Abstracts of the UV4Plants International Association of Plant UV Research 2nd Network Meeting

Bled (Slovenia), 15th - 18th of April 2018

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International Association of Plant UV Research

Edited by Alenka Gaberščik, Mateja Germ, Susanne Neugart, Gareth I. Jenkins, Matthew Robson, Dragan Abram

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Hidden deep in the heart of things
Thou carest for growth and life:
the seed becomes shoot, the bud a blossom,
the flower becomes fruit.
Tired I slept in my idle bed in the illusion that the work had an end.
In the morning I awoke to find
that my garden was full of flowers.

Rabindranath Tagore, Gitanjali (1861-1941)

Contents

About UV4Plants

The *International Association for Plant UV Research* (acronym UV4Plants; http://uv4plants.org/) was established in 2015 to build on the advantages and achievements of the UV4Growth COST Action. The activities of UV4Plants include the publication of an open-access journal entitled the *UV4Plants Bulletin* (http://bulletin.uv4plants.org/), publication of monographs, the organization of conferences and training events, and maintaining communication through different channels.

The key aims of UV4Plants are:

- To promote and foster a culture of research-excellence and good practice in Plant UV Research through the organisation of innovative events in research, public engagement and education.
- To provide channels for members to inform the Plant UV Research community about relevant activities or events of common interest.
- To enhance the usefulness of Plant UV Research by facilitating the transfer of knowledge from academia to stakeholders and the general public.
- To initiate and foster stakeholder contacts as part of an agenda of product development.
- To liaise with scientific funding bodies to influence their research agenda.
- To develop with its members the benefits of membership and the relevance of the Association.

Welcome to Bled

We are glad to welcome you to the 2nd Network Meeting of the International Association of Plant UV Research in Bled, Slovenia.

Bled belongs to the oldest touristic towns in Slovenia. It is located in the glacial landscape in the transition area between Radovljica depression and eastern foothill of Julian Alps. The islet in the middle of the lake has attracted people since prehistoric times. In the early 20th century it became a fine health resort.

The aim of this Network Meeting is to enhance the UV research domain by summarising the outcomes and presenting the achievements of the research field as well as to strengthen collaborative interactions across disciplines, connecting different universities and countries, and particularly by stimulating the research environment for the early stage researchers.

The meeting is co-organized by UV4plants and the Department of Biology, Biotechnical Faculty, University of Ljubljana.

We wish you a productive and enjoyable meeting!

Prof. dr. Gareth I. Jenkins
President UV4Plants Association

Prof. dr. Alenka Gaberščik
For Local Organizers

Honorary lecture

Microorganisms in the atmosphere: Impact of ultraviolet radiation

Lars Olof Björn

University of Lund

Microorganisms can be injected into the atmosphere by a number of mechanisms. Some organisms actively throw out spores. Other microorganisms can ascend during dust storms, or in droplets from wave-crests or bursting bubbles at sea. Turbulence can carry them up through the troposphere, but even without vertical air currents in the stratosphere they can be carried further upwards through a process called gravito-photophoresis. In the air they encounter dangers such freeze-thaw cycles, dry air, low temperature and ultraviolet radiation. Despite this they have been shown to travel worldwide, and sometimes be metabolically active while aloft. I shall try to give some information on what they have to endure, with emphasis on ultraviolet radiation. In general DNA seems to be the main target for lethal solar radiation. Organisms with a high proportion of cytosine+guanine in their DNA seem to have better resistance to UV than those with a low proportion. Also pigmentation contributes to UV resistance.

Molecular aspects of UV-B responses

UV-B control of plant architecture

Kerry Franklin

University of Bristol, UK

UV-B inhibits stem elongation in a variety of plant species. The molecular mechanisms underpinning this striking developmental adaptation have remained largely uncharacterised. We have shown that low dose UV-B, perceived by the UVR8 photoreceptor, regulates the abundance and activity of PHYTOCHROME INTERACTING FACTOR (PIF) transcription factors, inhibiting auxin biosynthesis and stem extension. UV-B serves as an important brake on elongation growth in dense vegetation, inhibiting shade avoidance once canopy gaps have been reached. UV-B signals, perceived by UVR8 also strongly antagonise stem elongation responses induced by high temperature. In this talk, I will discuss the different molecular mechanisms by which UV-B regulates shade avoidance and thermomorphogenesis.

Photoreception by UVR8 in *Arabidopsis* plants

L. Aranzazú Díaz-Ramos[1], Andrew O'Hara[2], Selvaraju Kanagarajan[2], Daniel Farkas[2], Åke Strid, Gareth I. Jenkins[1]

[1] *Institute of Molecular, Cell and Systems Biology, College of Medical, Veterinary and Life Sciences, Bower Building, University of Glasgow, Glasgow G12 8QQ, UK.*
[2] *School of Science & Technology, Örebro Life Science Center, Örebro University, SE-70182 Örebro, Sweden*

The photoreceptor UV RESISTANCE LOCUS 8 (UVR8) activates photomorphogenic responses in plants after exposure to ultraviolet-B (UV-B) light. Whereas the absorption spectrum of UVR8 peaks at 280 nm, the action spectra of several photomorphogenic UV responses show maximal photon effectiveness at 290-300 nm. To investigate this, the wavelength effectiveness of two UV responses were measured: UVR8 monomerisation and the accumulation of ELONGATED HYPOCOTYL 5 (HY5) transcripts, which has a key-role in UVR8-mediated responses. Monomerisation was maximal at 280 nm when both the purified protein and plant extracts were exposed. When exposing intact plants, monomerisation peaked at 290 nm, whereas the accumulation of HY5 transcripts, measured in the same plant tissue samples, was maximal at 300 nm. Possible explanations of the findings will be presented. UV-B perception by UVR8 is done via tryptophans located in the dimer interface. W285 and W233 are important for UV-B perception, however the contribution of the other 5 tryptophans in the dimer interface is unclear. Mutations of tryptophans W94F, W337F and W198/250/302F were found to decrease the efficiency in generating a response (HY5 transcript accumulation), when plants are exposed to different doses of UV-B compared to WT UVR8.

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Acknowledgement

Aranzazú Díaz-Ramos was supported by a PhD studentship from Consejo Nacional de Ciencia y Tecnología (CONACYT). Andrew O'Hara was supported by a UK Biotechnology and Biological Sciences Research Council PhD studentship (University of Glasgow) and Sven and Lily Lawski's Foundation for Scientific Research (University of Örebro). Selvaraju Kanagarajan was supported by the Carl Trygger Foundation. Daniel Farkas was supported by the Faculty for Business, Science, and Technology at Örebro University. Åke Strid acknowledges financial support for this work from the Knowledge Foundation (kks.se), FORMAS – a Swedish Research Council for Sustainable Development (formas.se), and the Faculty for Business, Science, and Technology at Örebro University. We thank the EU COST action FA0906 'UV4Growth' for supporting visits by A.O. to Örebro. We thank Konstancija Vasilenkaite and Monika Heilmann for undertaking preliminary experiments in this project. G.I.J. thanks the University of Glasgow for the support of his research.

Role of the ARIADNE12 ubiquitin E3 ligase and its putative substrate in long term adaptation to UV-B

Marie-Theres Hauser, Lisi Xie, Julia Richter, Karolina Słomińska, Lukas Zeh, Serap Afşar, Neha Nigam, Christina Lang-Mladek

Department of Applied Genetics and Cell Biology, University of Natural Resources and Life Sciences (BOKU), Muthgasse 18, 1190 Vienna, Austria

The ultraviolet (UV)-B inducible *ARIADNE 12 (ARI12)* gene of *Arabidopsis thaliana* is a member of the RING-between-RING (RBR) family of E3 ubiquitin ligases. Under low fluence rates of UV-B, *ARI12* is a downstream target of the UV RESISTANCE LOCUS 8 (UVR8) pathway while under high fluence rates, *ARI12* depends on the key light regulator CONSTITUTIVELY PHOTOMORPHOGENIC1 (COP1). Genetic analysis with transgenes expressing a genomic *pmARI12:ARI12-GFP* construct confirms the epistatic interaction between *COP1* and *ARI12* in growth responses to high fluence rate UV-B. *ARI12* T-DNA insertion mutants are more tolerant than wildtype to repeated UV-B exposures. To identify ARI12 targets yeast two hybrid analysis found a translational regulator which abundance is regulated by ARI12. A T-DNA insertion allele of this translational regulator is hypersensitive to repeated UV-B exposures. Double mutant analysis put *ARI12* and the interactor in the same pathway and shows that the higher tolerance to UV-B of *ari12* mutants depends on the presence of this translational regulator. The results will be integrated into current models of translational control mechanisms and UV-B.

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The research was supported by the Austrian Science Fund (FWF), the European Plant Phenotyping Network (EPPN) and the COST-Action UV4Growth.

Blue light triggered organellar movements in UV-protection in plants

Piotr Zgłobicki, Agnieszka Katarzyna Banaś

Department of Plant Biotechnology, Faculty of Biochemistry, Biophysics and Biotechnology of Jagiellonian University, Gronostajowa 7, Kraków, PL

Plants are dependent on light and inevitably subjected to stresses connected with excessive irradiation in the range of both visible and ultraviolet light (UV). Excessive irradiation can cause formation of potentially harmful reactive oxygen species. UV is absorbed by most of biomolecules ia. proteins, lipids and nucleic acids what can result in their damage. In DNA UV forms covalent bonds between adjacent pyrimidines creating dimers, mostly cyclobutane pyrimidine dimers (CPDs) and 6-4 pyrimidine-pyrimidones (6-4PPs) which block progress of the polymerases and can cause mutations or even cell death when remain unrepaired.

Protection from the effects of excessive irradiation can be obtained on three main levels: avoidance, screening and damage repair. First, which is known to serve as protection of photosyntetic apparatus from strong light, can be achieved by chloroplast movements. These are controlled by blue light photoreceptors, phototropins. In *Arabidopsis thaliana* it has been shown that phototropin2 plays also role in nuclear relocations.

The aim of this study was to establish whether chloroplast and nuclear movements can act to protect the genome from UV-caused damage. For this purpose total DNA as well as DNA from nuclear and chloroplast fractions was isolated after UV-irradiation. *Arabidopsis thaliana* Col-0 wild type was used together with phototropin mutants (phot1, phot2, phot1phot2) and chup1 - mutant deficient of actin binding protein required for chloroplast positioning. CPD and 6-4PP levels were measured by ELISA. Our result show that organellar movements serve as UV-protection mechanism for both nuclear and chloroplast genome.

