The vitality of native grassland plants in current urban climatic conditions in Gauteng, South Africa

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ABSTRACT

Plants are essential components of urban microclimates, as they can help mitigate some of the adverse effects of urbanisation, enhance environmental quality, and thus contribute to overall species well-being and the sustainability of cities. Urban planners and policymakers often incorporate green infrastructure and urban greening into their strategies to create healthier and more livable urban environments. Plants are primary producers, serving as a baseline for the attraction and habitat of other species; they also provide vital ecosystem services, such as climate amelioration. Landscape designers and horticulturalists can influence plant selection through built environment interventions, increasing urban ecosystem services and benefits. Based on the evidence of native plant preferences by insects and people and their natural adaptation to regional climatic extremes, we tested, through an experimental study, the potential of native grassland plants to survive in assemblages in current urban environments. The study specifically monitored the tolerance of nine native grassland plant species to urban environments over six months in Gauteng, South Africa. A stratified random sampling was done by monitoring permanent quadrats in two purposefully engineered urban native gardens. Plant vitality was evaluated using chlorophyll *a* fluorescence. General climate data were obtained from a local weather station. Microclimatic temperature and humidity data were collected at each site and quadrat using Hygrochron High-Resolution Temperature and Humidity data loggers. The results indicated that all nine native plant species functioned with good photosynthetic health and can be recommended as resilient species that tolerate current urban conditions. Correlation studies indicated that two forb species, *Haplocarpha lyrata* and *Scabiosa columbaria*, showed great tolerance to current urban conditions. This vitality is likely contributed to their winter dormancy morphologically based on below-ground biomass, and their physiological adaptation to tolerate both wet and dry habitat conditions. This points to the potential of grassland forb species for urban use and the potential for climate adaptation in grassland areas.

1. Introduction

As global urbanisation rises, city planning and designs are increasingly oriented toward resource-efficient systems while ensuring good living standards (Haaland and Van den Bosch, 2015). High-quality public green spaces are also critical for human well-being and security (UN-Habitat, 2016), especially in the Global South, where this is often lacking (Dobbs et al., 2019; Breed et al., 2023). Rising global temperatures have raised concerns about monitoring and establishing resilient urban plant assemblages adaptable to current and changing urban climates (Haase and Hellwig, 2022). Most research on urban green space is conducted in the Global North (Breed et al., 2023; Shackleton et al., 2021), with recent examples of plant adaptation studies in Europe (e.g. Hanzl et al., 2021; Cortinovis et al., 2022; Haase and Hellwig, 2022) and the USA (e.g. Hobbie and Grimm, 2020), and fewer studies found in the Global South or Africa.

Africa, specifically sub-Saharan Africa, represents the fastest urbanisation rate of any continent (Du Toit et al., 2018), which poses an increasing multitude of risks and socio-ecological challenges (Dodman et al., 2017), including biodiversity loss (Elmqvist et al., 2015) exacerbated by climate change. Like the broader sub-Saharan African region, South Africa's climate is anticipated to undergo heightened fluctuations,

featuring more frequent and intense precipitation peaks that could result in both floods and droughts. Additionally, temperatures are expected to rise, with an escalation in occurrences of hot extremes and heatwaves (Engelbrecht, 2019; Maure et al., 2018; Weber et al., 2018). More specifically, for 2021 to 2050, this means that temperatures in the South African interior are projected to rise at approximately 1.5 to 2 times the global temperature increase rate. Temperature increases of more than 3 °C are likely, with an increase in very hot days varying from 40 to more than 70 days per year. Rainfall will increase in certain regions, with an increase in extreme rainfall events (Council for Scientific and Industrial Research (CSIR), 2019). Gauteng, specifically the Tshwane municipality, under low mitigation, will experience an average temperature increase of more than 3 °C by 2050, with a possible increase of up to 49 days of very hot days, an average rainfall decrease or increase between −19 to 62 mm, with a 2-day increase in extreme rainfall days (CSIR, 2023).

Given current and future climate projections, plant species play a vital role in countering negative urbanisation impacts such as the heat island effect (Ngulani and Shackleton, 2020) and extreme temperatures (Marando et al., 2022), which endanger both people and biodiversity (Samways et al., 2020), by providing critical ecosystem services. Urban environments with extensive impervious surfaces and lower wind speeds (Luo and Lau, 2019; Vujovic et al., 2021) contribute to elevated urban temperatures, known as the urban heat island effect (Hobbie and Grimm, 2020; Vujovic et al., 2021). Comparable conditions exist in natural impervious surfaces, such as rocky outcrops and cliff faces (Richardson et al., 2010). Yet, urban evolutionary changes, such as habitat modification, create a unique combination of selective pressures (Alberti et al., 2020), that prompt species to adapt behaviourally, morphologically and physiologically (e.g. Alberti, 2015).

Temperate grasslands are found in Africa, Asia, Europe, North and South America, Australia, and Oceania (Scholtz and Twidwell, 2022), covering almost one-third of Earth's terrestrial surface (Bengtsson et al., 2019), but are often disregarded for their diversity and carbon sink capacity. Grasslands provide a wide range of provisioning, supporting, regulating, and cultural ecosystem services (Bengtsson et al., 2019) with a high global economic value (Liu et al., 2022). The grassland biome in South Africa is a fire-prone ecosystem particularly threatened by cultivation, plantation forestry, climate change (Mucina and Rutherford, 2006) and urban expansion, specifically in Gauteng province, where the study is located (Pfab et al., 2017). Much of this grassland biome is Highveld Grassland, one of the two richest primary grasslands globally in biodiversity, with less than 2 % protected (Mucina and Rutherford, 2006). Furthermore, Gauteng is encompassed by two of the nine national biodiversity priority areas, implying that biodiversity and ecosystem services are under serious threat at a global scale (Pfab et al., 2017).

Serving as food web foundations, vegetation cover, composition and structure are key determinants of habitat quality, influencing urban biodiversity (Beninde et al., 2015). Plant selection for their urban survival ability is crucial due to their roles in ecosystem functions and services, including climate regulation (Ngulani and Shackleton, 2020), soil health (e.g., Shelef et al., 2017; Kumar and Karthika, 2020) and native plants supporting various fauna such as invertebrates, birds, other vertebrates (e.g. Berthon et al., 2021; Nielsen et al., 2014) and insects through habitat and food provision (Cardoso et al., 2020; Samways et al., 2020). Vegetation is the urban biological component most intentionally dispersed through anthropogenic means (Avolio et al., 2021).

The capacity of plants to thrive amidst urbanisation and projected climate shifts relies on their acclimation ability, which is closely tied to their overall health and survival. Acclimation refers to how plants adjust their physiological and biochemical processes in response to environmental changes (Zandalinas et al., 2022). Consequently, species selection and prioritisation are essential, shaping the benefits and services landscape designers and horticulturalists add through continuous interventions.

This study considers plant vitality as a factor in selecting urban plant material towards current (and future) urban climatic conditions. Fluctuations in temperature and rainfall influence the vitality of plants. The ability of plants to acclimate to a changing environment is crucial for food security and ecosystem functions. Maximising the likelihood of survival can be achieved by actively selecting resilient plants in landscape planning and interventions. South Africa, like several other countries (Kiers et al., 2022), must reduce its dependence on extensive watering practices in light of current and future climate-change-induced aridity (Engelbrecht, 2019). Native species have developed strong adaptations to manage the regional climatic extremes (Threlfall et al. 2018). These extremes tend to intensify in urban environments, resulting in increased temperatures, reduced moisture, and a heightened risk of flooding. While grassland species have been proven to have potential for urban wasteland restoration (Fischer et al., 2013), the regional use of native species by landscape architects is seen as both a natural and cultural landscape conservation process (Nezhad et al., 2015; Breed, 2022).

