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Effects of natural solar UV-B radiation on three Arabidopsis accessions are strongly affected by seasonal weather conditions

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Abstract

Large numbers of studies have reported on the responses of plants that are exposed to a specific dose of ultraviolet-B (UV-B) radiation. However, in the natural environment UV-B is a highly dynamic variable with UV-B intensities depending on, amongst others, geographic, temporal, weather and climatic factors. Furthermore, UV-B effects on plants can potentially be modulated by other environmental variables, and *vice versa*. This study aimed to characterise UV-B effects on plant morphology and accumulation of UV-screening pigments within the context of an oceanic climate and to assess the potential seasonality of plant UV-B responses. *Arabidopsis thaliana* was grown outdoors under UV-blocking or transmitting filters. Genotypic differences in the adaptive response to UV-B were assessed at seven time-points over a 12 month period and involved the Arabidopsis accessions Ler, Col-0, and Bur-0. Strong seasonal effects were found on rosette morphology and total UV-screening pigment concentrations across the three accessions. Low temperatures were the main determinant of accumulation of UV-absorbing pigments, with no clear UV-B effect observed at any time throughout the year. There was a significant UV effect on morphology during the summer months, and this was most likely associated with stress. This study shows that UV-effects need to be analysed in the context of weather, and other co-occurring natural factors, and emphasizes the importance of a holistic, multifactorial approach for the investigation of environmentally relevant UV-effects

Keywords

Arabidopsis, Morphology, Photosynthesis, Ultraviolet radiation, UV-screening pigments, Weather.

Introduction

UV wavelengths (UV-B 280-315 nm; UV-A 315-400 nm) are only a minor component of the solar spectrum in the biosphere. Yet, these wavelengths can have a disproportionate effect on living organisms due to their energetic nature. There is an extensive body of literature on the potentially harmful effects of high levels of UV-B radiation on a broad range of organisms (Teramura and Sullivan, 1994; Rozema et al., 1997; Jansen et al., 1998). In plants, UV-B can negatively affect several targets, including genetic material and the photosynthetic machinery, triggering production of ROS and impairment of cellular processes. In parallel, UV-B induces expression of protective responses, including enhanced photorepair capacity, accumulation of UV-screening pigments and increases in total antioxidant capacity (Strid et al., 1994; Jansen et al., 1998; Morales et al., 2010). UV-B also induces morphological changes in plants, although it is not fully understood if and how these contribute to plant UV-B protection (Robson et al., 2015). The UV-B photoreceptor UVR8 plays a major role in controlling the plant UV-B response, and UVR8 mediated responses can already be observed under very low UV-B intensities (Brown et al., 2005; Brown and Jenkins 2008; Jenkins et al., 2014). As a result of the expression of protective responses under low UV-intensities, plants exposed to ambient levels of UV-B rarely display signs of distress (Searles et al., 2001; Ballaré et al., 2011; Jansen et al., 2012).

Much of what is known about plant UV-B responses comes from indoor studies whereby plants are daily exposed for a set number of hours to a standardised intensity of UV-B. In reality, UV-B is a fluctuating environmental variable, the intensities of which can vary dramatically across multiple timescales. On a daily basis, UV-B intensities vary in a predictable manner with the solar angle, but also in a much less predictable manner depending on factors such as cloud cover, albedo, and air pollution (Madronich et al., 1998; Calbó et al., 2005; Barnes et al., 2017). On a seasonal basis there are similar predictable and less predictable fluctuations in UV-B intensities, depending on geographic, climate and weather factors. This discrepancy between UV-B exposure in laboratory and natural conditions makes it difficult to compare and extrapolate data between the two experimental approaches. Indeed it is frequently found that results from indoor and outdoor experiments differ significantly from each other.

An additional factor that complicates the comparison of indoor and outdoor studies is that plants under outdoor conditions are simultaneously exposed to a broad range of environmental factors, which may act as stressors and/or signals. Some of these factors induce plant responses independently from UV-B, while others trigger interactive effects with UV-B radiation (Bornman et al., 2015). In principle, the responses driven by different environmental factors can be synergistic, additive or antagonistic (See editorial). For example, UV-B radiation has been shown to impede plant thermomorphogenesis in a UVR8 dependent manner (Hayes et al., 2017), and this can potentially contribute to increased sensitivity to high temperatures. Conversely, UV-B radiation induces production of a range of volatile isoprenes which have been associated with heat tolerance (Liu et al., 2017). Thus, interactions between the responses to UV-B and other environmental variables can be complex. This is also the message that arises from studies on the interaction between UV-B and drought. In some studies it was found that UV-B can diminish the negative effects of drought exposure (Kovacs et al., 2014; Robson et al., 2015;), while in another study it was found that exposure to UV-B and drought synergistically enhanced negative effects on photosynthesis (Doupis et al., 2016). A better understanding of how UV-B can alter plant responses to other environmental variables, and *vice versa*, is important to fully appreciate the

ecological role of UV-B radiation. Furthermore, a better understanding of interactions between UV-B and global climate change factors (e.g. extreme temperatures, drought, elevated CO_2) is critical for climate change predictions (Bornman et al., 2015).

A third factor that is not commonly considered when studying plant UV-responses is within species genetic variation. The ability of plants to adapt to local geographical and climatic conditions is an important selective force which has led to within species genetic variation (Shindo et al., 2007). Adaptations to local conditions have led to ecologically specialized accessions with optimised performance in a given region. As an example, *Arabidopsis thaliana* shows considerable genotypic and phenotypic variation, including different degrees of tolerance to stressors such as salinity, drought and extreme temperatures (Koornneef et al., 2004). Arabidopsis has a wide distribution, including Europe, Asia, north America and Africa. Across its natural distribution area there is significant variation in the intensity of UV-B experienced at ground level, depending on latitude and altitude (Liley & Mckenzie, 2006). Substantial differences in protection of photosystem II of photosynthesis amongst UV-exposed Arabidopsis accessions were reported by Jansen et al., (2010). Cooley et al., (2001) detailed differences in morphological responses to UV-B by different accessions. Significant understanding of the ecological role of UV-B radiation can be gained from studies of natural accessions. However, at present there is insufficient information about the behavior of such accessions under ambient UV-B conditions.

In this study we have explored effects of UV-B on plant morphology and UV-screening pigments across an entire calendar year under outdoor conditions. Specifically, we assessed the role of seasonality on plant UV-B responses. It was hypothesised that UV-B effects will be substantially modulated by other environmental factors. Furthermore, UV-responses of *Arabidopsis thaliana* accessions Ler and Col-0 were compared with those by a local accession, Bur-0, to identify differential adaptation to UV-B.

Materials and Methods

Plant Material

Seeds of three *Arabidopsis thaliana* accessions were kindly donated by Prof. Koornneef (Wageningen University, The Netherlands and MPIZ, Cologne, Germany), and had been propagated for several generations under controlled conditions prior to use in the described experiments. Burren-0 (Bur-0) originates in the Burren in the west of Ireland. Columbia-0 (Col-0) and Landsberg erecta (Ler) are the two accessions of *Arabidopsis thaliana* most commonly used in research.

