

## WATER DEMAND ASSESSMENT OF NATIVE AND EXOTIC ORNAMENTAL VEGETATION COMMUNITIES USING ENERGY BALANCE AND VEGETATION INDICES IN CHILE'S MEDITERRANEAN SEMI-ARID PLANNED URBAN GARDENS

### ÉVALUATION DE LA DEMANDE EN EAU DES COMMUNAUTÉS VÉGÉTALES ORNEMENTALES INDIGÈNES ET EXOTIQUES À L'AIDE DU BILAN ÉNERGÉTIQUE ET D'INDICES DE VÉGÉTATION DANS LES JARDINS URBAINS PLANIFIÉS DE LA ZONE MÉDITERRANÉENNE SEMI-ARIDE DU CHILI

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#### ABSTRACT

Urban green areas in central Chile are predominantly composed of exotic ornamental vegetation, which requires continuous irrigation under increasingly water scarcity driven by the ongoing megadrought. In response, municipalities and public policies are promoting the incorporation of native species into urban landscaping and ecological restoration. However, quantitative information on the water consumption of native vegetation under heterogeneous urban conditions remains limited. This study presents preliminar results from a four-year project aimed at quantifying the water demand of native (AEC1, AEC2) and exotic ornamental vegetation communities in a Mediterranean semi-arid region of Chile. Experimental gardens were instrumented with micrometeorological and soil sensors to estimate evapotranspiration (ET) using a surface energy balance approach coupled with Monin–Obukhov similarity theory and atmospheric stability corrections. Latent and sensible heat fluxes were calibrated against Eddy Covariance data, showing moderate to high performance, particularly for sensible heat flux (NSE: 0.54–0.78; R<sup>2</sup>: 0.63–0.82). Mean ET for a six-months period showed slight differences among vegetation groups, with higher values in AEC1 and AEC2 and lower values in EXOTIC. Under comparable irrigation management, ET normalized by NDVI and EVI revealed that AEC1 presented comparatively higher values. This suggests greater water use per unit of active vegetation, which may be associated with differences in canopy structure, physiological regulation, or direct soil evaporation. Overall, these preliminary findings highlight the potential of combining energy balance approaches and vegetation indices to characterize water-use dynamics in heterogeneous urban systems, supporting the development of native landscaping coefficients for sustainable irrigation management in water-limited Mediterranean environments. Nevertheless, continued evaluation over subsequent growing seasons remains essential, as vegetation structure and canopy development are expected to evolve over time, potentially modifying both the magnitude and trends of water use as plant communities become more fully established.

**Keywords:** Water demand assessment; Energy balance; Urban green areas; Water scarcity; Irrigation management.

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## RÉSUMÉ

Les espaces verts urbains du centre du Chili sont principalement composés de végétation ornementale exotique, qui nécessite une irrigation continue dans un contexte de pénurie d'eau croissante due à la mégasécheresse en cours. En réponse, les municipalités et les politiques publiques encouragent l'intégration d'espèces indigènes dans l'aménagement paysager urbain et la restauration écologique. Toutefois, les données quantitatives sur la consommation d'eau de la végétation indigène dans des conditions urbaines hétérogènes restent limitées. Cette étude présente les résultats préliminaires d'un projet de quatre ans visant à quantifier la demande en eau de communautés de végétation ornementale indigène (AEC1, AEC2) et exotique dans une région méditerranéenne semi-aride du Chili. Des jardins expérimentaux ont été équipés de capteurs micrométéorologiques et de capteurs du sol afin d'estimer l'évapotranspiration (ET) au moyen d'une approche fondée sur le bilan énergétique de surface, couplée à la théorie de similitude de Monin–Obukhov et à des corrections de stabilité atmosphérique. Les flux de chaleur latente et sensible ont été étalonnés par rapport à des données de covariance des tourbillons, avec des performances modérées à élevées, notamment pour le flux de chaleur sensible (NSE : 0,54–0,78 ;  $R^2$  : 0,63–0,82). L'ET moyenne sur une période de six mois a légèrement varié entre les groupes de végétation, avec des valeurs plus élevées pour AEC1 et AEC2 et plus faibles pour EXOTIC. À gestion d'irrigation comparable, l'ET normalisée par le NDVI et l'EVI a révélé des valeurs relativement plus élevées pour AEC1. Cela suggère une consommation d'eau plus importante par unité de végétation active, qui pourrait être liée à des différences de structure du couvert, de régulation physiologique ou d'évaporation directe du sol. Dans l'ensemble, ces résultats préliminaires montrent l'intérêt de combiner les approches de bilan énergétique et les indices de végétation pour caractériser la dynamique de l'utilisation de l'eau dans des systèmes urbains hétérogènes, et appuient l'élaboration de coefficients paysagers pour la végétation indigène en vue d'une gestion durable de l'irrigation dans les milieux méditerranéens soumis à des ressources en eau limitées. Il reste néanmoins essentiel de poursuivre l'évaluation au cours des saisons de croissance suivantes, car la structure de la végétation et le développement du couvert devraient évoluer au fil du temps, ce qui pourrait modifier à la fois l'ampleur et les tendances de l'utilisation de l'eau à mesure que les communautés végétales s'établissent pleinement.