The expression and subcellular localization of AtUVR3 6-4 PPs photolyase

Banaś Agnieszka Katarzyna[1, 2], Hermanowicz Paweł[1,2], Sztatelman Olga[1,3], Aggarwal Chhavi[1,4], Zgłobicki Piotr[1], Łabuz Justyna[2], Bażant Aneta[2], Jagiełło-Flasińska Dominika[1], Strzałka Wojciech[1]

[1]*Department of Plant Biotechnology, Faculty of Biochemistry, Biophysics, Biotechnology, Jagiellonian University, 30-387 Krakow, PL*
[2]*Malopolska Centre of Biotechnology, Jagiellonian University, 30-387 Krakow, PL*
[3] *Institute of Biochemistry and Biophysics, Polish Academy of Sciences, 02-106 Warszawa, PL*
[4] *Department of Gene Expression, Faculty of Biology, Adam Mickiewicz University, 61-614 Poznan, PL*

Pirymidine dimers (cyclobutane pyrimidine dimers (CPDs) and to a lesser extent pyrimidine–pyrimidone (6–4) photoproducts (6–4 PPs)) are the main DNA damages induced by UV. In most organisms, including plants, they are repaired by specialized enzymes, photolyases. Photolyases use blue light/UVA energy to directly split the dimers. Whereas most research are devoted to CPD photolyases our study focused on *Arabidopsis* 6-4 PPs specific photolyase encoded by *AtUVR3*. Using transient expression of GFP-fused AtUVR3 we showed that this protein is localized in all three plant compartments containing DNA, nuclei, chloroplasts and mitochondria (Banaś et al. 2017). In nucleus the photolyase marked uniformly the nucleoplasm and was enriched in nucleolus. The results obtained with a set of muteins and truncated proteins proved that a proper transport to the organelles required the C-terminal amino acids of AtUVR3. *Arabidopsis* plants overexpressing AtUVR3 very efficiently removed UV-induced 6-4 PPs from nuclear and chloroplast DNA as shown using ELISA. The level of *AtUVR3* mRNA was down-regulated by blue and red light mainly due to the retrograde signaling. Interestingly, in red light this regulation was modulated by phyA but only in the absence of phyB.

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Acknowledgement

This study was supported by the Polish National Science Centre [grant No. UMO-2011/03/D/NZ3/00210] and UMO-2016/22/E/NZ3/00326]; The Faculty of Biochemistry, Biophysics and Biotechnology is a partner of the Leading National Research Center (KNOW) supported by the Ministry of Science and Higher Education.

Molecular insight into the UV-B-induced inhibition of shade avoidance responses.

Tavridou E, Schmid-Siegert E, Sankar M, Fankhauser C, Ulm R

UV-B signaling and the shade avoidance syndrome (SAS) in response to a reduced red:far-red ratio elicit opposing responses in plants. SAS induces hypocotyl and petiole elongation, and leaf hyponasty, whereas UV-B-induced photomorphogenesis is associated with inhibition of hypocotyl and petiole elongation, and a generally more compact plant phenotype. In Arabidopsis, changes in the red:far-red ratio are primarily perceived by phytochrome B, whereas UV-B is perceived by the UV RESISTANCE LOCUS 8 (UVR8) photoreceptor. UVR8 signaling suppresses shade-induced hypocotyl and petiole elongation, as well as shade marker gene induction. Although key signaling events of both UV-B and shade pathways have been elucidated, the mechanistic understanding of the crosstalk between the two pathways remains less well understood. We will present our latest understanding of how UVR8 signaling represses responses to shade signals, highlighting the roles of shade- and UV-B-regulated bHLH transcriptional regulators.

Biochemical aspects of UV-B responses

Heterologous UVR8 production in plants opens up new approaches to functional and structural studies of the UVB photoreceptor

Åke Strid[1], Khuanpiroon Ratanasopa[1], Daniel Farkas[1,2], Leif Eriksson[2], Min Wu[2], Andrew O'Hara[1]

[1]*School of Science and Technology, Örebro University, SE-70182 Örebro, Sweden*
[2]*Department of Chemistry and Molecular Biology, University of Göteborg, SE-40530 Göteborg, Sweden*

The UVR8 photoreceptor regulates gene expression and is crucial for UV-induced accumulation of flavonoids in plants. As more research is being carried out with focus on UVR8 function, we see a growing palette of cell biological events that UVR8 is involved in regulating. One intriguing question is what the physiological function of UVR8 really is under a sky with an adequate ozone layer? What is the crucial UVR8 function that makes its gene still be present in almost all contemporary angiosperm and green algal genomes? Furthermore, at the biochemical level there are issues that have not been resolved with regards to UVR8 structure and function. These relate to its C- and N-terminal, its function in the dimeric and monomeric state, and interactions with other molecules. The biochemical function of UVR8 and its structure have mainly been studied using protein produced in E. coli. We have taken another approach, producing ample amounts of UVR8 in plants and studied its biophysical and biochemical characteristics. The plant-produced protein shows distinct features that differ from UVR8 produced in bacteria. These will be discussed and put into context.

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This study was supported by the Knowledge Foundation (kks.se) and The Swedish Research Council Formas, as well as the Faculty for Business, Science and Technology at Örebro University.

UVR8 and CRYs regulate growth, transcripts and metabolites in *Arabidopsis* plants exposed to short-term (6h) and long-term (21d) UV and blue radiation

Neha Rai[1], Yan Yan[1], Sari Siipola[1], Susanne Neugart[2], Andreas Albert[3], Barbro Winkler[3], Luis Morales[1], Pedro Aphalo[1]

[1] Vikki Plant Science Centre, University of Helsinki, Viikinkaari 1, 00014 University of Helsinki, Finland
[2] Leibniz Institute of Vegetable and Ornamental Crops, Theodor-Echtermeyer-Weg 1, 14979 Großbeeren, Germany
[3] Research Unit Environmental Simulation, Helmholtz Zentrum München, Ingolstädter Landstr. 1, 85764 Neuherberg, Germany

UV RESISTANT LOCUS 8 (UVR8) and CRYPTOCHROME 1 and 2 (CRY 1, CRY 2) are plant photoreceptors normally assumed to mediate perception of wavelengths in the UV-B (280-315 nm) and UV-A/blue (315-500 nm) regions of the spectrum, respectively. These photoreceptors play key roles in regulating photomorphogenesis and plant acclimation. However, information on the molecular mechanisms regulated by UVR8 and CRYs in sunlight/simulated sunlight is scant. In an experiment, performed in solar-simulation chamber, we studied the roles of UVR8 and CRYs on the regulation of growth, transcript and secondary metabolite accumulation in *Arabidopsis thaliana* leaves after exposures to UV-B, UV-A and blue radiation of different length: short-term (6h) and long-term (21d). We used four genotypes: wild-type Landsberg *erecta* (L*er*), *uvr8-2* (UV-B photoreceptor mutant), *cry1cry2* (double CRY mutant), and *uvr8-2cry1cry2* (triple mutant). We found that the triple mutant eventually died when the plants were exposed for 21d to UV-B. However, no drastic effect on growth was observed in other genotypes in response to UV and blue treatments, suggesting that absence of both UVR8 and CRYs simultaneously is fatal for the plants when exposed to UV-B. Quantitative real-time PCR was used to analyse transcript abundance of UV-B marker genes such as *CHALCONE SYNTHASE* (*CHS*), *REPRESSOR OF UV-B PHOTOMORPHOGENESIS 2 (RUP2)* and a light signalling gene, *EARLY LIGHT INDUCED PROTEIN* (*ELIP2*). We found that the changes in transcript abundance in response to UV were larger at 6h than at 21d. Our preliminary data indicated a UVR8 dependent increase in transcript abundance of these genes in response to UV-B and UV-A, whereas CRYs dependent increase in response to blue light. We also observed an increased accumulation of these transcripts in *cry1cry2* in response to UV-B and UV-A. This response was larger than in the wildtype and was missing in *uvr8-2* and *uvr8-2cry1cry2*, hence the enhanced response could be through UVR8. In an ongoing metabolite analysis, we have identified eight phenolic compounds: four flavonoids, all kaempferol derivatives, and four hydroxycinnamic acid derivatives. Further quantification and analysis, to be presented, will help explain the roles of the photoreceptors on the accumulation of these metabolites upon short and long-term exposure to UV and blue treatments.

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Amended synthesis of vitamin B_6 causes altered antioxidant responses to supplemental UV-B in *Arabidopsis thaliana*

Gyula Czégény[1], László Kőrösi[2], Åke Strid[3], Éva Hideg[1]

[1]*Department of Plant Biology, University of Pécs, H-7633 Pécs, Ifjúság útja 6., Pécs, Hungary*
[2]*Research Institute of Viticulture and Enology, University of Pécs, H-7634 Pécs, Pázmány Péter utca 4., Pécs, Hungary*
[3]*School of Science & Technology, Örebro Life Science Center, Örebro University, SE-70182 Örebro, Sweden*

We previously showed that UV-B can increase metabolic hydrogen peroxide (H_2O_2) concentrations in leaves and that it is able to convert H_2O_2 to hydroxyl radicals ($^{\bullet}OH$) (Czégény et al. 2014). Thus, efficient scavenging of H_2O_2 and $^{\bullet}OH$ are expected to be important aspects in a successful acclimation to UV-B. Vitamin B_6 has an essential role both in plant development and stress tolerance (Raschke et al. 2011). In addition to their coenzyme function in several biosynthetic pathways (Drewke and Leistner 2001), B_6 derivates are potent quenchers of ROS (Havaux et al. 2009, Matxain et al. 2009).

In this study, we used *Arabidopsis thaliana* mutants (*rsr4-1*) reduced in B_6 biosynthesis (Wagner et al. 2006) to investigate how vitamin B_6 derivates of contribute to the plants' acclimation to supplemental UV-B in growth chambers. In response to UV-B both mutant and wild type (C24) leaves altered their antioxidant profiles – including increases in B_6 derivates. Wild type plants avoided oxidative stress via increasing peroxidase acitivities. Mutants, however, showed elevated catalase and markedly decreased SOD activities, although these were not sufficient to maintain leaf photochemistry. Responses are also discussed in terms of changes in leaf B_6 profiles and ROS reactivities of these compounds.

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Moles or mass, that is the question: which one tells more about responses of flavonoid glycosides to UV radiation?

