INSTITUTE OF APPLIED PLANT NUTRITION

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RESEARCH ON SUSTAINABLE PLANT NUTRITION

Imprint

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IAPN – Institute of Applied Plant Nutrition

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Preface

Dear readers,

the year 2023 continued to be a time of transition for IAPN. Discussions and negotiations between IAPN's supporting parties on a new structure for the IAPN professorship overcame a number of hurdles and valuable new findings emerged in IAPN's ongoing research projects. University life and the formats of lectures and knowledge exchange returned to pre-pandemic conditions, so that lectures and practical courses in the Department of Crop Sciences could be held in person again. Scientific exchange at conferences and workshops was also resumed and the cornerstone for a new, current field of research was laid at IAPN.

Dr. Paulo Cabrita, postdoctoral scientist at IAPN, conducted research on the role of potassium and sodium on plant-water relations in sugar beet. By employing a novel, non-invasive leaf patch clamp method, he evaluated sugar beet's responses to fertilization and irrigation strategies and he obtained interesting new insights into the daily time courses of sugar beet leaf water status and along a period of controlled drought stress.

For future, more efficient nutrition of crops, Tingting Liu, PhD student at IAPN, investigates the complex interactions of potassium and nitrogen nutrition with nutrient-related functions in young maize roots. The efficient functioning of nutrient uptake and translocation processes in roots requires rapid morphological and physiological differentiation in the early developmental stages of young roots. Tingting Liu showed how the availability of potassium and nitrogen influences the development of impermeable suberin structures, which start to fulfil several important barrier functions in young roots just behind the root tips.

The interactions of potassium nutrition with morphological changes in crop leaves and their consequences for CO_2 movement within the leaf photosynthetic apparatus were in the research focus of Dr. Renata Callegari Ferrari, Humboldt-funded guest researcher at IAPN. With respect to the need for improved cropping systems that are tolerant to more extensive drought periods, the new knowledge on changes in the CO_2 conductance within the leaf mesophyll tissue is highly valuable.

With the onset of Johanna Marie Lass' PhD research project in October 2023, a new facet was added to IAPN's research topics. In her doctoral research, she focuses on the pathways of mineral ions into the plant when being administered as foliar fertilizers. The surfaces of plant leaves are usually considered to be protected against in- and efflux of substances by wax components in their cuticle. Nevertheless, foliar fertilization has been shown to be very efficient. So, the pathways of nutrients and their interactions with environmental conditions are in the center of Johanna Marie Lass' research.

I invite you to gain impressions of the latest scientific findings of IAPN and I hope you will discover interesting new perspectives.

Professor Dr. Klaus Dittert
Scientific director of IAPN

At IAPN, researchers work on their projects together with technical assistants and with students in an international atmosphere. The team uses advanced research methods, and it benefits from each other's knowledge and experience. (Photo: K+S)

IAPN at a Glance

Structure and development of the Institute of Applied Plant Nutrition – public-private partnership at the University of Göttingen

The Institute of Applied Plant Nutrition (IAPN) was initiated by Georg-August-Universität Göttingen and K+S Minerals and Agriculture GmbH following both institutions' impetus to strengthen the exchange in academic research and formation activities between the public academic institution and the private company sector. There is much common interest in questions related to sustainable nutrition of plants as well as in environmentally sound strategies for advancing agricultural systems of 21st century. Both partners have vital interest in promoting the formation of young scientists who, based on broad and solid knowledge, are capable of initiating, critically reflecting and developing new ideas and new research methods. IAPN is an Associated Institute and, as such, it is closely linked to the University of Göttingen and contributes to the University's core responsibilities, academic teaching and research. For both, the University and the Associated Institutes, the common rules of good scientific practice apply.

IAPN became active in 2012. Since then, IAPN's scientific and technical personnel were built up and a large number of methods and techniques were established. Researchers work on their projects together with Bachelor's and Master's students, who thereby get closely involved in IAPN's research activities. Moreover, many links to divisions of the Department of Crop Sciences and other University institutes have been established.

IAPN's objectives

Increasing demands for agricultural production and global changes necessitate progress in optimized crop nutrition, which can only be achieved with targeted research efforts. IAPN is committed to research and teaching on the role of resource-efficient use of nutrients in the plants' physiology. As an interface between research, teaching and practice we are involved in interdisciplinary knowledge exchange in a global network.

Our activities complement each other and mainly include:

- **Research**
  Focal point of our research is to improve our understanding of how the plant nutrients magnesium (Mg), potassium (K), and nitrogen (N) affect the self-protective mechanisms and performance of plants in situations of stress and deficiency. IAPN's research projects concentrate on water-use efficiency, photoprotection, photosynthesis, drought-stress tolerance, and salt tolerance. Additionally, we explore the significance of apoplastic barriers to radial nutrient and water flux in the root as well as interactions of plant nutrients and the environment.

- **Teaching**
  The IAPN team is very active in offering classical lectures to students, as well as laboratory and greenhouse courses and insights into practical research. The institute also offers opportunities for students to do their Bachelor's, Master's or PhD thesis or internship.

- **Knowledge exchange**
  IAPN cooperates with experts and research institutions in various countries. On a worldwide basis, we strive to maintain a fruitful interdisciplinary knowledge exchange during conferences and on research visits of IAPN scientists in foreign countries. Also, visiting scientists and students as well as agricultural advisors and extensionists from abroad spend time at IAPN regularly. This way, we are creating synergies for successful research and practical implementation of research results.

The IAPN team

In 2023, the team of IAPN consisted of up to eight members in scientific staff, administration, and technical as well as laboratory assistance. The institute's scientific director is Professor Dr. Klaus Dittert. Heading the institute is part of his duties as director of the Division of Plant Nutrition and Crop Physiology in the Department of Crop Sciences at the University of Göttingen, to which IAPN is closely associated. All administrative matters at IAPN are managed by Martina Renneberg. The technical and laboratory assistance is provided by Kirsten Fladung and Ulrike Kierbaum.

Dr. Paulo Cabrita continued his research on plant-water relation, using the leaf patch clamp pressure (LPCP) probe, which allows for a continuous and non-invasive assessment of the turgor pressure, and, consequently, the water status in plant tissues. He conducted a trial to address the role of K on plant-water relations, namely, the transport and distribution of water in plants grown in K-deficient soils.

