45 phosphorus trait-related genes to date. These can be transferred to our academic and commercial partners for evaluation for plant nutrient efficiency improvements under field conditions.

Building salt tolerant crops

Many commercial crops are sensitive to soil salinity, causing major yield losses every year. The Centre has led a number of studies aimed at increasing salinity tolerance in crop plants important to the Australian economy including wheat, barley, and grapevine, and the internationally significant legume, soybean.

GmSALT3 was identified by Centre researchers as a gene conferring salt tolerance to soybean plants and this information can now be used in breeding programs to ensure that tolerance is maintained in future cultivars of soybean that will be grown in areas prone to soil salinity.

Furthermore, the novel way in which this gene was found to confer salt tolerance is driving the search for similar genes in different crops to explore if it contributes to their salt tolerance.

New insights on the wheat HKT protein – uncovered in one of the foundation studies of the Centre as responsible for excluding toxic sodium ions from the shoot – has shown how the structure of this protein results in its effectiveness to transport sodium and confer salt tolerance in multiple crops including grapevine, wheat and barley.

Relevant modeling of climate
The Centre has worked at the frontline of plant research that uses systems to model dynamic climate conditions in physiological and ecological relevant ways. We developed pipelines that enable high throughput studies under dynamic environmental conditions using growth chamber technology. Spectral climate chamber facilities were developed that enable tight control of light, temperature and moisture to simulate local and regional field-like conditions from particular locations and seasons.

A key aspect of this work was the installation and application of the 'Grains Phenomics Climate Facility' that has enabled researchers to simulate daily and seasonal environments experienced by crops such as wheat, and for both current and future climate scenarios, including assessing the impacts of heat waves and drought on crop performance.

The Centre's work has also been at the forefront of improving our understanding of how changing climates affect carbon exchange between plants and the atmosphere in natural ecosystem across Australia and overseas. By understanding how climate affects plant energy metabolism across the Earth's surface, the Centre has been able to work with ecosystem modeling groups in the USA and UK to improve representation of plant metabolism in Earth System Models.

These models drive international policy settings and economic investment; as such, it is vital that they accurately predict future levels of atmospheric carbon dioxide and land surface temperatures.

Protein Turnover
Proteins are constantly being synthesised and degraded as plants grow, develop and adapt. A thorough understanding of protein turnover is essential to appreciate and understand the responses of plants to environmental and developmental cues.

The Centre built a technology that allows the tracking of shifts in the synthesis and/or degradation rates of thousands of proteins in model plants and utilised the technology to characterise different subcellular protein populations, specific plant tissues and plants grown in different environments.

Our understanding of the variables contributing to protein degradation allows the selection or modification of plants to create longer lasting proteins, thus reducing plant energy expenditure to manufacture replacement proteins. The Centre has applied this technology to study protein turnover in wheat, barley and maize to inform decisions for intelligent engineering of protein composition in these important crops.

Engagement in Agriculture Policy for the Future
The application of plant science in the form of agricultural technology within the Agricultural Industry can be accelerated through the support of policy and collaboration frameworks between industry, government and researchers.

PEB researchers led the formation of the Centre for Entrepreneurial Agri-Technology (CEAT) at the Centre's ANU node. Opened in 2018, CEAT now operates independently of PEB, but with a beneficial mission to create a collaborative innovation ecosystem and bring together plant and agricultural scientists with researchers from the environmental and computer sciences, engineering, business and economics, in order to best develop technological solutions for challenges being faced in modern agriculture.

Three PEB nodes have also lead a multi-university proposal for a *National Mission for Future Crop and Community Resilience to Government*, involving co-design with industry of longer term, higher risk and larger goals in research to accelerate the productivity of Agricultural production in Australia.

These initiatives aim to build a more proactive culture and develop an integrated system for effective translation of research findings into agricultural practice, policy and impact.

FORUMS

Scientific discussion and collaboration is a key to achieving impactful research. Over the years, PEB has provided numerous forums, structures and activities to encourage and support rich interactions occurring between our scientists, staff and the greater scientific community.

Centre Forums

PEB's Centre Forums have provided PEB's staff and students with valuable opportunities to connect face-to-face with one another, share ideas, forge collaborations, engage in training opportunities and interact with visiting international researchers.

Fifteen annual events and additional smaller forums that have been held across Australia have provided a routine occasion for our scientists to present their research to their PEB peers, thus creating visibility and connection-points for research across the Centre.

Team building activities have led to the forging of connections and genuine friendships across our Centre nodes and given a solid foundation to Team PEB.

In more recent years our staff and students have taken an active role in informing the design and delivery of PEB Forums, forming Committees that have guided organisation of these events in order to maximise benefit and impact.

Highlight: Three Minute Thesis

Our PEB Forum of 2016 played host to a novel opportunity for our students to flex their science communication muscles.

The PEB Three Minute Thesis (3MT) competition encouraged students to tell others about their research in just three minutes, armed only with a single, static presentation slide.

3MT is a competition concept that has been run out of many institutions around the world. The concept, which can encourage a deviation from scientific presentation norms, challenged our students to articulate their research concisely, logically and in a way that truly engaged their audience.

First prize in the 2016 PEB 3MT Competition was taken out by PhD student Fatimah (Zara) Rashid for her 3MT titled *How rice loves sunrise and sunset.*

Highlight: Grants to Enable New Collaborations

In 2018 PEB opened up its PEB Collaboration Awards scheme, aimed at encouraging and supporting novel PEB cross-nodal collaborations. PhD students and Early Career Researchers were encouraged to submit their proposal for a research project that could be conducted through a collaborative effort across two or more PEB nodes.

The scheme was announced at the 2018 PEB Forum, in a space ripe for cross-nodal conversations to be had ideas to be born and co-created plans to be made.

Seven projects were ultimately funded ranging from cross-nodal research activities to collaborative publication ideas.

Workshops

Centre Forums have provided the occasion for our researchers to engage in valuable in-person workshops and training opportunities. These have ranged from: career skills including in grant and publication writing and navigating academia with independence; soft skills such as those around effective science communication, engagement with the media and diversity and inclusion awareness; and technical training in PEB's research techniques and capabilities across nodes.

Highlight: Alternative Career Pathways

Not all scientists follow an academic career path. To highlight some of the many and varied career opportunities that are available to PEB students and researchers, the Centre has hosted a number of Alternative Career Pathway sessions over the years. These events have featuring informal presentations and Q&A opportunities with scientists who have undertaken an alternative career path to academic research, as well as non-scientists representing careers that overlap with the world of science.

A breadth of careers have been highlighted in these sessions, including those in industry, science media, professional options in patenting and trademarking, and roles within Government departments, Regulatory Bodies and for corporations such as the GRDC.

Questions and healthy discussions were encouraged and feedback suggests that some surprise options were revealed to many in attendance.

Invited Speakers

Visiting researchers have been invited from around the globe to share their insights, forge collaborations and even provide career opportunities to PEB researchers. Over the years PEB has hosted 190 international speakers including many from our Partner institutions, to speak on specialist topics.

PEB PEOPLE HIGHLIGHTS

"Science is not just a career. It's something that comes with a lot of passion."

Glenda Oh

"We want to change the way people feel about plants. We want them to realise the huge and important role that plants play in keeping us alive. If we empower people with the understanding of how a plant works and functions, how cellular processes work and what genetic modification actually involves then attitudes can change. Everyone benefits from knowing how stuff works."

Professor Harvey Millar

"PEB builds bridges between scientists, their science and the wider community. This endeavour is helped greatly by the fact that our PEB team are as enthusiastic about communicating their science as they are about doing it. We all see the value in letting the world know what we do as a Centre and why."

Karina Price

#PeopleofPEB

Science Communication

SCIENCE COMMUNICATION

Science and innovation are an important part of everyone's future. Providing our community with access to accurate information and creating a positive public dialogue about science is vital.

PEB's award winning Education and Outreach program has facilitated a better and more widespread understanding of the importance of plants and the role of plant energy biology in everyday life.

Using novel resources and activities, media engagement and the training of our researchers in science communication skills, we've connected people around the globe with plant energy biology and the importance of research. We strive to inspire students, teachers, end-users, policymakers and the general public.

In recognition of its impact, PEB's Education and Outreach program was named the 2013 Western Australian Science Awards Chevron Science Engagement Initiative of the Year and has been a three times finalist (2008, 2009, 2018).

Photography and imagery
PEB's vast collection of imagery has featured heavily in our public engagement activities over the years. The Centre has exhibited numerous photography displays and our pictures have played an important science communication role on our website and social media.

Highlight: Picturing Pollination

In 2013 the photography exhibition Pollination: *All's Fair in Love and War* was developed in collaboration with the Centre for Integrative Bee Research (CIBER) and toured Australia.

The series of images explore the relationship between plants and their greatest fans, their pollinators. The exhibit premiered at the WA Science Museum, before visiting Scitech, WA's Science Centre, the National Science and Technology Centre, Questacon in Canberra, and Landsdale Farm School, Perth.

Collaborative endeavours
PEB has pursued many collaborative education and outreach endeavours over the years. Such activities, created together with or hosted by organisations with a mutual interest in disseminating accurate information and engaging science, have broadened PEB's communications capabilities.

We've enjoyed working with organisations including Scitech, Questacon, partner Universities and other research Centres such as the ARC Centre of Excellence for Translational Photosynthesis and CIBER on ventures that have stimulated fresh ideas and provided us access to different audiences.