Pedro J. Aphalo[1], Nina Siipari[2], Riitta Julkunen-Titto[3]

[1]ViPS, Faculty of Biological and Environmental Sciences, 00014 University of Helsinki, FI
[2]Metabolomics Laboratory Unit, 00014 University of Helsinki, FI
[3]Department of Environmental and Biological Sciences, University of Eastern Finland, Joensuu, FI

In our research community it is customary to express the content of flavonoid glycosides as mass-per-mass or mass-per-area concentrations. In many cases reported masses have been based on equivalent masses for a different metabolite used as reference, in other words, neither real mass values nor molar values. One can think of flavonoids as being “assembled” from common units: one of several aglycones and one or more sugar-based moieties. This makes it interesting to ask research questions about these units, and their possible re-arrangements in time. In particular, the total mass concentration of flavonoids can increase without any increase in their total molar concentration, simply by addition of sugar residues to the existing aglycones. Their UV-B and UV-A absorbance depends mainly on the aglycone, rather than sugar moiety. So, we may ask how does UV-radiation affect the molar concentration of aglycones, and the average number of sugar residues per aglycone? Changes could take place at different time scales, given their different synthesis costs, possible reuse of sugar moieties and their different contributions to optical, biochemical and biophysical properties of cells. We explored this question by recording area, fresh and dry mass of samples, and measuring in the samples concentrations of both individual flavonoids and their aglycones. We propose that molar- and mass-based quantities for expression of flavonoid concentrations inform about different aspects of the response to UV radiation and that a richer interpretation can be obtained by taking into consideration both of them. In addition, when leaf thickness or tissue water content are affected by treatments, apparent responses to treatments will depend on the basis of expression used.

How do grapevine leaf phenolic contents respond to daily changes in environmental factors?

Kristóf Csepregi[1], László Kőrösi[2], Péter Teszlák[2], Éva Hideg[1]

[1]*Department of Plant Biology, University of Pécs, Ifjúság útja 6, 7624, Pécs, HU*
[2]*Research Institute for Viticulture and Oenology, University of Pécs, Pázmány Péter utca 4, 7634, Pécs, HU*

Grapevine leaves are rich in phenolic compounds, many of which are – among fulfilling other roles – efficient antioxidants (Csepregi et al. 2016, Csepregi and Hideg 2017). The long-term aim of a recently launched project is to explore the functional plasticity of phenolic compounds in grapevine leaves. Here we present results of a pilot study, registering and analysing hour-by-hour changes in photosynthesis, phenolic profiles and antioxidant capacities of South-facing Pinot noir leaves between 7 am and 7 pm during a clear summer day mid-July at Pécs (N46.071°, E18.156°). During this 12h period, photosynthetically active radiation (PAR) was 80-2130 µmol/m^2/s and UV radiation (UV-A+B) varied between 5-46.1 kJ/m^2 as physical dose measured on site. Local data were separated into UV-B (280-315 nm) and UV-A (315-400 nm) regions based on a model calculation (NCAR).
Total adaxial flavonoid content (measured as Dualex flavonoid index) varied between 88% and 112% of the daily average and showed strong positive correlations with PAR, UV-A, UV-B, leaf temperature and net CO_2 assimilation. Stomatal conductance (g_s) was positively correlated with PAR, UV-A and UV-B. However, substomatal CO_2 concentrations (C_i) were only correlated with PAR (positively) and not with UV. Hourly changes in leaf antioxidant capacities and phenolic profiles measured with HPLC-DAD complete the analysis.

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NACR, the 5.2 version of the TUV model was accessed via the National Center for Atmospheric Research at http://cprm.acom.ucar.edu/Models/TUV/Interactive_TUV/

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Shining light on the UVR8 independent pathway in the hunt for an alternative UV-B photoreceptor

Andrew O'Hara, Selvaraju Kanagarajan, Åke Strid

School of Science & Technology, Örebro Life Science Center, Örebro University, SE-70182 Örebro, Sweden

UV-B (280-315nm) makes up only a minor component of sunlight but can have a major impact on all organisms under the sun. Humans are not well evolved to cope with UV-B and often show signs of damage in the form of sunburn, aging and cancers via DNA damage and necrosis. Plants, which are absolutely dependent on sunlight as their source of energy for an array of processes, conversely rarely show signs of UV-B induced damage as they have evolved elaborate systems to utilize UV-B and can in fact produce their own sunscreens. How plants combat and adapt to UV-B is well understood but only recently has the UV-B photoreceptor UVR8 been discovered and the initial perception event resolved. A growing body of evidence has emerged that shows another photomorphogenic UVR8 independent pathway exists that responds to low levels UV-B and thus perhaps a secondary UV-B specific photoreceptor. Our aim is to determine the upstream components of the UVR8 independent pathway using a forward genetic approach, via a LUC based screen, and ultimately test the notion that another UV-B photoreceptor exists. In this talk I will give a background of UV-B perception and the UVR8 independent pathway. Furthermore, I will discuss the methodology we used and the progress we have made in elucidating this putative secondary UV-B receptor.

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The metabolic responses of cyanic and acyanic basil varieties to a UV-gradient

Louise Ryan, Marcel A.K. Jansen

School of Biological, Earth and Environmental Sciences, North Mall Campus, University College Cork, Cork, Ireland.

Responses of horticultural crops to UV are of commercial interest. The aim of this study was to elucidate the metabolic response of *Ocimum basilicum* to four doses of UV (0.06, 0.32, 1.39 and 4.37 kJ m^{-2} UV-be). The basil varieties chosen were Genovese Sweet Aroma II, a green variety and Red Dark Opal, a purple variety. Anthocyanins and UV-absorbing flavonoids were quantified in epidermal tissue layers of leaves of different ages using a Dualex, as well as in methanolic extracts. Overall, purple basil had a much higher anthocyanin content than green basil. UV had no effect on anthocyanin content. Remarkably, Dualex measurements showed that purple basil had a much lower concentration of UV-absorbing flavonoids in the epidermis than green basil, although extraction analysis showed a higher concentration in the purple basil. The content of UV-absorbing flavonoids increased with increasing UV-dose in the purple cultivar only. The data suggest accumulation of UV-absorbing flavonoids in different tissues in the two cultivars, and potential interactions between flavonoid and anthocyanin biosynthesis. This study elucidates the complexity of plant UV responses involving tissues, organ age, genotype, and competition between biosynthesis pathways.

Physiological aspects of UV-B responses

UV-B phototropism: of light and hormones

Lucas Vanhaelewyn[1], Péter Bernula[2], Alejandro Serrano[3,4], Carlos Ballaré[3,5], M. Veronica Arana[3,6], Dominique Van Der Straeten[1], András Viczián[2], Filip Vandenbussche[1]

[1]Laboratory of Functional Plant Biology, Faculty of Sciences, Ghent University, KL Ledeganckstraat 35, 9000 Gent, BE
[2]Institute of Plant Biology, Biological Research Centre, Temesvári krt. 62, 6726 Szeged, HU
[3]CONICET, (Consejo Nacional de Investigaciones Científicas y Técnicas)-AR
[4] IADIZA, Av. Ruiz Leal s/n Parque Gral. San Martín, Casilla de Correo 507, Mendoza 5500, AR
[5] IFEVA Universidad de Buenos Aires, Ave. San Martín 4453, C1417DSE, Buenos Aires, AR and IIIB-INTECH, Universidad Nacional de San Martín, B1650HMP Buenos Aires, AR
[6] INTA, Modesta Victoria 4450 - Valle Verde, Bariloche 8400, Rio Negro, AR

Phototropism manifests itself in many higher plant shoots as growth towards a blue or ultraviolet (UV) light source. Based on physiological assays, we have identified two photoreceptor controlled pathways which lead to phototropic growth in *Arabidopsis* upon UV-B (280-315 nm) radiation, namely the phototropin and the UV RESISTANCE LOCUS 8 (UVR8) pathway. The impact of these pathways differs at different stages of plant development, being the phototropin pathway more important in etiolated seedlings (Vanhaelewyn et al., 2016a), and the UVR8 pathway predominant in inflorescence stems. Furthermore, UV-B appears more effective than blue light to stimulate phototropism in inflorescences. The UV-B phototropic response is associated with a UVR8 signal gradient across the inflorescence tissue. Cell type specific complementation analysis of uvr8-6 mutant plants reveals that UVR8 signaling in various cell types within the inflorescence stem are of importance during the response. UV-B effects on plants are often highly dependent on hormones (Vanhaelewyn et al., 2016b). Our gene expression, mutant and reporter line analysis, and pharmacological assays indicate a role for both auxin and gibberellins in UV-B phototropism. A broader mechanistic and ecological context of UV-B phototropism will also be discussed.

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UVR8 and cryptochromes promote sunlight acclimation in *Arabidopsis thaliana*

Neha Rai[1], Alexey Shapiguzov[1], Sari Siipola[1], Fang Wang[1], Mikael Brosché[1], Pedro Aphalo[1], Luis O. Morales[1]

[1]*Vikki Plant Science Centre, University of Helsinki, Viikinkaari 1, 00014 University of Helsinki, Finland*

Plants use sunlight as a source of energy for photosynthesis but also as an important environmental cue to regulate growth, development and light acclimation. Wavelengths in the UV-B (280-315 nm) and UV-A/blue (315-500 nm) regions of the spectrum are perceived by UV RESISTANT LOCUS 8 (UVR8) and cryptochromes (CRY1 and CRY2), respectively. Despite recent advances in our understanding of how these photoreceptors promote photomorphogenesis, very little is known about the molecular mechanisms regulated by UVR8 and CRYs in sunlight grown plants. Here, a factorial experiment was designed to assess the roles of UVR8 and CRYs in regulating transcriptome wide changes, hormone accumulation, and growth competence of *Arabidopsis thaliana* plants exposed to solar UV-B, UV-A, and blue radiation. We show that UVR8 mediates transcript accumulation triggered by wavelengths below 350 nm while CRYs regulate transcriptional responses above 350 nm. Furthermore, the lack of functional UVR8 and CRYs produces altered transcriptional responses in uvr8-2 and cry1cry2 exposed to solar UV-B, UV-A and blue. While UVR8 promotes ABA and JA accumulation in response to solar UV, at least one of functional UVR8 or functional CRYs is needed for survival of plants under solar UV radiation.

