

Article

Endemic *Cyclamen purpurascens* Subsp. *immaculatum*: Linking Habitat Conditions to PSII Efficiency and Reproductive Output

Peter Turis ¹, Alena Sliacka Konôpková ²  and Daniel Kurjak ^{2,3,*} 

¹ Department of Biology and Environmental Studies, Faculty of Natural Sciences, Matej Bel University in Banská Bystrica, Tajovského 40, 974 01 Banská Bystrica, Slovakia; peter.turis@umb.sk

² Department of Integrated Forest and Landscape Protection, Faculty of Forestry, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia; alena.konopkova@tuzvo.sk

³ Institute of Forest Ecology, Slovak Academy of Sciences v.v.i., E. Štúra 1774, 960 01 Zvolen, Slovakia

* Correspondence: kurjakd@gmail.com

Abstract

Information on factors influencing fitness, flowering, and fruit production in *Cyclamen* species remains limited. This study evaluated these traits throughout the growing season in three populations of *Cyclamen purpurascens* subsp. *immaculatum* under contrasting environments: a young beech forest (half-shade), an old beech forest (shade), and an open meadow. Because this protected endemic taxon of the Western Carpathians (Veľká Fatra and Starohorské vrchy Mountains, Slovakia) cannot be sampled destructively, we used in situ observations and chlorophyll a fluorescence measurements. We found seasonal variation in photosystem II (PSII) efficiency and high environmentally driven inter-individual variability. Plants in the meadow exhibited significantly lower values of F_v/F_m , F_m/F_0 , and $Area$ parameters, likely reflecting combined microclimatic stress. These plants also produced significantly fewer flowers, suggesting reduced resource availability for reproduction. In contrast, no significant differences in fluorescence parameters were detected between the two forest habitats, which showed similar seasonal dynamics. However, plants in the young forest produced the most flowers and slightly more fruits than those in the old forest or open meadow. Overall, our results suggest that meadow habitats may be less suitable for this taxon, while old-forest environments are tolerated but may reduce reproductive output. Semi-shaded forest habitats may be important for long-term persistence of this taxon.

Keywords: Fatra Sowbread; cyclamen; chlorophyll fluorescence; quantum yield of PSII; flowering; fruit production; endemic



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1. Introduction

The Fatra Sowbread [*Cyclamen purpurascens* subsp. *immaculatum* (Hrabětová) Halda et Soják, Primulaceae] is an endemic plant of the Western-Carpathian mountains of Veľká Fatra and Starohorské vrchy in Slovakia [1]. It predominantly occurs in forest communities belonging to the association Moor 1952 [2], but occasionally grows also in meadow habitats near forest edges. As a narrow endemic with restricted distribution and legal protection status, the taxon may be vulnerable to habitat alteration and ongoing environmental changes. The taxon is legally protected in Slovakia and included in Annex II of the Habitats Directive (92/43/EEC). In the Red List of vascular plants of Slovakia, it is classified as Near Threatened [3,4].

The plants form a tuber embedded in the soil and leaf litter, and a stem grows from the tuber. During the vegetation season, leaves sprout from the top of the stem, whereas leaves remain on the plant throughout winter, with their replacement occurring in the next vegetation season [3]. The cold resistance of the leaves may be comparable to that of the related *Cyclamen purpurascens* Mill. subsp. *purpurascens*. It grows under similar climatic conditions in Central Europe and can be partially damaged at temperatures below -12°C [4]. The plants begin to flower at the end of June, with fruit ripening from the end of July to August of the following year [3]. Understanding the physiological performance and reproductive success of this taxon under contrasting habitat conditions is important for its long-term conservation.

The effectiveness of photosynthesis and the related reproductive ability of plants can vary significantly depending on both external and internal factors. Among the external factors, radiation intensity, air temperature, water availability, and minerals have a significant impact. In healthy plants, important internal factors include seasonal changes in pigments, which depend on the phenological phase and the age of the assimilation organs [5]. The effects of internal and external factors can intertwine; for example, drought induces oxidative stress, leading to the degradation of leaf pigments and premature senescence [6,7]. The morphology and phenology of the genus *Cyclamen* are often limited by summer drought and winter cold [8].

The quantum efficiency of photosystem II (PSII) can be assessed using chlorophyll a fluorescence measurements [9]. Chlorophyll a fluorescence represents light energy not utilised in photochemistry and emitted back into the environment. Changes in fluorescence intensity and kinetics following dark adaptation and subsequent illumination can indicate damage to the photosynthetic apparatus, enabling a more detailed evaluation of PSII functionality [10]. It should be noted that parameters from fast chlorophyll fluorescence kinetics primarily inform about the quantum efficiency of PSII in the dark-adapted state and do not directly reflect overall CO_2 assimilation rates or whole-plant photosynthetic performance. Nevertheless, the assessment of chlorophyll a fluorescence is one of the most frequently used tools for quick and non-invasive evaluation of the state of the photosynthetic apparatus in plants [9].

Changes in PSII efficiency, assessed by chlorophyll a fluorescence, are often used to study plant stress under high temperatures and drought (e.g., [11,12]). However, in principle, the method can be used to assess various environmental factors and their cumulative effects within a given locality, since stressors typically also affect pigment composition and the functionality of photochemical light-utilisation processes. Few authors have examined seasonal variation in plant PSII performance throughout the growing season, despite fluorescence measurements enabling rapid quantification of plant vitality. These data are also helpful as a basis for more modern methods of spatial ecosystem monitoring [13]. However, most species of deciduous perennial higher plants in the temperate zone have a different seasonal cycle from that of the cyclamen we studied. The phenophases of most species are more strictly coordinated, and leaves predominantly die off before winter. In contrast, cyclamen leaves persist through winter and are gradually replaced during the following vegetation season [3]. Previous studies on this taxon focused mainly on population characteristics, reproductive biology, and plant–animal interactions [3,14,15], whereas its photosynthetic physiology has not been studied. To our knowledge, chlorophyll fluorescence has not been investigated in *Cyclamen* species.