Highlight: A Botanical Event

In collaboration with Questacon, Australia's National Science and Technology Centre, we hosted two intimate, boutique PEB events in 2018. Hosted in the Questacon Q Lab, the A Boutique Botanical Adults Only evening journeyed attendees through exciting ways of improving plants for our future and highlighted important links between plant research and the glasses of gin that were being poured for visitors on the night!

A similar Teachers Only event provided ACT teachers with innovative activities, resources and real-world examples to inspire their students with and to connect them to the power of plants.

The events featured PEB's ACT Scientist of the Year, Dr Kai Chan, along with fellow plant scientists from PEB and the *ARC Centre of Excellence for Translational Photosynthesis.*

PEB on social media
PEB has embraced the social media era as a means of reaching global audiences with our stories and messages. Our presence on Facebook, Twitter, Instagram and YouTube has allowed us to engage with over 25,000 followers.

Highlight: Science is Amazing

Science is Amazing, a Facebook page which has amassed a following of over 20,000, has its origin on the back of dunny doors!

Science is Amazing was first launched by PEB in 2012 in collaboration with the International Centre for Radioastronomy Research (ICRAR). Funded by a National Science Week grant, the initiative focused on engaging new members of the community in science through a campaign of four quirky, funny and intriguing scientific posters placed in front of the eyes of a potential 5 million Australians - on the back of toilet doors in shopping centres and pubs.

The tag line, "from plants to planets, science is amazing," aimed to spark an interest in science where Australians least expected it. In an unexpected turn, a QR code redirection to a new Facebook page for the campaign led to an online following. The page became a site for contributing authors from PEB and ICRAR to promote public interest and engagement in science through facts, imagery and posts about topical science.

In 2015, *Science is Amazing* was given a second wind. The page was re-launched by an enthusiastic new team of PEB students and staff, along with scientists from a number of other Australian institutions, all creating content for and administering the page.

Virtual Plant Cell (VPC) is PEB's cutting-edge virtual reality (VR) education and outreach program. VPC capitalises on contemporary immersive technologies to teach plant cell biology and communicate research in a ground-breaking and fun way.

VIRTUAL PLANT CELL
plant energy biology

Viewed by hundreds of thousands around the globe since its inception, VPC has served as a fantastic platform for dialogue between our scientists and the community and is now recognised as incredibly effective teaching tool. It has led the way for educational VR, being introduced into classrooms and onto digital education platforms around the world.

VPC was named a finalist for the prestigious Western Australian Premier's Science Awards Science Engagement Initiative of the Year and for a TIGA Games Industry Award (Educational Game) for its impact.

VPC in the community

VPC originated as a public outreach tool. Capitalising on modern, immersive technologies to take audiences on rich journeys through the sub-microscopic inner world of a cell, PEB launched its first version of VPC on mobile devices during National Science Week 2016. By 2017 a range of VPC experiences spanning research topics including Surviving Salt, Protein Turnover and Phosphate Focus, were being interacted with across a range of VR headsets.

VPC has since featured around the world, including: at National Science Week festivals throughout Australia; during international science film festivals in Sweden and Russia; as an exhibit at the Bulgaria's Muzeiko - America for Bulgaria Children's Museum and at Eureka! The National Children's Museum in the United Kingdom; in Australian Parliament House; and as a dynamic 30 metre high visual on the Yagan Square digital tower in Perth's city centre.

Classroom VPC

PEB has focused efforts on enabling the use of VPC in formal and curriculum-aligned educational settings, leading the way for classroom VR. The development of our first, fully-interactive, curriculum-aligned *Virtual Plant Cell: Classroom VPC* experience was completed in 2018 for the Oculus Rift, complementing the Year 8 Australian cell biology curriculum. In a ground-breaking pilot study with Trinity College, Perth the *Practicality and Efficacy of using Virtual Reality to Teach Plant Cell Biology* was examined. The student and teacher response to VPC has been overwhelmingly positive with beneficial educational outcomes clearly seen. In 2019, PEB released its Report on the findings of the study, highlighting the incredible potential of VPC to impact education.

Highlight: Launching VPC for the Classroom

In 2018, PEB promoted *Classroom VPC* to the Education Sector, Government, and Industry at a bespoke event, *Virtual Plant Cell: A showcase of a leading virtual reality initiative for Australian STEM education.* The afternoon featured advocacy and a special address from the Honourable Alanna MacTiernan, Western Australian Minister for Regional Development; Agriculture & Food.

"We need more people to understand that agriculture is an exceptionally important and exciting area. There's no doubt that this technology offers a pathway into engagement" she said.

Students, teachers and delegates were able to experience VPC first-hand in Trinity College's state-of-the-art VR classroom. A special workshop for attending teachers enabled them to introduce VPC to their own schools.

Enabling educators

To equip educators with the know-how and resources they need to introduce VR into their teaching, PEB has provided support and informative workshops and presentations to over 500 educators. PEB's Outreach website is an online portal for VPC Teaching Resources, hundreds of which have been downloaded in over 20 different countries reaching students across the globe with VPC.

By providing a virtual taste of applied plant science, curriculum-aligned VPC resources continue to enhance STEM education and encourage the introduction of novel technologies into the classroom. VPC is inspiring the next generation of scientists towards career paths focused on advancing crop improvement and global food security.

POWERFUL PLANTS & PLANT POWERSTATION

Enthusing the next generation about plant science and science careers, and creating advocates for scientific discovery is a major aim of PEB. The Centre engages with school-aged students in a number of ways, including through school incursions by visiting PEB scientists and excursions to our laboratories and facilities spaces in order to showcase and discuss our science.

Powerful Plants is our multi-faceted, hands-on science program that teaches scientific method, critical thinking and the importance of plant research. The program has formed the basis of our engagement with over 3,500 primary and secondary students and teachers over the Centre's years.

Plant Powerstation is an adaptation of Powerful Plants, designed to enable PEB community outreach. Our staff have facilitated the engagement of over 50,000 members of the community in hands-on learning activities as part of Plant Powerstation public display stalls at festivals and Open Days across the country.

Activities within the Powerful Plants and Plant Powerstation suite include dynamic presentations that explore the power of plants and their impressive adaptations, tours, and hands on activities such as DNA extractions, salinity experiments and microscopy.

Presented by our students and researchers the programs create not only engaging experiences for audiences, but the ideal environment for our scientists to up-skill in science communications.

Highlight: Inspiring Young Female Scientists

On invitation from Canberra Girls Grammar School, PEB scientists contributed to the School's special X2 STEM Symposium during the 2019 National Science Week. The day of workshops and activities recognised the achievements of women in the field of STEM and aimed at inspiring young female scientists to be innovative thinkers and ethical problem solvers.

Together with the Australian Plant Phenomics Facility, PEB ran Powerful Plants workshops for year 5 and year 8 students that included hands on activities performing stomata peels and DNA extractions and a growth capsule virtual reality and thermal acclimation experiences.

The historical program, **Get into Genes (GIG)** - a research-based, curriculum-aligned workshop for secondary students and teachers - was presented by PEB in collaboration with the Australian Centre for Plant Functional Genomics (ACPFG) and Dairy Futures CRC from 2010 to 2013.

GIG showed how plant breeding and knowledge of genetics could improve crops, providing an important avenue to discuss the "how" and "why" of genetic modification. The program gave an opportunity for students and teachers to interact with top scientists in a working genetics lab, see research in progress and ask questions about science careers.

Bio-Bounce is the world's biggest and bounciest plant cell.

PEB's inflated innovation in community outreach is a 10 m by 13 m inflatable structure that captures all the elements needed for the molecular function of plants. The unique exhibit has provided an immersive and hands-on educational experience led by PEB scientists and staff for over 10,000 visitors. One of the main drivers behind the Bio-Bounce was to create an educational tool that helps the community to better understand how cells work and why researchers study them. Bio-Bounce gets people excited about science and helps the community make informed choices on new technologies in biology.

Bio-Bounce was launched in 2013 in Sydney to coincide with the 24th International Conference on Arabidopsis Research (ICAR). It has since been a feature at University Open Days and campus experiences, National Science Week events, several South West Super Science Spectacular festivals in Bunbury and at the Floriade Festival in Canberra.

Highlight: Floriade Festival

The Floriade Festival is Australia's biggest celebration of Spring. With one million flowers in bloom and 400,000 floristically enthused festival goers, Bio-Bounce was in a prime position at the 2013 Floriade Festival, to provide educational insights into how plant cells work and why researchers study them.

Over 1,800 festival goers jumped at the chance to experience Bio-Bounce and learn more about how plant works and why we study them. The experience helped visitors to visualise microscopic components of plants, increasing public understanding of why plants are so important.

Scientists from PEB's ANU node conducted parallel DNA extraction activities for Floriade spectators, providing information about genes and DNA.

Highlight: Bio-Bounce Targeted School Programs

Using short activities to explain to students what genes are, how they work, where photosynthesis occurs and the links to plant growth, energy and yield, Bio-Bounce has been used to engage many students in plant science.

Bio-Bounce has provided an incredibly engaging backdrop to the communication of plant science concepts in ways that are made easy to understand because everything is there to see, touch and explore.

Bio-Bounce has hosted many student groups over the years. Feedback from year 8 students suggested that after a Bio-Bounce experience, 99% better understood how plant cells worked.