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The interlink of UV transmittance and flavonoids in okra driven by diurnal changes

Susanne Neugart, Mark Tobler, Paul Barnes

Department of Biological Sciences, Loyola University New Orleans, 6363 St. Charles Avenue, 70118 New Orleans, LA, USA

The accumulation of UV-absorbing compounds (i.e. flavonoids) and the associated decrease in epidermal UV transmittance is one response of plants to UV exposure.[1] However, the degree and rapidity to which plants can modulate UV shielding is poorly understood.

Okra (*Abelmoschus esculentus*) plants were exposed to two solar radiation treatments (UV-transparent film (Aclar 22A) or UV-blocking film cut off near 390 nm (CFC)). After 4 weeks the following were measured in the youngest mature leaf over a day: epidermal UV transmittance (UVA-PAM), flavonoids (Dualex), UV-absorbance and antioxidant activity of leaf extracts (spectrophotometer).

Plant instantaneous UVB_{BE} intensities ranged between 0.02 J m^{-2} at 8:00 and 18:00 to 0.26 J m^{-2} at 12:00. UV transmittance decreased and flavonoids increased in the superior epidermis ~50% until 15:00 then returned close to morning values later in the day. The same pattern was found for the UV-absorbance and antioxidant activity. A correlation of instantaneous UVB_{BE} intensity or sum of UVB_{BE} 3 hours in advance of the flavonoid measurements had the highest relation.

There are strong interlinks and concomitant changes in okra UV transmittance, flavonoids, UV-absorbance and antioxidant activity in response to fluctuations in solar UV.

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The capacity of *Lepidium meyenii* plants to recover from UVB irradiation challenge

Thais Huarancca Reyes[1], Andrea Scartazza[2], Antonio Pompeiano[3], Lorenzo Guglielminetti[1,4]

[1]*DiSAAAa, Univ. Pisa, Italy*
[2]*IBAF, CNR, Italy*
[3]*CTM, ICRC, St. Anne's Univ. Hosp., Czech Republic*
[4]*NUTRAFOOD, Univ. Pisa, Italy*

Increased ultraviolet B (UVB) radiation due to global change can affect plant growth and metabolism. Crops in the Andean mountains have evolved under extreme conditions including intense UV. Maca (*Lepidium meyenii* Walpers) is a member of the radish family growing in above 4000 m of altitude where only highland grasses can survive. Since its initial reports in 1960s, maca has been the focus of recent attention mainly due to several studies of its nutraceutical properties. However, the exploration of its strategies to tolerate extreme environment has not been studied yet. This is the first study that reports the physiological strategies of maca to counteract and recover to repeated acute UVB irradiation. In detail, maca was daily exposed for 60 min to 1.69 W m^{-2} following a time course up to 14 days. Recovery of UVB treated and untreated plants was also evaluated. The results showed that increased UVB reduced biomass and photosynthetic related parameters, with a clear senescence induction in exposed leaves. A negative correlation between increased UVB and recovery was observed, with marked production of new biomass in long term treated plants. Moreover, multifactorial analysis based on biometric and physiological data suggested a differential UVB response between treatments.

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Effects of UV-B radiation on five cool-season turfgrasses

Lorenzo Guglielminetti[1,4], Thais Huarancca Reyes[1], Andrea Scartazza[2], Antonio Pompeiano[3], Marco Volterrani[1]

[1]DiSAAAa, Univ. Pisa, Italy; [2]IBAF, CNR, Italy; [3]CTM, ICRC, St. Anne's Univ. Hosp., Czech Republic; [4]NUTRAFOOD, Univ. Pisa, Italy

Light intensity affects the growth rate of plants. Adverse environmental factors, including UV-B radiation, may affect plants growth. Over the last decades, many studies have been published on the effect of UV-B radiation on plants. Mainly, these studies concerned crops, while only few experiments have involved turfgrasses. Therefore, we have chosen to examine some of the most commonly used cool-season turfgrasses. In detail, we checked the response of *Agrostis stolonifera*, *Festuca arundinacea*, *Poa pratensis*, *Poa supina* and *Lolium perenne* to survive in a severe UVB enriched environment. The results of the test showed many differences among the species responses to UV-B radiation, especially in the efficiency of PSII and gas exchange. Strong differences among the species were also found when survival ability and recovery rate were analyzed. For other parameters, the responses among species are less obvious. Chlorophyll content and carotenoids, although generally tend to decrease, seem to be dependent on species.

Caffeoylquinic acid derivatives as UVA protective pigments in sunflower leaves

Jana Stelzner, Roderich Römhild, Wolfgang Bilger

Botanical Institute, University of Kiel, Am Botanischen Garten 1-9, DE 24118 Kiel

Phenolic compounds in plants, especially when located in the upper epidermis, are well known to block UVA and UVB in order to protect the underlying tissue from the harmful radiation. Plants commonly store two groups of phenolic compounds that complement each other over the UV spectrum according to their absorption spectra: flavonoids are reported to serve as UVA attenuators whereas hydroxycinnamic acids (HCAs) screen well within the UVB region.
Analysis of epidermal transmittance revealed a substantial UVA shield in *Helianthus annuus*. Identifying responsible pigments by HPLC-MS, we found a surprising lack of flavonoids but dominant abundance of the HCAs chlorogenic and di-caffeoylquinic acid. Both display low UVA absorbance and thus, should contribute only little to UVA protection. However, leaves showed growth irradiance dependent shielding of up to 90%. Underpinning the screening role, microscopy of HCA autofluorescence revealed storage to occur predominantly in vacuoles of the upper epidermis.
UVA treatment in the absence of D1-repair resulted in photosystem II inactivation proportional to epidermal UVA transmittance. Our findings show that UVA protection can be achieved solely with HCAs, apparently through accumulation of high amounts.

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Interaction between UV-B and other factors

Conditional UV-effects; the environment as a modulator of plant UV-responses

Louise Ryan, Aoife Coffey, Marcel AK Jansen

School of Biological, Earth and Environmental Sciences, North Mall Campus, University College Cork, Cork, Ireland

UV-B can induce the expression of a range of protection responses. Indeed, it has been argued that plants rarely, if ever, experience UV stress. Nevertheless, some studies report UV-induced stress. While some of these studies used excessive doses of biologically effective UV radiation, other studies are based on the use of realistic UV-doses. To explain the discrepancy between various studies, we hypothesised that the balance between UV-acclimation and UV-damage is modulated by secondary environmental factors, some of which can be defined as stressors, and which may either nullify or amplify plant UV-responses. For example, year-round, outdoor filtration studies showed that low temperature is a more important factor controlling accumulation of UV-absorbing pigments in *Arabidopsis* than UV-radiation, the effects of which were not even significant during the summer months. Similarly, the effect of UV-radiation on root development in *Landoltia punctata* (duckweed) is nullified by root-length promoting drought stress. However, where plants are first exposed to UV-B, and only later to drought, UV has a significant inhibitory effect on root development. These data suggest that UV-B has induced a degree of drought tolerance that reduces the need for root elongation. Irrespective of the underlying physiological mechanism, the data show the relevance of multi-factor approaches when studying plant UV-responses.

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Effect of UV-B radiation on performance, flavonoids production and gene expression-associated to stress response in chili pepper (*Capsicum annuum* L.)

Tania Rodríguez-Calzada[1], Minjie Qian[2], Åke Strid[2]*, Susanne Neugart[3], Susanne Baldermann[3], Monika Schreiner[3], Irineo Torres-Pacheco[1], Ramon G. Guevara-González[1]*

[1] Biosystems Engineering Group, School of Engineering, Autonomous University of Queretaro-Campus Amazcala. Querétaro, México.
[2] School of Science and Technology, Örebro University, Sweden
[3] Department of Quality, Leibniz Institute for Ornamental and Horticultural Crops. Grossbeeren, Germany

It has been suggested that accumulation of flavonoids could be a key step for plant tolerance to different environmental stresses. Moreover, it has been recognized that abiotic stresses such as both drought and UV-B induce phenolic compounds accumulation, suggesting a role of these compounds in drought tolerance. The present study aimed to evaluate the effect of UV-B exposure on chili pepper plant performance, phenolic compounds production, and gene expression associated with drought stress response. Additionally, the phenotypic response to drought stress of these plants was studied. Evaluated UV-B induced a reduction both in stem length, stem dry weight and number of floral primordia. UV-B treatments in well-watered plants advanced fructification by approximately 1 week in comparison to non UV-B treated controls. Flavonoids measured in leaves significantly increased in UV-B treatments. Combining drought and UV-B radiation significantly increased chlorogenic acid in both leaves and roots, whereas luteolin-6-C-pentoside-8-C-hexoside was increased only in leaves. Gene expression of the phenylalanine ammonia lyase (*pal*) and chalcone synthase (*chs*) genes also increased in UV-B treatments. On the other hand, gene expression related to oxidative response such as superoxide dismutase (*sod*) and peroxidase (*pod*) was not induced by UV-B. Drought stress on UV-B non-treated plants induced phenolic compounds accumulation in leaves, as well as *sod* and *pod* gene expression

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Water availability and UV radiation effects on silicon accumulation differ in the C4 proso millet and C3 barley

Mateja Grašič[1], Aleksandra Golob[1], Mateja Germ[1], Katarina Vogel-Mikuš[1,2], Alenka Gaberščik[1]

[1]Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, SLO
[2]Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, SLO

Silicon (Si) is a beneficial element for plants. C3 and C4 plants show different pattern of Si deposition in leaves, therefore we expected differences in Si accumulation in the C4 *Panicum miliaceum* L. and C3 *Hordeum vulgare* L. As Si uptake is facilitated by transpiration flow, we hypothesised that water shortage will hinder uptake of Si and possibly also other elements. In addition, plant resistance to drought could be increased by ambient ultraviolet radiation (UV+), thus reduced UV may worsen negative effects of water shortage (W–). We performed pot experiment with both species and applied four different treatments, namely W+UV+, W+UV–, W–UV+, and W–UV–. After 3 weeks we measured morphological, biochemical, physiological, and optical leaf traits, and performed element analyses. The measurements of photochemical efficiency of PS II during and after the experiment revealed that neither barley nor proso millet exhibited water shortage stress. For barley, water shortage significantly decreased the uptake of Si, Ca, P, S, Cl, but not K, while for proso millet, factorial analysis revealed significant effect of both water availability and ambient UV radiation on Si, Ca, P, and S, yet the differences among the treatments were not always significant.