**Mots clés :** Evaluation de la demande en eau; Bilan énergétique; Espaces verts urbains; Pénurie d'eau; Gestion d'irrigation.

## Introduction

The growing water scarcity in Chile's semi-arid Mediterranean region, intensified by the megadrought and climate change, has significantly increased the pressure on sustainable water use in agriculture and urban areas (Garreaud et al., 2019; IPCC, 2023). In this context, urban green spaces play a fundamental role in thermal regulation, mitigating urban heat islands, and contributing to the well-being of the population. However, a large portion of these areas are dominated by exotic ornamental species, often referred to as highly dependent on irrigation, resulting in increasingly unsustainable landscape systems under water-restriction scenarios (Pauchard et al., 2006). In response, various public and municipal initiatives have promoted the use of native species adapted to water stress conditions, particularly those belonging to the agroecological groups (AEC) AEC1 and AEC2, identified for their hardiness and ornamental potential (Musalem, 2019).

Despite the growing interest in using native species in urban landscaping, a significant gap remains in quantitative information regarding their actual water requirements under the heterogeneous and dynamic conditions characteristic of urban gardens and complex green spaces. Most available research has been conducted under controlled conditions, using individual species in containers or lysimeters, limiting its applicability to mixed vegetation systems where canopy structure, spatial heterogeneity, and microclimate significantly modify evapotranspiration and surface-atmosphere energy exchange (Egerer et al., 2018; Allen et al., 2020). In this context, approaches based on energy balance and remote sensing have emerged as promising tools for estimating the water

consumption of heterogeneous vegetation cover by integrating micrometeorological and spectral variables.

This paper presents the preliminary results of the first year of a four-year research project aimed at quantifying the water demand of native and exotic ornamental plant communities under semi-arid Mediterranean conditions in Chile. The specific objectives of this stage were: (i) to calibrate an energy balance-based monitoring system to estimate evapotranspiration in heterogeneous vegetation covers; (ii) to preliminarily compare the evapotranspiration dynamics of AEC1, AEC2, and exotic vegetation communities; and (iii) to evaluate the potential of vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), to normalize and analyze relative differences in water consumption among vegetation covers.

## Methodology

**Study area:** the trials were conducted at an ornamental nursery and garden, Jardín y Viveros Pumahuida, located in Huechuraba, Santiago, Chile, between coordinates -33.354 latitude and -70.691 longitude, at an altitude of 490.87 meters above sea level. On October of 2024, three gardens were established within the nursery: two 250 m<sup>2</sup> gardens, where exotic species and AEC1 species were transplanted, respectively, and one 1000 m<sup>2</sup> garden, where AEC2 species were transplanted. An Eddy Covariance system was installed in the AEC2 garden, which required a larger plot area due to the system's larger measurement footprint.

**Proximal sensors and recorded variables:** A set of sensors was installed in each garden to record variables for the subsequent estimation of the energy balance components. Table 1 provides details of each sensor.