Highlight: Bio-Bounce on Tour

National Science Week 2015 saw the Bio-Bounce make its way around the country. Leaving its home in Perth it bounced its way to the National Science Week events Science Alive! in Adelaide and Science in ACTion in Canberra.

Sitting alongside Bio-Bounce with the Plant Powerstation, PEB scientists engaged over 2,500 excited members of the community at Science Alive!, and another 500 at Science in ACTion.

Through a joint initiative with the ARC Centre of Excellence in Translational Photosynthesis the workshop *Jump into the exciting world of plant cells* was delivered to 100 students and members of the public during Science in ACTion 's Schools Day. Photosynthesis activities, DNA extractions, explorations of DNA processes and dynamic activities in the Bio-Bounce were aplenty.

PLANTARIUM

Plantarium is PEB's spectacular full-dome visual showcase. An exciting collaboration with the Scitech Planetarium led to this production - a custom created film which plays for audiences across the science Centre's 18m domed screen.

Plantarium tells an immersive story of local research and provides an exploration of the insides of laboratories and the insides of plant cells. The film features dynamic visualisations of plant cell network data and captivating time lapses of plants twisting in response to light changes in PEB growth chambers.

Screened at Scitech in combination with Question & Answer sessions with PEB scientists, Plantarium has allowed for a unique forum to explore the benefits of the Centre's research, address community questions and empower the public with a better understanding of plant science and exciting local research.

Highlight: Gifted and Talented

PEB relished the opportunity to participate in an Evolve Devolve evening with Scitech's impressive cohort of Gifted and Talented (GT) students.

Plantarium was screened to audiences of enthusiastic secondary students and their parents and coupled with presentations by PEB scientists that highlighted the important roles that evolution and genetics play in our plant energy biology research.

The receptive audience took up this opportunity to raise, and have answered by PEB researchers, their many questions about plant science and genetics.

"I learned about insertion of new genes into plant cells and how it is achieved and why we do it."
"I really enjoyed it."
Scitech's GT students on Plantarium

Highlight: A Private Screening for PEB

Plantarium features research contributed by PEB scientists from across our Australian nodes. Our 2015 PEB Annual Forum - a gathering of the Centre's researchers from across the country, in Perth - presented an unique opportunity for the viewing of the film by the whole Centre.

PEB researchers gathered below the Scitech Planatarium's 18 metre domed screen for a special private screening of Plantarium, watching as their science came to life around them.

PEB recognises that the Australian and global media presents a valuable avenue to achieve broad community reach for the communication of our science.

The Centre has issued over 100 public media releases over the years, providing our scientists with opportunities to tell their stories and generating over 1,000 exciting pieces of coverage for PEB's research, people and achievements. Our stories have been published around the world in print, online, on the radio and via television and podcast pieces.

Highlight: Stressed out plants send animal-like signals

PEB drew attention in 2015 with a media release suggesting that, in spite of not having a nervous system, plants use GABA, a signalling molecule normally associated with animals, when they encounter stress. The research was published in *Nature Communications* by a PEB team at the University of Adelaide.

"We've discovered that plants bind GABA in a similar way to animals, resulting in electrical signals that ultimately regulate plant growth when a plant is exposed to a stressful environment." said senior author Professor Matthew Gilliham.

The story was run over 50 times by media around the globe and featured on the Channel Eleven children's science program, Scope.

While it was known previously that plants produce GABA when stressed, the novel finding in this research was that plants use GABA as a signal to respond to that stress. In identifying how plants use GABA as a stress signal a new tool is in hand to help the global effort to breed more stress resilient crops.

Highlight: An on-air demo of gene technology

In 2018, PEB's Chief Investigator Professor Rachel Burton appeared in the ABC Catalyst two-part series 'Feeding Australia'. This exciting documentary series explored innovations in food and agriculture to sustainably feed a growing population into the future.

The ABC Catalyst team visited the Waite Campus at the University of Adelaide, where Prof. Burton demonstrated to host Professor Clare Collins the mechanism behind the gene technology CRISPR-Cas9. Using a clever piece of science communication, Prof. Burton demonstrated how this technology can be used to edit plant DNA with a fun, hands on DNA model fashioned from foam pool noodles. *"I think there's a massive potential for CRISPR and I think that we're going to think of some very smart ways to apply it"* said Prof. Burton. The Series aired on ABC and iView, with the first episode broadcasting during National Science Week.

Training

Professional training provides our staff and students with both the tools and confidence to be excellent scientists and science communicators.

To equip our researchers with skills to effectively communicate to a broad range of audiences PEB has provided training workshops and opportunities for the Centres students and staff. The focus of these was on interacting effectively with media and social media. By building a stronger understanding of best practice interaction with the media, the Centre aims to strengthen its ability to reach Australians with accurate scientific information in the future.

Highlight: Media Skills for Scientists

To achieve confidence in working with the media PEB researchers took part in a practical, full day workshop on Media Skills for Scientists

Delivered by freelance journalist Michelle Wheeler, the workshop gave PEB scientists an opportunity to practice honing their messages while working with live radio journalist, Lisa Barnes. They then tested out their interview techniques in front of a camera with television journalist Louise Momber. The working journalists shared their insights, expertise and tips giving participants the chance to learn the ins and outs of mainstream media. Participants came away feeling more confident about working with the media and better prepared for when a reporter calls.

"I've attended a couple of media training workshops in the past and this was the best so far" said Dr Sandra Tanz, a PEB Postdoctoral Researcher.

"I really liked meeting a couple of journalists and the practice in giving a radio interview and an interview in front of the camera" said Dr Sandra Tanz.

PEB PEOPLE HIGHLIGHTS

"I really enjoy being able to pursue the questions that interest me most. Being a scientist allows you to think creatively and analytically to solve problems."

Dr Samantha McGaughey

"A big part of PEB's success is due to the great diversity of the team. Putting many ideas and thoughts together leads to creativity and efficiency."

Dr Katharina Belt

"I love being a scientist because there is no better feeling than discovering something new. I hope my work can provide a tangible contribution to food security in a world with a more extreme climate."

Dr Andrew Scafaro

#PeopleofPEB

People

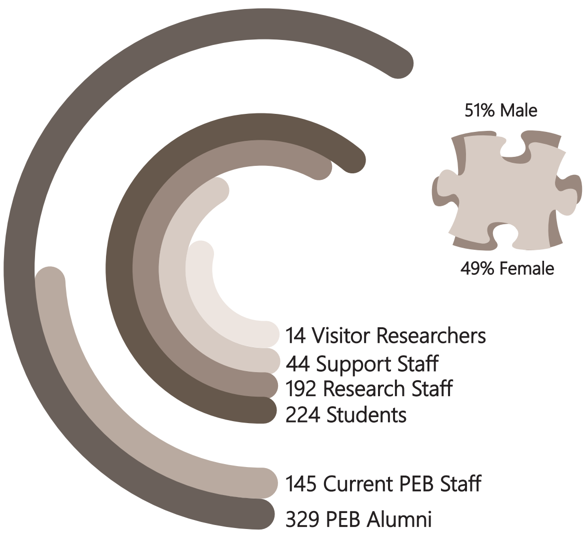
TEAM PEB

Science is as good as its people. For 15 years, PEB has brought together a collection of the world's best researchers, students and professional staff to make up Team PEB.

International researchers from complementary disciplines, collaborations across Universities, with affiliate researchers and Industry Partners, the incorporation of the best support and administrative staff and connections forged with international networks have kept our work at the cutting edge and allowed the Centre to perform research of the scale required to truly address the different aspects of the energy efficiency challenge in plants.

Team PEB is comprised of almost 500 remarkable individuals. Many researchers, students and professional staff, fostered over the Centre's history, have gone on as **PEB Alumni** to take up successful positions around the globe.

A Snapshot of Our People:



#PeopleofPEB

PEB has committed to excellence in recruitment, training and education of Students. We are proud of the many PEB students who have authored publications, claimed awards and seen other career success.

Independently funded **Affiliate Researchers** of the Centre have allowed PEB to extend its research and build new collaborations, bringing added expertise and an expanded focus.

Collaborative efforts with both formal and informal **Centre Partners** has broadened PEB's research capacity over the years and allowed us to draw on global expertise and opportunity.

In 2019, PEB launched a campaign to highlight the **People of PEB**, giving visibility to the individuals that make up the Centre and highlighting their stories from behind the science.

The People of PEB series showcases the diverse talents and backgrounds of our researchers, gives scientists an opportunity to voice personal experiences and inform positive public stereotypes of scientists by providing personal and relatable examples.

The series had the added value of promoting inclusiveness within PEB and fostering connections between our national nodes.

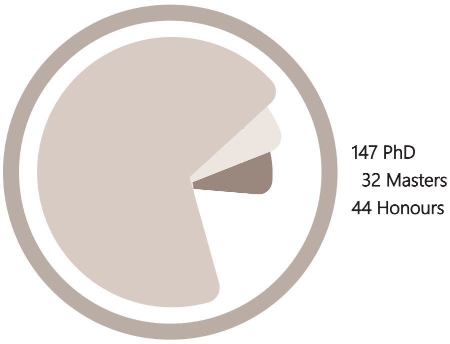
The campaign is shared across social media using the hasthtag #PeopleofPEB and at www.plantenergy.edu.au/people

PEB invests heavily in research training at all levels. PEB students and staff are provided with access to a wide range of training opportunities during their time in the Centre allowing the development of scientific and professional skills for success.