Renata Callegari Ferrari is a visiting scientist from Brazil and through the Georg-Forster scheme, she was awarded an Alexander von Humboldt Fellowship that started in 2022. She joined the Division of Plant Nutrition and Crop Physiology in the Department of Crop Sciences at the University of Göttingen with Klaus Dittert as her scientific host. In 2023, she closely collaborated with the IAPN team and with Dr. Tino Kreszies from the Division of Plant Nutrition and Crop Physiology. After completing her PhD in 2021, her thesis in the field of plant physiology had been selected for the Highlight Recognition award by the University of São Paulo. Now, her research focuses on assessing photosynthesis in barley grown with different K supply under drought stress.

Tingting Liu, in her PhD project, investigated the role of apoplastic barriers – suberin lamellae and Casparian strips – for K and N transport. She presented recent research results at the 55th annual conference of the German Society of Plant Nutrition in September 2023. Two months later, an article of her and Dr. Tino Kreszies as co-author was published in the *Journal of Plant Physiology*, entitled "The exodermis: A forgotten but promising apoplastic barrier".

In October 2023, Johanna Marie Lass joined the IAPN team as a PhD student. Her PhD project focuses on the effectiveness of nutrient application via the leaf, specifically on the stomatal uptake of foliar fertilizers. It is entitled "Importance of stomatal regulation and sulfur metabolism in relation to environmental factors and consequences for nutrient uptake via the leaf". Johanna Maria Lass had obtained her Bachelor's and Master's degrees from 2018 to 2023 at Georg-August-Universität Göttingen at the Faculty of Agricultural Sciences with a focus on crop science.

Throughout the year, the IAPN team was supported by numerous graduate and undergraduate student assistants who helped in plant cultivation, measurements, and the preparations of plant, soil, gas, biochemical and molecular samples. We are very grateful for their contributions.

The IAPN team: Dr. Renata Callegari Ferrari, Kirsten Fladung, Tingting Liu MSc., Ulrike Kierbaum, Martina Renneberg, Dr. Paulo Cabrita, Professor Dr. Klaus Dittert (missing: Johanna Marie Lass). (Photo: IAPN)

IAPN experiment with sugar beet; youngest fully expanded leaves marked for optical assessment of pigments. (Photo: Cabrita)

Research

Linking plant nutrition and plant physiology

The growing world population, changing dietary habits and climate change place great demands on agricultural research. Increasingly, the focus in agriculture and agricultural sciences is on questions pertaining to the efficient use of arable land, pasture, water and plant nutrients. IAPN addresses these issues.

Our research projects concentrate on understanding the connection between plant physiology, plant nutrients and climatic as well as environmental impacts on plant production. Since the founding of IAPN, the institute's scientists contribute to the international advancements of research especially on the plant nutrients Mg, K and N, and their relation to crop water-use efficiency, drought stress tolerance, photosynthesis, photoprotection, and the functioning and morphologic development of crop roots.

The research at IAPN provides contributions to scientific solutions of a number of problems:

- Relevance of nutrients for stress tolerance in plants under changing climate conditions.
- Connection between mineral nutrition, fertilizers and water-use efficiency in the soil/plant system.
- Understanding alterations in the plants' physiology in response to fertilization.
- New strategies for improving fertilizer recommendations and management.

In 2023, IAPN's research activities were still restricted by the fact that it hasn't been possible to identify a new structure for the junior professor position at IAPN. However, some major results were published in 2023 and the current research topics and projects will be introduced on the following pages.

The role of potassium and sodium in plant-water relations

Research project conducted by Dr. Paulo Cabrita

K is basically involved in nearly all aspects of plant growth, from basic metabolic processes to stress responses, making it a crucial nutrient for plant health and productivity. One of the most studied aspects is its role on the regulation of turgor pressure in plant cells by serving as an osmoticum, i.e., a substance that can be easily exchanged across plant cell membranes so that changes in its concentration affect water movement, contributing to the buildup of pressure inside plant cells. Being surrounded by a cell wall, plant cells are able to function under considerably high pressure, in the order of 10^6 Pascal (Pa), that is about 10 times the normal atmospheric pressure under which we live. Or put in another way, it is roughly the pressure that water exerts at 100 m deep in the ocean. The regulation of such pressure values in plant cells, and the corresponding water content, is thus of crucial importance as many physiological processes depend on the maintenance of high turgor pressure.

At the cell level, K's role as an osmoticum and its importance on regulating turgor pressure and water exchange are well known and have been differently looked at. Specifically, its role on the opening and closing of stomata is one of the best-known examples. However, at the whole plant level, the effect of K on the transport and distribution of water between the different parts of the plant body has been seldomly addressed and quantified. Considering the experience and expertise gained by Paulo Cabrita on non-invasive and continuous methods to study plant-water relations, a trial was planned to address the role of K on plant-water relations, namely, the transport and distribution of water in plants grown in K-deficient soils. Sugar beet (*Beta vulgaris* L. 'Danicia KWS Öko') was chosen as a model plant, due to its well-known high requirement of K. Additionally, considering the positive response of sugar beet to sodium (Na), the physiological role of Na as an alternative to K was also considered.

For the trial, which was carried out from April to November 2023, sandy loam soil collected from a field deficient in K, nearby Gieboldehausen, Lower Saxony, and previously used in a small trial, was selected. As shown in Table 1, compared to soil mineral (nitrate + ammonium) nitrogen (N_{min}), Mg and manganese (Mn), the amount of K and phosphorus (P) was very low, making this soil classified as extremely deficient in both these elements, while having a very high Mg, Mn, and N_{min} content. The very high value of N_{min} is explained by the remaining of an N-fertilization made for a previous trial some months before the start of this study. Therefore, considering the assessed N-value and the N-requirement for sugar beet, no specific N-fertilization was carried out. The amount of the remaining macronutrients and micronutrients varied between sufficient and very high, suggesting that no further measures were needed regarding these elements. Although classified as having a low pH for this soil type with such content of organic matter, due to its closeness to the recommended pH value of 6.3, its pH was also not corrected. Therefore, under this scenario, potassium chloride (KCl), sodium chloride (NaCl), and triple superphosphate ($Ca(H_2PO_4)_2$) were chosen as fertilizers and applied following the corresponding replacement fertilization values per 12 L pot carrying 10.5 kg of soil shown in Table 2, with 4 replicates per treatment. The amount of NaCl applied was chemically equivalent to that of KCl used.