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Effects of UV-B on low levels of gamma radiation in Scots pine

Dajana Blagojevic[1, 2], YeonKyeong Lee[1, 2], Lie Xie[2, 3], Brede Dag Anders[2, 4], Ole Christian Lind[2, 4], Brit Salbu[2, 4], Knut Erik Tollefsen[2, 3], Line Nybakken[2, 4], Knut Asbjørn Solhaug[2, 4], Jorunn Elisabeth Olsen[1, 2]

[1]Department of Plant Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, 1432 Ås, Norway
[2]Centre of Environmental Radioactivity, Norwegian University of Life Sciences, 1432 Ås, Norway
[3]Norwegian Institute for Water Research, Section of Ecotoxicology and Risk Assessment, 0349 Oslo, Norway
[4]Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, 1432 Ås, Norway

In plants, ambient UV-B radiation has been suggested to prime protective responses towards various stressors. Also, it may speculated whether UV-B could affect sensitiviy towards gamma radiation. Using a ^{60}Co gamma source and fluorescent UV-B-tubes under controlled conditions, we aimed to investigate the effect of UV-B on responses to low levels of gamma radiation in seedlings of Scots pine. After 6 days of gamma exposure (1-540 mGy h^{-1}) plant size was reduced with increasing dose rate ≥40 mGy h^{-1}. Combined UV-B-gamma (≤100 mGy h^{-1}) for 6 days resulted in a slight trend only of additional decrease in plant size. H_2O_2 levels were then increased with increasing gamma dose rate but no significant effect of UV on ROS or total antioxidant capacity was observed. On the other hand, increased DNA damage (Comet assay one hour after light on in the morning), with increasing gamma dose rate was then observed with an additive effect of gamma and UV-B. However, although the gamma dose-rate-dependent growth-inhibiting effect and cell damage (at ≥100 mGy h^{-1}) persisted after termination of exposure there was no clear after-effects of UV-B. To shed further light on interactive UV-gamma effects, experiments with pre-exposure to UV-B before gamma or combined UV-B gamma treatment are conducted and results from these studies where UV-B-induced antixidants are analysed, will be discussed.

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Exogenous hydrogen peroxide affects leaf UV-B responses

Arnold Rácz, Gyula Czégény, Éva Hideg

Department of Plant Biology, University of Pécs, Ifjúság útja 6, 7624, Pécs, HU

Efficient hydrogen peroxide (H_2O_2) detoxification is a key factor in the acclimation to supplemental moderate UV-B doses in growth chamber experiments. UV-inducible oxidative stress is mainly avoided due to the increased activity of peroxidase enzymes (Czégény et al. 2016), although non-enzymatic antioxidants, such as flavonoids, are also expected to contribute (Csepregi & Hideg 2017). The aim of our work was to study whether marked increases in class-III peroxidase (POD) isoforms upon UV-B treatment (Rácz et al. 2018) are brought about by H_2O_2 directly and whether a pre-treatment of model plants with H_2O_2 affected UV-B responses. Four weeks old tobacco plants were grown under 200 μmol m^{-2} s^{-1} PAR in growth chambers and irrigated with H_2O_2 for three days before exposure to daily supplementary UV-B treatment (6.9 kJ m^{-2} d^{-1} b.e.) for 4 days. Leaf H_2O_2 contents were determined according to Mátai & Hideg (2017); POD activities were measured using ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)); non-invasive pigment and photosynthesis measurements were carried out with a Dualex Scientific™ optical sensor and the MAXI-version of the Imaging PAM, respectively.

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A tale of two factors: Can UV-B modify drought responses?

A. Mátai, D. Nagy, É. Hideg

Department of Plant Biology, University of Pécs, Ifjúság útja 6, 7624, Pécs, HU

The present work is aimed at studying the effect of supplementary UV-B radiation on the responses of *Nicotiana benthamiana* plants to drought in growth chambers. An earlier study showed that a preceding exposure to drought stress improved the UV-B tolerance of tobacco plants (Hideg et al. 2003). In the present study we applied lower (6.9 $kJ/m^2/d$ biologically effective) UV-B doses as supplementary to 175 $\mu mol/m^2/s$ PAR in growth chambers and either reverse order of the factors (UV-B followed by drought), or their parallel application. UV-B exposure as a single factor did not limit leaf photochemistry (Klughammer and Schreiber, 2008) but resulted in a marked increase in leaf flavonoid content. Limited watering (maintained for 10 days) as single factor increased leaf flavonoid content but had no significant effect on leaf photochemistry. An increase in both non-enzymatic total and ROS-specific antioxidant capacities, as well as higher peroxidase enzyme activity indicate that tolerance was achieved by shifting the antioxidant-prooxidant balance towards protection. In plants exposed to drought after a 4-days pre-treatment by UV-B, tolerance to the same 10-days of drought required a smaller increase in antioxidant capacities, especially in younger leaves that developed after the UV-B treatment.

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Effects of UV radiation and reduced rainfall on leaf morpho-physiological traits of naturally growing *Erica scoparia* plants

C. Rodriguez-Hidalgo[1], D. Verdaguer[1], J. Font[2], J.A. González[3], L. Díaz-Guerra[1], L. Llorens[1]

[1]*Department of Environmental Sciences, Faculty of Sciences, University of Girona, Campus Montilivi, C/Maria Aurèlia Capmany i Farnés 69, E-17003, Girona, Spain*
[2]*Faculty of Sciences and Technology, University of Vic – Central University of Catalonia, E-08500, Vic, Spain*
[3]*Department of Physics, Polytechnic School, University of Girona, Campus Montilivi, C/Maria Aurèlia Capmany i Farnés 61, E-17003, Girona, Spain*

Due to climate change, increases in UV radiation and decreases in precipitation levels are expected in the Mediterranean basin, likely influencing the physiological performance of plant species such as Erica scoparia, which is a dominant species in Mediterranean heathlands. The aim of this study was to analyze UV radiation and rainfall level effects on the leaf physiological performance of naturally growing E. scoparia shrubs. Eighteen plots were subjected to the combination of three UV conditions (UV exclusion, UV-B exclusion and ambient UV) and two rainfall levels (natural and reduced rainfall). Throughout one year, leaf functional traits were measured once per season. Regarding LMA (leaf mass area), plants under UV-A plots showed lower LMA under reduced rainfall. Reponses of leaf gas exchange rates to UV were dependent on the season. Specifically, in winter, plant exposure to UV-A radiation increased stomatal conductance and transpiration rates. Accordingly, UV-A plants showed lower water use efficiency, although this effect did not depend on the season. At the biochemical level, UV-A enhanced leaf chlorophyll b content in plants grown under reduced rainfall, while it reduced leaf content of UV-B absorbing compounds in plants under natural rainfall.

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The effect of growth under blue light and UV-B radiation on *Arabidopsis thaliana* photoreceptor mutants transferred outdoors into full sunlight

Marieke Trasser[1,2,3], Craig C. Brelsford[1], Saara M. Hartikainen[1], Pedro J. Aphalo[1], Luis O. Morales[1], T. Matthew Robson[1]

[1] *Viikki Plant Science Centre (ViPS), Faculty of Biological and Environmental Sciences, P.O. Box 65, 00014, University of Helsinki, Finland*
[2] *Faculty of Sciences, University of Montpellier, Place Eugène Bataillon, 34095, Montpellier, France*
[3]*Institute of Molecular, Cell and Systems Biology, University of Glasgow, G12 8QQ, United Kingdom*

Plants are sessile organisms able to perceive changing light conditions via numerous photoreceptors and attune their growth and photosynthetic abilities accordingly. This capacity to use light cues allows plants to prevent damage in fluctuating sunlight. Blue light and ultraviolet-B radiation (UV-B) are candidate regions of the spectrum to promote these responses triggering accumulation of potentially-photoprotective compounds, such as flavonoids and anthocyanins (Brelsford et al. 2018). We aimed to test if a change in photoprotective-compound accumulation in response to specific spectral cues impacted the photosynthetic capacity plants exposed to a high light. We compared *Arabidopsis thaliana* wild-type plants with mutants deficient in blue and UV-B photoreception, namely cryptochrome 1 and cryptochrome 2 double-mutant, phototropin 1 mutant, uvr8 mutant, as well a triple-mutant for both cryptochromes 1 and 2, and UVR8. We grew plants in under a broad LED spectrum either with or without blue light combined with a UV-B or no UV-B treatment in a factorial design. We compared their flavonoid and anthocyanin content as well as their maximum quantum efficiency of photosystem II (Fv/Fm), before and after transfer outdoors to a high-light treatment administered at the end of the growth period. The leaf epidermal flavonoid content was three times greater when plants were grown under UV-B radiation in addition to blue light compared with conditions where these regions were attenuated. This response was mainly governed by cryptochromes as well as UVR8 photoreceptors, while the epidermal anthocyanin content was mostly influenced by blue light via cryptochromes. After high light treatment, Fv/Fm was enhanced in plants that had previously been grown under both UV-B radiation and blue light. This suggests that both these regions could acts as spectral cues playing a key role in photoprotection under fluctuating light conditions in plants (Moriconi et al. 2018).

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Ecology

Understanding the role of photodegradation as a driver of litter decomposition in drylands now and in the future

Paul W. Barnes[1], Heather L. Throop[2], Steven R. Archer[3]

[1]*Department of Biological Sciences and Environment Program, Loyola University New Orleans, New Orleans, LA, USA*
[2]*School of Earth and Space Exploration and School of Life Sciences, Arizona State University, Tempe, AZ, USA*
[3]*School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA*

Decomposition of leaf litter is a key component of biogeochemical cycles but the mechanisms driving it in arid and semiarid ecosystems (drylands) remain unresolved. While a number of studies have demonstrated the importance of photodegradation (photochemical mineralization driven by ultraviolet and photosynthetically active radiation) in driving decomposition in drylands, how this process interacts with other determinants of decomposition (e.g., microbial decomposition and soil-litter mixing) and how these multiple drivers shift over time in response to ongoing changes in climate and land use remain poorly understood. Here we summarize findings from coordinated field and laboratory studies probing interactive effects of sunlight and soil-litter mixing on woody and herbaceous leaf litter decomposition. We use a generalized conceptual model to identify potentially important avenues by which changes in climate and land use could alter the relative importance of these interacting drivers and address some of the uncertainties and challenges associated with predicting future litter decomposition dynamics in these moisture-limited ecosystems.