Although several studies consider the survival and adaptation of plant species to climatic conditions (Waldvogel et al., 2020; Anderson and Song, 2020; Teixeira et al., 2022), none have focused on monitoring stress tolerance. Various environmental interactions and genetic traits influence abiotic stress tolerance in plants (Jha et al., 2014). Chlorophyll *a* fluorescence, a light-use efficiency sensitive optical signal generated during plant photosynthesis (Porcar-Castell et al., 2014), is a sensitive and unique tool for evaluating plant vitality across various conditions because it offers easy-to-use, non-destructive, real-time, cost-effective and quantitative insights (Kalaji et al., 2016; Samborska et al., 2019; Strasser et al., 2000) into the photosynthetic efficiency and overall health of plants (Herritt et al., 2020; Strasser et al., 2000). Its sensitivity to stress factors and its ability to provide early warnings make it an invaluable tool for researchers, agronomists, and anyone working with plants (Strasser et al., 2000). The use of chlorophyll fluorescence is extensively discussed in studies by Strasser et al. (2000) and Kalaji et al., (2014; 2017).

Previous studies on plant stress tolerance have mainly focused on the agricultural sector and crops (Herritt et al., 2020; Linn et al., 2020), examining the factors contributing to the success of invasive species (Díaz-Barradas et al., 2020) and exploring plant performance trade-offs (Jung et al., 2020). Similarly, in Africa, studies on plant stress tolerance have mainly examined crop responses in the agricultural sector (e.g. Dlamini, 2021; Mabhaudhi et al., 2017; Fenta et al., 2014), with some investigations on the water stress responses of native fynbos and succulent karoo species (Jacobsen et al., 2007), and the photosynthetic potential of the desert plant Welwitschia mirabilis (e.g. Berner et al., 2021; Krüger et al., 2017). Only one recent urban plant stress study was identified that focused on the decline of oak trees (*Quercus robur*) in Potchefstroom (Ludick et al., 2023). An untapped opportunity exists for monitoring plant stress, particularly concerning temperature and moisture in urban environments.

The study objective was to evaluate the suitability of native grassland plant species to flourish in current urban settings and their ability to withstand urban-induced extreme temperatures and altered moisture levels. The main question asks: What is the tolerance (survival capacity) of the selected native grassland plant species to temperature and humidity extremes in typical urban environments?

The study aims to guide appropriate urban plant selection considering the effect of heat islands in urban settings. Despite the popularity of indigenous species in the South African green industry (Breed, 2022), there are no local guidelines for landscape designers or horticulturists regarding native grassland species selection to enhance ecosystem functions or services while being tolerant against extreme urban conditions.

2. Material and methods

2.1. Study area

Situated in Gauteng province, the Metropolitan Municipality of Tshwane (Tshwane) (City of Tshwane, 2015), which includes Pretoria, spans 6 368 km2, making it the largest metropolitan municipality and ranking fifth in population size nationally (Statistics South Africa [Stats SA], 2011). This area experiences a continental-type climate due to its altitude exceeding 1000 m above sea level, with high summer maximum and low winter minimum temperatures (South African Weather Service (SAWS), 2021). With a 'Cwa' Köppen-Geiger climate classification, Tshwane has hot, rainy summers and dry winters, receiving minimal winter rainfall. This region lies amidst savannah and grassland biomes, featuring diverse topography at an average altitude of 1350 m (Mucina and Rutherford, 2006; Monama, 2016; SAWS, 2021).

The study was conducted in two native intervention gardens (Fig. 1) implemented on the University of Pretoria campus, 10 km East of Tshwane's central business district. These purposefully designed gardens featured introduced native grassland species for research purposes. A relatively untouched section of natural Moot Plain grassland close to the native gardens served as a natural reference area with similar plant composition. The study areas were relatively small and isolated, with moderate urban foot traffic. Urban variability and daily interferences were acknowledged, so no site controls were imposed. Refer to Table A.1 (Appendix A supplementary material) for specific conditions.

The first intervention site was the Future Africa Native (FA) (25°45′07.4 "S 28°15′40.1" E) garden at the Future Africa Research Complex (Future Africa), Hillcrest campus. It was established in October 2018 for research and featured more than 70 plant species. The second intervention site was the Javett Native (JA) garden (25°45′23.9 "S 28°13′45.9" E) at the JAVETT-UP Art Centre (Javett), Hatfield campus, established in January 2019 and accommodating more than 40 plant species for research. Both gardens primarily featured native grassland plants from Gauteng and Tshwane areas.

The Moot grassland reference site (GL) (25°44′35.00 "S

28°15′44.26" E) at the Hillcrest Campus was historically a widespread vegetation type but is now protected due to its rarity (Le Roux, 2022; University of Pretoria, 2020). Over a century old, first as part of a grazing farm and then a University-owned experimental farm (inferred from Rautenbach et al., 1960; Nel, 2008), it is relatively undisturbed, though grazing occurred historically. Since 2019, controlled bi-annual burning has been re-established since fire plays a crucial role in grassland distribution (Leys et al., 2018; Puttick et al., 2022). Hosting native grassland species, it is the established reference for comparing native plant cover refugia (Breed et al., 2022; Van Der Walt, 2023), tolerance and vitality with the Future Africa and Javett native gardens. Study area specifics are in Table A.1 (Appendix A supplementary material).

2.2. Experimental design

2.2.1. Interferences

In the native gardens, typical urban disturbances were present, but using fertilisers or pesticides was prohibited. Interferences included light pollution, irrigation, trampling, weeding, trimming, mulch importation, seed harvesting, and foreign matter disposals such as plastic. These interferences arise from varying management regimes and moderate student foot traffic near the sites. In contrast, the Moot grassland, being more isolated, only experienced a controlled burning regime every second year.

2.2.2. Plant species selection

The composition of native plant species at the intervention sites was chosen from commercial stock in 2017–2018, from recommendations of native grassland plant growers (see Breed et al., 2022). The species were selected to be mainly grassland species native or near-native to the Tshwane bioregion. The temperate grasslands of southern Africa consist of herbaceous plant communities of graminoids (mostly perennial grasses of the Poaceae Family) and a forb component of long-lived perennials that has significant below-ground biomass (corms, rhizomes, tubers or bulbs), which allows them to disappear in winter and re-appear in spring (Carbutt et al., 2011). Species that were easy to source,

Fig. 1. Location of the intervention sites (Future Africa and Javett Native gardens) and the reference site (Grassland) in Tshwane (Image Source: Google Earth, © 2023 Airbus).

believed to be relatively tolerant against temperature and moisture extremes, and maintenance-friendly were selected. Considering that native graminoids and forbs often disappear below ground in the winter (Carbutt et al., 2011), the assemblages also included some regional evergreen species and dwarf shrubs selected for winter plant presence. The selection further considered diverse composition, plant functional types (Symstad et al., 2000), structural diversity (Koricheva et al., 2000) and overlapping flowering periods for pollinator attraction (Hunter, 2011), with the objective of influencing insect abundance and diversity positively.

Based on input from plant growers, nine native grassland plant species (see Table 1 and Table D.1 Appendix D supplementary material) were chosen for plant tolerance monitoring in each of the native study sites, namely FA and JA, with the GL as a reference where possible. Among these plant species, only two (*Hypoxis hemerocallidea* and *Scabiosa columbaria*) were naturally present in the GL.

2.3. Baseline soil measurements

Grab soil sampling was conducted to evaluate potential variations in soil moisture, soil organic matter content, and soil organic carbon levels between the three study sites in summer and winter. Soil sampling sites were relatively undisturbed in the grassland, but disturbed in the Future Africa and Javett native gardens, where 100 mm of topsoil were recently imported for garden establishment in pre-existing urban conditions. The grassland remains untouched, except for biennial burning. Maintenance, including occasional weeding, occurs in the Future Africa and Javett gardens, causing soil disturbance.