A leaf patch clamp pressure (LPCP) probe applied on a leaf of a sugar beet plant. (Photo: Cabrita)

Table 1 – Soil parameters (sandy loam soil)*

Organic matter (%)	pH	N_{min} (mg.kg^{-1})	K (mg.kg^{-1})	P (mg.kg^{-1})	Mg (mg.kg^{-1})	Mn (mg.kg^{-1})
2.8	6.1	101.6	22.5	17.3	229	2209

* Parameters were obtained according to the protocols from the Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (VDLUFA), namely, the extraction methods N_{min} for nitrate and ammonium, CAL for P and K, $CaCl_2$ for pH and Mg, and CAT for Mn.

Table 2 – Treatments

Treatment	K (g.pot^{-1})	P (g.pot^{-1})	Na* (g.pot^{-1})
Control	0	0	0
K	10.1	0	0
KP	10.1	3.5	0
Na	0	0	5.9
NaP	0	3.5	5.9
P	0	3.5	0

* The amount of Na used was chemically equivalent to that of K.

The use of the leaf patch clamp pressure (LPCP) probes allows for a continuous and non-invasive assessment of the turgor pressure, and, consequently, the water status in plant tissues. Thus, applying several probes on different leaves, one can get a picture of the whole plant water status and its dynamics through time. As exemplified by previous studies conducted at IAPN and in the case of sugar beet, the leaf patch reaction that counteracts the pressure exerted by two magnets applied on a leaf, called the output pressure (P_p), is a function of the turgor pressure within the leaf patch. Both parameters are reverse to one another, that is, the higher the turgor pressure in the leaf patch, the lower the P_p measured. Therefore, the minimum diel P_p value corresponds to the maximum diel turgor pressure in the leaf and vice versa. With such approach, one can thus follow the diel changes in turgor pressure, i.e., plant water status, its dynamics, and determine the effects from treatments on water transport and distribution as well as the coupling between plant water status dynamics and, for example, processes like photosynthesis.

As shown in Figure 1A, the diel pattern of the P_p, i.e., turgor pressure, changes of three leaves of a sugar beet plant is mostly similar under well irrigated conditions, at the beginning of the period considered and after the irrigations, the latter marked by arrows. Both the diel maximum and minimum turgor pressures are simultaneously reached. Higher turgor pressure values happen at night (Fig 1A), just before dawn when the relative humidity is highest (Fig 1B), while lower turgor pressure, i.e., higher P_p values (Fig 1A), is reached early afternoon when the temperature is highest and the relative humidity is lowest (Fig 1B). Between irrigations, the diel P_p values increase with time as well as the difference between the maximum and minimum values, ΔP_p. This means that, as time passes, the turgor pressure within the leaf decreases and the difference between its daily maximum and minimum increases. These results reflect the plant's coping with its physiological water needs for growth, transpiration, and metabolism as well as satisfying all these needs under changing weather conditions (Fig 1B) and a decreasing soil water supply.

It is also observed that these changes vary between the leaves, suggesting not only different dynamics but also that priorities are set regarding water transport and distribution within the plant body. For example, the changes in leaf 1 are relatively bigger than those observed on the other two leaves. This happened to a point at which the decrease in P_p

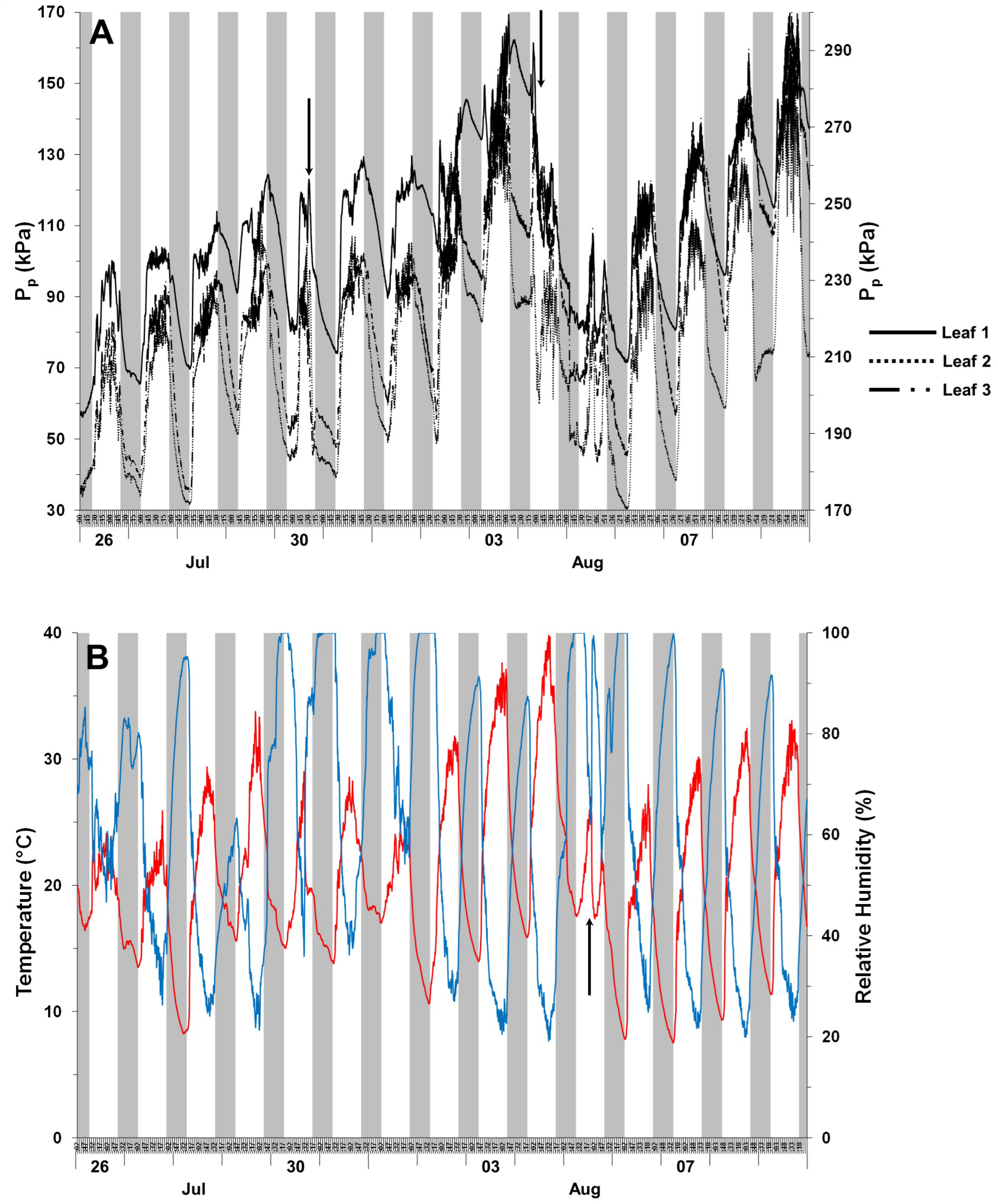

Figure 1: A) Leaf patch-clamp probe output pressure, P_p, of a sugar beet plant fertilised with both K and P (Table 1). Due to large differences in the pressure outputs, data from leaf 1 refer to the right vertical axis and the other two leaves to the left axis. B) Weather parameters, temperature (red curve) and relative humidity (blue curve), for the time period considered in A). Black arrows indicate watering events either from irrigation (A) or rain (B), and grey areas mark the night time. (Figures: Cabrita)