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The effects of blue light and UV radiation on spring and autumn phenology in understorey seedlings of *Acer platanoides*

C.C. Brelsford[1], M. Trasser[1,2], T.M. Robson[1]

[1]*Viikki Plant Science Centre (ViPS), Faculty of Biological and Environmental Sciences, University of Helsinki, Finland.*
[2]*Biologie des Plantes, UFR, Université Montpellier, 34060 Montpellier, France*

Trees utilise multiple cues to time their bud burst and leaf out in spring, so that they can capitalise on favourable conditions for photosynthesis, and likewise time leaf senescence come autumn. Whilst the effects of temperature and photoperiod on phenology have been well studied, light quality is often not considered. The amount of blue light (400-500 nm), UV-A (315-400 nm), and UV-B (290-315 nm) reaching the ground changes with latitude, day length and the time of year, and yet little is known about how this affects plant phenology.
We hypothesised that these types of spectral changes may be exploited by plants via their blue and UV photoreceptors as cues for bud burst and leaf senescence. To this end, we monitored the leaf phenology of *Acer platanoides* seedlings under forest stands in southern Finland over two years, growing under filter treatments attenuating either UV radiation below 350 nm, all UV radiation, or blue and UV radiation, along with a filter transparent to the full solar spectrum.
The attenuation of radiation below 350 nm delayed bud burst by 4 days and leaf senescence by 9 days; whereas the attenuation of blue light in addition to UV radiation delayed bud burst by 7 days and leaf senescence by 15 days.
This result suggests that these short-wavelength regions of solar radiation can have a cumulative effect hastening leaf phenological stages. In nature, large seasonal changes in these regions may be perceived as cues for phenology interacting with red and far-red light, and other environmental factors known to mediate leaf development and senescence. By understanding which photoreceptors interact to trigger these responses we hope to improve future models of the environmental control of phenological events in trees.

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Saxifraga hostii response to modified UV-B regime at two altitudes in the Julian Alps

Tadeja Trošt Sedej, Tina Erznožnik, Jerneja Rovtar

University of Ljubljana, BF, Dept. of Biology, Večna pot 111, SI-1000 Ljubljana, Slovenia

Alpine plants have evolved strategies to survive harsh conditions prevailing at high altitudes, including high ultraviolet (UV) and visible radiation, extreme temperatures, dryness, lack of nutrients and strong winds.

The present field experiment researched UV-B effect combined with other environmental factors at the alpine plants, which evolutionary adopted variable morphological and physiological mechanisms to survive the alpine climate. The alpine plants *Saxifraga hostii* Tausch subsp. *hostii* were exposed to environmental UV-B and reduced UV-B radiation levels at two different altitudes (1000 m a.s.l. and 1400 m a.s.l.) in the Julian Alps. Chosen morphological (specific leaf area, palisade and spongy mesophyll thickness, epidermis thickness and stomata features) optical (leaf transmittance, reflectance), biochemical (chlorophyll a and b, carotene, anthocyanin, UV absorbing compounds content) and physiological (photochemical efficiency Fv/Fm, Y, transpiration) features of the plant were investigated three times during the growing season.

UV-B radiation plays an important role in providing tolerance to harsh alpine environments in interaction with other environmental factors and is hypothesised to induce biochemical, morphological and physiological responses of the plants.

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Photodegradation of the plant cuticle increases biological decomposition by facilitating uptake of non-rainfall moisture

J. Robert Logan[1], Kathryn M. Jacobson[2], Peter J. Jacobson[2], Paul Barnes[3], Sarah E. Evans[1]

[1]*W. K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, USA*
[2]*Biology Department, Grinnell College, Grinnell, IA, USA*
[3]*Departmen of Biological Sciences, Loyola University New Orleans, New Orleans, LA, USA*

To date, most photodegradation studies have focused on sunlight's role in accelerating decomposition by degrading biologically recalcitrant compounds or slowing decomposition by directly inhibiting microbial growth. We propose a physical mechanism by which photodegradation of the water-repellant cuticle increases litter's ability to absorb atmospheric water, facilitating subsequent biological decomposition. We studied this mechanism in the hyperarid Namib Desert, which experiences high annual UV and large inputs of non-rainfall moisture in the form of fog and dew. Field observations showed enhanced cuticle degradation and coincident fungal growth on the sun-facing side of *in situ* standing grass litter. Artificial removal of the cuticle from grass stems accelerated mass loss by 400% over 6 months relative to controls with intact cuticles. Furthermore, results from the first 18 months of an ongoing field experiment show enhanced decomposition under high UV and an unusual pattern of *increasing* rates of mass loss over time, coinciding with an increasing capacity to absorb water. This process is likely to be important in systems with large proportions of standing dead litter, high sunlight, and non-rainfall moisture, which includes many arid and semi-arid grasslands.

UV and blue light enhance tree litter decomposition in a temperate forest by accelerating the decomposition rate

M. Pieristè[1,2*], M. Chauvat[2], T. Kotilainen[1], A.G. Jones[3], M. Aubert[2], M.T. Robson[1], E. Forey[2]

[1]*University of Helsinki, P.O. Box 65 (Viikinkaari1), 00014 Helsinki, Fi,*
[2]*Université de Rouen, 44 Place Emile Blondel, 76821 Mont Saint Aignan cedex, F*
[3]*Earthwatch Institute, Mayfield House, 256 Banbury Road, Oxford, OX2 7DE, UK*

Sunlight is one of the main environmental factors driving the decomposition of plant litter (Gallo et al. 2009), and, alongside warm temperatures and high humidity, can accelerate the decomposition process by the direct breakdown of organic matter through photodegradation (Almagro et al. 2015). This process is mainly driven by radiation at the high-energy short-wavelength end of the solar spectrum (UV radiation and blue light). Although this process is widely studied in arid environments, few studies have been carried out in temperate environments (Ballaré, Austin, 2017). The present study aims to test how solar radiation, and particularly UV-B, UV-A, and blue light, affects decomposition of leaf litter from different tree species under a temperate forest canopy. Litter mass loss and C:N of three species: European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*), differing in their leaf traits and consequently decomposition rate were analysed over a period of 7-10 months in litterbags made using filters that attenuated different regions of the solar spectrum. We expected less mass loss when UV and blue light were excluded, and a lower C content in leaf-litter from the full-spectrum treatment due to photodegradation by UV and blue light. Over the entire period, mass loss was smallest in the absence of UV radiation and blue light, similarly to that in the dark treatment, and this litter had a low C:N ratio compared with litter exposed to the full spectrum treatment. Moreover, the filter treatment had a greater effect on decomposition than the biotic community composition as controlled through mesh size. Litter from the three species responded differently to the filter treatments, suggesting the effect to depend on litter quality and especially on the initial C:N, known to affect decomposition rate (King et al., 2012). Knowing the role that UV-mediated photodegradation plays in decomposition is crucial to estimating the contribution of temperate forests to carbon cycling under a scenario of climate change whereby poleward range shifts by temperate tree species will expose them to novel combinations of temperature, day length and solar spectral irradiance. This study shows that even under the reduced irradiance found in the understorey of a temperate forest UV radiation remains important in accelerating litter decomposition, increasing mass loss and C released into the atmosphere. Blue light was also revealed to make an important contribution to these decomposition processes alongside UV radiation.

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How does the snow-pack moderate UV-screening and spring recovery photosynthetic capacity in *Vaccinium vitis-idaea* leaves?

T. Solanki[1*], S. Neimane[2], S.M. Hartikainen[1], P.J. Aphalo[1], J. Albert Porcar-Castell[3], J. Atherton[3], A. Heikkila[4], T.M. Robson[1]

[1]*Viikki Plant Science Centre (ViPS), Faculty of Biological and Environmental Science, 00014, University of Helsinki, Finland*
[2]*Dept. Plant Physiology, University of Latvia, LV-1004, Riga, Latvia*
[3]*Viikki Plant Science Centre (ViPS), Faculty of Agriculture and Forestry, 00014, University of Helsinki, Finland.*
[4]*Finnish Meteorological Institute, 00101 Helsinki Finland.*

At high northern latitudes in the boreal forest, winter precipitation in the form of snow has decreased and is predicted to continue to do so in the future (Jylhä et al. 2008). Reduced snow cover exposes plants to temperature fluctuations at may delay the spring recovery of photosynthesis. Such a change has potentially negative consequences for net annual carbon assimilation. Plants employ several photoprotective mechanisms against photoinhibition, and can adjusting their UV-screening to acclimate to the sunlight they receive (Adams et al. 2004). However, above the snow unstable temperatures and high light can still cause photodamage (Loik et al. 2004). Here, we aimed to test the importance of exposure to sunlight and fluctuating temperatures for leaves at different heights on hummocks of *Vaccinium vitis-idaea* (an evergreen shrub) growing in central Finland. We monitored the optical properties of these leaves during the winter and subsequent spring recovery. The leaves that were exposed above the snow all winter maintained higher epidermal UV-screening than those that remained under the snow, although these values converged in late May following snow melt. The photosynthetic capacity of leaves, measured as the quantum yield of photosystem II (F_v/F_m), revealed a strong vertical gradient in photoinhibition which was highest the upper-hummock leaves and lowest in leaves that were under the snow through early spring. This study reaffirms that seasonal changes in snow cover and temperature are important in regulating photosynthetic capacity, but we also show that those phenolics involved in UV-screening and as antioxidants, accumulate in leaves that receive more winter irradiance. These phenolic compounds may function to mitigate some of the detrimental effects on photosynthesis of concomitant high light and low temperatures above the snow pack during winter.