Seeds of *Arabidopsis thaliana* accessions Ler, Col-0 and Bur-0 were cold-treated for a minimum of seven days before being sown into trays containing sieved John Innes No.2 compost (J. Arthur Bowers, William Sinclair Horticulture Ltd., Firth Rd., Lincoln, LN6 7AH). The flats were covered with transparent film and kept at 21°C under a 16 hour light/ 8 hour dark photoperiod, with 60-80µmol m^{-2} s^{-1} PAR. The transparent film was taken off once a substantial number of seeds had germinated. The seedlings were pricked out into 200ml pots with John Innes No. 2 compost while still at the cotyledon stage (Fig. 1). When the seedlings had grown in to the 1.02 stage (Boyes et al., 2001) they were moved to a glasshouse and next to a cold frame to facilitate acclimation to natural weather conditions (Fig. 1). Plants were considered to be ready for experimental use at

the Boyes 1.04 stage. At the onset of this stage plants were transferred to outdoor conditions for a total of 10 days. This experimental approach was repeated seven times across the year, exposure to outdoor conditions taking place in January, February, May, July, September, October and November.

UV-exposure Conditions

A UV-filtration approach, using natural solar light, was used in order to manipulate UV-levels. Three distinct filtration treatments were used; (1) UV-A/B (exposure to visible light + UV-A + UV-B) using 95µm thickness UV transparent cellulose acetate filter (Kunststoff-Folien-Vertrieb GmbH, Hamburg, Germany); (2) UV-A (exposure to visible + UVA) using 125µm thickness UV-B blocking mylar filter (Polyester film, Tocana Ltd., Ballymount, Dublin, Ireland); (3) UV-0 (exposure to visible) using a UV opaque filter (poly-tunnel plastic, BPI Visqueen, Stevenston, U.K.). The cellulose acetate and mylar were changed after 20 days exposure to solar light to prevent changes of the light spectrum caused by degradation of the plastic. The transmission of the filters was routinely measured using a spectrophotometer (Shimadzu – UV visible spectrophotometer- 160A).

Boxes measuring 50cm x 50cm were assembled using opaque corri-board (See Coffey et al., 2017). The lids of these boxes comprised the filters that were positioned above the Arabidopsis plantlets. Each filtration treatment comprised four independent replicates. The boxes were randomly positioned at a sun exposed site in Cork, Ireland ($51^{o}53'58"N$ $8^{o}29'14"W$). The boxes were slightly angled to make possible air circulation with the northern edge of the frame raised above the ground. Four individual plants of each accession were placed in each box.

Plant parameters

After ten days of growth under outdoor conditions, both leaf and rosette morphology were quantified. Rosettes were first dissected and then immediately photographed for processing with ImageJ (Abramoff et al., 2004). Morphological parameters such as rosette diameter (mm), biomass (mg) and leaf area (mm^2) were all determined. The smallest leaves (defined as having a petiole of less than 2mm) were not included in analysis.

Total UV-absorbing pigments were extracted from leaf number four and normalized using the area of that specific leaf. Leaves, including the petioles were put in to micro-tubes with 1ml acidified methanol (1%HCL, 20%H_2O, 79% CH_3OH) and incubated in the dark at 4°C for four days. Absorbance was recorded at 330nm on a spectrophotometer (Shimadzu – UV visible spectrophotometer- 160A). Absorbance was normalized per leaf using leaf area.

Imaging chlorophyll *a* fluorometry (Imaging PAM Waltz, Germany) was used to determine the maximal quantum yield of photosystem (PS) II (Fv/Fm). Fv/Fm values were determined after plants had been grown for ten days under outdoor conditions under different filtration treatments. Whole rosettes were dark adapted for a minimum of 20 minutes before Fv/Fm was determined using an Imaging PAM (Waltz, Germany). Three measurements were taken at random from each rosette and pooled per rosette.

Statistical Analysis

Statistical relationships between plant growth responses and environmental variables such as temperature, hours of sunshine and global solar radiation and UV treatment, were tested using multiple regression analysis with IBM SPSS Statistics 21. As a first step, it was established that all data sets were suitable for regression analysis and that there was no violation of the assumption of linear multicollinearity and homoscedasticity. The meteorological data used for this study were obtained from Met Eireann (65/67 Glasnevin Hill, Dublin 9, D09 Y921). It was found that there was a high degree of correlation between the independent variables temperature, hours of sunshine and global solar radiation. For this reason, these variables were analysed in separate regressions.

To acquire a more comprehensive understanding of the influence of UV treatment under varying weather conditions (seasonality), the months of January and July were selected as case studies and analysed in more detail. Prior to such analysis, all data sets were assessed for normality. The biomass dataset was non-normal, and a square root transformation was applied prior to statistical analysis. All data were analysed statistically using parametric interaction ANOVAs, with multiple comparison test being carried out using Tukey's range test.

Results

Arabidopsis plants at the Boyes 1.04 growth stage were transferred to outdoor conditions where the plants were kept for 10 days. In all cases plants grew during the outdoor period, and this was seen as increases in the number of leaves, and rosette diameter.

The data on plant biomass, rosette diameter and leaf area (Fig. 2A, B, C, respectively) show that the rate of growth is season dependent. Plants in July and September display the greatest rosette diameter, leaf area and aboveground weight. Rosettes are smallest and weigh least in January. A similar seasonality patterns is revealed using chlorophyll *a* fluorometry, with Fv/Fm values as low as 0.65 in January, and greater than 0.80 in October. Concentrations of UV absorbing pigments displayed a distinctly different seasonal pattern (Fig. 3), with high concentrations of pigments measured in the winter, and in many cases some 3-4-fold lower concentration in summer.

To analyse these plant growth responses in the context of weather conditions, a full set of meteorological data were obtained from the Irish meteorological service (Met Eireann) to cover the period of the growth trials (details see Coffey et al., 2017). Temperatures during the trial period ranged between 3.1 and 15.6°C. Total hours of sunshine and UV-B doses ranged between 3 to 7 hours and between 1.18×10^6 to 2.58×10^7 J/m^2 per day, respectively. Monthly means of global solar radiation during the trial ranged between 6.46×10^7 and 5.7×10^8 J/m^2. The meteorological parameters temperature, global solar radiation, hours of sunshine and UV-B irradiance were all significantly correlated with each other. The correlation between the meteorological parameters means that they lack independence and have to be analysed in separate multiple regressions. The dependant variables were expressed as follows: Dependent variable = constant + (B1 x Temp) + (B2 x uv-a/b) + (B3 x uv-a). B1, 2 and 3 are slope coefficients of the independent variables, used to obtain the R^2 values, i.e. the percentage variation in the dependent variable which can be attributed to the independent variable. The significance of the relationship and thus the R^2 variable is determined by an F-test. The constant in a multiple

regression is the value of the dependent variable when all other variables are zero. As this scenario is outside the scope of the observed data, changes in the constant have not been analysed. Regression analysis of meteorological parameters versus the measured biological responses identified several significant correlations (R^2 values) (Table 1). Using temperature as the independent variable produced the highest R^2 values indicating that temperature is the strongest determinant of plant size and total UV absorbing pigment content (Table 1). Temperature accounted for between 49 and 74% of the variation in rosette diameter, leaf area, total UV absorbing pigments and Fv/Fm for Ler, Col-0 and Burren-0. Hours of sunshine accounted for between 7 and 41% of the variation in biological responses, while global solar radiation and UV-B irradiance contributed 15 – 49% and 9 - 37%, respectively (Table 1).