Sampling occurred twice in 2020, during summer (March) and winter (July). Four samples were randomly collected from each area in each collection period, ensuring that previously sampled locations were excluded. The Agricultural Research Council used standard measurement methods to calculate soil moisture, organic matter and carbon. Soil moisture was calculated by weighing samples, drying them at 105 °C, weighing them again and then calculating the sample water weight loss, which is then used to calculate the percentage of soil moisture. Soil organic matter was measured through the Loss on Ignition method, whereby samples were placed for four to six hours in a 600 °C oven. Soil organic carbon was determined following the rapid titration method given by Walkley and Black (1934).

2.4. Macro- and microclimate

The study considered the potential impacts of temperature, moisture/humidity and rainfall on plant vitality, due to their relevance to current urban climatic conditions. Data on temperature, moisture/humidity and rainfall extremes were collected from the Hillcrest campus weather station, approximately 500 m from the FA garden. To assess the

microclimate of each study area (FA, JA and the GL), Hygrochron High-Resolution Temperature and Humidity data loggers from Maxim Integrated, also called i-buttons, were placed in each quadrat, capturing local variations in temperature and humidity. These i-buttons autonomously recorded hourly data in a secured memory system. The durable stainless-steel casing protects against environmental dangers such as dirt, moisture, and shock. The temperature range of the device is – 20 °C to + 85 °C, and 0 % to 100 % for relative humidity (Maxim Integrated, 2020).

The buttons were protected against water, such as irrigation and rain, by a cover that consisted of a polyethylene cup turned upside down. The button and cup were suspended on iron rods, using polyethylene cable ties, approximately 30 cm above the ground.

Weather data were obtained from the Hatfield weather station for the six-month measurement period (October 2020 to March 2021) to demonstrate the weather conditions during the plant vitality monitoring (see Appendix B supplementary material). Rainfall data (Fig. 3) seven days before each measurement was considered and obtained from the Hatfield Weather Station for October 2020 to March 2021. The maximum and minimum temperature and relative humidity (see Appendix C supplementary material) three days before each measurement (October 2020 to March 2021) were considered and obtained from the i-buttons to demonstrate microclimate conditions directly before the plant stress was measured. Measuring the microclimate in these microhabitats enables us to determine whether these microclimates and their variables influenced plant stress levels. These possible relationships were investigated through correlation studies between weather and plant vitality parameters.

2.5. Monitoring of selected native plant species

Based on observed micro-habitats, permanent stratified random sampling quadrats were placed in each study site. The FA and JA sites had four quadrats each, and the GL site had five. Circular quadrats, favoured for accommodating an i-button sensor on an iron rod in the centre, were chosen, and a standardised 2 m diameter (3.14 m^2) was employed for vegetation analysis, following grassland recommendations (Kent, 2011). A 1 m rope was attached to the i-button pole to establish circular shapes, forming a circle when kept taut while walking around the pole. Within each circular quadrat, the nine designated native species were identified, with plant vitality assessed by sampling leaves from three plants of the same species. Not all i-buttons had all nine species present.

Fieldwork spanned one year (May 2020 to May 2021), focusing on a consistent six-month period (October 2020 to March 2021) with concurrent plant stress and i-button data for the nine native grassland species studied. Plant dormancy and system faults resulted in inconsecutive stress and i-button readings for six of the 12 months.

2.6. Plant vitality

In plants, sunlight is absorbed by chlorophyll molecules, primarily within the photosynthetically active radiation of 400 to 700 nm. This absorbed energy follows two competing paths: photochemical, where it is used for chemical processes like photosynthesis, and non-photochemical, where it is released as heat and light, specifically chlorophyll fluorescence, a measure of plant stress (Strasser et al., 2000; Hansatech, 2018; McCree, 1972). Competition exists between these two processes for the absorbed energy. As one process's rate decreases, the other's rate increases. When less energy is used for photochemistry (photosynthesis), more energy is released as heat and chlorophyll fluorescence, a non-photochemical process unrelated to photosynthesis (Hansatech, 2018). Plant stress from various sources like temperature, pollutants, or nutrient deficiency impacts the plant's ability to efficiently channel absorbed solar energy into the photochemical process. Consequently, this stress affects chlorophyll fluorescence emission intensity,

Table 1
Summary of lowest PI$_{total}$ and F$_v$/F$_m$ values recorded for each species as well as their flowering periods.

Species	PI$_{total}$ (Lowest value)	F$_v$/F$_m$ (Lowest value)	Flowering Period
Crossandra greenstockii (CG)	November 2020	March 2021	Summer
Dicliptera eenii	February 2021	March 2021	Summer
Elionurus muticus	March 2021	March 2021	Summer
Hypoxis hemerocallidea	March 2021	February 2021	Summer
Haplocarpha lyrata	December 2020	February, March 2021	Summer
Lantana rugosa	October 2020	March 2021	Spring, Summer
Scirpoides burkei	March 2021	March 2021	Summer
Scabiosa columbaria	January 2021	February 2021	Year-round
Themeda triandra	December 2020	October 2020	Spring and summer

indicating lowered photosynthetic performance. As stress rises, energy dissipation via chlorophyll fluorescence increases, which indicates plant stress (Hansatech, 2018).

Plant vitality, which can be significantly affected by urban climatic conditions, was evaluated by analysing the fluorescence signal from leaves' chlorophyll. A non-modulated Handy Plant Efficiency Analyser (Handy PEA) fluorimeter (Hansatech Instruments Ltd technology) was used to measure the chlorophyll fluorescence signal of dark-adapted plants. Dark-adapted samples are light-deprived to fully oxidise their reaction centres, preparing them for photochemistry. This suppresses fluorescence yield before light saturation and ensures accurate fluorescence signal measurements (Hansatech, 2018). The measurement process followed guidelines outlined in the system manual for the Handy PEA + instrument (Hansatech, 2018) and publications by Strasser et al. (2000). Monthly samples of the nine plant species in each native study site were collected inside the quadrats, where present.

2.7. Data analysis

Soil analysis was done in a quadruplicate manner. Each site had four samples taken, the data of which were then averaged to a single data point in Fig. 2.

The fluorescence data from the Handy PEA was extracted using the PEA Plus software application (v. 1.13). The statistics programme, IBM SPSS Statistics programme [Version 28.0.1.0 (1 4 2)] was used to analyse the data. The data was analysed over six months, from October 2020 to March 2021, responding to plant dormancy in winter (Carbutt et al., 2011). During each sampling period, three leaves were obtained from three different plants from each of the nine selected plant species (if found within any quadrat) and dark-adapted for approximately two hours. Subsequently, a leaf clip was attached to the leaf and chlorophyll fluorescence measurements were taken (Hansatech, 2018). The maximum quantum yield of photochemistry (F_v/F_m) and the total performance index (PI_{total}) are two of several JIP test parameters used to evaluate plant vitality. Refer to Strasser et al. (2000) and Kalaji et al., (2014; 2017) for a comprehensive explication.

The maximum quantum yield of the photochemistry parameter (F_v/F_m) assessed photosystem II functionality between different plant species. F_v/F_m represents the maximum quantum yield of a stable charge separation for the dark-adapted state (Kalaji et al., 2017), with F_v representing the maximum variable fluorescence and F_m the maximum chlorophyll α fluorescence yield in the dark-adapted state (Kalaji et al., 2014). The Performance Index (PI) serves as an indicator of plant or sample vitality (Strasser et al., 2000), representing the internal strength of the sample against external constraints (Hansatech, 2018). It provides quantifiable insights into the current state of plant performance amid stress (Strasser et al., 2004). PI_{tot} is highly responsive to environmental stress (Tsimilli-Michael and Strasser, 2013) and closely linked to plant activity outcomes, including survival and growth in stress conditions (e. g., Yusuf et al., 2010; Strasser et al., 2007, 2010). The Total Performance Index (PI_{total}) allows for comparisons within a species, not between species.