values during the night, i.e., the increase in turgor pressure, in leaf 1 no longer happens as in leaves 2 and 3. In the two nights before the second irrigation (Fig 1A), the P_p values of leaf 1 at night were higher than they were during the day. That is, the turgor pressure during the night was lower than that during the day and opposite to that observed on the other two leaves. This result indicates that leaf 1 at this time was under a different water status than that of the other two leaves. While the P_p diel pattern of leaves 2 and 3 during this period was similar and still within the range of normally hydrated tissues, leaf 1 was showing a dehydrated status that is observed on plasmolyzed tissues. In such state, the water within plant cells is no longer sufficient to keep turgor pressure. Consequently, the cell membrane detaches from the cell wall, and the cell is no longer under the needed high pressure as normal plant cells. The cell is no longer turgid. Under such conditions, P_p changes are mostly determined not by changes in turgor pressure as before and as in leaves 2 and 3, but by the changes in pressure of the cell walls and intercellular air spaces that depend on temperature, among other factors. In such scenario, plant cells can no longer control their water status to a situation that, if left unchecked, can lead to an irreversible status and consequent failure. However, the state observed here was still reversable as indicated by the leaves recovering to their normal diel pattern, as seen by the sharp decrease in P_p values (Fig 1A), i.e., increase in turgor pressure, once more water became available after irrigation or after rain (Fig 1B).

The diel decrease in P_p values observed on hydrated tissues in the afternoon until a minimum is reached, just before dawn on the next day, (Fig 1A) can be well described by an exponential function. There is an exponential increase in leaf turgor pressure as stomata close in the evening and transpiration ceases at night, allowing the plant to replenish the water lost by transpiration, and redistribute it between its tissues. Therefore, a time constant, τ, can thus be determined and factors that affect the buildup of turgor pressure and water distribution should be reflected in τ values. The time constant, τ, for such period of time was thus compared between the plants under the treatments described in Table 2 (Fig 2). The plants that recuperated and replenished their water losses faster were those fertilized with K and P, showing a higher time constant, τ. The changes in turgor pressure during the evening leading to higher turgor pressure values just before the next dawn, where bigger in plants fertilized with both K and P. In these plants, the faster water dynamics can be due to a higher and fitter hydraulic conductivity between tissues as well as better stomatal control or, most likely, a combination of both that was not met in the other treatments. Also, one concludes that both K and P were crucial in reaching such a state, as application of just one of these nutrients does not improve water status as compared to the control plants (Fig 2). Additionally, in K-deficient soils, Na can be used alternatively to K as it does not seem to affect the transport and distribution of water when compared to control plants or K-fertilization alone (Fig 2). The LPCP methodology can be thus quite useful, not only to evaluate the plants response to fertilization in terms of plant-water relations and improve water management regimes, e.g., irrigation scheduling, but also it contributes to a clearer picture of important physiological processes when combined with other methods, like gas exchange measurements.

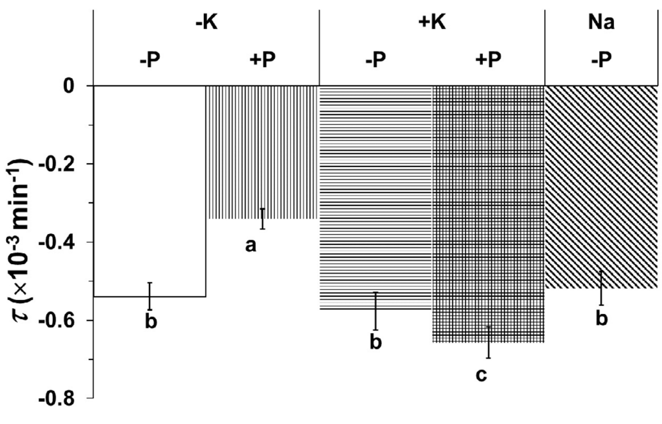

Figure 2: Time constant, τ, of the decrease of LPCP output pressure, P_p, (mean ± SE) between 17 and 24 h (n = 4, $p < 0.05$) obtained from fitted measured P_p value curves with $R^2 > 0.8$. Statistically significant values are marked by different letters. (Figure: Cabrita)

Understanding the role of potassium as a mitigator of drought stress in photosynthesis

Research project conducted by Dr. Renata Callegari Ferrari
Scientific collaboration with Dr. Tino Kreszies

K is present in soils in four forms, i.e., in solution, as exchangeable, non-exchangeable and lattice/structural K each of which is in equilibrium with the other (Spark et.al., 1990). K is taken up in large quantities by crop plants and this process relies on the availability of K in the ionic form (K^+) and on the abundance of weak complexes in the soil. Once taken up by the plant, it exists mostly as a free ion, and plays fundamental roles. A key role of K for physiological processes is related to the maintenance of osmotic and electric homeostasis, directly affecting photosynthesis and agricultural yield.

Deficiency of K has been shown to induce a decrease in the rate of assimilation (A_n) and in stomatal (g_s) and mesophyll (g_m) conductances. Optimal K nutritional status, on the other hand, can mitigate the effects of abiotic stresses such as drought for example by sustaining A_n. Furthermore, K helps to maintain osmotic pressure in vacuoles, tissue water content, and prevents oxidative stress. However, in this context, the association between g_m and K nutrition under drought stress has not been clarified in much detail and needs further study. According to the Intergovernmental Panel on Climate Change, climate prospects include more frequent droughts events that will impact agriculture. Therefore, it is essential to deepen our understanding of the impact of K on photosynthesis. This will contribute to developing new targets for crop improvement and new strategies for more resilient agricultural practices. At this background, Renata Callegari Ferrari investigates the role of K nutrition in photosynthesis during drought stress using barley (*Hordeum vulgare* L.) as a model species.