Graphs of rosette diameter as a function of temperature visualize the positive association between growth and temperature, as well as the relative lack of impact of genotype (Fig. 4A, B, C). Further exploration of the correlation between temperature and the biological responses included the UV filters as independent variables (Table 2). The UV-A/B and UV-A treatments were compared to the UV-0 treatment which acted as a control. This approach allowed for identification of the impact that the filters had on the fit of the regression, within the context of the seasonal trend, which was largely dominated by temperature. The slope in table 2 (Beta coefficient) indicates how much the dependant variable varies with each independent variable when all others are held at a constant. The part number squared describes the contribution that each independent variable makes to the total R^2, and thus to the variation in the dependant variable. From the Part No. Squared it is evident that temperature accounts for a large part of the R^2 value for all biological responses, but there is also evidence that the UV-A/B treatment contributes significantly to the regression (Table 2). Specifically, leaf area and rosette diameter are significantly affected by the UV-A/B treatment, in Ler, Col-0 and Bur-0 (Table 2). Between 3-7% of the variation in the R^2 value is accounted for by the UV-A/B treatment and the sign associated with these values indicates UV has a negative impact (Table 2). Thus, UV-B has a negative impact on the positive slope-values (Fig. 4A, B, C; Table 2) of the relationship between temperature and rosette diameter. The graphs of rosette diameter as a function of total, seasonal UV-dose (Fig. 4 D, E, F) show an overall positive relationship. This reflects the close association between seasonal fluctuation in UV and other growth promoting weather conditions. However, in this instance the, positive association is diminished by the actual UV-filtration treatment (Table 2). Thus, in both types of analysis the UV-A/B treatment has negative effect on leaf area and rosette diameter as indicated by the slope values (Table 2).

Across the yearlong study, and across all three accessions studied, there was no significant filter effect on photosynthetic efficiency measured as Fv/Fm (Table 2). Yet, a significant relationship of Fv/Fm with temperature was found, as temperature increases so did the efficiency of PSII (Table 2). UV-absorbing pigments were also not affected by filter type in the three accessions (Fig. 3 & Table 2). UV-absorbing pigments increased during the winter months and decreased during the summer months, this trend was the reverse of the trend observed for Fv/Fm and other plant growth parameters (Fig. 2). Graphs of UV-screening pigments as a function of temperature visualize the negative association between pigments and temperature, as well as the near complete lack of impact of genotype (Fig. 5A, B, C). UV-B treatment also has no effect on the slope-values (see Table 2) that detail the relationship between temperature and UV screening pigments. Similarly, graphs of pigments as a function of total, seasonal UV-doses (Fig. 5D, E, F) show a weak overall negative relationship, and no impact of filters (Fig. 2 & Table 2).

To further explore the dataset, two months were chosen for more detailed analysis. January and July were chosen as representative of the months with the highest and the lowest incidents of UV-B. In January, there was no significant effect of UV treatment on the morphology of accessions (Table 3). There were, however, significant differences between the accessions in rosette diameter ($F(2, 27) = 22.613$. $p=0.0001$) (Table 3). Both Col-0 and Bur-0 had larger rosette diameters than Ler, 21% and 16% respectively (Table 3). The only other significant effect was on UV-screening pigments; UV-A treated plants had higher total UV-absorbing pigment levels than the UV-B treated plants and while this difference was significant the actual difference between the treatments was small ($F(2, 27) = 0.772$, $p=0.001$) (Table 3).

In July, there was clear evidence of a UV effects on biomass, rosette diameter and leaf area of exposed plants. The biomass of plants grown under the UV transmitting filters was between 42 and 52% less than that of plants grown under the UV-0 treatment ($F(2, 18)=12.137$, $p=0.0001$) (Table 3). Rosette diameter was between 18 and 37% less ($F(2, 18)=670.466$, $p=0.0001$) and leaf area was between 33 and 48% less ($F(2,18)=19.929$, $p=0.0001$) compared to plants grown under the UV-0 treatment (Table 3). In July, there was also a significant difference between the rosette diameters of the three accessions, Bur-0 was on average 18% larger than Ler and 17% larger than Col-0 ($F(2, 18)=167.933$, $p=0.05$) (Table 3). No effects of accession or filter were found on either Fv/Fm or total UV-absorbing compounds.

Discussion

Plant growth and development

This study was set over the course of a year to determine if, and how, plant UV-B responses are moderated by seasonal meteorological factors, and *vice versa*. The Irish climate is described as oceanic and characterised by high levels of rainfall, relatively low hours of direct sunshine, and a lack of temperature extremes. Due to these mild climatic conditions, some plant species display nearly year round growth, enabling the study of interactions between growth and climatic variables such as temperature, hours of sunshine, global radiation and UV irradiance, throughout the four seasons.

The data show that significant variations in plant growth and concentrations of total UV-absorbing pigments occur throughout the year. It was found that variations in growth, morphology, and photosynthesis are predominantly linked to seasonal changes in temperature. Not unexpectedly, biomass, rosette diameter, leaf area and Fv/Fm all increased with higher temperatures and decreased again as temperatures dropped. Overall, the seasonal pattern of growth was not substantially distorted by the three distinct UV-filter treatments. In fact, no effect of the UV-filtration treatment was observed across the winter months. However, there were significant UV mediated differences in biomass and morphology found over the summer months. *Arabidopsis thaliana* accessions Ler, Col-0 and Bur-0 exhibited a more dwarfed phenotype when grown under UV-A/B or UV-A in the months of May and July. A slightly more compact plant is considered a typical morphological response to UV-B exposure (Robson et al., 2015). The UVR8 photoreceptor was first discovered as a mutant unable to undergo such UV-mediated dwarfing (Heijde and Ulm, 2012; Jenkins 2014). However, a more dwarfed phenotype can also be an indication of plant stress. Stress-induced Morphogenic Responses (SIMR) can produce a dwarf

phenotype in response to exposure to a range of unfavourable conditions (Potters et al., 2007). UV-induced stress is considered rare in plants under ambient conditions, however there are two reasons why stress may have occurred in this study; 1) plants used in this experiment came from a greenhouse and could potentially have experienced an initial UV shock when placed outdoors; 2) *Arabidopsis thaliana* set seed and die back during the summer months, thus would not normally be exposed to high, summer UV-intensities in combination with high levels of PAR and elevated temperatures. Measurements of Fv/Fm generated no evidence of plant stress. Yet, a substantial decrease in accumulated biomass was noted, a feature not typically seen as part of a UVR8 mediated re-direction of plant growth. Furthermore, in a parallel experiment under the same weather conditions it was noted that the Arabidopsis mutant uvr8-1, which lacks functional UVR8, also displayed dwarfing and growth inhibition during the summer months (Coffey et al., 2017). Finally, plants grown under UV-A radiation displayed similar dwarf morphology as plants grown under UV-A/B, further emphasizing that the observed change in rosette diameter is not necessarily associated with UV-B, but rather is a general UV-response. Thus, based on the observation of parallel reductions in biomass, leaf area and rosette diameter, plus the observation of a similar response in the uvr8-1 mutant, we conclude that the UV-A/B induced change in morphology is not UVR8 mediated acclimation, but rather a stress response that we speculate to be the result of exposure to high summer temperatures, high PAR, drought in combination with either UV-A or UV-B.