PEB Students

Our students are essential to our success. PEB has had the privilege of training 223 students over the past 15 years at an Honours, Masters and PhD level.

PEB Students Breakdown



We develop our students by providing technical and professional training that enhances knowledge and skills in current technologies, techniques and theories in biological and computational sciences. A dedicated Mentoring To Independence program provides our students with additional, targeted support (page 47).

Training

Access to both PEB-led and external training to improve professional, statistical and science skills have been facilitated over the years of the Centre. Opportunities to skill build have addressed a range of areas ranging from technical know-how to grant applications and CV writing, to media training and to industry engagement.

PEB workshop development and delivery by staff has further provided opportunities for our people to gain experience in leadership and organisational roles.

Highlight: Industry Engagement Showcase

To better enable our researchers to engage with Industry, PEB hosted an event series in 2020 in collaboration with the ARC Centre of Excellence in Translational Photosynthesis. This activity saw our researchers learn how to best engage with industry, policy makers and non-academic audiences and effectively pitch their research with a view towards achieving partnerships and investment.

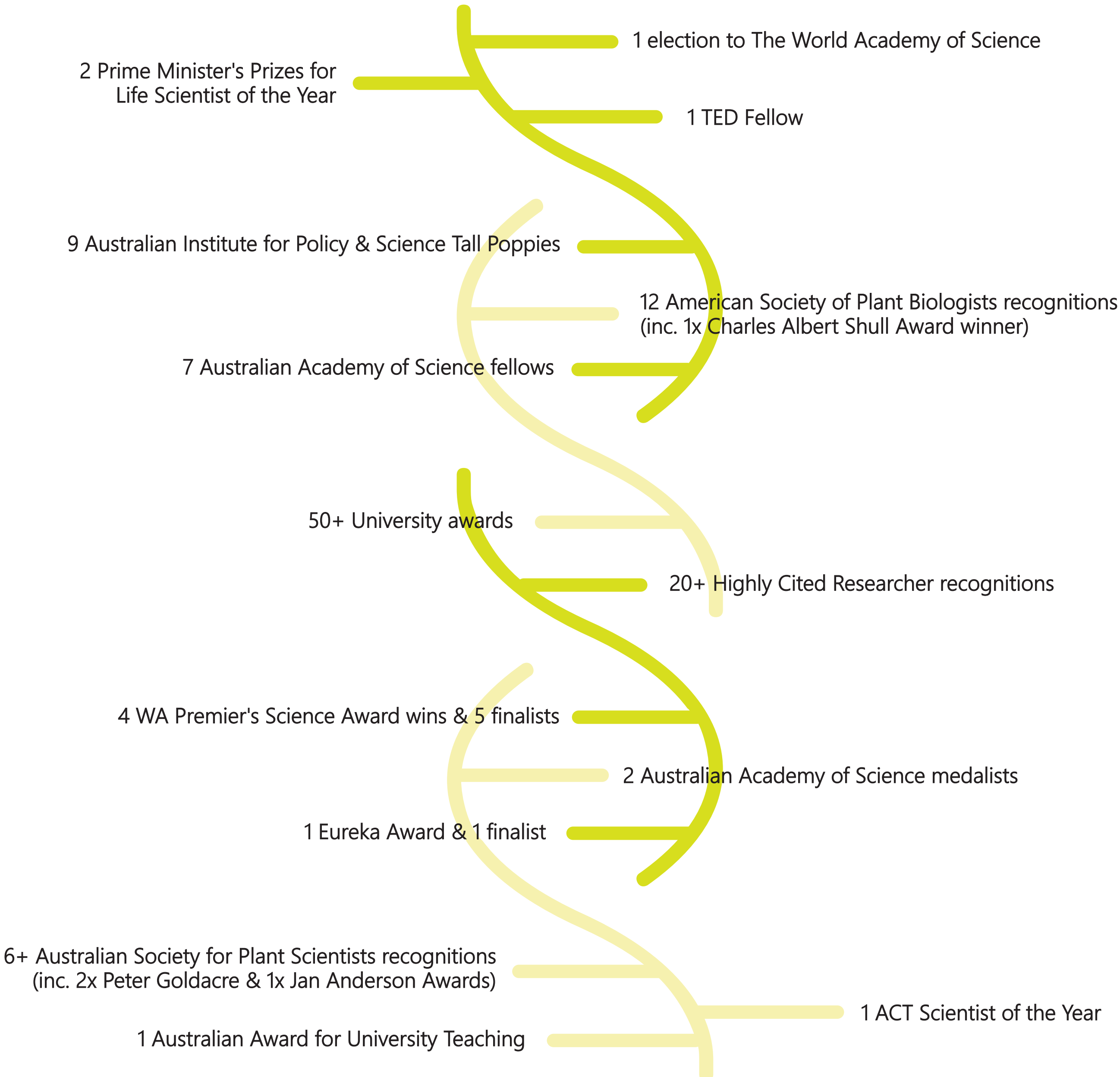
The activity served a dual purpose of providing greater visibility to potential Industry partners of engagement and investment with our research.

Training and information sessions saw our researchers gain insight into the industry landscape and develop their pitching and communication skills. The series culminated in a valuable Industry Engagement and Showcase Event in which PhD students and early career researchers pitched projects and engaged in valuable discussions with our Partners from the Grains Research and Development Corporation (GRDC).

AWARDS & RECOGNITIONS

PEB's scientists and staff have been the recipients of numerous awards and recognitions within the life of the Centre. Such awards and recognitions, including those from State and Federal Governments, key societies, Universities, Academies and significant Industry bodies have been given in recognition of the many outstanding scientific and professional achievements of PEB's staff and students.

Below is a snapshot of some of the over 200 awards received.



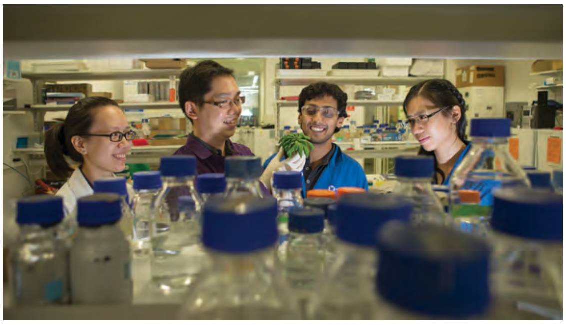
Throughout their time in the Centre, PEB aims to enable postdoctoral researchers and postgraduate students with advancement of their flexible skills and building of their professional networks. This establishes independence in our scientists for their time at PEB and future careers.

To this end, PEB have established Mentoring to Independence (M2I) a PEB program that aims to "do as it says" through three goals with associated activities and measurable outcomes.

M2I Goal 1: Train PEB students and Early Career Researchers (ECRs) in research excellence, in collaboration and in how to open new areas for discovery.

M2I Goal 2: Provide transferable skills for multiple career paths for current PEB students and ECRs.

M2I Goal 3: Establish a mentoring relationship for students and ECRs in PEB with other members of the PEB community or its partners.



PEB has, further, committed to achieving Gender Equity in the Centre's processes and activities. Through surveys and consultation with our staff and students we have established a series of practical aims, family friendly policies and principles together with ongoing disclosure of key indicators to supplement and complement processes already underway in our Partner Universities.

"I attribute a part of my success to the fantastic research environment within PEB, a collaborative atmosphere among researchers and excellent support and mentorship."

Dr Sunita Ramesh

M2I Outcomes

M2I Goal 1:
PEB students and ECRs have received personalised support for grant and fellowship application writing and processes, oral presentations at conferences and paper and review writing. The success of this is evidenced by student and ECR achievements in first-authored publications, seminar and poster awards and research and grants successes.

M2I Goal 2:
Student and ECRs have opportunities to attend internal and external work skills training, advice sessions on job applications and CV presentation and Industry Engagement events. Success is seen in attendance, feedback, transferable skills gained and the tracking of future career successes by PEB Alumni.

M2I Goal 3:
Student and ECRs are encouraged, and aided when required, to establish professional mentoring relationships. The Centre has surveyed the value of its mentoring program and conducts exit interviews and surveys for staff and students as well as uses Alumni analysis to define the long-term benefits of mentoring.

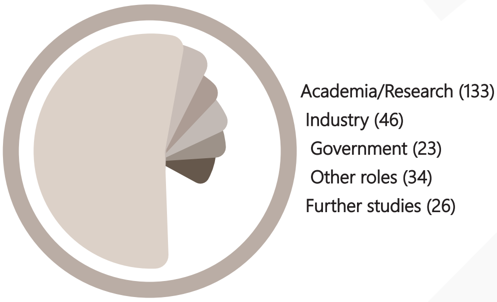
Gender equity:
A series of collaborative awards from PEB for female-led research teams, PhD scholarship opportunities for female supervisors, family-friendly practices in meeting times and opportunities for part-time appointments and research conferences have all been enacted by the Centre. Their use is tracked within the Centre and in our reporting to Funders.

PEB ALUMNI

Since opening its doors in 2005, PEB has been home to almost 500 of the world's best researchers, students and support staff. Bringing together capability and expertise from around the globe and providing the resources, interactive environment and inspiration to ensure cutting edge research outcomes has also given rise to an impressive PEB alumni body.

With experiences and independence nurtured at PEB, our 300+ alumni have moved on to a breadth of remarkable careers in academia, government, industry and alternative professional sectors. A further 150+ staff remain working at PEB in 2021 and beyond.

Where our alumni have ended up?