Statistical tests included one-way ANOVA with Tukey HSD Post Hoc tests and independent-sample T-tests to identify significant differences. For F_v/F_m, these tests evaluated species variations across sites and months, inter-species differences across all sites and months, distinctions between months across all sites, and variances between sites across all months. For PI_{total}, the tests were to identify significant differences both within a species per month and site, and between species. Additionally, the parameter Fv/Fm (maximum quantum yield of photochemistry) was employed to compare photosystem II functionality for each species across study sites and months.

One-way ANOVA was conducted to reveal significant parametric differences between the nine selected plant species (for F_v/F_m) and within each species (for PI_{total}), where the means of more than two groups had to be compared. A Tukey HSD post hoc test was performed where a significant difference was observed to investigate the statistical differences between groups. Where only two groups or cases were within groups, the Independent-Samples T-Test was used where equal variance was assumed if Levene's test for Equality of Variances was higher than the alpha level ($p = 0.05$). The two-sided *p*-value was used to determine significance.

The relationships between maximum quantum yield and weather variables were investigated using the Pearson product-moment correlation coefficient. These weather variables included average total rainfall seven days before stress measurement, average maximum and
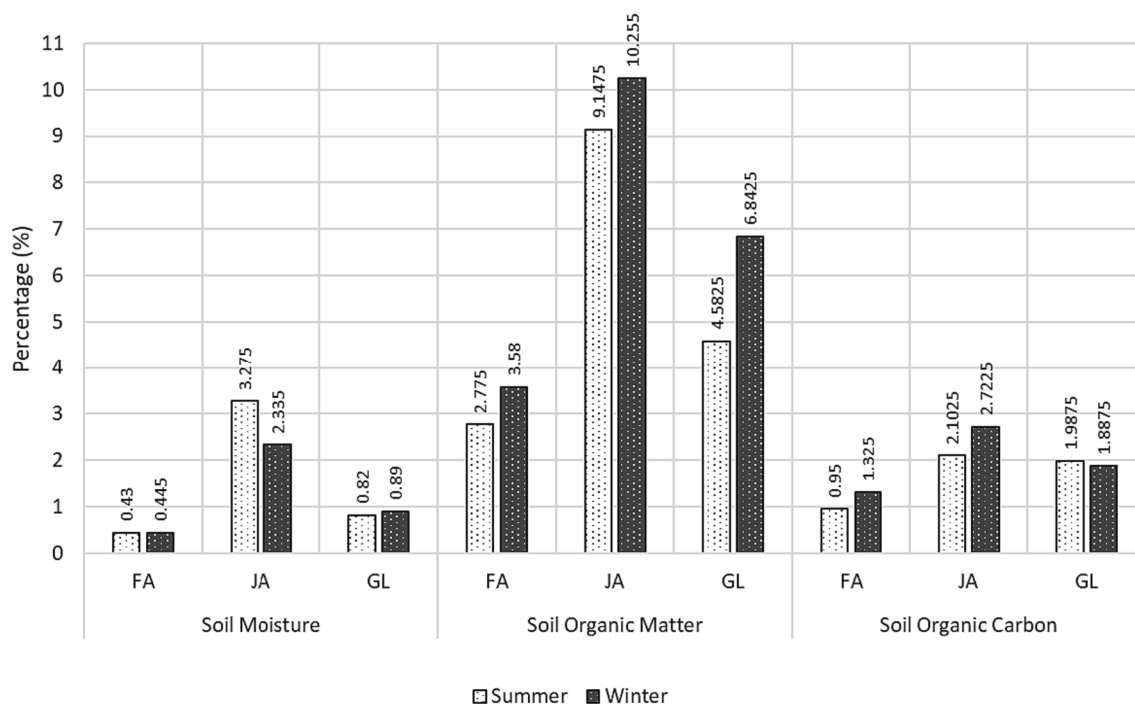

Fig. 2. Average soil moisture, soil organic matter, and soil organic carbon percentage of each study site in the summer and winter of 2020.

minimum temperature, and relative humidity three days prior. The Pearson product-moment correlation coefficient was also used to explore the relationship between each species' maximum quantum yield and the total performance index with the various weather variables.

3. Results

3.1. Baseline soil and weather measurements

In 2020, soil moisture (SM), soil organic matter (SOM), and soil carbon (SOC) were measured at each study site. Soil measurements were taken to establish a baseline for current and future studies that may be conducted for insight into the possible relationship between soil and plant health. Analysis (see Fig. 2) revealed variations among the sites. JA exhibited the highest soil moisture, organic matter and organic carbon percentages, while FA had the lowest values.

3.2. Plant vitality

3.2.1. Weather conditions before plant vitality measurement

3.2.2. Plant vitality assessment

3.2.2.1. Combined maximum quantum yield of photochemistry (F_v/F_m).
The differences in mean F_v/F_m between the study sites, the months and the plant species were investigated (Fig. 4). Although the three study sites did not differ significantly, Tukey's post hoc HSD tests revealed that the months from OCT20 to JAN21 had significantly ($p < 0.001$) higher mean F_v/F_m values than FEB21 and MAR21. *Scripoides burkei* had a significantly ($p < 0.001$) higher, while in contrast *Dicliptera eenii had* a significantly ($p < 0.001$) lower F_v/F_m than the other eight species.

The significance of the mean Total Performance Index and Maximum Quantum Yield value and variations for each of the nine native grassland plant species over six months are given in Fig. 5 and Fig. 6.

Significant differences existed between the months for the mean F_v/F_m values of all species, but only three species had significant differences between the months for PI$_{total}$. Specific significant differences are indicated in Fig. 5 and Fig. 6, with different letters denoting significant differences ($p < 0.05$) between six months.

3.2.3. Correlations

3.2.3.1. Correlation between combined F_v/F_m and weather data.
There was a small positive correlation (Table 2) between F_v/F_m and Max T_{avg}, $r = 0.205$, $n = 1019$, $p < 0.001$, and Min T_{avg}, $r = 0.072$, $n = 1019$, $p = 0.021$ with higher maximum and minimum temperatures associated with higher maximum quantum yield. There was a small negative

correlation between F_v/F_m and Min RH$_{avg}$, $r = 0.217$, $n = 1019$, $p < 0.001$, with lower minimum relative humidity associated with higher maximum quantum yield.

3.2.3.2. Correlation between PI$_{tot}$ and F_v/F_m per species and weather data.
There were several positive correlations between each species' maximum quantum yield and the total performance index with the various weather variables, as shown in Table 3.

4. Discussion

4.1. Plant vitality assessment

The maximum quantum yield of photochemistry (F_v/F_m) is one of several JIP test parameters used to assess plant vitality. F_v/F_m values between approximately 0.75 and 0.85 indicate that photosystem II is not damaged (Quiles, 2005; Hansatech, 2018; Björkman and Demmig, 1987; Pfündel, 1998). Stress conditions lead to photoinhibition, damaging the photosystem II complex and lowering these values (e.g. Björkman and Demmig, 1987; Van Wijk and Krause, 1991; Tyystjärvi and Aro, 1996).

Performance Index (PI) is an indicator of the plant or sample vitality (Strasser et al., 2000) by assessing the overall performance and efficiency of the photosynthetic apparatus. It considers several chlorophyll fluorescence parameters, such as light energy absorption, the maximum quantum yield of photosystem II (PSII), electron transport efficiency and energy dissipation efficiency (Swoczyna et al., 2019). It gives us quantitative information on plant vitality under stress (Strasser et al., 2004). It provides a more holistic view of the photosynthetic performance of the plant than individual parameters alone, allowing the evaluation of the efficiency of light absorption, energy transfer, and electron transport within the photosynthetic system.