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Assessing scale-wise similarity of curves with a thick pen: as illustrated through comparisons of spectral irradiance

S.M. Hartikainen[1], A. Jach[2], A. Grané[3], T.M. Robson[1]

[1]*Viikki Plant Science Centre (ViPS), Faculty of Biological and Environmental Science, 00014, University of Helsinki, Finland;*
[2]*Department of Finance and Statistics, Hanken School of Economics, PB 479, Helsinki, Finland;*
[3]*Department of Statistics, Universidad Carlos III de Madrid, C/ Madrid, 126, Getafe, Spain*

Forest canopies create dynamic light environments in their understorey, where spectral composition changes among patterns of shade and sunflecks, and through the seasons with canopy phenology and sun angle. Plants use spectral composition to adjust their growth strategy for optimal resource use. Quantifying the ever-changing nature of the light environment is technically challenging with respect to data collection because of the simultaneous variation occurring in multiple regions across the spectrum of solar radiation. It is also methodologically challenging to analyse the full-spectrum because of signal complexity and multivariate comparisons. To address these issues, we collected simultaneously-measured spectral irradiance from forest understoreys over a wide wavelength range (300-800 nm) using an array spectroradiometer. To analyse and compare spectra, taking into account their multi-scale nature and multivariate lay-out, we used a novel method of Fryzlewicz and Oh (2011) termed thick pen transform, which is simple and visually-interpretable. With help of thick pen transform and thick pen measure of association, we found that sunlight position in the forest understorey (shade, semi-shade, sunfleck) was the most important factor in determining shape-similarity of spectral irradiance. Likewise, the contributions of stand identity and time of year could be identified. Spectra recorded in sunflecks were consistently the most similar, irrespective of differences in their maximum value. In average terms, the degree of cross-dependence increased with increasing scale, sometimes shifting from negative (dissimilar) to positive (similar) values, and often with different rates of change. We conclude that the interplay of sunlight position, stand identity and date, as well as scale, should not be ignored when quantifying and comparing spectral composition in the forest understorey. Technological advances mean that array spectroradiometers, which can collect large amounts of data in very short time are being widely-adopted, not only to measure irradiance under pollution, clouds, atmospheric changes, and in biological systems, but also spectral changes at small scales in the photonics industry. We consider that TPT and TPMA are methods applicable for spectral analysis in any field and can be a useful tool to analyse large datasets.

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Altitude effect on the content of UV-B absorbing compounds in pollen grains of *Pinus* spp.

Daniela Festi[1], Marc Macias-Fauria[2], Alistair Seddon[3]

[1]Institute of Botany, University of Innsbruck, Sternwartestr. 15, A-6020 Innsbruck, AUT
[2]Oxford University Centre for the Environment, South Parks Road, OX1 3QY Oxford, UK
[3]Department of Biological Sciences, University of Bergen, Postboks 7803, 5020 Bergen, NO

UV-B absorbing compounds, such as para-Coumaric Acid (pCA), contained in the sporopollenin of pollen grains have been proposed as a next generation proxy to infer past UV-B radiation. However, current understanding of the drivers of their modern variability in pollen is still limited and needs to be tested if these molecules are to be applied in palaeoecological reconstructions of UV-B irradiance.
Our study aims to improve the current knowledge on the modern relationship linking UV-B radiation and pCA stored in pollen grains, by measuring the pCA content of Pinus spp. pollen collected along two altitudinal transects in the Austrian Alps and Spanish Pyrenees. We anticipate that the amount of pCA in the sporopollenin will increase in line with conciment increases of UV-B with altitude. Pollen grains were collected directly from the trees during dehiscence, their content in pCA was analysed by THM-GC/MS following the methodology by Seddon et al (2017). To enable the establishment of a quantitative UV-B – pCA relationship, UV-B radiation has been monitored from March to October by sensors located at different altitudes along both mountain locations. In this contribution the first results from the Pyrenees and the Alps are presented and discussed.

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Evolutionary aspects

Was UV radiation tolerance the key evolutionary factor allowing plants to colonize land?

Javier Martínez-Abaigar

Facultad de Ciencia y Tecnología, Universidad de La Rioja, Madre de Dios 53, 26006 Logroño (La Rioja), Spain

In a specific moment of evolution, the aquatic organisms colonized land. A number of different evolutionary lineages played important roles in this process, including not only chlorophyllose organisms but also several groups of fungi. Which were the key factors allowing the water-to-land transition? And, in particular, what was the role of the tolerance to UV radiation, whose levels were noticeably higher in the terrestrial than in the primeval aquatic environment? Each evolutionary group of organisms could have developed specific adaptive strategies to enhanced UV, for example the accumulation of characteristic protective compounds, which could be accumulated in different cell compartments depending on their preferential role as UV screens or antioxidants. Nevertheless, the UV-B molecular receptor UVR8 is highly conserved from the basal lineages of green algae to seed plants. Thus, it is plausible to think that other evolutionary pressures, such as water deficit, were stronger than enhanced UV in land colonization. In this context, UV adaptations could have modulated the different adaptations of the organisms to water shortage, given that there exist common physiological mechanisms between UV tolerance and desiccation tolerance.

Photoreactivation in green macroalgae

Frauke Pescheck, Wolfgang Bilger

Botanical Institute, Christian Albrechts University Kiel, Am Botanischen Garten 5, 24118 Kiel, GER

In contrast to higher plants most green macroalgae do not employ UVB screening by pigments to protect themselves against UVB-induced cellular damages. However, this seems to be no disadvantage for them as representatives of non-UVB screening green algae, like *Ulva intestinalis*, can be found as major components of the eulittoral community populating highly irradiated habitats.
Interestingly, we found that *in situ* almost no UVB-induced DNA damage accumulates over a summer day in *U. intestinalis*. This strongly suggests that repair of UVB-induced DNA dimers, especially by photoreactivation, should be of great efficiency in non UVB screening green macroalgae.
To test this we compared the DNA repair rate of *U. intestinalis* to that of *Cladophora* sp. which is a UVB screening green macroalga. We determined the rate coefficients of photoreactivation and dark repair at different light quality and quantity. From spectral transmittance of both algae and the *in vivo* action spectrum of photoreactivation we calculated the species-specific biologically effective photoreactivating irradiance, i.e. the internal UVA, present in sunlight and compared it to the DNA damaging irradiance.
With respect to incident UVA *Ulva* proved to repair faster but not with respect to internal UVA.

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Plant invasions in high UV-B environments - Evidence for local adaptation of exotic species in New Zealand?

Maria Hock[1,2], Rainer W. Hofmann[3], Caroline Müller[4], Alexandra Erfmeier[1,5]

[1]Kiel University, Institute for Ecosystem Research / Geobotany, Olshausenstr. 75, 24118 Kiel, DEU
[2]Martin Luther University Halle-Wittenberg, Institute of Biology / Geobotany and Botanical Garden, Am Kirchtor 1, 06108 Halle, DEU
[3]Lincoln University, Faculty of Agriculture and Life Sciences, Ellesmere Junction Road/Springs Road, Lincoln 7647, NZL
[4]Bielefeld University, Faculty of Biology/Chemical Ecology, Universitätsstraße 25, 33615 Bielefeld, DEU
[5]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5E, 04103 Leipzig, DEU

UV-B radiation intensity is higher in the southern hemisphere than in the northern hemisphere and may thus act as an environmental filter for colonizing species, particularly for non-indigenous plants from Europe in New Zealand. Successful plant invaders can cope with novel environmental constraints in the invaded range via plastic responses or via rapid adaptation to local selection factors.

We conducted a multi-species experiment in two common gardens each in the native and invaded range. In Germany and New Zealand, respectively, we included native and exotic origins of eight species to test for adaptation to higher UV-B radiation in the invaded range. In each common garden, plants were exposed to three radiation treatments: a) natural sunlight, b) exclusion of UV-B while transmitting UV-A, and c) exclusion of UV-B and UV-A.

We found an overall limiting effect of UV-B in both common gardens that hints at a more pronounced UV response in the invaded range. Consistently for both experiments, the respective 'home origin' displayed both enhanced productivity and aboveground biomass allocation, thus providing evidence for recent evolutionary processes in the invaded range The results support the hypothesis that UV-B might be considered a selection factor in plant invasions.

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Maternal effect of solar UV modified the responses to UV-B and blue light in *Vicia faba*

Yan Yan[1], Susanne Neugart[2], Frederick L. Stoddard[3], Pedro J. Aphalo[1]

[1]*University of Helsinki, ViPS, University of Helsinki, FI*
[2]*Leibniz-Institute of Vegetable and Ornamental Crops, Großbeeren, DE*
[3]*Department of Agricultural Sciences and ViPS, University of Helsinki, FI*

Our research aims to assess the maternal effect of solar UV and its effects on plant responses to UV-B and blue light at the physiological and molecular levels. Here, we used two accessions of faba bean (*Vicia faba* L.), accession ILB938 from high altitude in Ecuador, where UV radiation is strong, and cultivar Aurora from Sweden, where UV level is low. Mother plants were grown outdoors under filters that attenuate short UV (wavelength below 350nm) or are transparent to sunlight. The harvested seeds were then sown in growth chambers with UV-B and blue light treatments.
The stomatal response to UV-B was different in the two accessions. UV decreased stomatal conductance in Aurora ($P < 0.001$). In ILB938, however, the UV effect depended on the presence of blue light: without blue light, UV induced stomatal closure, but when blue was present, UV did not affect stomatal conductance.
In Aurora, solar UV had a maternal effect on plant growth responses to UV-B radiation when blue was absent: UV-B decreased leaf and stem dry weights of plants whose mother generation had been exposed to short UV ($+UV_{offspring}$), while UV-B had no significant effect on the descendants of non-UV-treated plants ($-UV_{offspring}$). In Aurora $+UV_{offspring}$ plants, the UV-B effect on leaf dry weight depended on the presence of blue light: UV-B decreased leaf dry weight when blue was absent and it induced leaf growth when blue was present. Stem dry weight inhibition by UV-B was stronger when blue light was absent.
In ILB938, maternal solar UV modified plant growth response to blue light. Blue light increased height in $+UV_{offspring}$ plants, but it decreased plant height in $-UV_{offspring}$ plants. Blue light increased leaf dry weight significantly in $+UV_{offspring}$ plants while it did not affect - $UV_{offspring}$ plants.
Flavonoids were analysed using HPLC-MS. Quercetins were more abundant in both cultivars than kaempferols. UV-B and blue light significantly increased quercetin concentration. The presence of blue light strengthened UV-B induction of quercetin accumulation. The maternal effect of solar UV led to a significantly stronger induction effect of UV-B light on quercetin accumulation. Total flavonoids concentration was higher in Aurora, while ILB938 had higher phenolic acid concentration.
Our study shows that solar UV can have maternal effects on multiple plant responses to blue and UV-B light radiation, and these depend on the genotype.

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Application of knowledge

UV-A and UV-B radiation differentially regulate morphological features, flavonoid content, phenylpropanoid biosynthesis gene expression, and yield in cucumber (*Cucumis sativus* L.)