UV-absorbing pigments

UV-mediated increases in UV-absorbing pigments are amongst the most commonly reported plant UV-responses (Rozema et al., 1997; Jansen et al., 1998; Neugart et al., 2014). However, in this study no UV-B-mediated changes in the concentrations of UV-absorbing pigments were noted, notwithstanding significant effects of UV-radiation on biomass, leaf area and rosette diameter. Rather, temperature was identified as the primary driver behind the seasonal changes in UV absorbing pigments. Previous studies also reported that the strong effect of temperature on concentrations of UV absorbing pigments can mask smaller changes induced by UV (Leyva et al., 1995; Bilger et al., 2007). Outdoor studies on lichens and mosses revealed that seasonal variations in environmental conditions elicited much larger changes in UV-absorbing pigments than UV-B (Gehrke, 1999; Bjerke et al., 2005). Long term field studies in Tierra del Fuego (southern Argentina) show that UV-B induced increases in UV-B absorbing pigments can be observed in some years, but not in many others. The lack of UV-induced changes in total UV-absorbing pigment concentration does trigger questions about the importance of UV-sensing by plants. This is an intriguing question. Yet, it should be recognized that although this study failed to reveal a UV-induced change in the total concentration of UV screening pigments, this does not necessarily mean that no changes in UV-B absorbing pigments occur. For example, it cannot be excluded that some redistribution of flavonoids between epidermis and underlying mesophyll cells takes place, such a redistribution might be visualized using Dualex and other optimal measurements. Furthermore, not just the total amounts of flavonoids but also the flavonoid profile can be modified by environmental variables. Studies using supplemental UV-B have shown UV-induced changes in the ratio between quercetins and kampferols, as well as in the specific flavonoid-glycosylation pattern (Hectors et al., 2014; Neugart et al., 2014). For example, kale (*Brassica oleracea* var. sabellica) exposed to a low temperature of 5˚C accumulated almost twice as much of the polyphenol, kaempferol-3-O-sophoroside-7-O-glucoside, as plants at 15˚C.

However, kale plants at 15˚C accumulated ca 25% more kaempferol-3-O-caffeoyl-sophoroside-7-O-glucoside (Neugart et al., 2014). These subtle shifts in flavonoids with different hydroxylation and/or glycosylation status can be visualized through HPLC analysis, or as alteration in antioxidant activity measured with, for example, the Folin-Ciocalteu assay. Outdoor studies on birch trees have also revealed changes in concentrations of individual phenolic compounds change in response to UV-B radiation rather than the size of the total phenolic pool (Kotilainen et al., 2009; Morales et al., 2010). At present, the function of these subtle changes in phenolic profile is not clear. Thus, an important quest will be to characterize specific UV and/or temperature induced changes in the phenolic profile, and to analyse the scope for cross-protection.

Genotypes

Genotypic differences between accession can be significant and have the potential to enhance our understanding of the ecological role of specific adaptations. Cooley et al., (2001) compared the responses of seven accessions exposed to supplementary UV-A and UV-A/B under outdoor conditions in the period May to June. Several morphological parameters were measured and compared. Plant responses were found to range from UV insensitive, promotive to inhibitory, and results varied with treatment, accession and the parameter measured (Cooley et al., 2001). No such accession specific responses were observed in this paper. In the study by Cooley et al. (2001) Ler and Col-4 responded to supplemental UV-A/B, but not to UV-A, by reducing leaf area, width and length and petiole length significantly. These data on inhibitory UV effects during the summer period, are similar to those reported in this paper. However, the current study goes one step further, and shows that the UV-responses are highly dependent on seasonal factors, and that distinct results will be obtained depending on the time of year. It is concluded that a fixed time point approach does not necessarily show the full scope of variation in plant UV-responses.

In conclusion

Arabidopsis is widely used for mechanistic studies of plant responses but is seldom used in outdoor trials. This study highlights the potential discrepancies between findings obtained under controlled conditions and in the outdoors. Responses routinely observed under laboratory conditions, including UVR8 mediated changes in total UV-absorbing pigments, and plant morphology, were not observed in this outdoor study. This study finds a clear UV induced morphological effect, though only in the summer, and possibly associated with plant stress. Conversely, low temperatures were identified as a major regulator of the accumulation of UV-absorbing pigments. This study shows that UV-effects need to be analysed in the context of weather, and other co-occurring natural factors, and emphasizes the importance of a holistic, multifactorial approach for the investigation of environmentally relevant UV-effects

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References

Abràmoff, M. D., Magalhães, P. J. & Ram, S. J. 2004. Image processing with imageJ. *Biophotonics International*, 11(7), 36-42.

Ballare, C.L., Caldwell, M.M., Flint, S.D., Robinson, S.A. and Bornman, J.F., 2011. Effects of solar ultraviolet radiation on terrestrial ecosystems. Patterns, mechanisms, and interactions with climate change. *Photochemical & Photobiological Sciences*, *10*(2), pp.226-241.

Barnes, P.W., Robson, T.M., Tobler, M.A., Bottger, I.N. and Flint, S.D., 2017. Plant Responses to Fluctuating UV Environments. *UV-B Radiation and Plant Life: Molecular Biology to Ecology*, p.72.

Bilger, W., Rolland, M. & Nybakken, L. 2007. UV screening in higher plants induced by low temperature in the absence of UV-B radiation. *Photochemical & Photobiological Sciences*, 6(2), 190–195.

Bjerke, J. W., Gwynn-Jones, D. & Callaghan, T. V. 2005. Effects of enhanced UV-B radiation in the field on the concentration of phenolics and chlorophyll fluorescence in two boreal and arctic-alpine lichens. *Environmental and Experimental Botany*, 53(2), 139–149.

Bornman, J. F., Barnes, P. W., Robinson, S. A., Ballare, C. L., Flint, S. D., & Caldwell, M. M. (2015). Solar ultraviolet radiation and ozone depletion-driven climate change: effects on terrestrial ecosystems. *Photochemical & Photobiological Sciences*, *14*(1), 88-107.

Brown, B. A, Cloix, C., Jiang, G. H., Kaiserli, E., Herzyk, P., Kliebenstein, D. J. & Jenkins, G. I. 2005. A UV-B-specific signaling component orchestrates plant UV protection. *Proceedings of the National Academy of Sciences of the United States of America,* 102(50), 18225–30.

Boyes, D. C., Zayed, a M., Ascenzi, R., McCaskill, a J., Hoffman, N. E., Davis, K. R. & Görlach, J. 2001. Growth stage-based phenotypic analysis of Arabidopsis: a model for high throughput functional genomics in plants. *The Plant Cell,* 13(7), 1499– 510.

Brown, B. A. & Jenkins, G. I. 2008. UV-B signaling pathways with different fluence-rate response profiles are distinguished in mature Arabidopsis leaf tissue by requirement for UVR8, HY5, and HYH. *Plant Physiology,* 146(2), 576–88.