4.2. Combined maximum quantum yield of photochemistry (F_v/F_m)

No significant mean F_v/F_m value differences were found between the GL, FA, and JA sites. Since the mean values consistently exceeded the 0.75 threshold, all nine plant species could acclimate to the conditions at all the study sites.

Mean F_v/F_m values consistently exceeded the optimal threshold value of 0.75 each month, indicating photosystem II's excellent quantum efficiency. Lower values emerged in February and March 2021, potentially due to reduced rainfall and high temperatures (>30 °C), with the lowest temperature recorded in March 2021 (5 °C). Similar rainfall and temperature extremes were seen in October 2020. However, the distinction lies in February and March 2021, having lower minimum relative humidity (RH) on days with extreme temperatures. While October 2020 saw rainfall two days prior to measurements, February 2021 received rain four days prior and March 2021 seven days before
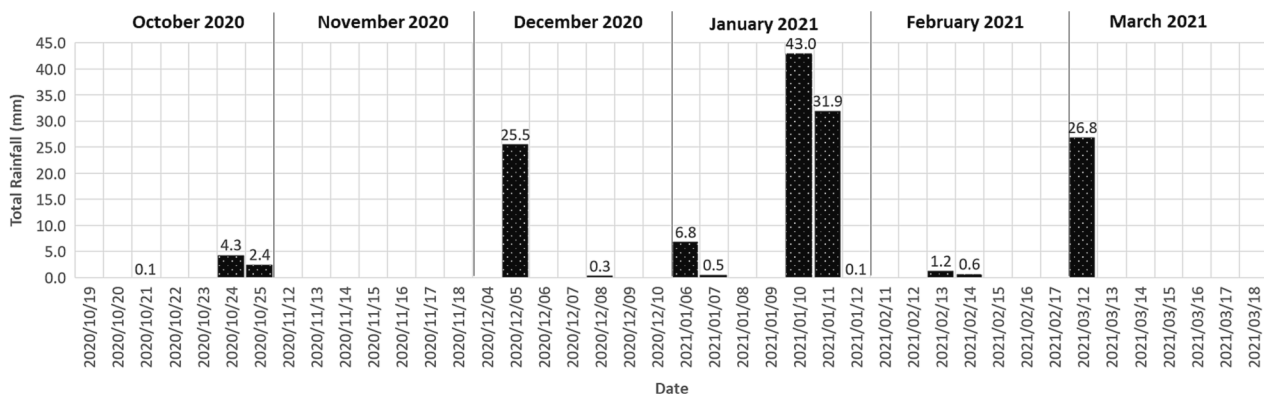

Fig. 3. Total rain (mm) from the weather station seven days before the day of plant stress measurement during the plant tolerance period, October 2020 – March 2021.
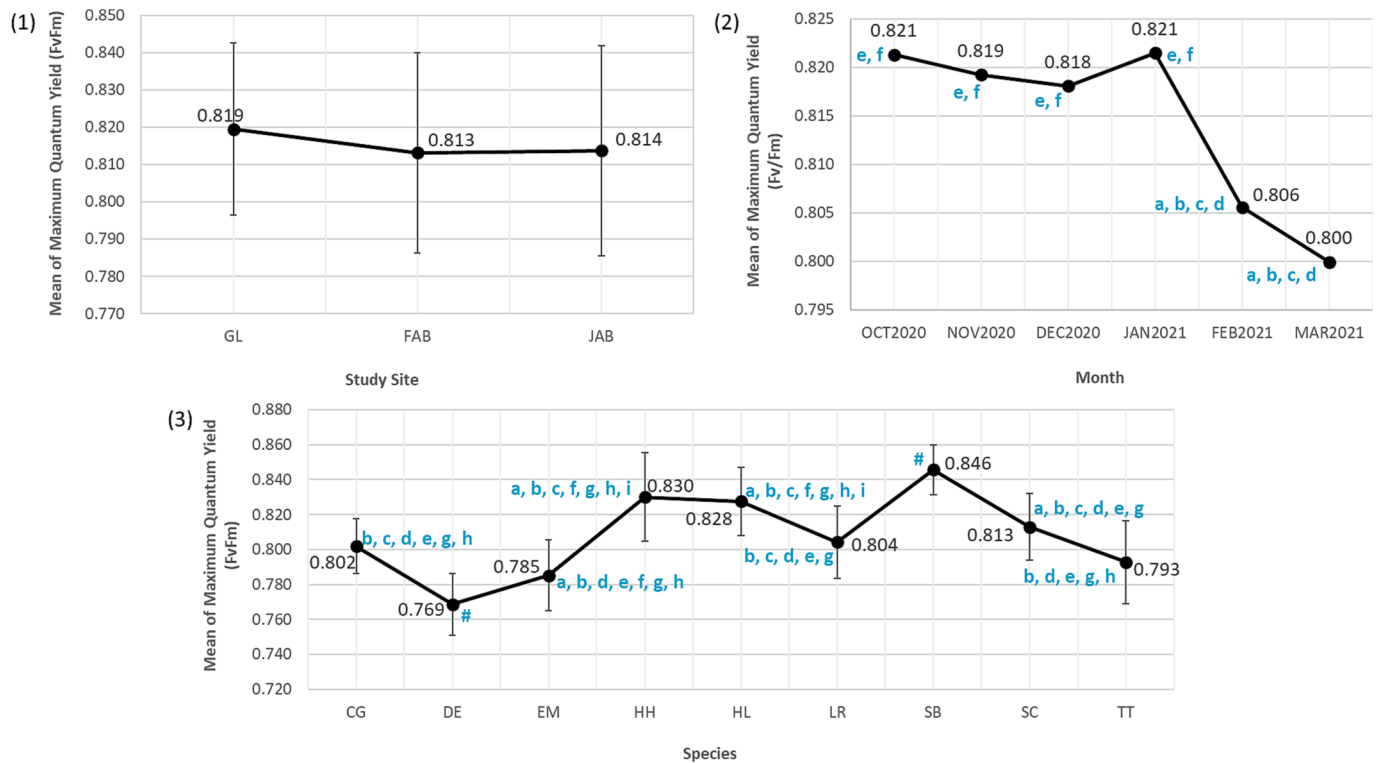
Fig. 4. (1) Variation of the mean F_v/F_m value between the three native study sites. No significant difference (p < 0.05) difference exists between the mean values of F_V/F_M of the study sites. (2) Monthly variation of the mean F_v/F_m value across all study sites collectively. The letters denote significant differences ($p < 0.05$) differences with a specific month: (a) OCT2020, (b) NOV2020, (c) DEC2020, (d) JAN2020, (e) FEB2020, (f) MAR2020. (3) Variation of the mean F_v/F_m value between the nine species of plants. The letters denote significant ($p < 0.05$) differences with a specific species: (a) CG, (b) DE, (c) EM, (d) HH, (e) HL, (f) LR, (g) SB, (h) SC, (i) TT. The error bars represent the standard deviation (mean ± SE).

the measurements.

Despite consistently high maximum temperatures (>30 °C), including three days before measurement (>27 °C), and many microclimate temperatures surpassing 40 °C, all plant species exhibited good photosynthetic performance in all months. This suggests their potential acclimation to current urban climatic conditions, such as high temperatures (Luo and Lau, 2019; Hobbie and Grimm, 2020; Vujovic et al., 2021). However, it is worth noting that native garden sites received irrigation, which likely contributed to their ability to withstand elevated temperatures. Consequently, irrigation must be acknowledged as contributing to the results of this study. Future research could control irrigation to assess plant stress tolerance once the species are well established. During winter (June and July), irrigation was halted to mimic natural grassland conditions. Yet, data for these months were unattainable due to plant dormancy (i.e. deciduous plants shedding their leaves and dying back underground during winter), which prevented sampling.