Highlights by sector:

Academia:

Dr Caitlin Byrt
At PEB: Postdoctoral Researcher (DECRA)
Now: Group leader
Organisation: Australian National University

Industry:

Dr Tomaz Tiago
At PEB: PhD student, Research Associate
Now: Head of Crop, Research and Operations
Organisation: SUN Pharma

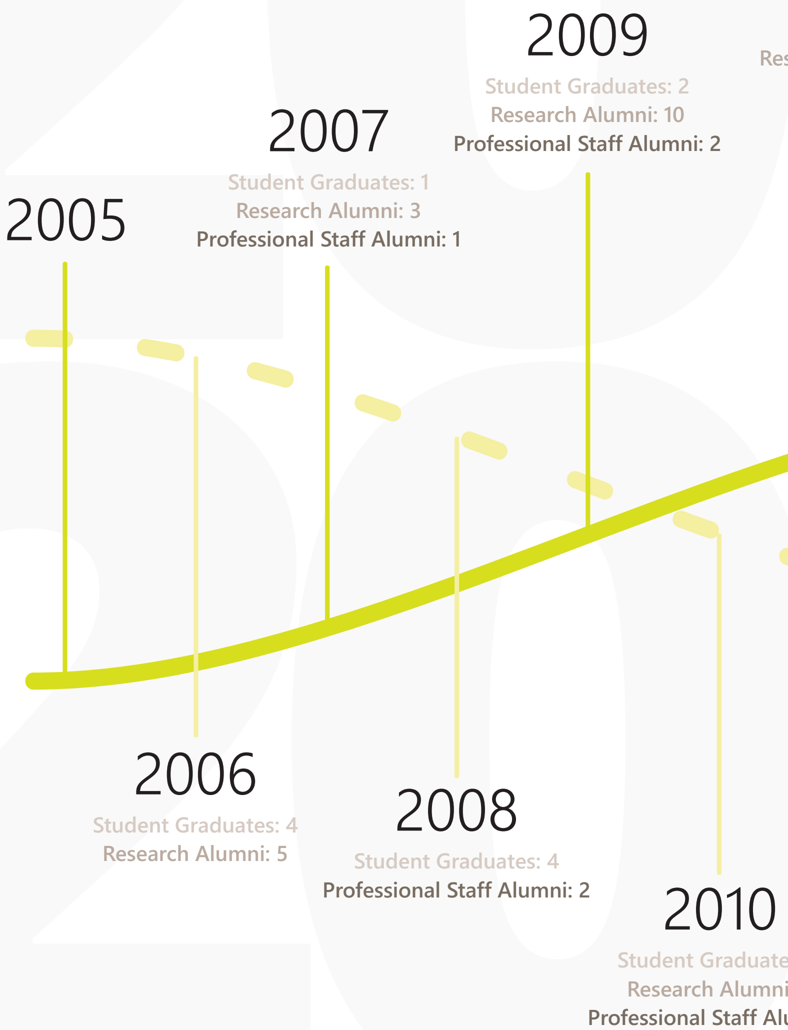
Government:

Dr Nazia Nisar
At PEB: PhD student, Postdoctoral researcher
Now: Policy Officer
Organisation: Australian Department of Agriculture and Water Resources

Other Roles:

Dr Ralitza Alexova
At PEB: ARC Super Science Fellow
Now: Education Specialist
Organisation: Muzeiko America for Bulgaria Children's Museum

Timeline 2005-2020



PEB has provided an excellent training ground for 37 Honours, 29 Masters and 88 PhD students who upon graduating have moved on to careers around the globe.

Student Highlights

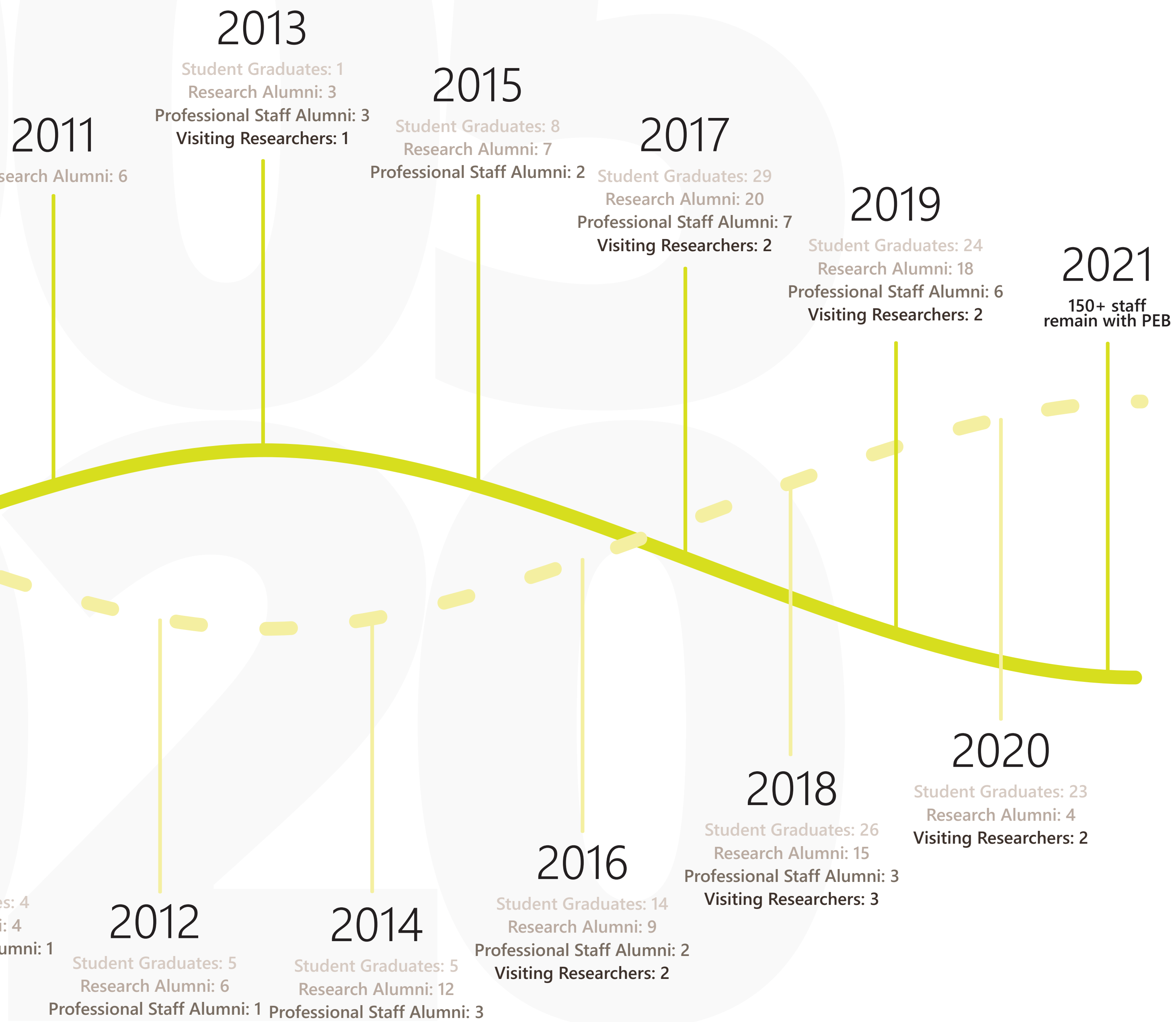
Dr Estee Tee
At PEB: PhD Student
Now: Postdoctoral Researcher
Organisation: John Innes Centre

Dr Muhamad Hafiz Che Othman
At PEB: PhD student
Now: Senior Lecturer
Organisation: The National Universiti of Malaysia

PEB has been home to many professional and support staff. Experience gained at PEB has enabled many of these 33 professional staff alumni to transition to impressive new opportunities.

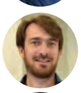
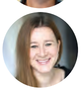
Professional Staff Highlight

Yvonne Vander Ploeg
At PEB: Education & Communications Manager
Now: Director
Organisation: BioLAB: The Victorian BioScience Education Centre

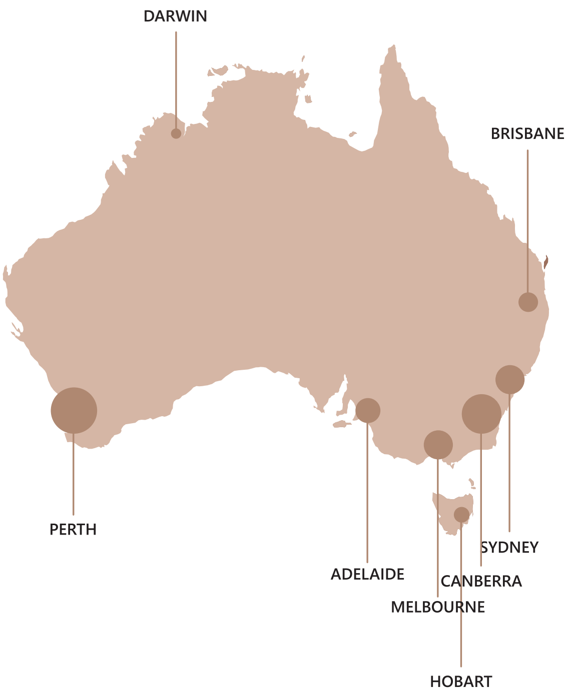


ALUMNI ACROSS THE WORLD

Our 300+ alumni have journeyed on from their time with PEB to take up exciting opportunities all around the world.