A detailed time-course drought experiment has been conducted to monitor gas exchange in barley cv. Avalon subjected to various K treatments (in mg K kg^{-1} soil): low K (5), mid-low K (35), optimal K (80) and luxury K (160). A low-K soil from a long-term field experiment conducted by the University of Göttingen was used in this experiment, which required extensive testing of mixtures of soil and other substrates and combining them with fertilization measures. Barley plants were monitored for internal leaf K concentration, relative water content (RWC), and gas exchange.

Leaf K concentration reflected the differences in soil K treatments in which the plants were grown (Fig. 1a). Under well-watered conditions, plants of the low K treatment showed a trend of reduced A_n and g_s under saturating light (Fig. 1b). As drought intensified, the relationship between RWC and A_n confirmed the beneficial effect of higher leaf K in sustaining photosynthesis as reported in the literature (Fig. 1b). Lastly, a trend towards higher leaf internal CO_2 concentration (C_i) was observed in plants of the lower K treatments, even though g_s showed a similar range of values across different K levels as water availability decreased (Fig. 1b). This indicates that a high C_i did not result in proportional A_n increments, possibly suggesting an impairment in mesophyll conductance (g_m) mechanisms.

Overall, this experiment was important to establish the thresholds for drought and K levels under climate chamber conditions for subsequent experiments monitoring g_m. Next, the experimental requirements for g_m monitoring were set up and a long measuring time span (c. 6.5 months) was performed to include sufficient biological replicates of all four K treatments under well-watered and drought-stressed conditions. Data on chlorophyll a fluorescence, calibration curves under varying light conditions, and a range of A/C_i ratios in ambient (21% O_2) and non-photorespiratory conditions (2% O_2) were performed (examples shown in Fig. 1c) and will be used for g_m estimation. Moreover, K nutrition and plant water status were also monitored. These physiological parameters will be correlated with the transcriptomic sequencing of barley leaves, leading to an integrative approach that will provide an in-depth characterization of photosynthesis under varied K nutrition and drought stress. For the RNA-Seq analysis financial support from K+S was received.

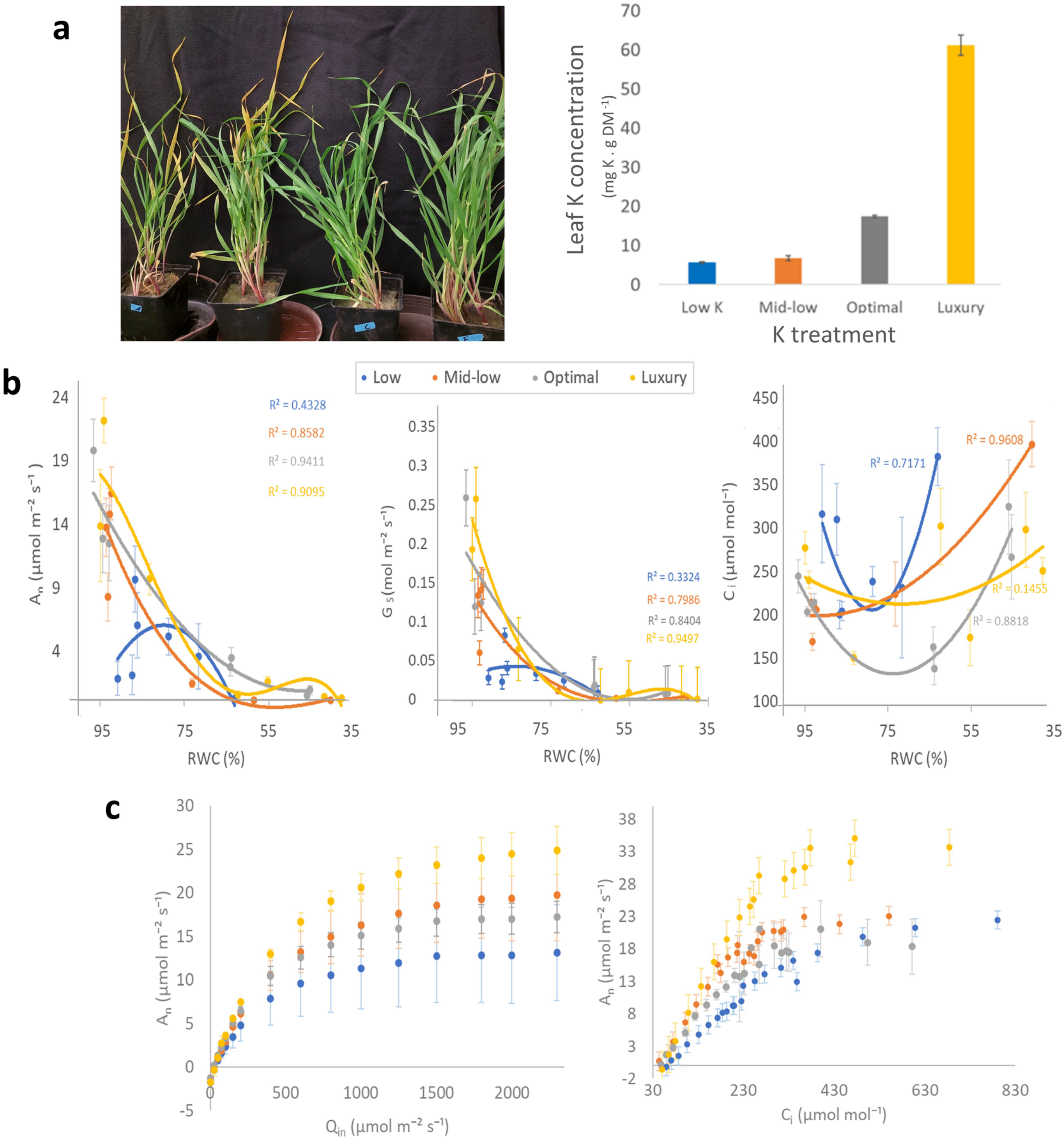

Figure 1: Time-course drought experiment conducted on barley cv. Avalon in 2023 at IAPN. a) Morphological aspects of plants growing under four different K levels (in mg K^+ kg^{-1} soil), from left to right: low K (5), mid-low K (35), optimal K (80) and luxury K (160); and leaf K concentration according to treatment. b) Gas exchange parameters, A_n, g_s, and C_i monitored every day since the start of drought for 10 consecutive days. c) Light and A/c C_i curves monitored in the time-course experiment. (Data = mean of four biological replicates ± SE). (Figure: Callegari Ferrari)

The exodermis: The forgotten apoplastic barrier in plant roots

PhD research project of Tingting Liu
Supervisors: Dr. Tino Kreszies and Professor Dr. Klaus Dittert

The focus of Tingting Liu's work is on understanding the role of apoplastic barriers (suberin lamellae and Casparian strips) for K and N transport in the roots of cultivated plants. Suberin lamellae and Casparian strips can deposit in the exodermis and endodermis of the root, acting as two interfaces to influence nutrient and water transport. These barriers not only reduce the absorption of nutrients and water by the roots but also prevent the leakage of ions from the vascular system, which plays a vital role in regulating the nutrient status of the plant.