The present study aimed to assess seasonal variation in PSII efficiency and reproductive performance in *Cyclamen purpurascens* subsp. *immaculatum* plants growing under contrasting environmental conditions. We assumed that meadow individuals would experience greater stress associated with high irradiance, elevated temperatures, and drought

than individuals growing in forest habitats. Additionally, temperature conditions likely differ between the south-facing and north-facing slopes, which may also influence plant performance. Therefore, we expected reduced PSII efficiency in individuals growing in an open meadow area due to higher irradiation and associated microclimatic stress. Reduced PSII efficiency may indicate reduced physiological fitness and potentially lower assimilate accumulation, which could in turn be reflected in reduced reproductive output in meadow plants. We expected the highest PSII performance and reproductive output in individuals growing in the young forest, where the more heterogeneous light conditions and associated microclimatic conditions may be more favourable than in the older forest stand.

2. Materials and Methods

2.1. Experimental Design

As *Cyclamen purpurascens* subsp. *immaculatum* is a legally protected taxon, the experimental design was intentionally restricted to non-invasive, in situ methods to avoid any disturbance to natural populations. The study was conducted in compliance with Slovak national legislation regarding the protection of endangered species. All measurements were performed without removing or damaging plant material. As the study involved only observational and measurements of chlorophyll fluorescence, no special permits were required (Figure 1).



Figure 1. Flowering individual of *Cyclamen purpurascens* subsp. *immaculatum* (left) and cyclamen leaves dark-adapted using leaf clips prior to non-destructive in situ measurements of chlorophyll a fluorescence (right).

The measurements of the *Cyclamen purpurascens* subsp. *immaculatum* were performed near the village of Motyčky (district of Banská Bystrica, Central Slovakia). Three nearby locations with different vegetation characteristics and different slope orientations were selected for the study (Table 1). The location Forest_S was situated in a young, approximately 30-year-old beech forest stand on a south-facing slope, the location Forest_N was in an older, approximately 70-year-old beech forest on a north-facing slope, and the location Meadow was on a north-facing slope in a meadow near the forest edge. As the sites differed in habitat structure and exposure, differences in solar radiation were expected. Therefore, at each site, the radiation intensity was measured (in lux; HHLM-1, Omega Engineering, Norwalk, CT, USA) at various times between April and October. Overall, measurements were taken nine times over five different days. Since radiation was measured in lux and photosynthetically active radiation (PAR, $\mu\text{mol m}^{-2} \text{s}^{-1}$) is more relevant for photosynthetic studies, lux values were additionally converted to approximate PAR values assuming natural sunlight conditions ($1 \mu\text{mol m}^{-2} \text{s}^{-1} \approx 54 \text{ lx}$) [16]. The mean, minimum,

and maximum radiation values, including both the original illuminance values (lx) and the corresponding estimated PAR values, are presented in Table 1. These values represent the range and average of measurements obtained during the study period and are provided as a general characterisation of radiation conditions in the studied habitats.

Table 1. Site characteristics of the selected localities.

Locality	Vegetation Characteristics	Slope	Light Conditions	Min. Measured Radiation (lx/ $\mu\text{mol m}^{-2} \text{ s}^{-1}$)	Max. Measured Radiation (lx/ $\mu\text{mol m}^{-2} \text{ s}^{-1}$)	Mean Measured Radiation (lx/ $\mu\text{mol m}^{-2} \text{ s}^{-1}$)	Variation Coeff. of Radiation
Forest_S	young beech forest stand (approx. 30-year-old)	south-facing	half-shaded	214/3.96	12,950/239.81	3968/73.49	1.05
Forest_N	older beech forest stand (approx. 70-year-old)	north-facing	shaded	488/9.04	4982/92.26	1962/36.34	0.91
Meadow	meadow near the forest edge	north-facing	fully exposed	3098/57.37	16,096/298.07	11,340/210	0.36

Chlorophyll a fluorescence was recorded with a Plant Efficiency Analyser (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK). The selected leaves were subjected to a half-hour dark adaptation period and then exposed to a saturating pulse of high-intensity light ($3500 \mu\text{mol m}^{-2} \text{ s}^{-1}$, 1 s). Measurements at the three localities were performed sequentially on the same day in randomised order. The evaluated parameters included F_m , F_0 , F_v , and $Area$ and the ratios F_v/F_m and F_m/F_0 . F_m represents the maximum fluorescence value measured during a one-second light pulse, F_0 is the basal fluorescence and F_v represents variable fluorescence ($F_v = F_m - F_0$). $Area$ is the area above the fluorescence intensity curve, indicating the pool of electron acceptors on the reducing side of Photosystem II (PSII). Therefore, the parameter $Area$ represents the proportion of electrons transported through PSII out of the total number of electrons. The ratio F_v/F_m represents the maximum quantum yield of PSII when all reaction centres are open and is widely used as an indicator of light-energy conversion efficiency under optimal conditions. It is also considered a sensitive indicator of plant physiological status [9,17]. The ratio F_m/F_0 provides a simple index of the potential photochemical capacity of PSII. Because F_0 is relatively stable and F_m reflects changes in the redox state of Q_A and the efficiency of electron transport, the F_m/F_0 ratio may be used as a rapid, non-destructive indicator of alterations in the functional state of the photosynthetic apparatus, particularly under stress conditions [18]. Although the reciprocal parameter F_0/F_m is more commonly applied, it primarily reflects the non-photochemical processes within PSII rather than PSII performance itself [19]. Since both parameters are functionally dependent ($F_m/F_0 = \frac{1}{F_0/F_m}$), F_m/F_0 was used because its interpretation was more intuitive in the context of the other evaluated fluorescence parameters.