	Name	Current Position	Location
	Dr Chris Cazzonelli	Senior Lecturer, Laboratory Head Western Sydney University	Sydney
	Prof. Dr. Kristina Kühn	Professor, Head of Department Martin Luther University of Halle-Wittenberg	Germany
	Dr Kai Xun Chan	Flanders Research Foundation Fellow VIB-UGent Center for Plant Systems Biology	Belgium
	Prof. Lei Li	Professor, Laboratory Head Nankai University	China
	Dr Pip Wilson	Manager, Wheat - Genetic Technologies Grains Research and Development Corporation	Canberra
	Dr Olivier Van Aken	Associate Professor, Laboratory Head Lund University	Sweden
	Dr Sabine Kahlau	Head of Molecular Biology Targetomix	Germany


ROMANIA
POLAND
IRAQ
IRAN
ISRAEL
CHINA
SOUTH KOREA
JAPAN
THAILAND
BULGARIA
PAKISTAN
SAUDI ARABIA
MALAYSIA
PHILIPPINES
SINGAPORE
AUSTRALIA


DARWIN
BRISBANE
PERTH
SYDNEY
ADELAIDE
CANBERRA
MELBOURNE
HOBART

ADMINISTRATION

PEB's ability to function as a co-ordinated and productive national research Centre has been reliant on an extensive team of support staff.

Operations

Operational staff have overseen day-to-day through to big picture activities for the Centre, providing direction, oversight and support.

Tim Kaethner	Chief Operations Officer	2006-2008	UWA
Diane Stewart	Operations Manager	2008-2010	UWA
Jude Moyle	Operations Manager	2010-2013	UWA
Geetha Shute	Chief Operations Officer	2014-2021	UWA
Rebecca Vandeleur	Operations and Research Manager	2014-2021	UA
Derek Collinge	Lab Manager and Senior Technical Officer	2014-2021	ANU
Corey Worchester	Operations Manager	2014-2017	ANU
Naomi Hawley	Operations and Program Officer	2017-2019	ANU

Administration, Purchasing and Accounts

Centre administrative, purchasing and accounts staff have readily assisted PEB researchers with important administrative activities to keep research moving forward.

Jennifer Gillett	Administrative Officer	2009-2015	UWA
Jeya Jeybalan	Administrative Officer	2015-2016	UWA
Lara Webber	Administrative Officer	2017	UWA
Rochelle Hook	Administrative Officer	2017-2018	UWA
Jennifer Rhodes	Administrative Officer	2020	UWA
Deborah Yeoman	Purchasing & Accounts Officer	2014, 2017-2020	UWA
Katherine Ward (Wellburn)	Purchasing & Accounts Officer	2015-2017	UWA
Sally Holder	Purchasing & Accounts Officer	2021	UWA

Science Communications

PEB's ability to provide opportunities for showcasing of the Centre's science and to support researchers in their development of science communication skills has been guided and facilitated by professional Communications team members.

Katynna Gill	Science Communication	2007-2011	SYD
Rebecca Harper	Education & Outreach Officer	2011-2012	ANU
Yvonne Vander Ploeg	Education & Communications Manager	2006-2009	UWA
Alice Trend	Science Communications Officer	2010-2013	UWA
Susan Cossetto	Education, Training, Outreach Officer	2013	ANU
Karina Price	Science Communications Officer	2014-2021	UWA

IT Support

Computational and Information Technology staff have helped PEB's research to progress in contemporary ways as well as have provided researchers with day to day IT support.

Hayden Walker	Senior Computer Officer	2011-2019	UWA
Ian Castleden	Database/Systems Engineer	2014-2020	UWA
Pejman Leylabadi	IT Support Officer	2016	UWA

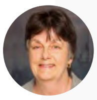
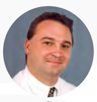
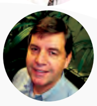
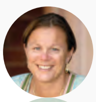
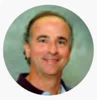
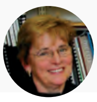
Laboratory Support

Essential support for the laboratory and research needs of our scientists has been provided by dedicated staff members, together with staff appointed in individual lab groups.

David Gaze	Laboratory Assistant	2006-2007	UWA
Rosemarie Farthing	Plant Growth Analysis Facility Technician	2008-2021	UWA
Lucy Hayes	Laboratory Technician	2014-2017	ANU
Matthew Spence	Technical Officer	2015-2017	ANU

SCIENTIFIC ADVISORY COMMITTEE

Throughout its years of operation, PEB has benefitted from the guidance of a Scientific Advisory Committee (SAC) consisting of scientist and end-user representatives.

	Emeritus Professor Ian W. Dawes | FAA	2008-2020 (SAC Chair: 2014-2020)
	Professor Dale Sanders | FRS	2014-2020
	Dr Allan Green	2018-2020
	Honorary Professor Fiona Cameron	2018-2020
	Dr Tina Barnsby | OBE	2018-2020
	Dr Juan Juttner	2018-2020
	Professor Elizabeth S. Dennis | FAA FTSE	2005-2017
	Emeritus Professor Margaret Clayton	2014-2017
	Professor Dr Detlef Weigel | FRS	2014-2017
	Dr Stephen Thomas	2014-2017
	Dr Wayne Gerlach	2005-2013
	Clinical Professor Fiona Wood | FRCS, FRACS, AM	2005-2013
	Emeritus Professor Christopher Leaver | CBE, ARCS, DIC, FRS, FRSE	2005-2013
	Professor Robert Last	2010-2013
	Professor Richard P Oliver	2010-2013
	Emeritus Professor David Day	2012-2013
	Emeritus Professor Adrienne E Clarke | AO, FAA, FTSE	2005-2009
	Dr Richard Brettell	2005-2007

PERSONNEL LIST

UNIVERSITY OF WESTERN AUSTRALIA

Surname	First Name	Position in 2020
Abzalov	Aygul	PhD student
Agudelo Romero	Patricia	Alumni
Alexova	Ralitza	Alumni
Ali	Adnan	Alumni
Almalky	Atef Jarallh H	Alumni
Alqahtani	Saad	Masters student
Andrews	Jessica	Alumni
Armarego-Marriott	Tegan	Alumni
Baer	Boris	Alumni
Baer-Imhoof	Barbara	Alumni
Bandehagh	Ali	Alumni
Bani	Mario Donald	PhD student
Barrington	Guy (Grace)	Alumni
Bates	Tiffane	Affiliated Bee Yard Manager
Belt	Katharina	Alumni
Bernath-Levin	Kalia	Affiliated Postdoctoral Researcher
Bersoult	Anne	Alumni
Bogdanovich	Ozren	Alumni
Boussardon	Clement Raymond	Alumni
Boykin	Laura	Alumni
Brar	Kamalpreet	PhD student
Broda	Martyna	PhD student
Buckberry	Sam	Affiliated Postdoctoral Researcher
Bussell	John	Alumni
Cahn	Jonathan	Alumni
Cao	Hui	PhD student
Carroll	Adam	Alumni
Castaños Sanchez dela Barquera	Clara Elisa	PhD student
Castleden	Ian	Database/Systems Engineer
Chabikwa	Tinashe	Alumni
Chan	Chee Seng	Alumni
Chateigner-Boutin	Anne-Laure	Alumni
Che	Ping	Alumni
Che Othman	Muhamad Hafiz	Alumni
Chiwocha	Sheila	Alumni
Chor	Yen Yeen	Alumni
Cincu	Emilia	Alumni
Clarke	Michael	Alumni
Colas des Francs-Small	Catherine	Postdoctoral Researcher
Considine	Michael	Affiliated ARC Future Fellow
Cornford	Victoria	Affiliated Honours student
Corral	Maxime	Alumni
Cremen	Naomi	Alumni
Daly	Alexandra	Honours student
de Mendoza	Alex	Alumni
Delannoy	Etienne	Alumni
den Boer (Beckers)	Susanne	Alumni
Dennis	Michael	Honours student
Dewi	Juwita Ratna	PhD student
Dissanayake	Bhagya	PhD student
Dorett	Sarah	Alumni
Dosselli	Ryan	Alumni
Dowd	Sam	Alumni
Du	Xianwen	Alumni
Duffy	Ciara	PhD student
Duncan	Owen	Alumni
Edera	Alejandro	Alumni
Elder	Katie	Alumni
Eubel	Holger	Alumni
Falcon De Longevialle	Andeol	Alumni
Farthing	Rosemarie	Laboratory Technician
Fenske	Ricarda	Alumni
Fisher	Mark	Postdoctoral Researcher
Fleay	Benjamin	Alumni
Ford	Ethan	Alumni
Forsyth	Henry	Masters student
Francisco	Perry	Alumni
Frazer	Thomas	Alumni
Fujii	Sota	Alumni
Funnekotter (Williams)	Anna	Alumni
Garmier	Marie	Alumni
Gaze	David	Alumni
Ghifari	Abi	PhD student
Gillett	Jennifer	Alumni
Gill-Hille	Mabel	PhD student
Glen	Angela	Alumni

UNIVERSITY OF WESTERN AUSTRALIA (cont)