Different plant species exhibited varying results, but all maintained mean F_v/F_m values above 0.75, indicating functioning photosystem II (PSII). Notably, *Scirpoides burkei* demonstrated a significantly higher optimum F_v/F_m than the other species, whereas *Dicliptera eenii* exhibited a considerably lower optimum F_v/F_m. *Scirpoides burkei*, a graminoid, possess thick and robust leaves (Wentzel, 2023b) in contrast to the other species' thinner and more delicate leaves. The relatively thin leaves of *Dicliptera eenii* were prone to wilt upon collection. *Dicliptera eenii* prefers semi-shade (Wentzel, 2023a), while the remaining species prefer full sun. Grassland species receive shade from taller grasses and dwarf shrubs. *Dicliptera eenii*'s exposure to full sun could explain its lower mean F_v/F_m. Nonetheless, the full-sun conditions did not induce significant stress in *Dicliptera eenii*.

4.2.1. Variation of F_v/F_m value between species within sites

Only *Hypoxis hemerocallidea* and *Scabiosa columbaria*, naturally occurring in the GL, were successfully measured, offering a reference for the FA and JA sites. They demonstrate acclimation within the GL environment, with thick-leaved *Hypoxis hemerocallidea* displaying a significantly higher mean F_v/F_m value. Peak performance occurred in January 2021, marked by the second-highest maximum temperature among all months, the highest minimum temperature in the GL, and the highest total rainfall seven days before measurements. This suggests their potential to tolerate extreme temperatures and moisture, potentially influenced by the combined factors. While maximum and minimum temperatures were consistently high three to four days before measurements, they were not the highest or lowest across all months.

Scirpoides burkei was absent in FA. All species maintained mean F_v/F_m values above 0.75, signifying no significant stress. *Dicliptera eenii* displayed the lowest optimal F_v/F_m value, while the hairy-leaved *Haplocarpha lyrata* had the highest. This discrepancy may be attributed to *Dicliptera eenii*'s preference for semi-shade conditions, but it did not lead to PSII damage. The mean F_v/F_m values remained consistently above the threshold of 0.75 throughout all months, indicating acclimatisation to the environment.

In January 2021, like the GL, the highest mean F_v/F_m value was observed, with significant differences only noted compared to February and March 2021. Microclimatic conditions resembling the GL were present, but the FA had a higher minimum temperature three to four days before measurements.

All species were present in JA, and their mean F_v/F_m values remained above the 0.75 threshold, indicating no significant stress. Like FA, *Dicliptera eenii* exhibited the lowest mean F_v/F_m values, while *Scirpoides burkei* had the highest, followed by *Hypoxis hemerocallidea* and *Haplocarpha lyrata*. In March 2021, there was a significantly lower mean F_v/F_m value, but it still exceeded 0.75. This was likely influenced by higher
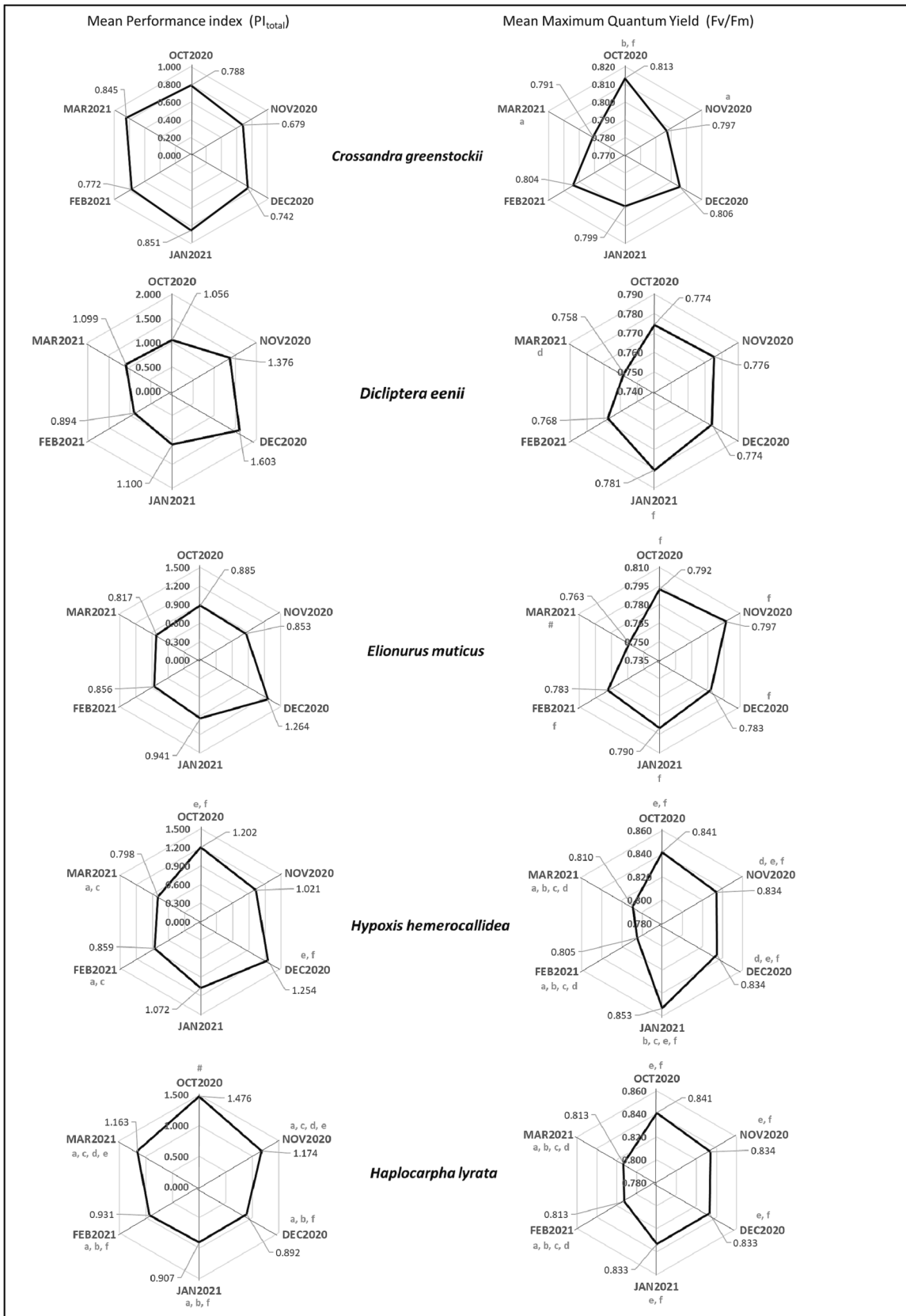
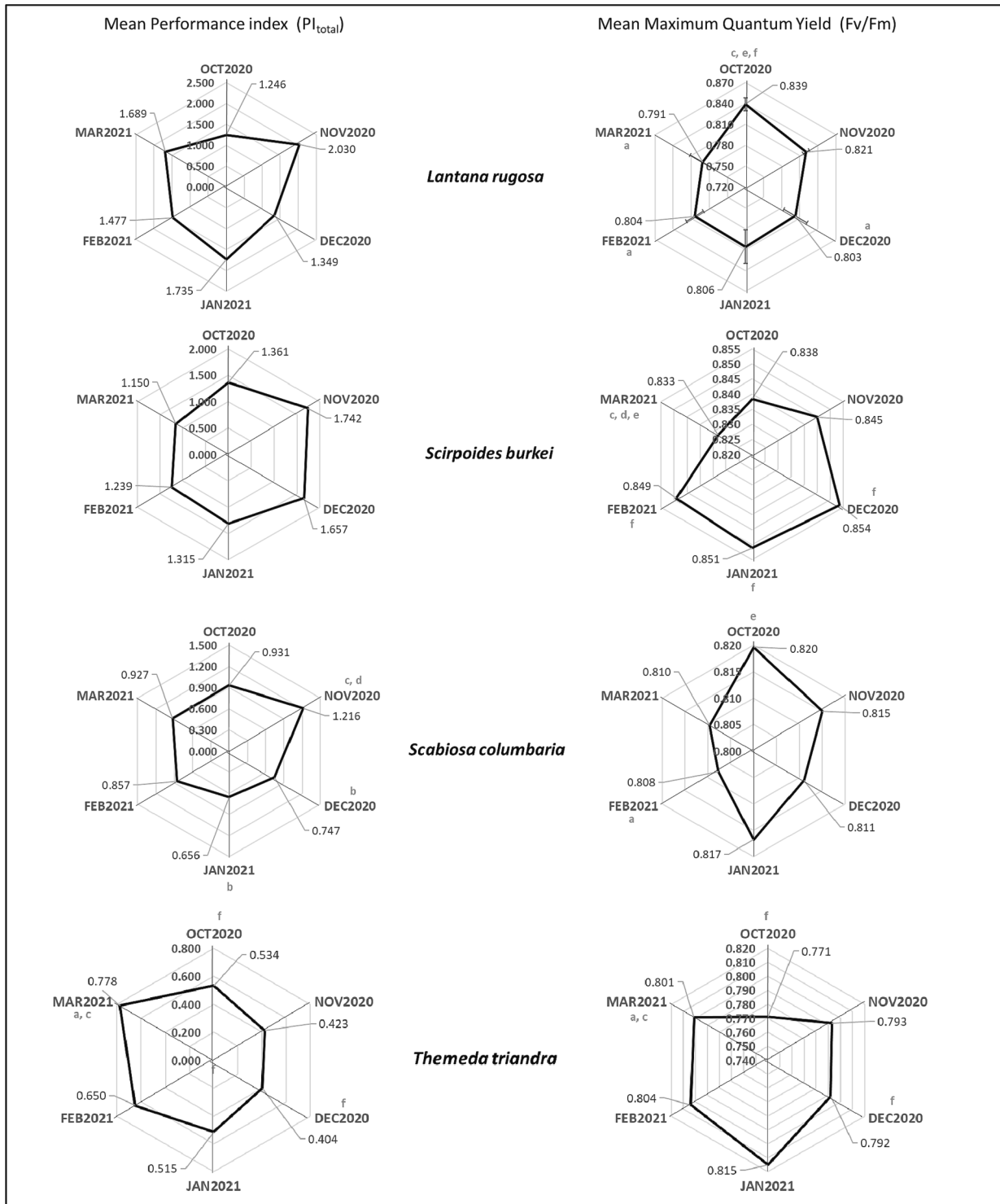**Fig. 5.** Mean PItotal and Fv/Fm for the tested native grassland plant species from OCT2020 to MAR2021.