The chlorophyll a fluorescence measurements on selected individuals of cyclamen were conducted during the different phenological phases. The first measurement (18 March) was conducted during the dormancy period, immediately after the snow had melted. The second measurement (21 June) was conducted during the period of intensive growth of new vegetative and generative organs in cyclamen populations. The third measurement (20 August) was performed during the flowering stage when the highest proportion of individuals were in bloom. The last measurement (7 November) was conducted during the period of vegetative dormancy and before the snow.

At each locality, at least ten individuals were marked for repeated measurements. At the beginning of the experiment, 2–3 leaves per individual were labelled and used for chlorophyll fluorescence measurements. Fully expanded, mature leaves were selected to ensure consistency among measurements. The same leaves were used throughout the period; however, if a leaf senesced, it was replaced with a new leaf from the same plant whenever possible. Due to the specific life cycle of *Cyclamen purpurascens* subsp. *immaculatum*, spring measurements were performed on leaves formed during the previous year. During summer, some older leaves senesced while new leaves gradually developed; consequently, measurements during this period represented a combination of older and newly formed leaves. In autumn, measurements were performed on leaves formed during the current year. The same procedure was applied consistently across all study plots.

In addition to chlorophyll fluorescence, the numbers of flowering individuals, flowers per individual, fruiting individuals, and developing fruits per individual were recorded simultaneously.

2.2. Statistical Analysis

To avoid pseudoreplication, mean values were first calculated for each individual and sampling date, and these data were used to assess the statistically significant differences between dates and locations.

The effects of locality, sampling date, and their interaction were evaluated using analysis of variance (ANOVA), followed by Tukey's HSD test for multiple comparisons when significant interaction effects were detected. Prior to ANOVA, normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Because F_v/F_m and F_m/F_0 values deviated from the normal distribution, F_v/F_m values were transformed using the arcsine square-root transformation, whereas F_m/F_0 values were log-transformed in order to improve distributional properties. Given the relatively high number of observations, moderate deviations from normality were considered acceptable for the applied parametric analyses [20]. However, the figures present the original non-transformed values for clarity and easier biological interpretation.

Differences in proportional data (proportion of flowering individuals, proportion of fruiting individuals of total plants, proportion of fruiting individuals among flowering plants) were analysed using Pearson's chi-square (χ^2) tests.

Differences in count data (number of flowers per individual, number of fruits per individual, and number of fruits per flowering individual) were evaluated using the non-parametric Kruskal–Wallis test, as the data did not meet the assumptions of normality and homogeneity of variance. When significant differences were detected, post hoc pairwise comparisons were performed using Dunn's test. Statistical analyses were conducted using R software version 4.2.0 [21].

3. Results

The light conditions on the trial plots differed significantly (Table 1). The lowest values of light radiation were recorded in the older beech forest on the north-facing slope (Forest_N). On average, measured values were approximately twice as high in the younger beech forest on the south-facing slope (Forest_S). The average values measured in the meadow were nearly three times and six times higher, respectively, compared to the two forest localities. In addition to differences in overall values, the spatial variability of light also differed among localities. The coefficient of variation was markedly higher in forest stands (Forest_S: 105%, Forest_N: 91%), indicating pronounced heterogeneity of light conditions under the canopy. In contrast, the meadow showed substantially lower variability (36%), reflecting more uniform irradiance despite much higher overall exposure.

Chlorophyll fluorescence measurements confirmed statistically significant differences among localities, sampling dates within the year, and the locality $\times$ date interaction (Table 2). The values at the Forest_S and Forest_N localities were similar and generally higher than those recorded in the meadow, which exhibited the highest variability among individuals (Figure 2a,c,e). The decreases in the values measured in the meadow were more pronounced in the parameters *Area* and F_m/F_0 in June and November, respectively. Moreover, the values of F_v/F_m measured in March and June in the meadow were lower than those in the forest localities.

Table 2. Results of two-way ANOVA for chlorophyll fluorescence parameters measured at different localities (forest with south-facing exposure, forest with north-facing exposure, meadow) and on different dates (locality, date and their interactions were evaluated as factors).

Parameter	Source of Variability	Degrees of Freedom	Sum of the Squares	Mean Square	F-Statistic	p Value ¹
F_v/F_m	Locality	2	0.03862	0.019311	15.569	8.97×10^{-7} ***
	Date	3	0.02976	0.009919	7.997	6.34×10^{-5} ***
	Locality $\times$ Date	6	0.02476	0.004127	3.327	0.00446 **
	Residuals	127	0.15752	0.00124		
<i>Area</i>	Locality	2	0.1579	0.07895	14.496	2.14×10^{-6} ***
	Date	3	0.0842	0.02806	5.152	0.00215 **
	Locality $\times$ Date	6	0.099	0.0165	3.029	0.00841 **
	Residuals	127	0.6917	0.00545		
F_m/F_0	Locality	2	117,213	58,607	45.389	1.34×10^{-15} ***
	Date	3	169,937	56,646	43.87	$<2 \times 10^{-16}$ ***
	Locality $\times$ Date	6	68,503	11,417	8.842	4.67×10^{-8} ***
	Residuals	127	163,985	1291		

¹ ** $p \leq 0.01$; *** $p \leq 0.001$.