Calbó, J., Pagès, D. & González, J. A. 2005. Empirical studies of cloud effects on UV radiation: A review. *Reviews of Geophysics,* 43(2), 1–28.

Coffey, A., Prinsen, E., Jansen, M.A.K. and Conway, J., 2017. The UVB photoreceptor UVR8 mediates accumulation of UV-absorbing pigments, but not changes in plant morphology, under outdoor conditions. *Plant, cell & environment*, 40, 2250-2260.

Cooley, N. M., Higgins, J. T., Holmes, M. G. & Attridge, T. H. 2001. Ecotypic differences in responses of Arabidopsis thaliana L. to elevated polychromatic UV-A and UV-B+A radiation in the natural environment: a positive correlation between UV-B+A inhibition and growth rate. *Journal of Photochemistry and Photobiology. B, Biology*, 60(2-3), 143–50.

Doupis, G., Bosabalidis, A.M. and Patakas, A., 2016. Comparative effects of water deficit and enhanced UV-B radiation on photosynthetic capacity and leaf anatomy traits of two grapevine (*Vitis vinifera* L.) cultivars. *Theoretical and Experimental Plant Physiology*, *28*(1), pp.131-141.

Gehrke, C. 1999. Impacts of enhanced ultraviolet-B radiation on mosses in a subarctic heath ecosystem. *Ecology,* 80(6), 1844–1851.

Hayes, S., Sharma, A., Fraser, D.P., Trevisan, M., Cragg-Barber, C.K., Tavridou, E., Fankhauser, C., Jenkins, G.I. and Franklin, K.A., 2017. UV-B perceived by the UVR8 photoreceptor inhibits plant thermomorphogenesis. *Current Biology*, *27*(1), pp.120-127.

Hectors, K., Van Oevelen, S., Geuns, J., Guisez, Y., Jansen, M.A.K. & Prinsen, E., 2014. Dynamic changes in plant secondary metabolites during UV acclimation in arabidopsis thaliana. *Physiologia Plantarum*, 142 (2), 219-230.

Heijde, M. and Ulm, R., 2012. UV-B photoreceptor-mediated signalling in plants. *Trends in plant science*, *17*(4), pp.230-237.

Jansen, M. A. K., Gaba, V. & Greenberg, B. M. 1998. Higher plants and UV-B radiation: balancing damage, repair and acclimation. *Trends in Plant Science,* 3(4), 131–135.

Jansen, M.A.K, Martret, B.L. and Koornneef, M., 2010. Variations in constitutive and inducible UV-B tolerance; dissecting photosystem II protection in *Arabidopsis thaliana* accessions. *Physiologia plantarum*, *138*(1), pp.22-34.

Jenkins, G. I. 2014. The UV-B photoreceptor UVR8: from structure to physiology. *The Plant Cell,* 26(1), 21–37.

Koornneef, M., Alonso-Blanco, C. & Vreugdenhil, D. 2004. Naturally occuring genetic variation in *Arabidopisis thaliana*. *Annual Review of Plant Biology,* 55(1), 141–172.

Kotilainen, T., Venäläinen, T., Tegelberg, R., Lindfors, A., Julkunen-Tiitto, R., Sutinen, S. & Aphalo, P. J. 2009. Assessment of UV biological spectral weighting functions for phenolic metabolites and growth responses in silver birch seedlings. *Photochemistry and Photobiology,* 85(6), 1346–1355.

Kovács, V., Gondor, O.K., Szalai, G., Majláth, I., Janda, T. and Pál, M., 2014. UV-B radiation modifies the acclimation processes to drought or cadmium in wheat. *Environmental and experimental botany*, *100*, pp.122-131.

Leyva, A., Jarillo, J. A., Salinas, J. & Martinez-Zapater, J. M. 1995. Low Temperature Induces the Accumulation of Phenylalanine Ammonia-Lyase and Chalcone Synthase mRNAs of *Arabidopsis thaliana* in a Light-Dependent Manner. *Plant Physiology,* 108(1), 39–46.

Liley, J. Ben & Mckenzie, R. L. 2006. Where on Earth has the highest UV? *National Institute of Water and Atmospheric Research* (NIWA), 2–3.

Liu, H., Cao, X., Liu, X., Xin, R., Wang, J., Gao, J., Wu, B., Gao, L., Xu, C., Zhang, B. and Grierson, D., 2017. UV-B irradiation differentially regulates terpene synthases and terpene content of peach. *Plant, cell & environment*.

Madronich, S., McKenzie, R. L., Björn, L. O. & Caldwell, M. M. 1998. Changes in biologically active ultraviolet radiation reaching the Earth's surface. *Journal of Photochemistry and Photobiology B: Biology,* 46(1-3), 5–19.

Morales, L. O., Tegelberg, R., Brosch, M., Keinnen, M., Lindfors, A. & Aphalo, P. J. (2010). Effects of solar UV-A and UV-B radiation on gene expression and phenolic accumulation in *Betula pendula* leaves. *Tree Physiology,* 30(7), 923–934.

Neugart, S., Fiol, M., Schreiner, M., Rohn, S., Zrenner, R., Kroh, L.W. and Krumbein, A., 2014. Interaction of moderate UV-B exposure and temperature on the formation of structurally different flavonol glycosides and hydroxycinnamic acid derivatives in kale (*Brassica oleracea* var. *sabellica*). *Journal of agricultural and food chemistry*, *62*(18), pp.4054-4062.

Potters, G., Pasternak, T. P., Guisez, Y., Palme, K. J. & Jansen, M. A.K. 2007. Stress- induced morphogenic responses: growing out of trouble? *Trends in Plant Science,* 12(3), 98–105.

Robson, T., Hartikainen, S.M. and Aphalo, P.J., 2015. How does solar ultraviolet-B radiation improve drought tolerance of silver birch (Betula pendula Roth.) seedlings? *Plant, cell & environment*, *38*(5), pp.953-967.

Robson, T., Klem, K., Urban, O. and Jansen, M.A.K, 2015. Re-interpreting plant morphological responses to UV-B radiation. *Plant, cell & environment*, *38*(5), pp.856-866.

Rousseaux, M.C., Scopel, A.L., Searles, P.S., Caldwell, M.M., Sala, O.E. and Ballaré, C.L., 2001. Responses to solar ultraviolet-B radiation in a shrub-dominated natural ecosystem of Tierra del Fuego (southern Argentina). *Global Change Biology*, *7*(4), pp.467-478.

Rozema, J., van de Staaij, J., Björn, L. O. & Caldwell, M. 1997. UV-B as an environmental factor in plant life: stress and regulation. *Trends in Ecology & Evolution*, 12(1), 22–28.

Searles, P.S., Flint, S.D. and Caldwell, M.M., 2001. A meta-analysis of plant field studies simulating stratospheric ozone depletion. *Oecologia*, *127*(1), pp.1-10.

Shindo, C., Bernasconi, G. & Hardtke, C. S. 2007. Natural genetic variation in Arabidopsis: Tools, traits and prospects for evolutionary ecology. *Annals of Botany,* 99(6), 1043–1054.

Strid, Å., Chow, W.S. and Anderson, J.M., 1994. UV-B damage and protection at the molecular level in plants. *Photosynthesis Research*, *39*(3), pp.475-489.