Maize is distinct from other common crops due to its root anatomy with an endodermis and a uniform exodermis. Barley is another distinctive crop as it only develops an endodermis under optimal growth conditions. However, a new exodermis can be induced for example under severe salinity in the old root zone which is a so called "inducible exodermis". Onions, in contrast, have a dimorphic exodermis that contains two different cell types: long cells and short cells. The dimorphic exodermis has a different deposition pattern in suberin lamellae and Casparian strips. On one hand, the Casparian strips deposit initially on long cells, followed by suberin deposition either simultaneously or subsequently. On the other hand, the short cells either have no suberin lamellae or delayed suberin deposition at a later stage. As a result, these short cells allow an easy movement of water and nutrients, which are referred to as the passage cells. The distinct types of the exodermis are illustrated in Figure 1.

Despite the widespread presence of the exodermis in most plant roots and their important role in nutrients absorption and transport, its function has not received the same attention as the endodermis. This is because the model plant of many molecular biologists, *Arabidopsis thaliana*, has no exodermis. Hence, Tingting Liu chose maize as the research subject to explore the individual contributions of the endodermis and exodermis in the absorption and transport of K and N nutrients.

In 2023, Tingting Liu supervised Bachelor's and Master's students to conduct a hydroponic experiment in maize with different K supply levels. Simultaneously, she initiated another experiment in soil investigating the impact of N deficiency on suberin development. Maize plants were grown with two different N fertilizer levels for a month in the climate chamber. Then she measured the suberin content of the endodermis and exodermis respectively in maize roots through gas chromatography-mass spectrometry, as well as generating suberin-stained root cross-sections. The results indicated that, under reduced N levels, there was an increase in the aerenchyma in the root cortex (Figure 2), possibly to save metabolic costs of cortex cells. However, there was no significant difference in suberin content. This result is contrasting to the response of roots to K deficiency, where the development of aerenchyma in the cortex did not show a remarkable difference, and suberin deposition occurred earlier under low K supply. These results suggest that the response of suberin to nutrients is nutrient-specific.

In conclusion, this work contributes to our understanding of the complex mechanisms of how apoplastic barriers govern K and N uptake and transport in plants.

The PhD project is funded by the Chinese Scholarship Council and K+S.

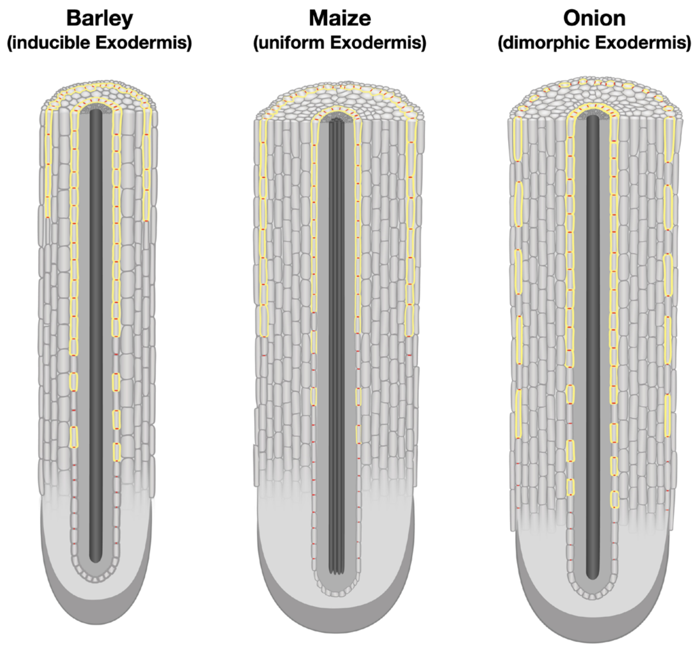

Figure 1: Diagrams of the development of endodermis and exodermis in barley, maize, and onion roots. Red dots/stripes indicate Casparian strips. Yellow-bordered cells indicate suberin lamellae. The inducible exodermis is a type of exodermis in plant roots that is induced by a particular extreme environmental factor. The uniform exodermis found in maize roots consists of only one suberized cell type. The dimorphic exodermis found in onion roots is characterized by alternated long cells and short cells. Long cells are suberized and short cells are not. The latter are called passage cells where water and nutrients can easily pass through. (This figure was published in *Journal of Plant Physiology*, Volume 290, Liu T. and Kreszies T., The exodermis: A forgotten but promising apoplastic barrier, Fig. 2, Copyright Elsevier 2023)

Master's student Justus Palisaar and one of his maize plants. (Photo: Liu)