Overall, the seasonal course of values was inconsistent among localities: individuals growing in the forest reached their minima and maxima in different months than those in the meadow (Figure 2b,d,f). However, the trend for Forest_S and Forest_N was noticeable and consistent: the values of F_v/F_m and F_m/F_0 followed a similar trend with an increase during the summer months and a decrease at the beginning and end of the vegetative period (in March and November), while fluctuations in the *Area* parameter were moderate. In contrast, the values measured in the meadow were highly variable; apart from August, there were consistent significant declines in one of the parameters, even in June.

Differences in the formation of flowers and fruits between the localities were also observed (Table 3). The proportions of flowering and fruiting individuals varied between localities, with the highest values recorded in Forest_S. However, these differences were not statistically significant. In terms of flower production, similar values were observed at the two forest localities. In contrast, individuals in the meadow produced 44% and 36% fewer flowers than those in Forest_S and Forest_N, respectively.

Forest_S exhibited both the highest flowering intensity and the highest fruit production. Although Forest_N showed relatively high flower production, its overall reproductive output (fruits per total individual) was low due to the limited fruit set, with only 21% of flowers developing into fruits. In contrast, despite having the fewest flowers per individual, the meadow population exhibited a moderate fruit set, resulting in an overall reproductive output comparable to Forest_N.

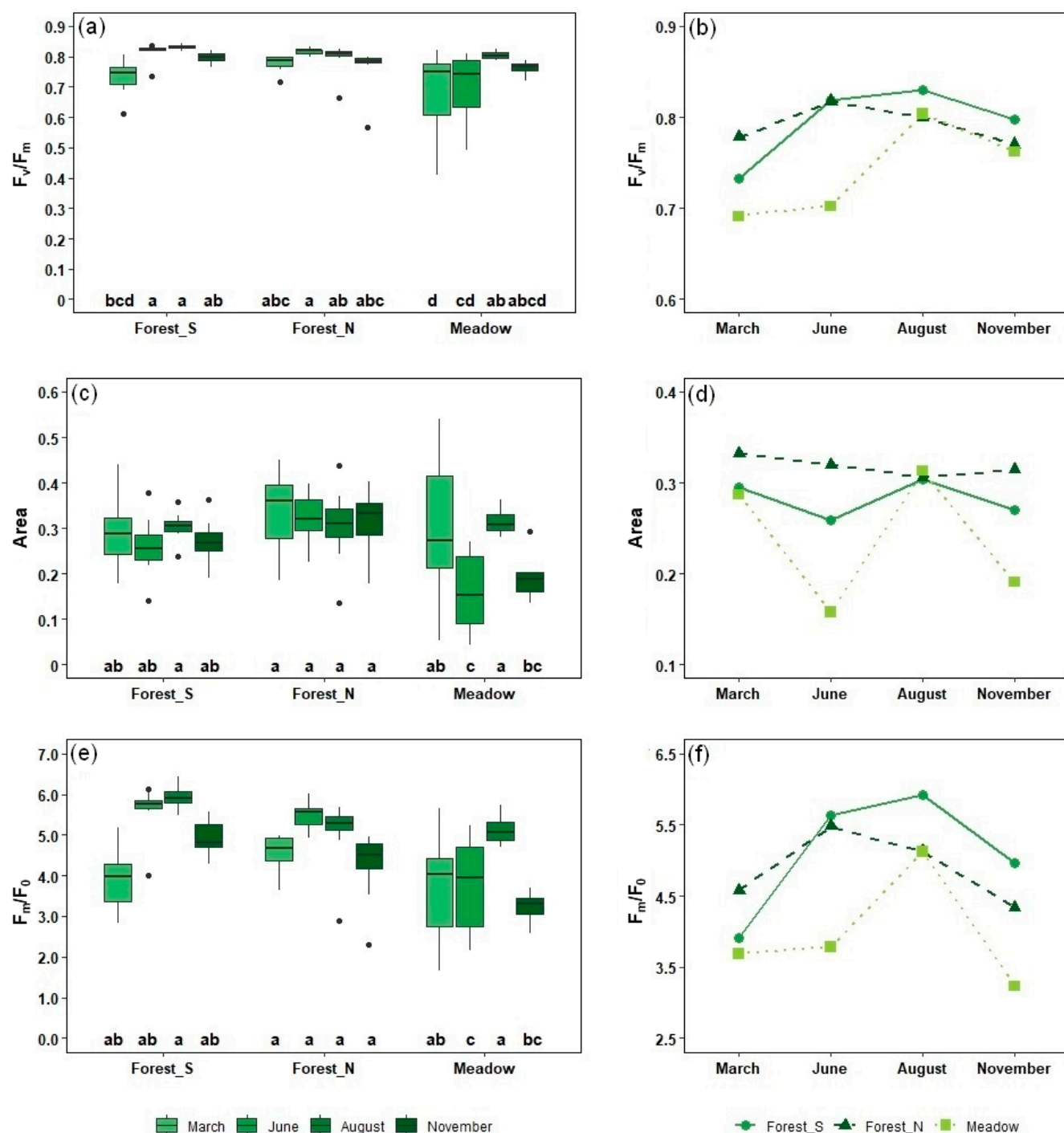


Figure 2. Chlorophyll a fluorescence parameters assessed at different localities (Forest_S—forest with south-facing exposure; Forest_N—forest with north-facing exposure; Meadow) and on various dates: (a) boxplots of F_v/F_m values; (b) seasonal trends in mean F_v/F_m values; (c) boxplots of $Area$ values; (d) seasonal trends in mean $Area$ values; (e) boxplots of F_m/F_0 values; and (f) seasonal trends in mean F_m/F_0 values. Different letters indicate statistically significant differences among groups according to Dunn's post hoc test at $p \leq 0.05$.