Teramura, A.H. and Sullivan, J.H., 1994. Effects of UV-B radiation on photosynthesis and growth of terrestrial plants. *Photosynthesis Research*, *39*(3), pp.463-473.

R^2 values from the multiple regression model, using data from all seven months. Dependent variable = Constant + (B1 x Temp) + (B2 x uv-a/b) + (B3 x uv-a), asterisks are used to indicate significance of the R^2 value (* = p ≤0.05, **=p≤0.001, *** = p≤ 0.0001).

	Temperature			*Hours of sunshine*			*Global solar radiation*			*UV-B*		
	Ler	Col-0	Bur-0	Ler	Col-0	Bur-0	Ler	Col-0	Bur-0	Ler	Col-0	Bur-0
Rosette	0.73 ***	0.61 ***	0.74 ***	0.30 ***	0.30 ***	0.3 ***	0.36 ***	0.39 ***	0.39 ***	0.22 ***	0.31 ***	0.26 ***
Leaf Area	0.74 ***	0.65 ***	0.63 ***	0.36 ***	0.41 ***	0.31 ***	0.43 ***	0.49 ***	0.43 ***	0.28 ***	0.37 ***	0.34 ***
Total Phenolics	0.7 ***	0.72 ***	0.7 ***	0.17 **	0.21 ***	0.27 ***	0.2 ***	0.22 ***	0.27 ***	0.09	0.11 *	0.16 *
Fv/Fm	0.49 ***	0.55 ***	0.61 ***	0.07	0.12 **	0.16 **	0.15 ***	0.26 ***	0.26 ***	0.09	0.18 *	0.17 *

Table 2. Slopes (beta coefficient), their significance and the Part Nos. Squared from a multiple linear regression model (Dependent variable = Constant + (B1 x Temp) + (B2 x uv-a/b) + (B3 x uv-a)) including temperature and the 3 filters as independent variables. The slope informs if a particular variable is making a statistically significant and unique contribution to the equation. The Part No. Squared describes the unique contribution that independent variable makes to the total R^2 and thus to the variation in the dependent variable.

		Ler			*Col-0*			*Bur-0*		
		Slope	Sig	Part No. Squared	Slope	Sig	Part No. Squared	Slope	Sig	Part No. Squared
Leaf area	Temp	0.82	***	0.67	0.78	***	0.6	0.77	***	0.6
	UV-A/B	-0.30	***	0.07	-0.26	**	0.05	-0.21	**	0.03
	UV-A	-0.17	*	0.02	-0.10	ns	7.7x10-3	-0.07	ns	4.23x10-3
Rosette Diameter	Temp	0.82	***	0.67	0.73	***	0.53	0.82	***	0.69
	UV-A/B	-0.27	***	0.06	-0.33	***	0.08	-0.24	**	0.04
	UV-A	-0.13	ns	0.01	-0.16	ns	0.02	-0.04	ns	1.37x10-3
Fv/Fm	Temp	0.69	***	0.47	0.74	***	0.54	0.77	***	0.6
	UV-A/B	-0.10	ns	8.1x10-3	0.001	ns	1x10-6	-0.10	ns	6.89x10-3
	UV-A	-0.14	ns	0.01	-0.07	ns	3.14x10-3	-0.16	ns	0.02
Total Phenolic	Temp	-0.84	***	0.72	-0.84	***	0.72	-0.84	***	0.7
	UV-A/B	-0.03	ns	5.29x10-4	-0.08	ns	4.6x10-3	-0.01	ns	8.1x10-5
	UV-A	0.07	ns	3.6x10-3	0.003	ns	9x10-6	-0.67	ns	3.36x10-3

Table 3. Summary of two-way ANOVAs on the effects of accession and filter type on biomass (mg), rosette diameter(mm), leaf area (mm^2) and total UV-absorbing pigments in Arabisdopsis grown outdoors for 10 days in January 2013 and July 2013.

Main Effects			January				July			
			Biomass (mg)	Rosette Diameter(mm)	Leaf Area(mm^2)	Total Phenolics	Biomass (mg)	Rosette Diameter(mm)	Leaf Area (mm^2)	Total Phenolics
Accession	Ler		11.26 a	12.06 a	8.75 a	0.0152 a	137.54 a	31.05 a	73.01 a	0.0054 a
	Col-0		11.39 a	15.23 b	10.10 a	0.0161 a	142.66 a	31.40 a	78.31 a	0.0068 a
	Bur-0		12. 18 a	14.29 b	11.56 a	0.0160 a	150.77 a	37.69 b	78.55 a	0.0068 a
Filter	UV-A/B		11.14 a	13.21 a	9.0824 a	0.014 a	105.21 a	25.90 a	54.28 a	0.0058 a
	UV-A		11.06 a	13.92 a	9.8979 a	0.018 b	126.60 a	33.38 b	68.89 a	0.0058 a
	UV-0		12.63 a	14.46 a	11.4301 a	0.016 ab	217.71b	40.85 c	102.77 b	0.0073 a
		Df				ANOVA				
F value Ecotype		**2**	0.556	22.613	2.736	0.772	0.213	167.933	0.226	2.903
	Sig		ns	***	ns	ns	ns	*	ns	ns
F value	Filter	**2**	1.761	2.856	1.961	9.505	12.137	670.466	19.929	2.837
	Sig		ns	ns	ns	**	***	***	***	ns
Genotype x Filter		**4**	0.482	0.406	0.558	0.83	0.187	57.349	0.956	0.863
	Sig		ns	ns	ns	ns	ns	ns	ns	ns
	Total Jan	**27**								
	July	**18**								

ns= not significant, * = p ≤0.05, **=p≤0.001, *** = p≤ 0.0001, according to two-way ANOVA. Comparisons to be made within columns Means in the same column and same main effect with the same letter are not significantly different, p>0.05 according to Tukey tests.

Legends to the figures

Figure 1. Preparation of plant material used in exposure studies.

Figure 2. The biomass (mg), panel (a), rosette diameter (mm) panel (b) and leaf area (mm^2) panel (c) of rosettes of Arabidopsis accessions Landsberg erecta (Ler), Columbia-0 (Col-0) and Burren-0 (Bur-0) grown for 10 days outdoors at 7 different time-points throughout the year. Biomass and leaf area data represents data for leaf 4 of the rosettes. Error bars represent the standard deviation from the mean of 4 replicates. Starting rosette diameter, biomass and leaf area of the whole rosettes was 9 mm or less, no more than 5 mg and less than 50 mm^2 respectively. Filter specifications: UV-A/B (visible + UVA and UVB), UV-A (visible + UVA) and UV-0 (visible).

Figure 3. Total UV-absorbing pigments in leaf 4, extracted with a 1% acidified methanol solution and normalized using leaf area. Data show pigment content for Arabidopsis accessions Landsberg erecta (Ler), Columbia-0 (Col-0) and Burren-0 (Bur-0) grown for 10 days outdoors, at 7 different time-points throughout the year. Error bars represent the standard deviation from the mean of 4 replicates.

Figure 4. Pearsons correlation between rosette diameter and 2 independent variables temperature and UV-B for 3 Arabidopsis accessions, Ler (a, d), Col-0 (b, e) and Bur-0 (c, f). ♦= UV-A/B ■= UV-A ▲=UV-0.