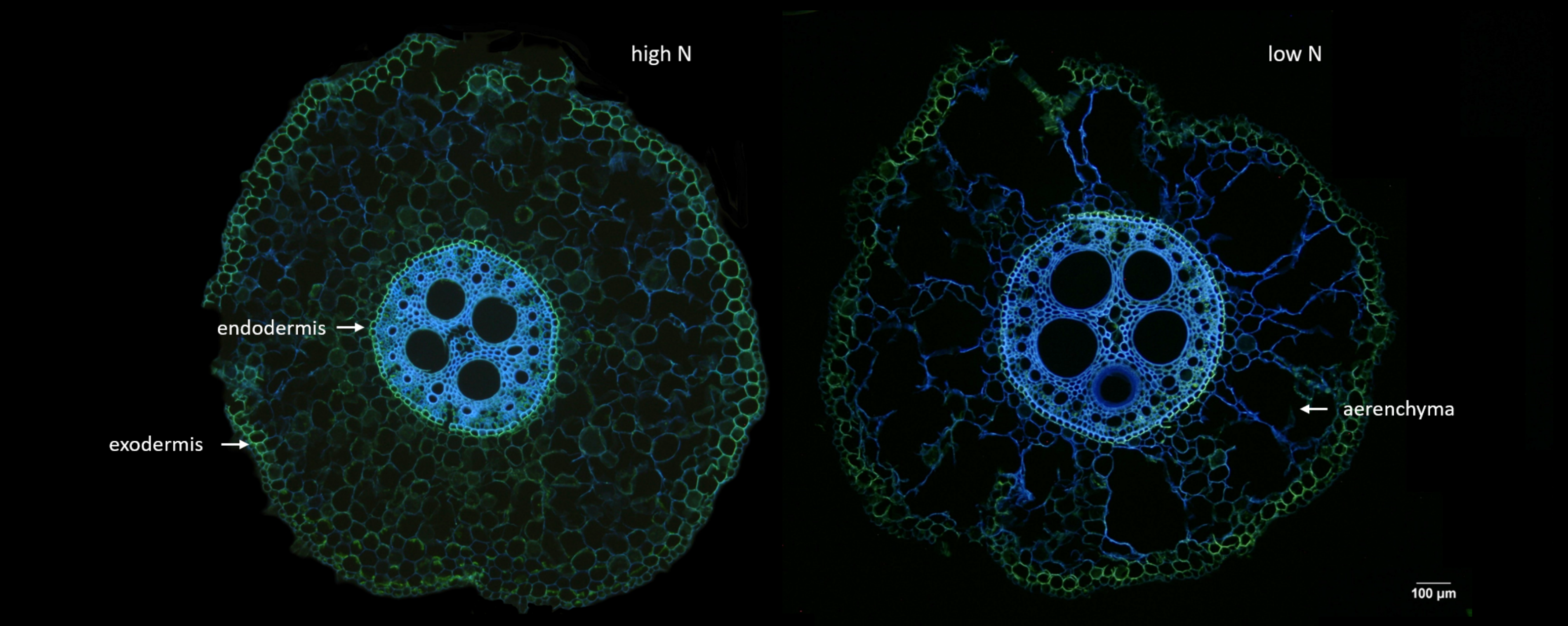

Figure 2: Through Fluorol Yellow 088 staining, suberin lamellae in the endodermis and exodermis of the 5% position of the root from the root tip grown in soil can be observed under the microscope; left: high/sufficient N supply (110 mg kg^{-1} N); right: low N supply (6 mg kg^{-1} N). Bar = 100 µm. (Photo: Palisaar, Liu)

Importance of stomatal regulation and sulfur metabolism in relation to environmental factors and consequences for nutrient uptake via the leaf

PhD research project of Johanna Marie Lass
Supervisors: Dr. Tino Kreszies and Professor Dr. Klaus Dittert

In her PhD research project, Johanna Marie Lass explores the impact of the anion component of salts employed as foliar fertilizers. The primary focus is on nutrient uptake efficiency while examining the role of stomata.

Polar substances, such as salts, can enter plant leaf surfaces via two routes: one through the water-repellant cuticle, for which the model of dynamic water pores was established, and the other through the stomata. Although stomata are considered non-infiltrative for water droplets, there is increasing evidence that nutrients can diffuse into the stomata through thin water films along the guard cells. Experiments on the uptake of foliar fertilizers, such as nanoparticles, have shown that stomata might play a crucial role in nutrient uptake into the leaf. It was shown that the uptake of foliar fertilizers is higher when more stomata are present. However, it is a common practice to apply nutrients at dusk when humidity is high, and when the stomata of C3 and C4 plants are usually closed. Therefore, it is necessary to clarify the significance of stomata for the uptake of nutrients via the leaf, while considering the relevant environmental conditions. Additionally, the foliar fertilizers' physicochemical properties are an important factor with respect to the efficiency of nutrient uptake. Nutrients like Mg can only be applied to the leaf as a salt with an accompanying anion, such as sulfate, chloride, carbonate, or nitrate. Different salts' effectiveness in plant nutrition are being examined with a focus on crops, and potential phytohormonal effects concerning the stomata will be studied.

In 2023, Johanna Marie Lass ran pre-tests to establish methods required for the determination of stomata conductance and gas exchange in conjunction with foliar applications. The pre-tests included measurements of photosynthetic CO_2 fixation, porometric measurements of stomata conductance, and a few microscopy techniques were tested and adjusted. Furthermore, methods for distinguishing nutrients in the leaf from foliar-applied nutrients like the use of isotopic markers were discussed and tested. The goal of the project is to determine the effect of foliar-applied nutrients on stomata regulation and the implications for the uptake-efficiency of foliar-applied nutrients. In addition, Johanna Marie Lass' research aims at providing more detailed information about the proportion of nutrient uptake via the stomata and to differentiate this from the cuticular pathway.

The PhD project is funded by K+S and it is scheduled for a duration of three years.

Measuring gas exchange parameters with a GFS (Walz) after application of leaf fertilizer on maize plants. (Photo: Lass)

Teaching

Teaching at the University of Göttingen

An important objective of IAPN is to provide students with knowledge on nutrition and physiology of plants. For this, alongside classical lectures, practical parts and lab training units are included in the teaching activities. So, students get insight into the importance of plant nutrition and the different functions of single plant nutrients. Of course, students have options of doing a thesis at IAPN, at undergraduate, Master's and PhD level.

As the professorship for "Applied Plant Nutrition" at IAPN was vacant in 2023, the university educational programs of the professorship of Klaus Dittert including plant nutrition teaching modules in one Bachelor and three Master programs were continued. In contrast, the IAPN-specific lectures and courses were halted.

Knowledge Exchange

Interdisciplinary discourse with scientists and practitioners

IAPN strives to expand its international and national cooperation with professionally complementary institutions and researchers. In addition, IAPN consciously turns to practice-oriented research. The institute not only aims to intensify its transfer activities of the already available scientific knowledge into practice but also to formulate open research questions jointly with national and local practitioners and scientists.

IAPN at the 55th annual conference of the German Society of Plant Nutrition

From September 25th to 27th 2023, the 55th annual conference of the German Society of Plant Nutrition (Deutsche Gesellschaft für Pflanzenernährung e.V., DGP) took place at the University of Hohenheim. The conference was organized by the Institute of Crop Science, University of Hohenheim in memory of Dr. Margarete von Wrangell, professor of Plant Nutrition. In 1923 she was appointed as Germany's first female professor. Invited speakers were from Austria, China, Geneva, Germany, Japan, Pakistan, Switzerland, and Turkey. Tingting Liu and Renata Callegari Ferrari presented posters about their latest research.