Table 3. Number of flowers and fruits on the individual trial plots (Forest_S—forest with south-facing exposure, Forest_N—forest with north-facing exposure, Meadow).

Parameter	Forest_S	Forest_N	Meadow	Test Statistic	p Value ¹
Proportion of flowering individuals	0.67	0.57	0.63	$\chi^2 = 0.40$	0.82

Table 3. Cont.

Parameter	Forest_S	Forest_N	Meadow	Test Statistic	p Value ¹
Proportion of fruiting individuals (total)	0.47	0.21	0.25	$\chi^2 = 3.02$	0.22
Proportion of fruiting individuals (flowering)	0.70	0.38	0.40	$\chi^2 = 2.18$	0.34
<i>Flowers per total individual</i>	1.13 a	1.00 a	0.63 b	H = 6.12	0.047 *
<i>Fruits per total individual</i>	0.67 a	0.21 b	0.25 b	H = 5.91	0.051 *
Fruit set (fruits/flowers ratio)	0.59	0.21	0.40	$\chi^2 = 4.18$	0.124

¹ Different letters indicate statistically significant differences among groups according to Dunn's post hoc test at $p \leq 0.05$ (*) and $p \leq 0.1$ (.). χ^2 denotes the chi-square test statistic and H denotes the Kruskal–Wallis test statistic.

4. Discussion

4.1. Seasonal Variation in PSII Efficiency Under Contrasting Habitat Conditions

In the present study, we observed differences in seasonal patterns of chlorophyll fluorescence parameters between individuals growing in meadow and forest localities. Karlsson and Werner [22,23] state that air temperature significantly affects leaf shedding, morphology, and cyclamen flowering. Accordingly, differences between forest and meadow habitats were also confirmed in this study. However, the average temperature is not the only important factor in the initial stages of the vegetation period and the amplitude of fluctuation may also affect the efficiency of the photosynthetic apparatus.

In general, the quantum efficiency of PSII in June was higher in forests, suggesting more favourable and less stressful conditions for cyclamen compared to later sampling periods. We found that seasonal changes in F_v/F_m and F_m/F_0 followed the expected pattern in both forest localities: the highest values were observed in June and August. Similarly, values peaked in August for individuals in the meadow. Generally, chlorophyll content in plants tends to be highest during active growth and flowering [5]. Carotenoids accumulate more in flowers and fruits during flowering, and their content decreases in leaves. As leaves age, the chlorophyll content decreases as well. This aligns with our results, as we found consistently high fluorescence parameter values during the phenophase of flowering of the greatest number of cyclamens and seed dispersal across the trial plots. The trend in pigment concentration is similar in evergreen trees, with plants reaching maximum chlorophyll content in August and a significant decrease in September [5]. In November, we observed a negligible reduction in F_v/F_m but a more substantial decrease in the parameters F_m/F_0 and *Area*, especially in plants growing in the meadow. However, whether this decrease in PSII quantum efficiency was due to November frosts, more severe stress from high radiation, or heat and drought during the growing season remains unclear. Photosystem II is relatively sensitive to damage from high temperatures [24], but not from mild drought stress [25]. Nonetheless, these two factors often co-occur, leading to substantial PSII impairment [26]. Moreover, exposure to high temperatures and excessive light can inhibit the reparation or regeneration of photosystem II [27]. Along with drought effects, this can lead to leaf senescence and altered autumn phenology [28].

As reported by Klančnik et al. [29], the concentration of chlorophylls in cyclamen leaves increases with the canopy's closure, while the content of carotenoids and anthocyanins decreases. However, pigment composition and leaf optical properties were not measured in this study; therefore, interpretations involving these traits are based on previous literature. In shaded environments, reduced photoinhibition risk is often associated with higher chlorophyll concentrations, which may improve light harvesting efficiency under low irradiance conditions [17]. Moreover, the purple abaxial epidermis typical for cyclamen leaves may reduce light transmittance [29]. The study of assimilation pigments in *Cyclamen purpurascens* Mill. growing in “forest gaps” suggests that plants may gradually

adapt to changes in radiation intensity and UV levels through increasing the anthocyanin content in leaves during the growing season [30].

However, unlike most *Cyclamen* subspecies, no substantial variegation was observed in *Cyclamen purpurascens* subsp. *immaculatum* on the upper leaf side [29,31]. The leaves are predominantly dark green with a reddish abaxial side, which, in the context of the above-mentioned findings, may reflect occurrence in relatively shaded habitats rather than fully open environments. The reduced PSII quantum efficiency observed in meadow individuals is consistent with the more adverse growing conditions in this habitat. Nevertheless, finding comparative data for the *Cyclamen purpurascens* subsp. *immaculatum* is exceptionally difficult due to its very limited distribution area [32] and the lack of research performed on this taxon.

4.2. Relationship Between PSII Efficiency and Reproductive Performance

One of our hypotheses was that reduced PSII efficiency may indicate decreased physiological fitness and lower assimilate accumulation, which could subsequently be reflected in reduced flower formation and fruit set, particularly in individuals growing in the meadow. This assumption was based on the expectation that open meadow habitats, compared to forest stands, are characterised by higher irradiance, greater temperature fluctuations, and potentially lower soil moisture, which may increase exposure to heat and drought stress. Such environmental stressors can impair the photosynthetic apparatus, thereby reducing PSII efficiency. A decline in PSII performance may reflect stress-induced limitations in photosynthetic capacity and carbon assimilation, thereby reducing the availability of assimilates. Reduced assimilate availability may, in turn, constrain reproductive investment, affecting both flower formation and fruit set. Consistent with this pattern, declines in the quantum yield of PSII under stress conditions have repeatedly been associated with reduced reproductive output.