Figure 5. Pearsons correlation between accumulated UV-absorbing pigments, and the 2 independent variables temperature and UVB for 3 Arabidopsis accessions, Ler (a, d), Col-0 (b, e) and Bur-0 (c, f). ♦= UV-A/B ■= UV-A ▲=UV-0.

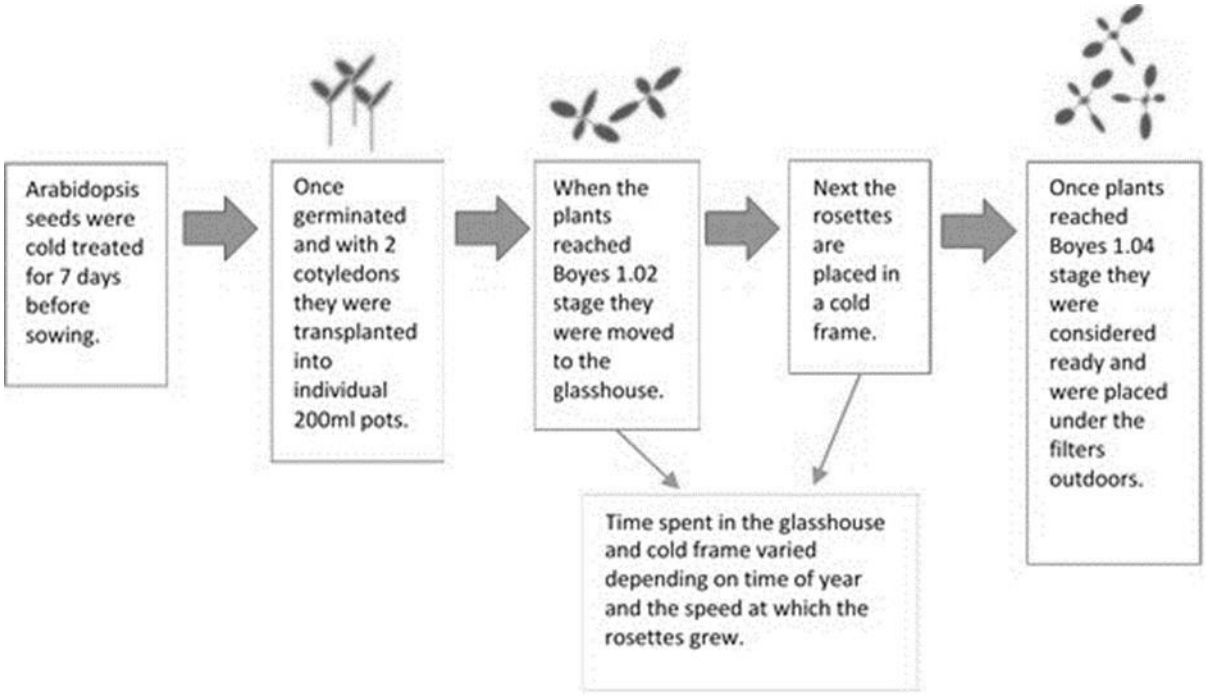

Arabidopsis seeds were cold treated for 7 days before sowing.
Once germinated and with 2 cotyledons they were transplanted into individual 200ml pots.
When the plants reached Boyes 1.02 stage they were moved to the glasshouse.
Next the rosettes are placed in a cold frame.
Once plants reached Boyes 1.04 stage they were considered ready and were placed under the filters outdoors.
Time spent in the glasshouse and cold frame varied depending on time of year and the speed at which the rosettes grew.

Figure 1

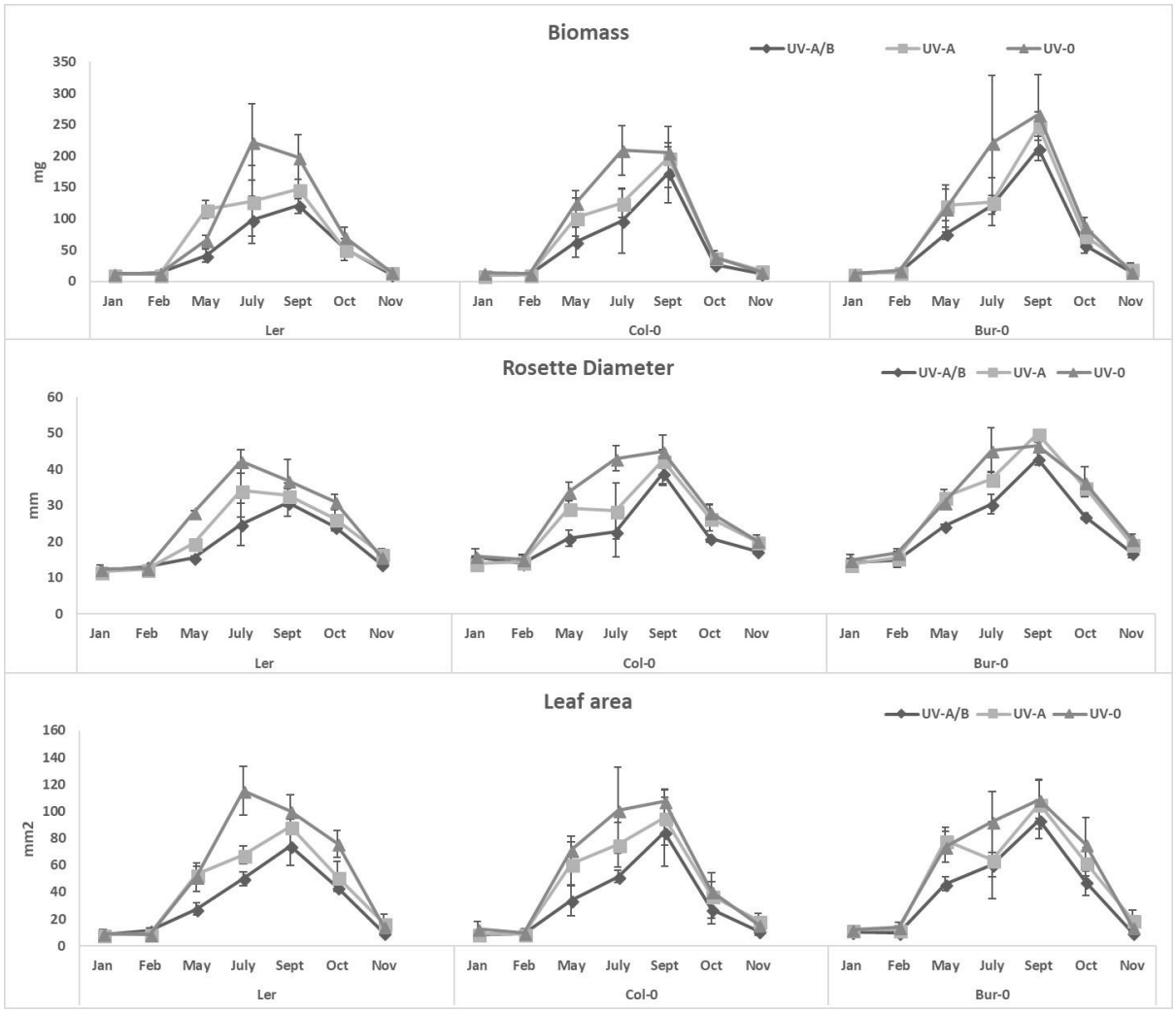

Biomass
UV-A/B
UV-A
UV-0
mg
350
300
250
200
150
100
50
0
Jan Feb May July Sept Oct Nov
Ler
Col-0
Bur-0
Rosette Diameter
mm
60
50
40
30
20
10
0
Leaf area
mm2
160
140
120
100
80
60
40
20
0

Figure 2.