Minjie Qian[1], Irina Kalbina[1], Eva Rosenqvist[2], Marcel A.K. Jansen[3], Åke Strid[1]

[1]School of Science and Technology, Örebro University, SE-70182 Örebro, Sweden
[2]Section of Crop Sciences, Department of Plant and Environmental Sciences, Copenhagen University, Højbakkegård Allé 9, DK-2630 Taastrup, Denmark
[3]School of Biological, Earth and Environmental Sciences Butler Building, University College Cork, Distillery Field, North Mall, Cork, Ireland

Two cucumber cultivars, greenhouse cv. 'Hi Jack' and outdoor cv. 'Masterpiece,' were exposed to 4h UV-A or UV-B daily for 14 days to study the effect of UV on plant growth. UV-B exposure led to smaller plants of both cultivars with regards to almost all parameters measured, including internode and petiole length, leaf area, and plant dry weight. UV-A exposure also led to smaller plants (shorter internodes and petioles, smaller leaf), albeit to a much smaller extent than for UV-B exposed plants. Leaf thickness was increased in UV-A-treated plants of both cultivars, whereas plant dry weight, and stem sturdiness only increased in 'Hi Jack'. UV-A led to increased flavonoid content in both cultivars, while UV-B only induced flavonoid accumulation in 'Masterpiece'. For phenylpropanoid biosynthesis genes, expression of *PAL4*, *PAL10*, and *CHS2* was induced by both UV-A and UV-B. To test the effect of UV treatment on fruit yield, plants were transported into a full-size greenhouse for growth under normal cucumber production conditions following 14 days of UV exposure. Neither UV-A nor UV-B exposure had any significant effect on either fruit number or fruit fresh weight compared with control plants. Thus, UV can be exploited as a tool to create sturdy, compact seedlings that can survive transport.

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Biochemical and molecular insights in UV-B-driven changes in phenolics profile of peach fruit

M. Santin[1], L. Lucini[2], A. Castagna[1], G. Rocchetti[2], M-T. Hauser[3], A. Ranieri[1,4]

[1]Department of Agriculture, Food and Environment, University of Pisa, via del Borghetto 80, 56124 Pisa, I
[2]Department for Sustainable Food Process, Università Cattolica del Sacro Cuore, Via Emilia Parmense, 84, 29122 Piacenza, I
[3]Department of Applied Genetics and Cell Biology, University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Vienna, A
[4]Interdepartmental Research Center Nutrafood ''Nutraceuticals and Food for Health'', University of Pisa, Via del Borghetto 80, 56124 Pisa, I

UV-B radiation as a post-harvest tool to increase health-promoting value of plant food has been widely studied in recent years. The UV-B-induced modulation of antioxidant compounds is species- and cultivar-dependent, and it varies according to duration and intensity of the UV-B exposure. In light of above, this work aimed to investigate how post-harvest UV-B treatments altered the phenolic profile of peach fruit, in terms of phenolic subclasses and specific compounds with particular attention to the esterification with different sugars, mainly referring to anthocyanins and flavonols. Melting flesh yellow peaches (*Prunus persica L.*, cv. Fairtime) were treated with 10 or 60 min of UV-B radiation (2.31 W m^{-2}), then fruit were kept at room temperature under white light, and skin was sampled after 24 or 36 h. Flavonoids were identified by UHPLC-ESI/QTOF-MS analysis.
UV-B exposure determined a general decrease of flavonoid compounds after 24 h in UV-B-treated samples, maybe due to their reaction with UV-B-induced ROS. However, after 36 h, a higher accumulation of most compounds was detected, more evident in the 60 min-treated fruit. Indeed, RT-PCR revealed that transcription of *CHS*, *CHI*, *F3H* and *F3'H* increased, as well as some regulatory and UVR8 pathway-related genes.

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Using UV light to control mildew in commercial horticulture crops (UV Robot)

Phillip Davis

Stockbridge Technology Centre, Cawood, Selby, North Yorkshire, YO8 3TZ, UK

We will provide an introduction to a new 4 year NWE INTERREG funded project titled UV Robot. Horticultural experts in Belgium and the UK together with Belgian expertise in automation and French expertise in data analyses will jointly develop innovative robots that can autonomously apply UV treatments in commercial glasshouses. The project will have three major focuses 1) develop a robot to automate UV applications in glasshouses, 2) refine the dose and timing of UV applications for real world control of mildew and 3) to develop strategies for including UV treatments in wider Integrated Pest Management programs. Our work will develop UV disease control strategies for five important crops strawberry, tomato, cucumber, lettuce and basil. The overall aim of the project will be to reduce our reliance on intense pesticide use for control of mildew and to reduce pesticide residues in fresh produce. At the end of the project the developed robots will be available for growers with a user-friendly interface and a crop specific implementation strategy. Demonstration across the NWE region and extensive communication during and after the project will inform growers to ensure innovation roll-out. Pesticide use and spray residues on harvested produce will decrease drastically in the NWE region.

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Light quality characterization under climate screens and shade nets for controlled environment agriculture

T. Kotilainen[1*], R. Hernández[2], T.M. Robson[1]

[1] *University of Helsinki, Viikinkaari 1, 00790 Helsinki, FI*
[2] *North Carolina State University, 2721 Founders Drive, 27695 Raleigh, NC, USA*

Most studies of screens and nets used in horticultural applications consider only the reduction in total irradiance that they cause and not how they affect spectral composition, despite that the few studies examining the spectral composition generally reveal large differences in the transmitted spectral irradiance (e.g. Arthurs et al. 2013; Kitta et al. 2014).

We recorded the spectral composition of irradiance and calculated spectral photon ratios under a variety of climate screens and shade nets commonly used in horticulture. Some climate screens entirely attenuate UVB and most of UVA radiation, whilst in general not drastically altering spectral transmittance for other wavebands. Ratios calculated from spectral irradiance measured under the shade nets showed clearly the strong effect of the net colour; blue, amber and green coloured nets create light conditions that deviate more from the outdoors values compared with black and brown nets.

There is a need for standardized methods to report and compare materials used in horticultural applications (Castronuovo et al. 2017). Manufacturers, growers, horticultural consultants and researchers alike would benefit from the availability of detailed information when selecting the most appropriate materials for climate screens and shade nets.

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Evaluation of different clones of grapevine regarding local meteorological conditions

Tjaša Jug[1], Andreja Škvarč[1], Ivan Žežlina[1], Denis Rusjan[2]

[1] Chamber for Agriculture of Slovenia, Unit Nova Gorica, Pri hrastu 18, 5000 Nova Gorica, SLO
[2]Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, SLO

Clonal selection is a crucial procedure for achieving a suitable grape to produce high quality wine. Grape quality of Slovenian clones was monitored during ripening between 2012 - 2017. Grape quality parameters were correlated with the minimal, maximal and average daily solar irradiation in vine growing season obtained by a meteorological station.
There was a strong correlation (r >0.89) between solar irradiation and yield per vine in all clones, except for 'Malvazija' (r = 0.60). A strong correlation (r>0.74) was obtained from all studied clones for their contents of total soluble solids and minimal daily solar irradiation. Whereas the content of glucose+fructose of 'Zelen', 'Pinela', 'Refošk' and 'Malvazija' grapes was better correlated with minimum irradiation r>0.91. On the other hand, the yeast assailable nitrogen (YAN) at 'Zelen', 'Rebula' and 'Malvazija' was very strongly correlated with solar irradiation, but 'Refošk' and 'Barbera' only correlated with minimum solar irradiation, while 'Pinela' was not strongly correlated with solar irradiance at all.
We can conclude that the known response to solar irradiance could be a useful tool for a varietal characterization under local climate conditions, especially in the near future when more extreme meteorological conditions are expected.

Post-harvest UV-B radiation and peach fruit metabolites. More complex than expected

M. Santin[1], L. Lucini[2], A. Castagna[1], G. Chiodelli[2], M-T. Hauser[3], A. Ranieri[1,4]

[1]Department of Agriculture, Food and Environment, University of Pisa, via del Borghetto 80, 56124 Pisa, I
[2]Department for Sustainable Food Process, Università Cattolica del Sacro Cuore, Via Emilia Parmense, 84, 29122 Piacenza, I
[3]Department of Applied Genetics and Cell Biology, University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Vienna, A
[4]Interdepartmental Research Center Nutrafood ''Nutraceuticals and Food for Health'', University of Pisa, Via del Borghetto 80, 56124 Pisa, I

The possibility to modify the metabolic profile of plants and fruit using eco-friendly tools, rather than transgenic approaches, gained interest in the last decades. Due to its ability to stimulate the transcription of specific phenylpropanoid genes, UV-B radiation represents a good candidate to achieve this goal. However, few studies have been conducted so far on the effects of post-harvest UV-B treatments on fruit metabolomics.
Based on these considerations, melting flesh yellow peaches (*Prunus persica L.,* cv. Fairtime) were exposed to UV-B radiation (2.31 W m^{-2}) for 10 and 60 min and then skin was sampled at two different recovering times, 24 and 36 h. Through UHPLC-ESI/QTOF-MS followed by PLS-DA and Volcano analysis, we observed a general decrease of phenolics, especially anthocyanins, flavones and dihydroflavonols, after 24 h. However, after 36 h, a general increase was detected, particularly for the three subclasses mentioned, suggesting active transcription of biosynthetic genes after an initial phenolic consumption to counteract the potentially disruptive effects of UV-B radiation. Moreover, other metabolic classes, such as terpenoids, alkaloids and lipids, were affected by UV-B as well, with different variations according to each class.

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Towards the development of a Holocene proxy for UV-B radiation using *Pinus* spp. pollen grains

Alistair Seddon[1,2]

[1]*Department for Biological Sciences, University of Bergen, Norway*
[2]*Bjerknes Centre for Climate Research, University of Bergen, Norway*

Incoming ultraviolet radiation (UV-B) has experienced large changes throughout Earth's history with major consequences for biodiversity and ecosystem functioning, but reconstructing past UV-B on millennial timescales or longer remains a major challenge. It has been suggested that UV-B absorbing compounds found within the sporopollenin of pollen exines (e.g. *p*-Coumaric acid) are enriched in high UV-B environments. Studies have proposed that variations of these compounds in fossil-pollen could be used for reconstructing UV-B over thousands of years. However, although more palaeoecologists are becoming interested in the potential use of pollen-chemistry approaches, so far the majority of palaeo-UV-B studies have used correlative methods to determine the pollen response. Here, I present a new research strategy related to the future the development of this proxy designed for use on *Pinus* spp. pollen. The strategy uses techniques borrowed from experimental UV-B ecological research and aims to improve both methodology and fundamental ecological understanding. It does this by addressing three challenges related to (i) analytical precision; (ii) uncertainty characterisation, and (iii) understanding the dose-response relationship between pollen chemistry and UV-B.

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Author index

Index

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