For example, transient declines in F_v/F_m under heat stress have been associated with reduced pollen viability, grain number, and final yield in wheat [33,34]. Similarly, heat stress during anthesis and grain filling significantly decreased grain number and yield in parallel with marked reductions in chlorophyll fluorescence parameters [35,36]. Moreover, recent reviews emphasise the mechanistic link between heat-induced declines in PSII efficiency, premature senescence, and reduced assimilate availability [37]. Collectively, these findings suggest that lower PSII quantum yield may be associated with diminished reproductive performance, although the relationship remains indirect.

However, our hypothesis was only partially supported. As expected, individuals growing in the meadow produced the fewest flowers on average and had the lowest PSII efficiency overall. However, as was mentioned, the link between PSII fluorescence parameters and fruit formation is indirect, as reproductive success depends on multiple factors, including pollinator availability, resource allocation, and environmental conditions beyond photosynthetic capacity. Although high PSII quantum efficiency and relatively high flower production were observed in the older forest (Forest_N), individuals growing there produced the fewest fruits. Notably, only 21% of flowers developed into fruits in this locality. In contrast, although the meadow exhibited fewer flowers per individual, approximately 40% of the flowers were converted into fruit. In the young forest, fruit set reached 59%, coinciding with relatively high flower production. This may reflect lower pollinator activity in dense forests. Meadow species generally produce larger and more abundant flowers, making open habitats more attractive to pollinators such as bumblebees, butterflies, and bees [38,39]. Consequently, the likelihood of pollination may be higher in open habitats than in closed-canopy forest stands. Moreover, even a well-functioning PSII cannot reach its full potential when light availability is a limiting factor.

Overall, our results suggest that individuals growing in the younger forest, which had moderate environmental conditions, showed not only high PSII quantum efficiency but also the highest number of flowers, resulting in the highest number of fruits produced. Therefore, such conditions appear to be optimal not only for cyclamen plant survival but also for their reproduction.

4.3. Limitations of the Study and Open Questions

The present study design involves certain aspects that should be considered when interpreting the results. Although we measured solar radiation, differences among populations were certainly influenced not only by the light regime itself, but also by other related environmental conditions (e.g., soil moisture, temperature, slope orientation, and competition with accompanying vegetation). Additional supportive data would allow for a more robust interpretation of the observed patterns. Also, the characterisation of the radiation environment has certain methodological limitations. Illumination intensity was estimated from lux measurements, which were further converted to approximate PAR values using a standard coefficient. Although the spectral composition of light differs considerably between forest understories and open habitats, direct PAR measurements would provide more precise information about the radiation environment. Nevertheless, the measured differences in illumination intensity, based on directly measured lux values and the corresponding estimated PAR values ($\mu\text{mol m}^{-2} \text{s}^{-1}$), among the studied habitats were substantial and likely sufficient for a general comparison of light conditions among localities.

Another limitation is the relatively low number of studied populations, which is partly related to the restricted occurrence and conservation status of the studied taxon. Available literature suggests that *Cyclamen purpurascens* subsp. *immaculatum* represents a narrow endemic with a very limited distribution area, occupying only tens of km² of suitable habitats, restricted to several localities in the Western Carpathians [32]. Its occurrence is associated with specific habitat conditions, mainly limestone beech forests, and populations are distributed discontinuously within ecologically suitable microhabitats. Due to the geographically restricted distribution area and relatively uniform habitat specificity of the taxon, we do not expect substantial environmental differences among localities, apart from microclimatic variables.

Interpretation of chlorophyll fluorescence parameters was limited by the technical capabilities of the instruments used. The fluorometer did not allow for measurements of more advanced parameters, such as non-photochemical quenching or performance index, and no portable device for non-destructive estimation of chlorophyll or pigment indices was available during the study. Nevertheless, despite these limitations, the present study provides one of the first ecophysiological insights into this endemic and protected taxon and may serve as a basis for future studies focused on the environmental ecology and conservation of *Cyclamen purpurascens* subsp. *immaculatum*.

5. Conclusions

Protecting endangered and endemic species plays a significant role in preserving biodiversity. The basis of adequate protection is a thorough knowledge of their biology. The results of our research provide insights into the impact of microclimatic conditions on the state of the assimilation apparatus and generative reproduction of the endemic *Cyclamen purpurascens* subsp. *immaculatum*. The monitored chlorophyll fluorescence parameters together with reproductive output suggest that moderately open forest stands with partial canopy cover provide more suitable conditions than either open meadows or densely shaded forest habitats. Therefore, maintaining structurally diverse forest habitats with heterogeneous light conditions may support the long-term persistence of plants such as *Cyclamen*.

men purpurascens subsp. *immaculatum*. From this perspective, forest management practices preserving partial canopy cover seem more suitable than large-scale clear-cutting, which may cause abrupt microclimatic changes, stronger competition from accompanying vegetation, and mechanical disturbance of the forest floor. Nevertheless, because only a limited number of populations were studied and several habitat-related factors may have affected the observed patterns, further research involving replicated sites and additional environmental variables is needed to confirm these findings in greater detail.