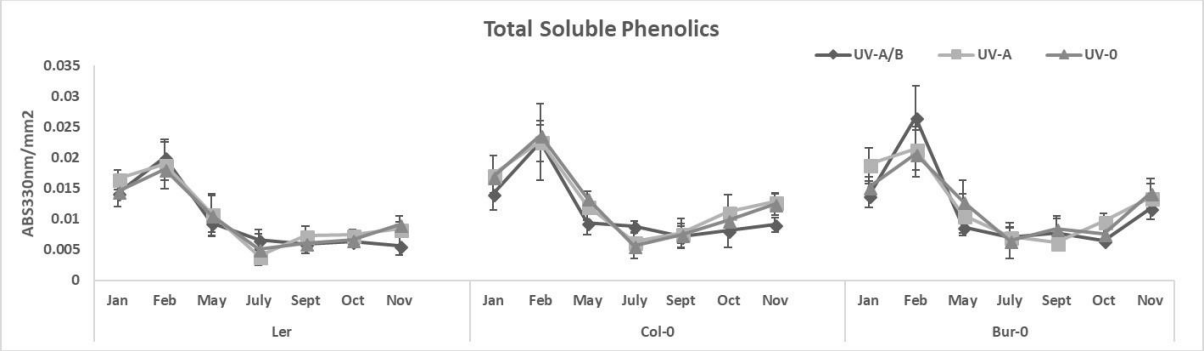

Total Soluble Phenolics
UV-A/B
UV-A
UV-0
ABS330nm/mm2
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Jan Feb May July Sept Oct Nov
Ler
Jan Feb May July Sept Oct Nov
Col-0
Jan Feb May July Sept Oct Nov
Bur-0

Figure 3.

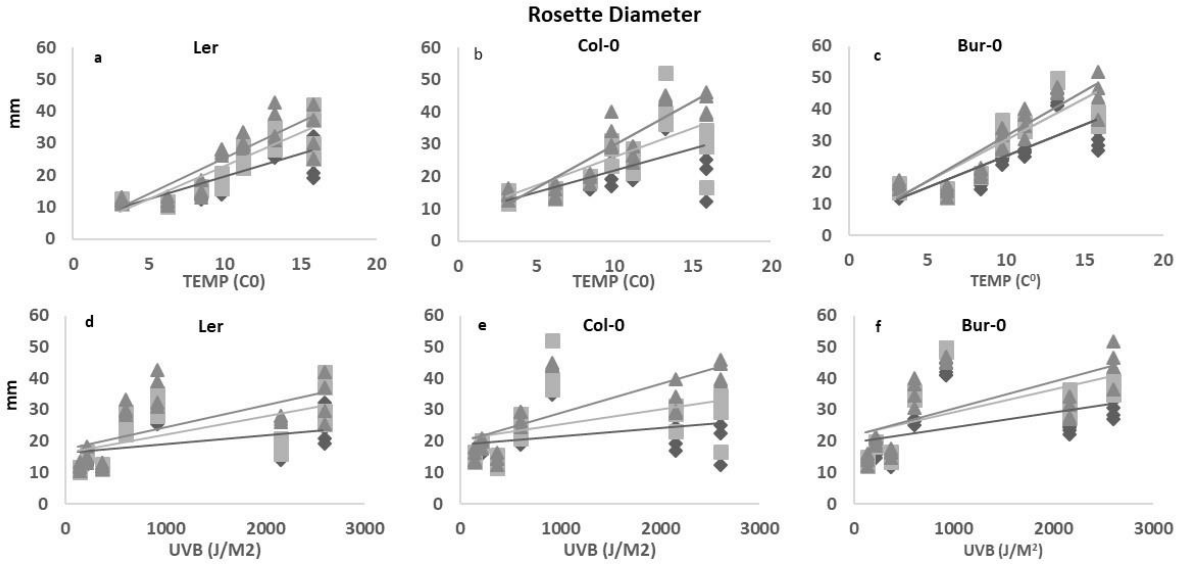

Rosette Diameter
a
Ler
b
Col-0
c
Bur-0
d
Ler
e
Col-0
f
Bur-0
mm
mm
TEMP (C0)
TEMP (C0)
TEMP (C⁰)
UVB (J/M2)
UVB (J/M2)
UVB (J/M²)

Figure 4.

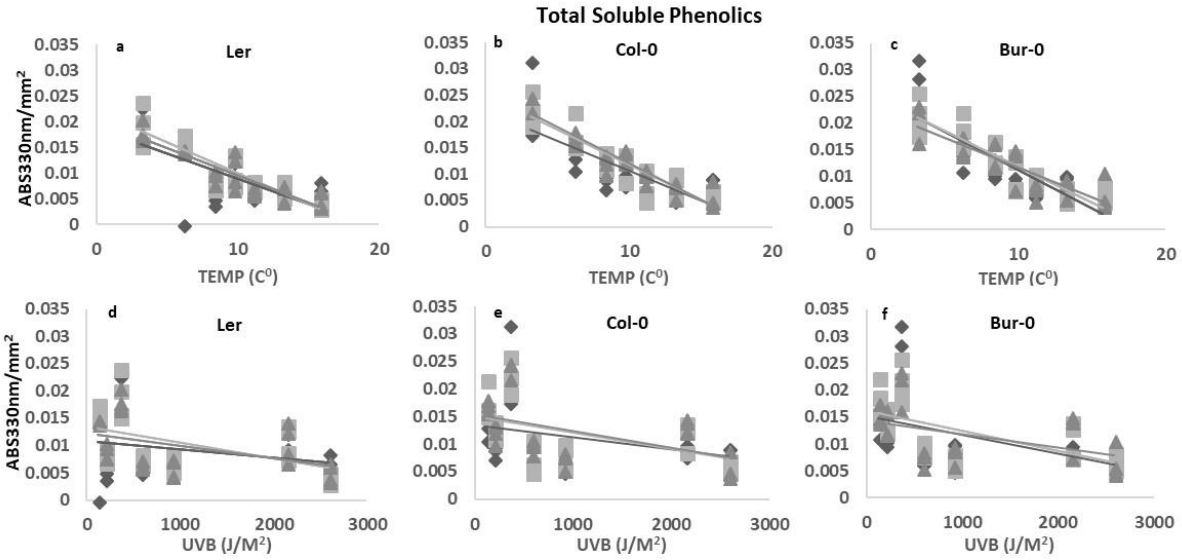

Total Soluble Phenolics
a
Ler
b
Col-0
c
Bur-0
d
Ler
e
Col-0
f
Bur-0
ABS330nm/mm²
TEMP (C⁰)
UVB (J/M²)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
1000
2000
3000

Figure 5.