Tingting Liu presented a poster on "Comparative analysis of suberin lamellae formation and nutrient uptake in maize roots under K deficiency: soil vs. hydroponic growth conditions". She presented her research results on how suberin lamellae develop and how they influence plant nutrient uptake under two contrasting cultivation methods: soil and hydroponics.

Renata Callegari Ferrari's poster was entitled "Gas exchange profiling during drought mirrors the role and dynamics of potassium in barley".

IAPN at the 29th conference of the Working Group on Foliar Fertilization and Biostimulants

Johanna Marie Lass attended the 29th conference of the "Arbeitskreis Blattdüngung und Biostimulanzien e.V." which took place in Dülmen at the Hanninghof research centre of YARA GmbH & Co. KG on December 14th 2023. The workshop focused on topics like the effectiveness of boron as a foliar fertilizer or the effects of foliar fertilizers in grapevine production. Biostimulants were the second point of emphasis. Evidence of the mode of action of biostimulants and the legal categorization of their use were addressed. One of the highlights was the guided tour of YARA's greenhouses and an overview of their current experiments. The speakers were invited from Turkey, the Czech Republic, and Germany.

Publications

Work published in peer-reviewed journals and proceedings (including non-IAPN publications of IAPN employees, e.g., reports on previous research activities)

Herrmann, A.; Verma, S.; Techow, A.; Kluß, C.; Dittert, K.; Quakernack, R.; Pacholski, A.; Kage, H. and Taube, F. (2023) Assessing nitrous oxide emissions and productivity of cropping systems for biogas production using digestate and mineral fertilisation in a coastal marsh site. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1231767

Jordan-Meille, L.; Denoroy, P.; Dittert, K.; Cugnon, T.; Quemada, M.; Wall, D.; Bechini, L.; Marx, S.; Oenema, O.; Reijneveld, A.; Liebisch, F.; Diedhiou, K.; Degan, F. and Higgins, S. (2023) Comparison of nitrogen fertilisation recommendations of West European Countries. European Journal of Soil Science, 74(6). https://doi.org/10.1111/ejss.13436

Liu, T. and Kreszies, T. (2023) The exodermis: A forgotten but promising apoplastic barrier. Journal of Plant Physiology, 290,154118. https://doi.org/10.1016/j.jplph.2023.154118

Mock, A.; Ingold, M.; Vazhacharickal, P. J.; Sourav, S. K.; Dittert, K. and Buerkert, A. (2024) Nitrogen fixation of lablab and finger millet in South-India. Journal of Plant Nutrition and Soil Science, 187(2), 225–232. https://doi.org/10.1002/jpln.202300319

Najdenko, E.; Lorenz, F.; Olfs, H. W. and Dittert, K. (2023) Development of an express method for measuring soil nitrate, phosphate, potassium, and pH for future in-field application. Journal of Plant Nutrition and Soil Science, 186(6), 623-632. https://doi.org/10.1002/jpln.202300166

Piepel, M. F.; Dittert, K. and Olfs, H. W. (2023) Ion-selective electrodes for quick on-farm determination of ammonium and potassium concentrations in pig slurry. Journal of Plant Nutrition and Soil Science, 186(3), 266-275. https://doi.org/10.1002/jpln.202200088

Suriyagoda, L. and Dittert, K. (2023) Phosphorus and Silicon Fertilization with Improved Water Management as Potential Remedies for Growing Rice Seedlings in Heavy Metal and Metalloid Contaminated Soil. Communications in Soil Science and Plant Analysis, 54(19), 2699-2715. https://doi.org/10.1080/00103624.2023.2240373

Suriyagoda, L.; Sirisena, D.; Rathnayake, U.; Dittert, K.; Gamage, D. and Chandrajith, R. (2023) Variation in essential mineral element and toxic trace element concentrations in the seeds of Sri Lankan rice varieties as affected by milling and soil fertility. Journal of Plant Nutrition, 46(18), 4401-4419. https://doi.org/10.1080/01904167.2023.2240361

Conference talks – papers – posters

Callegari Ferrari, R.; Dittert, K. and Kreszies, T. (2023): The dynamics between potassium nutrition and gas exchange in barley. Plant Environmental Physiology Group's (PEPG's) Field Techniques Workshop, September 10th–15th 2023, Quinta de Sao Pedro, Portugal

Callegari Ferrari, R.; Dittert, K. and Kreszies, T. (2023): Gas exchange profiling during drought mirrors the role and dynamics of potassium in barley. Annual conference of the German Society of Plant Nutrition (DGP), September 25th– 27th 2023, Stuttgart, Germany

Liu, T.; Dittert, K. and Kreszies, T. (2023): Comparative analysis of suberin lamellae formation and nutrient uptake in maize roots under potassium deficiency: soil vs. hydroponic growth conditions. Annual conference of the German Society of Plant Nutrition (DGP), September 25th–27th 2023, Stuttgart, Germany

Cooperation in Science

Partner	Location
Al-Quds Open University	Jerusalem, Palestine
Bodengesundheitsdienst	Ochsenfurt, Germany
Chamber of Agriculture	Hannover and Oldenburg, Germany
Institute of Sugar Beet Research (IfZ)	Göttingen, Germany
International Magnesium Institute (IMI)	Fuzhou, China
Julius Kühn-Institut, Institute for Crop and Soil Science	Braunschweig, Germany
K+S Analytik- und Forschungszentrum (AFZ)	Unterbreizbach, Germany
K+S Minerals and Agriculture GmbH	Kassel, Germany
LUFA Nord-West, Institut für Düngemittel und Saatgut	Hameln, Germany
Sabanci University, Biological Sciences and Bioengineering Program	Istanbul, Turkey
SKW Stickstoffwerke Piesteritz GmbH	Lutherstadt Wittenberg, Germany
Thünen-Institute – Institute of Climate-Smart Agriculture	Braunschweig, Germany
University of Göttingen	Göttingen, Germany
Plant Pathology and Crop Protection	
Division of Quality and Sensory of Plant Products	
Functional Agrobiodiversity	
Division of Agricultural Engineering	
University of Hohenheim, Institute of Fertilization and Soil Matter Dynamics	Stuttgart, Germany
University of Halle, Institute of Plant Nutrition	Halle, Germany
University of Kassel, Organic Plant Production and Agroecosystems Research	Witzenhausen, Germany
Christian-Albrechts-University of Kiel, Institute of Crop Science and Plant Breeding	Kiel, Germany
University of Peradeniya	Peradeniya, Sri Lanka
University of São Paulo	São Paulo, Brazil

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