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References

1. Kliment, J. Komentovaný prehľad vyšších rastlín flóry Slovenska, uvádzaných v literatúre ako endemické taxóny. (An annotated overview of higher plants of the flora of Slovakia, mentioned in the literature as endemic taxa). In *Bulletin Slovenskej Botanickéj Spoločnosti Pri Slovenskej Akadémii Vied/Supplement*; Slovenská Botanická Spoločnosť Pri SAV: Bratislava, Slovakia, 1999.
2. Kanka, R.; Turis, P.; Chilová, V. Phytosociological Characteristic of the Plant Communities with the Occurrence of Endemic Species *Cyclamen Fatrense*. *Hacquetia* **2008**, *7*, 21–32. [[CrossRef](#)]
3. Turis, P. Ekobiológia, Vybrané Populačné Charakteristiky, Rozšírenie a Ochrana Cyklámenu Fatranského vo Východnej Časti Areálu. (Ecobiology, Selected Population Characteristics, Distribution and Protection of Fatra Sowbread in the Eastern Part of the Area). Ph.D. Thesis, Institute of Landscape Ecology, Slovak Academy of Science, Nitra, Slovakia, 2009.
4. Debussche, M. Frost and *Cyclamen* under Mediterranean Climatic Conditions. *J. Cyclamen Soc.* **2003**, *27*, 14–18.
5. Petrik, P.; Petek-Petrik, A.; Konôpková, A.; Fleischer, P.; Stojnic, S.; Zavadilova, I.; Kurjak, D. Seasonality of PSII Thermostability and Water Use Efficiency of in Situ Mountainous Norway Spruce (*Picea abies*). *J. For. Res.* **2023**, *34*, 197–208. [[CrossRef](#)]
6. Hajibarat, Z.; Saidi, A. Senescence-Associated Proteins and Nitrogen Remobilization in Grain Filling under Drought Stress Condition. *J. Genet. Eng. Biotechnol.* **2022**, *20*, 101. [[CrossRef](#)] [[PubMed](#)]
7. Tan, S.; Sha, Y.; Sun, L.; Li, Z. Abiotic Stress-Induced Leaf Senescence: Regulatory Mechanisms and Application. *Int. J. Mol. Sci.* **2023**, *24*, 11996. [[CrossRef](#)]
8. Debussche, M.; Garnier, E.; Thompson, J.D. Exploring the Causes of Variation in Phenology and Morphology in Mediterranean Geophytes: A Genus-Wide Study of *Cyclamen*. *Bot. J. Linn. Soc.* **2004**, *145*, 469–484. [[CrossRef](#)]
9. Brestič, M.; Živčák, M. PSII Fluorescence Techniques for Measurement of Drought and High Temperature Stress Signal in Crop Plants: Protocols and Applications. In *Molecular Stress Physiology of Plants*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 87–131.
10. Maxwell, K.; Johnson, G.N. Chlorophyll Fluorescence—A Practical Guide. *J. Exp. Bot.* **2000**, *51*, 659–668. [[CrossRef](#)]
11. Barboričová, M.; Filaček, A.; Mlynáriková Vysoká, D.; Gašparovič, K.; Živčák, M.; Brestič, M. Sensitivity of Fast Chlorophyll Fluorescence Parameters to Combined Heat and Drought Stress in Wheat Genotypes. *Plant Soil Environ.* **2022**, *68*, 309–316. [[CrossRef](#)]
12. Münchinger, I.K.; Hajek, P.; Akdogan, B.; Caicoya, A.T.; Kunert, N. Leaf Thermal Tolerance and Sensitivity of Temperate Tree Species Are Correlated with Leaf Physiological and Functional Drought Resistance Traits. *J. For. Res.* **2023**, *34*, 63–76. [[CrossRef](#)]