Surname	First Name	Position in 2020
Gopal Krishnan	Priya Darshini	Alumni
Grassl	Julia	Affiliated Postdoctoral Researcher
Gräwe	Cathrin	Alumni
Gutmann	Bernard	Alumni
Hahne	Dorothee	Alumni
Hall	Andrew	Alumni
Hammani	Kamel	Alumni
Haywood	Joel	Research Associate
Heazlewood	Joshua	Alumni
Heidarvand	Leila	Alumni
Hermawaty	Dina	PhD student
Hewitt	Timothy	Alumni
Holt	Shannon	PhD student
Holzmann	Cristian	Alumni
Honkanen	Suvi	CSIRO Fellow
Hook	Rochelle	Alumni
Hooper	Cornelia	Postdoctoral Researcher
Hosking	Georgia	Alumni
Howell	Katharine (Kate)	Alumni
Huang	Shaobai	Affiliated ARC Future Fellow
Huynh	Sang Dang	PhD student
Ito	Jun	Alumni
Ivanova	Aneta	Affiliated Postdoctoral Researcher
Jacoby	Richard P.	Alumni
James nee Franklin	Amy	Alumni
Jeybalan	Jeya	Alumni
Johnston	Brady	PhD student
Kahlau	Sabine	Alumni
Karpievitch	Yuliya	Alumni
Keech	Olivier	Alumni
Kelly	James	PhD student
Kerbler	Sandra	Alumni
Khan	Mudammad Adil	PhD student
Kidd	Brendan	CSIRO Fellow
Kindgren	Peter	Alumni
Kinene	Tonny	Alumni
King	Michaela	Alumni
Kotra	Vinay	Alumni
Kratz	Madlen	PhD student
Krishnan	Priya	Alumni
Kubiszewski-Jakubiak	Szymon	Alumni
Kwok Van Der Giezen	Farley	PhD student
LaGrange	Alistair	Alumni
Le	Ha Xuyen	PhD student
Lee	Alex Chun Pong	Postdoctoral Researcher
Lee	Xin Chien	Alumni
Leske	Brenton	PhD student
Li	Ying	Masters student
Li	Jing	Alumni
Li	Lei	Alumni
Lister	Ryan	Chief Investigator
Liu	Sheng	Alumni
Liyanaarachchi	Vindya	Alumni
Lloyd	James	Postdoctoral Researcher
Long	Rowena	Alumni
Luo	Lawrence	Masters student
Ly	Florence	Alumni
Maina	Solomon	Alumni
Maki	Hisae	Alumni
Mann	Julia	Alumni
Marsh	Jacob	Alumni
Maseva-Shayawabaya	Chipo Audrey	Alumni
Mayor	Alfred	Alumni
Mcdowell	Rose	PhD student
Mederian Kotuwe	Achala Sanjeevanie Jayasena	Alumni
Mehta	Ritu Sanjaybhai	Alumni
Melonek	Joanna	Research Fellow
Meyer	Etienne	Alumni
Millar	Harvey	Director
Millman	Michael	Alumni
Moafa	Mohammed Abdullah	Masters student
Mohamed	Sufyaan	Alumni
Moo	Teck Lim	Alumni
Moran	Jessica	PhD student
Morelle	Geoffrey	Alumni
Moss	Dylan	PhD student

UNIVERSITY OF WESTERN AUSTRALIA (cont)

Surname	First Name	Position in 2020
Moyle	Jude	Alumni
Muhamad Hafiz	Che Othman	Alumni
Munns	Rana	Chief Investigator
Murcha	Monika	Affiliated ARC Future Fellow
Murugasan	Dhanusha	Masters student
Mylne	Joshua	Affiliated ARC Future Fellow
Nelson	Clark	Alumni
Nelson	David C	Alumni
Ng	Sophia	Alumni
Nguyen (Viet)	Trung	PhD student
Nonis	Samuel	PhD student
Oh	Glenda	PhD student
O'Leary	Brendan	Postdoctoral Researcher
Oliva	Marina	Postdoctoral Researcher
O'Neill	Damian	Alumni
Ostersetzer-Biran	Oren	Alumni
O'Toole	Nicholas	Alumni
Palanivelu	Nithya	Alumni
Pang	Pauline	Alumni
Pattrick	Cameron	Alumni
Paynter	Ellen	Alumni
Peng	Yan	Alumni
Peso	Marianne	Alumni
Petereit	Jakob	PhD student
Pflueger	Jahnvi	Lab Manager
Pflueger	Christian	Postdoctoral Researcher
Poland	Veronica	Alumni
Poppe	Daniel	Research Associate
Porri	Aimone	Alumni
Pouvreau	Benjamin	Alumni
Pracharoenwattana	Itsara	Alumni
Price	Karina	Science Communications Officer
Pruzinska	Adrianna	Alumni
Purdy	Sarah	Alumni
Reboucas Amorim	Alefe	Masters student
Riseborough	Julie-Anne Marjorie	Alumni
Roffa	Issa	Alumni
Royan	Santana Ashanth	PhD student
Rudler	Danielle	Alumni
Salih	Karzan	Alumni
Salone	Veronique	Alumni
Sappl	Pia	Alumni
Schepis	David	Alumni
Secco	David	Alumni
Sew	Yun Shin (Michelle)	Alumni
Sharma	Tara	Alumni
Shingaki-Wells	Rachel Nanami	Alumni
Shute	Geetha	Chief Operations Officer
Shyam	Sourav	PhD student
Signorelli	Santiago	Research Associate
Simmons	Rebecca	PhD student
Small	Ian	Chief Investigator
Small Platell	Ghislaine	Alumni
Smith	Steven	Alumni
Soet	Ashley	Alumni
Solheim	Cory	Alumni
Srivastava	Akansha	Alumni
Stanley	Will	Alumni
Staudinger	Christiana	Alumni
Stehl	Luca	Alumni
Stewart	Diane	Alumni
Stroeher	Elke	Affiliated Postdoctoral Researcher
Stuart	Tim	Alumni
Sukhoverkov	Kirill	PhD student
Sun	Yueming (Kelly)	Alumni
Swain	Tessa	PhD student
Szewczak	Robert	Alumni
Tan	Dennis	Alumni
Tan	Yew-Foon	Alumni
Tang	Dave	Alumni
Tang	Ting	Alumni
Tang	Yean Yee (Sunday)	Alumni
Tang	Anqiang	PhD student
Tanz	Sandra	Alumni
Taylor	Nicolas	Affiliated ARC Future Fellow
Timmins	Matthew	Alumni

UNIVERSITY OF WESTERN AUSTRALIA (cont)

Surname	First Name	Position in 2020
Tivendale	Nathan	Postdoctoral Researcher
Tomaz	Tiago	Alumni
Tong	Cen	Alumni
Tonti-Filippini	Julian	Alumni
Tran	Thien Dao Anh	Masters student
Trend	Alice	Alumni
Troesch	Josua	Alumni
Tse	Sze Wai (Anna)	Alumni
Tuckey	Andrew	Honours student
Vacher	Michael	Alumni
Vadlamani	Grishma	Affiliated Postdoctoral Researcher
Van Aken	Olivier	Alumni
Vander Ploeg	Yvonne	Alumni
Vargas Landin	Dulce Beatriz	PhD student
Vincis Pereira Sanglard	Lilian Maria	PhD student
Wainana	James	Alumni
Walker	Hayden	Alumni
Wallace	Michael	PhD student
Wang	Yimin	PhD student
Ward (Wellburn)	Katherine	Alumni
Waters	Mark	Senior Lecturer
Webber	Lara	Alumni
Welch	Mat	Alumni
Whitby	Michael	Alumni
Wijeweera	Samalka	PhD student
Winger	Alison	Alumni
Wiszniewski	Andrew (Andy)	Alumni
Yang	Fei	Alumni
Yang	Yingdie	PhD student
Yao	Jiaren (Hugh)	PhD student
Yapa Mudiyanselage	Akila Wijerathna	PhD student
Yeoman	Deborah	Accounts and Purchasing Officer
Zareie	Reza	Alumni
Zeelenberg	David (Frank Andrew)	Alumni
Zhang	Jingjing	Alumni
Zhong	Xiao	PhD student
Zhou	Wenxu	Alumni
Yap	Aaron	Alumni

UNIVERSITY OF ADELAIDE

Surname	First Name	Position in 2020
Ahmad Sohaimi	Muhammad Khairul Hisyam	PhD student
An	Feng	Alumni
Ang	Kum Foeng (Maple)	Alumni
Athman	Asmini	Alumni
Balacey	Suzanne	PhD student
Bayer	Luciano Caravia	Alumni
Bose	Jayakumar (Jay)	Affiliated Researcher DECRA
Brewer	Philip	ARC Future Fellow
Burton	Rachel	Chief Investigator
Byrt	Caitlin	Alumni
Cowley	James	PhD student
David	Rakesh	Alumni
Dayod	Maclin	Alumni
Feng	Xueying	PhD student
Ford	Melanie	PhD student
Gill	Alison	Honours student
Gilliham	Matthew	Chief Investigator
Gowder Shekharappa	Chethana	PhD student
Henderson	Sam	Alumni
Herliana	Lina	PhD student
Hocking	Bradleigh	Alumni
Kamram	Muhammad	Alumni
Karem	Ghazwan	PhD student
Kaur	Satwinder	Alumni
Khairil Anwar	Nur Syuhada	Alumni
Khor	Shi Fang (Sandy)	Research Assistant
Long	Yu	Alumni
Mafakheri	Ali	Alumni
Matros	Andrea	Research Fellow
McGaughey	Samantha	Alumni
McKay	Daniel	PhD student
Meng	Ying	PhD student
Neumann	Kylie	Alumni
Pearson	Allison	Alumni