Fig. 6. Mean PItotal and Fv/Fm for the tested native grassland plant species from OCT2020 to MAR2021.

Table 2
General Pearson correlations between plant vitality and weather variables.

Variable	Rainfall	Max T_{avg}	Min T_{avg}	Max RH_{avg}	Min RH_{avg}
1. F_v/F_m	0.047	**0.205****	0.072*	−0.024	−0.217**

* $p < 0.05$ (2-tailed).
** $p < 0.01$ (2-tailed).

overall minimum temperatures and lower overall maximum

temperatures recorded by the i-buttons, along with rainfall occurring seven days before measurements.

4.3. Total performance index (PI) and maximum quantum yield of photochemistry (F_v/F_m) of species

Certain plant species showed an increasing pattern in their total PI values during the transition from spring to summer (October 2020 to February 2021), suggesting that these plants emerged from a winter dormancy period, characterised by reduced energy demands and slow

Table 3

Pearson correlations between plant vitality and weather variables for nine species of native grassland plants.

Variable	F_v/F_m	PI_{total}	Rainfall	Max T_{avg}	Min T_{avg}	Max RH_{avg}	Min RH_{avg}
Crossandra greenstockii							
1. F_v/F_m	–	0.200	0.142	**0.248****	0.005	0.001	−0.269
2. PI_{total}	0.200	–	0.204	**−0.234***	0.266*	−0.033	**0.234***
Dicliptera eenii							
1. F_v/F_m	–	−0.046	0.146	0.102	**0.0301***	−0.011	0.114
2. PI_{total}	−0.046	–	0.021	−0.013	−0.007	0.161	0.103
Elionurus muticus							
1. F_v/F_m	–	**−0.215***	−0.094	**0.284****	0.151	**−0.343****	**−0.467****
2. PI_{total}	**−0.215***	–	0.051	0.002	0.016	0.115	0.085
Hypoxis hemerocallidea							
1. F_v/F_m	–	**0.424****	**0.348****	0.108	**0.261****	0.001	−0.115
2. PI_{total}	**0.424****	–	0.042	−0.134	**0.171***	−0.152	−0.001
Haplocarpha lyrata							
1. F_v/F_m	–	**0.308****	0.081	**0.299****	0.130	−0.123	**−0.310****
2. PI_{total}	**0.308****	–	−0.226	**0.191****	**−0.233****	**−0.247****	**−0.431****
Lantana rugosa							
1. F_v/F_m	–	−0.179	−0.094	0.110	0.041	−0.081	−0.054
2. PI_{total}	−0.179	–	0.044	−0.159	0.077	−0.090	−0.084
Scirpoides burkei							
1. F_v/F_m	–	**0.281***	0.126	0.094	0.086	0.066	0.049
2. PI_{total}	**0.281***	–	−0.086	0.054	−0.142	−0.085	−0.099
Scabiosa columbaria							
1. F_v/F_m	–	−0.061	0.059	**0.132***	0.024	**0.117***	−0.040
2. PI_{total}	−0.061	–	**−0.172****	−0.032	−0.147	−0.100	−0.078
Themeda triandra							
1. F_v/F_m	–	0.255	0.373	**−0.475***	−0.048	0.289	**0.547***
2. PI_{total}	0.255	–	0.153	**−0.611****	−0.219	0.277	**0.569***

* $p < 0.05$ (2-tailed).
** $p < 0.01$ (2-tailed).

photosynthetic factories. As plants transition out of winter dormancy, their metabolic activity becomes more active, increasing PI_{total} values. Conversely, some plants showed decreased PI_{total} values between October and November 2020, marked by no rainfall. Still, the possibility of irrigation compensating for this decrease exists unless there is an irrigation system malfunction. Without irrigation, the decline in PI_{total} values during November 2020 could be attributed to the lack of precipitation. While the absorption of nitrogen from rainwater may have minimal effects on plant performance (Oguz et al., 2022), the general availability of water plays a more significant role in keeping the stomata open, facilitating the plant's absorption of CO_2 (Tombesi et al., 2015).

Only *Hypoxis hemerocallidea* and *Scabiosa columbaria* were measured in the GL, while *Scirpoides burkei* was exclusively measured in JA. The lowest values recorded for all species' F_v/F_m and PI_{total} were above the threshold, and these values often coincided with their flowering periods (Table 1). Throughout the six-month measurement period, all species maintained a F_v/F_m value above the 0.75 threshold, indicating their ability to acclimate to the urban environment. Most species exhibited minimal significant differences in mean F_v/F_m and PI_{total} values between the months, indicating they effectively adapted to their environments. *Hypoxis hemerocallidea* and *Haplocarpha lyrata* showed occasional differences in F_v/F_m values between months, indicating some fluctuations in plant vitality. However, their vitality remained high overall, and these species thrived in their environments. Considering the consistent acclimatisation and photosynthetic performance across all months and sites, these plants can be recommended as resilient species well-suited to current climatic conditions in urban environments.