13. Yang, Z.; Tian, J.; Wang, Z.; Feng, K. Monitoring the Photosynthetic Performance of Grape Leaves Using a Hyperspectral-Based Machine Learning Model. *Eur. J. Agron.* **2022**, *140*, 126589. [\[CrossRef\]](#)
14. Turis, P. Veľkosť a Hustota Populácií Cyklámenu Fatranského (*Cyclamen fatrense Halda et Soják*) v Bukovskej Doline v Starohorských Vrchoch. Population Size and Density of Cyclamen Fatrense Halda et Soják in Bukovská Valley, Starohorské Vrchy Mountains. *Nat. Carp.* **2008**, *12*, 207–210.
15. Turis, P.; Vidlička, L. Relationship of Animals to the Cyclamen *Cyclamen fatrense Halda et Soják*: Pollinators, Consumers and Occasional Visitors. *Biologia* **2013**, *68*, 517–524. [\[CrossRef\]](#)
16. Thimijan, R.W.; Heins, R.D. Photometric, Radiometric, and Quantum Light Units of Measure: A Review of Procedures for Interconversion. *Horts* **1983**, *18*, 818–822. [\[CrossRef\]](#)
17. Mathur, S.; Agrawal, D.; Jajoo, A. Photosynthesis: Response to High Temperature Stress. *J. Photochem. Photobiol. B Biol.* **2014**, *137*, 116–126. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Bresson, J.; Vasseur, F.; Dauzat, M.; Koch, G.; Granier, C.; Vile, D. Quantifying Spatial Heterogeneity of Chlorophyll Fluorescence during Plant Growth and in Response to Water Stress. *Plant Methods* **2015**, *11*, 23. [\[CrossRef\]](#)
19. Roháček, K. Chlorophyll Fluorescence Parameters: The Definitions, Photosynthetic Meaning, and Mutual Relationships. *Photosynthetica* **2002**, *40*, 13–29. [\[CrossRef\]](#)
20. Lumley, T.; Diehr, P.; Emerson, S.; Chen, L. The Importance of the Normality Assumption in Large Public Health Data Sets. *Annu. Rev. Public Health* **2002**, *23*, 151–169. [\[CrossRef\]](#) [\[PubMed\]](#)
21. R Foundation for Statistical Computing. *R Core Team Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2022.
22. Karlsson, M.; Werner, J. Temperature Affects Leaf Unfolding Rate and Flowering of Cyclamen. *HortSci* **2001**, *36*, 292–294. [\[CrossRef\]](#)
23. Karlsson, M.G.; Werner, J.W. Temperature after Flower Initiation Affects Morphology and Flowering of Cyclamen. *Sci. Hortic.* **2001**, *91*, 357–363. [\[CrossRef\]](#)
24. Kurjak, D.; Konôpková, A.; Kmeť, J.; Macková, M.; Frýdl, J.; Živčák, M.; Palmroth, S.; Ditmarová, L.; Gömöry, D. Variation in the Performance and Thermostability of Photosystem II in European Beech (*Fagus sylvatica* L.) Provenances Is Influenced More by Acclimation than by Adaptation. *Eur. J. For. Res.* **2019**, *138*, 79–92. [\[CrossRef\]](#)
25. Kubov, M.; Fleischer, P.; Rozkošný, J.; Kurjak, D.; Konôpková, A.; Galko, J.; Húdoková, H.; Lalík, M.; Rell, S.; Pittner, J.; et al. Drought or Severe Drought? Hemiparasitic Yellow Mistletoe (*Loranthus europaeus*) Amplifies Drought Stress in Sessile Oak Trees (*Quercus Petraea*) by Altering Water Status and Physiological Responses. *Water* **2020**, *12*, 2985. [\[CrossRef\]](#)
26. Raja, V.; Qadir, S.U.; Alyemeni, M.N.; Ahmad, P. Impact of Drought and Heat Stress Individually and in Combination on Physio-Biochemical Parameters, Antioxidant Responses, and Gene Expression in *Solanum Lycopersicum*. *3 Biotech* **2020**, *10*, 208. [\[CrossRef\]](#)
27. Murata, N.; Takahashi, S.; Nishiyama, Y.; Allakhverdiev, S.I. Photoinhibition of Photosystem II under Environmental Stress. *Biochim. Biophys. Acta (BBA)—Bioenerg.* **2007**, *1767*, 414–421. [\[CrossRef\]](#)
28. Wu, C.; Peng, J.; Ciais, P.; Peñuelas, J.; Wang, H.; Beguería, S.; Andrew Black, T.; Jassal, R.S.; Zhang, X.; Yuan, W.; et al. Increased Drought Effects on the Phenology of Autumn Leaf Senescence. *Nat. Clim. Change* **2022**, *12*, 943–949. [\[CrossRef\]](#)
29. Klančnik, K.; Levpušček, M.; Gaberšček, A. Variegation and Red Abaxial Epidermis Define the Leaf Optical Properties of Cyclamen Purpurascens. *Flora* **2016**, *224*, 87–95. [\[CrossRef\]](#)
30. Ravnjak, B. Physiological Response of Local Populations of Species Cyclamen Purpurascens Mill. to Forest Gaps. *Appl. Ecol. Environ. Res.* **2019**, *17*, 11489–11508. [\[CrossRef\]](#)
31. Bavcon, J.; Ravnjak, B. New Varieties of the Common Cyclamen (*Cyclamen purpurascens* Mill.) in Slovenia. *Horticulturae* **2023**, *9*, 206. [\[CrossRef\]](#)
32. Kučera, J.; Turis, P.; Zozomova-Lihova, J.; Slovak, M. Cyclamen Fatrense, Myth or True Western Carpathian Endemic? Genetic and Morphological Evidence. *Preslia -Praha-* **2013**, *85*, 133–158.
33. Xu, J.; Lowe, C.; Hernandez-Leon, S.G.; Dreisigacker, S.; Reynolds, M.P.; Valenzuela-Soto, E.M.; Paul, M.J.; Heuer, S. The Effects of Brief Heat During Early Booting on Reproductive, Developmental, and Chlorophyll Physiological Performance in Common Wheat (*Triticum aestivum* L.). *Front. Plant Sci.* **2022**, *13*, 886541. [\[CrossRef\]](#)
34. Choudhary, M.; Yan, G.; Siddique, K.H.M.; Cowling, W.A. Heat Stress during Meiosis Has Lasting Impacts on Plant Growth and Reproduction in Wheat (*Triticum aestivum* L.). *Agronomy* **2022**, *12*, 987. [\[CrossRef\]](#)
35. Miroslavljević, M.; Mikić, S.; Župunski, V.; Abdelhakim, L.; Trkulja, D.; Zhou, R.; Špika, A.K.; Ottosen, C.-O. Effects of Heat Stress during Anthesis and Grain Filling Stages on Some Physiological and Agronomic Traits in Diverse Wheat Genotypes. *Plants* **2024**, *13*, 2083. [\[CrossRef\]](#)
36. Porter, J.R.; Gawith, M. Temperatures and the Growth and Development of Wheat: A Review. *Eur. J. Agron.* **1999**, *10*, 23–36. [\[CrossRef\]](#)

37. Pant, K.K.; Naik, J.; Barthakur, S.; Chandra, V. High-Temperature Stress in Wheat (*Triticum aestivum* L.): Unfolding the Impacts, Tolerance and Methods to Mitigate the Detrimental Effects. *Cereal Res. Commun.* **2025**, *53*, 1171–1197. [[CrossRef](#)]
38. Tian, H.; Harder, L.D.; Wang, A.; Zhang, D.; Liao, W. Habitat Effects on Reproductive Phenotype, Pollinator Behavior, Fecundity, and Mating Outcomes of a Bumble Bee–Pollinated Herb. *Am. J. Bot.* **2022**, *109*, 470–485. [[CrossRef](#)] [[PubMed](#)]
39. Hanula, J.L.; Horn, S.; O'Brien, J.J. Have Changing Forests Conditions Contributed to Pollinator Decline in the Southeastern United States? *For. Ecol. Manag.* **2015**, *348*, 142–152. [[CrossRef](#)]

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