UNIVERSITY OF ADELAIDE (cont)

Surname	First Name	Position in 2020
Phan	Hoai Thi Thanh	PhD student
Phillips	Aaron	PhD student
Philpot	Amanda	Alumni
Piechatzek	Adriane	PhD student
Qiu	Jiaen	Postdoctoral Researcher
Qu	Yue	ARC Research Associate
Ramesh	Sunita	Alumni
Sai	Na (Charlotte)	PhD student
Scharwies	Johannes	Alumni
Schnell	Nicholas	Alumni
Schulz	Jakob	PhD student
Shelden	Megan	Affiliated Researcher DECRA
Sohaimi	Muhammad Khairul Hisyam Ahmad	PhD student
Sullivan	Wendy	Research Assistant
Tyerman	Stephen	Chief Investigator
Vandeleur	Rebecca	Operations and Research Manager
Wang	Chuang	Alumni
Wang	Lin	Alumni
Watts-Williams	Stephanie	Affiliated Research Fellow
Wege	Stefanie	Affiliated Postdoctoral Researcher
Wignes	Jonathan	Alumni
Wu	Yue	Alumni
Xu	Bo	Affiliated Postdoctoral Researcher
Yan	Yunqi	Alumni

AUSTRALIAN NATIONAL UNIVERSITY

Surname	First Name	Position in 2020
Abdul Bahar	Nur Hazwani	Alumni
Ahmad Rashid	Fatimah Azzahra	Alumni
Albrecht-Borth	Veronica	Alumni
Almonte	Andrew	Alumni
Alves Negrini	Ana Clarissa	Alumni
Armstrong	Anna	Alumni
Asao	Shinichi	Research Fellow
Atkin	Owen	Chief Investigator
Au	Eng Kee	Alumni
Badger	Murray	Alumni
Bloomfield	Keith	Alumni
Borevitz	Justin	Chief Investigator
Bothwell	Helen	Postdoctoral Researcher
Bowerman	Andrew	Postdoctoral Researcher
Brown	Timothy (Tim)	APPF ANU Node Director
Cao	Michelle	Alumni
Carmody	Melanie	CSIRO Fellow
Cazzonelli	Chris	Alumni
Chan	Kai Xun	Alumni
Cheng	Riyan	Alumni
Chew	Lisa	Alumni
Chia	Ming-Dao	Technical Officer
Chong	Caroline	Alumni
Coast	Onoriode	Research Fellow
Collinge	Derek	Senior Technical Officer
Copas-Stewart	Patricia	Alumni
Cossetto	Susan	Alumni
Cousins	Asaph B.	Alumni
Crisp	Peter	Alumni
Cullerne	Darren	Alumni
Cuttriss	Abby	Alumni
Drieberg Wilkins	Hannah	Alumni
Dunstone	Gareth	Alumni
Dwyer	Simon	Alumni
Egerton	Jack	Alumni
Eichten	Steven	Alumni
Estavillo	Gonzalo	Alumni
Fan	Yuzhen	PhD student
Ferguson	Scott	Honours student
Forster	Britta	Alumni
Gaju	Reshmi	Alumni
Ganguly	Diep	Postdoctoral Researcher
Garcia	Andreas	PhD student
Gordon	Matthew J.	Alumni
Graham	Stephen	Alumni
Hammer	Julia	Alumni
Harper	Rebecca	Alumni
Hawley	Naomi	Alumni

AUSTRALIAN NATIONAL UNIVERSITY (cont)

Surname	First Name	Position in 2020
Hayes	Lucy	Alumni
Hazel-Pickering	Sarah	Alumni
Heussler	Alison	Alumni
Hou	Xin	PhD student
Hussain	Dawar	Alumni
Jones	Ashley	Postdoctoral Researcher
Kariyawasam	Buddhima	Divisional Visitor
Kee Au	Eng	Honours Student
Khin	Nay Chi	PhD student
Kondilios	James	Technical Officer
McQuinn	Ryan	Postdoctoral Researcher
Moore	Marten	Postdoctoral Researcher
Mortimer	Matt	Honours student
Moyle	Leonie	Visiting Academic
Murray	Kevin	Postdoctoral Researcher
Nguyen	Chuong	Alumni
Nisar	Nazia	Alumni
Phua	Su Yin	Alumni
Pitt	Matt	Alumni
Pogson	Barry	Deputy Director
Pornsiriwong	Wannarat "Nok"	Alumni
Posch	Brad	PhD student
Pye	Will	Alumni
Reddiex	Adam	Postdoctoral Researcher ECR
Rivers	John	Alumni
Rossel	Jan Bart	Alumni
Rungrat	Tepsuda	Alumni
Scafaro	Andrew	Postdoctoral Researcher
Shah	Shahen	Alumni
Shashikanth	Marri	Alumni
Simonsen	Anna	Affiliated Researcher DECRA
Smith	Aaron	PhD student
Spence	Matthew	Alumni
Stanley	David	Technical Officer
Stone	Bethany	Alumni
Streich	Jared	Alumni
Supple	Megan	Alumni
Taghavi-Namin	Sarah	Alumni
Takahashi	Shunichi	Alumni
Tee	Estee	Alumni
Tucker	Josephine	Alumni
Warthmann	Norman	Alumni
Watkins	Jacinta	PhD student
Wilson	Phillipa (Pip)	Alumni
Woo	Nick	Alumni
Worcester	Corey	Alumni
Xiang	Jen	Alumni
Xiong	Xiaofeng	Alumni
Yadav	Arun	Affiliated Postdoctoral Researcher ECR
Yee	Suyan	Technical Assistant
Zhai	Deping	PhD student
Zhang	You	Alumni
Zhu	Lingling	PhD student

LA TROBE UNIVERSITY

Abeynayake	Shamila	Alumni
Berkowitz	Oliver	Research Fellow
Chen	Yanqiong (Alison)	Alumni
Chen	Zhongyu	Alumni
De Clercq	Inge	Alumni
Ding	Wona	Alumni
Flis	Anna	Alumni
Gillingham	Emma	Honours student
Harris	Hayden	Alumni
Hartmann	Andreas	PhD student
Haslem	Asha	Alumni
He	Cunman (Frank)	PhD student
Jain	Ritushree	Postdoctoral Fellow
Jost	Ricarda	Research Fellow
Kushner	Yafit	Alumni
Li	Lu	Alumni
Liew	Lim Chee	Research Fellow
Linn	Joshua	Alumni
Lozano	Diego	PhD student
Lu	Li	Alumni

LA TROBE UNIVERSITY (Cont)

Surname	First Name	Position in 2020
Lyu	Wehhui	Alumni
Mao	Chunli	PhD student
Meng	Xiangxiang	PhD student
Narsai	Reena	Research Fellow
Osorio	Marina Borges	Alumni
Radomiljac	Jordan	Alumni
Ren	Meiyan	PhD student
Selinski	Jennifer	Alumni
Wang	Yinan	Alumni
Wang	Yan	Research Fellow
Whelan	James (Jim)	Chief Investigator
Xu	Yue	Alumni
Xu	Lin	Alumni
Yi	Changyu (Joe)	PhD student
Ying	Yinghui (Wendy)	Alumni
Zanganeh	Fatemeh	Alumni
Zhang	Xinhua (Anna)	Alumni
Zhou	Xishi	Alumni
Zhu	Yanqiao	Alumni

UNIVERSITY OF SYDNEY

Barthet	Michelle	Alumni
Gill	Katynna	Alumni
Ho	Angela	Alumni
Simms	Renee	Alumni
Smith	Penny	Alumni

FLINDERS UNIVERSITY

Day	David	Alumni
Smith	Chevaun Anne	Alumni

To find out more about the ARC Centre of Excellence in Plant Energy Biology visit:

plantenergy.edu.au

• News about Centre activities and people.
• Updates on progress towards our research goals.
• Opportunities to join the Centre's research team.
• Opportunities to benefit from or invest in the Centre's research outcomes.
• Details of our more than 1000 research publications.
• Access to our free educational and teaching resources.

Many of the images contained within this document were captured by the staff and students of the PEB. For more, see: plantenergy.edu.au/outreach/multimedia

facebook.com/PlantEnergyBiology instagram.com/PlantEnergyBiology

youtube.com/PlantEnergyBiology twitter.com/PlantEnergyBiol

plant energy **biology**
ARC CENTRE OF EXCELLENCE

THE UNIVERSITY OF WESTERN AUSTRALIA

School of Molecular Sciences
4th Floor Bayliss Building
35 Stirling Highway, Crawley, 6009 WA
Phone: 61 8 6488 4416
Fax: 61 8 6488 4401

Australian National University

Research School of Biology
Linnaeus Building, Building 134
Linnaeus Way, Acton, 0200 ACT
Phone: 61 2 6125 3741
Fax: 61 2 6125 5075

THE UNIVERSITY of ADELAIDE

School of Agriculture Food and Wine
Waite Campus
Private Mail Bag 1, Glen Osmond, 5064 SA
Phone: 61 8 8303 6663
Fax: 61 8 8303 7116

LA TROBE UNIVERSITY • AUSTRALIA

School of Life Science
AgriBio
5 Ring Road, Bundoora, 3086 VIC
Phone: 61 3 9032 7488

Australian Government
Australian Research Council

Layout by Eyecue Design | Perth


plantenergy.edu.au
plant energy biology
ARC CENTRE OF EXCELLENCE