Significant differences between sites could primarily be attributed to temperature and soil condition variations. *Crossandra greenstockii* and *Hypoxis hemerocallidea* both exhibited significantly higher PI_{total} values in JA, with *Hypoxis hemerocallidea* also showing a notably higher F_v/F_m value in JA. This could be linked to slightly lower maximum and higher minimum temperatures in JA compared to FA. Additionally, JA had the highest average initial soil moisture, organic matter, and organic carbon percentages overall, with more clay-based soil that retains more moisture, while FA had sandier soil. On the other hand, *Scabiosa columbaria*

obtained higher PI_{total} values in the GL, potentially due to the higher soil moisture, soil organic matter, and soil organic carbon. The GL had slightly higher maximum and lower minimum temperatures than FA, but differences in soil conditions likely made it a more suitable environment for *Scabiosa columbaria*.

4.4. Correlation

The correlation results revealed significant correlations between the plant vitality and the maximum and minimum temperature, as well as minimum relative humidity. Additionally, some correlations were observed between plant vitality, precipitation, and maximum relative humidity.

Comparing plant vitality, it is essential to note that the maximum quantum yield can be compared across different plant species. At the same time, the total performance index is relevant only within the same species. Analysing the combined F_v/F_m for all nine native grassland plant species revealed a positive correlation with minimum and maximum temperatures, indicating that these plants fare well in current urban climatic conditions. As South Africa is predicted to experience rising minimum and maximum temperatures (CSIR, 2019), plant photosynthetic performance is also expected to increase. These plant species could, therefore, potentially acclimate to anticipated future temperature increases. However, when assessing specific plant species, it becomes evident that some are currently more resilient to urban climatic conditions and may possess the capacity to endure anticipated future increases in both minimum and maximum temperatures, along with a heightened frequency of hot days.

Two species, *Lantana rugosa* and *Scirpoides burkei*, did not correlate significantly with weather data, making it challenging to conclude their current vitality in urban climatic conditions. *Crossandra greenstockii* exhibited some contrasting results regarding the F_v/F_m and PI_{total} correlations with maximum temperature, preventing definitive conclusions. *Elionurus muticus* displays potential resilience to increasing maximum temperatures and decreasing minimum relative humidity. However, it showed possible vulnerabilities with decreasing maximum

relative humidity. *Dicliptera eenii* and *Hypoxis hemerocallidea* exhibited increased photosynthetic potential with higher minimum temperatures, but increased precipitation also boosted plant vitality in *Hypoxis hemerocallidea,* implying a potential vulnerability to predicted future decreases in precipitation. *Themeda triandra*, while performing well, currently appears to be the most vulnerable to urban climate conditions, with decreased photosynthetic potential associated with increasing maximum temperature and decreasing minimum relative humidity.

In contrast, *Haplocarpha lyrata* displayed increased plant vitality with rising maximum temperature and showed promise in coping with lower minimum temperatures and relative humidity, potentially making it less vulnerable to extreme temperatures and relative humidity fluctuations. *Scabiosa columbaria* demonstrated potential resilience to urban climate conditions, as its photosynthetic potential increased with higher maximum temperature and relative humidity and decreased precipitation. Therefore, it could be less vulnerable to temperature extremes and drought periods.

5. Conclusions and recommendations

Urbanisation significantly affects the natural environment and human health (Li et al., 2022; Zhang et al., 2022). With its rich biodiversity and high urbanisation rates, South Africa is under strain to protect species while coping with increased demand for urban living. Mitigation strategies are required to adapt to and mitigate urban climatic influences and minimise the vulnerability of people and other species. One possible mitigation strategy consists of increasing resilient vegetation types to counter increases in runoff, decreases in humidity and the urban heat island effect.

This study aimed to investigate the ability of selected native grassland plants to survive current urban conditions. Three study sites in Tshwane were chosen, containing native plant species, two intervention sites and one undisturbed natural site as a reference. These sites mimic typical urban conditions, surrounded by built-up areas with, e.g. irrigation and foot traffic interferences.

i. All nine native grassland plant species functioned with good photosynthetic health over six months (spring and summer), with mean F_v/F_m values consistently exceeding the 0.75 threshold for stress tolerance.

ii. Despite high maximum temperatures, including days exceeding 27 °C and microclimate temperatures above 40 °C, all plant species thrived throughout the study, suggesting their adaptation to current urban climatic conditions. Most sites received irrigation, which might have increased plant vitality during high temperatures.

iii. The nine native grassland plant species were well suited to their respective urban sites, showing resilience and minimal stress in their current urban conditions. Where significant differences in PI_{total} or F_v/F_m values emerged between sites, factors like higher maximum and lower minimum temperatures or soil condition disparities likely contributed. *Scirpoides burkei* (graminoid) generally exhibited a more efficient PSII function than *Dicliptera eenii* (creeper), suggesting it produced more usable energy. Consequently, *Scirpoides burkei* demonstrates higher resilience and tolerance. This rationale extends to other plant species as well. Nevertheless, it remains vital to plant species in optimal sun aspects aligned with their specific needs.

iv. Correlation studies suggest that *Haplocarpha lyrata* (forb) and *Scabiosa columbaria* (forb) might be less vulnerable to temperature extremes and drought periods. *Elionurus muticus* (graminoid) and *Hypoxis hemerocallidea* (forb) seemed somewhat vulnerable to reduced precipitation and lower minimum relative humidity. *Themeda triandra* (graminoid) is more sensitive to temperature extremes and drought periods, although it currently thrives in urban settings. Increased maximum temperature and decreased

minimum relative humidity were linked with reduced photosynthetic potential in *Themeda triandra*. All nine native grassland species are recommended as resilient choices for planting in urban conditions with extreme temperature and moisture variations. However, *Haplocarpha lyrata* and *Scabiosa columbaria* appear less susceptible to temperature extremes and drought periods.

These are the first results known to us assessing native grassland plant species' vitality in urban conditions, marking a pioneering effort in this regard. These findings could serve as a benchmark for forthcoming studies, aiding in identifying species resilient to anticipated climate changes, such as increased heat and drought. This information can guide the selection and testing of tolerant native grassland plant species for future use. Future research should encompass a broader range of native grassland species and compare their photosynthetic performance and vitality with other 'ornamental' and mainstream garden plants, further enhancing our understanding.

Several limitations and challenges must be considered for future studies. The study focused solely on monitoring temperature, humidity and precipitation, overlooking other urban environmental factors. Uncontrolled interferences, common in urban settings, existed at all the study sites, including irrigation, light pollution, trampling, weeding, trimming, mulch import, and foreign materials such as plastic. These interferences typically result from routine maintenance, while native garden sites are situated next to walkways used daily by students and, therefore, frequented by people. The exception is the more isolated grassland site, which only undergoes a controlled burning regime. It is worth noting that irrigation at both garden sites may have significantly influenced plant resilience to high temperatures. Therefore, future studies in more established gardens should consider controlling irrigation when assessing plant stress tolerance.

The study confirmed that specific native grassland species thrive in current urban climates, displaying tolerance to extreme temperature and moisture fluctuations. Notably, *Haplocarpha lyrata* and *Scabiosa columbaria* emerged as potential candidates less vulnerable to future urban climate changes. These forb species, known for their mid-winter dormancy, presence in habitats with diverse moisture and soil conditions, and continuous conspicuous spring and summer flowering, could gain popularity among both humans and insects.

CRediT authorship contribution statement

Martiné van der Walt: Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jacques M. Berner:** Conceptualization, Methodology, Validation, Writing – review & editing. **Christina A. Breed:** Conceptualization, Methodology, Data curation, Investigation, Project administration, Resources, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111332.

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