**Table 1.** Description of the measuring instruments used for the project.

| Proximal sensor               | Model        | Variable                                                     | Unit                           |
|-------------------------------|--------------|--------------------------------------------------------------|--------------------------------|
| Infrared thermometer          | SI-411       | Soil surface temperature                                     | °C                             |
| Four-component net radiometer | SN-501       | Incoming and outgoing shortwave and longwave radiation       | W m <sup>-2</sup>              |
| Soil heat flux plates         | HFP01        | Soil heat flux at 5 cm depth                                 | W m <sup>-2</sup>              |
| Thermocouples                 | TCAV type L  | Soil temperature at 5 cm depth                               | °C                             |
| Soil moisture sensors         | GS1          | Soil moisture at 5 and 40 cm depth                           | m <sup>3</sup> m <sup>-3</sup> |
| CLIMAVUE weather station      | CLIMAVUETm50 | Meteorological variables                                     | —                              |
| Eddy Covariance system        | CSAT3A/EC150 | H and LE fluxes, in addition to atmospheric gas measurements | —                              |

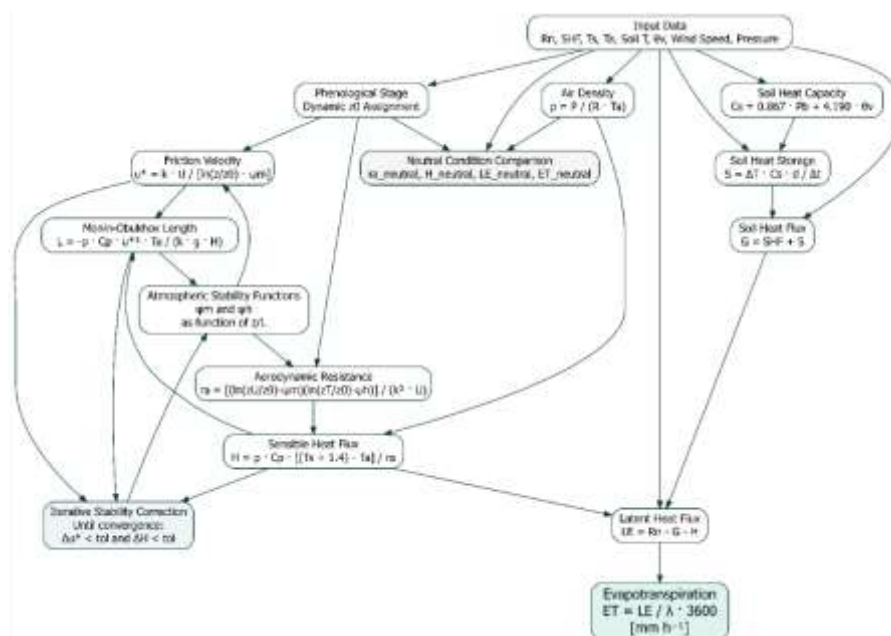
## Estimation of energy balance components

The estimation of each component follows the workflow schematized in Figure 1. The diagram represents the methodological procedure used to estimate evapotranspiration (ET) through a surface energy balance approach ( $R_n = G + H + LE$ ) coupled with Monin–Obukhov similarity theory and iterative atmospheric stability corrections. The process starts from micrometeorological and soil input data, including net radiation ( $R_n$ ), measured soil heat flux (SHF), surface temperature ( $T_s$ ), air temperature ( $T_a$ ), soil temperature (Soil T), soil water content ( $\theta_v$ ), wind speed ( $U$ ), and atmospheric pressure ( $P$ ). Additional parameters used in the calculations include soil bulk density ( $P_b$ ), soil layer depth ( $d$ ), time interval ( $\Delta t$ ), wind and temperature measurement heights ( $z_U$  and  $z_T$ ), surface roughness length ( $z_0$ ), von Kármán constant ( $k$ ), specific heat of air ( $C_p$ ), gas constant for dry air ( $R$ ), gravitational acceleration ( $g$ ), and latent heat of vaporization ( $\lambda$ ). From these variables, air density, soil

heat capacity, and soil heat storage are calculated. Total soil heat flux ( $G$ ) is then obtained by adding the measured soil heat flux at plate depth (SHF) and soil heat storage ( $S$ ).

In parallel, the surface roughness length ( $z_0$ ) is dynamically assigned according to the phenological stage of the vegetation cover. The aerodynamic component is estimated through an iterative procedure based on the Monin–Obukhov length ( $L$ ), atmospheric stability functions for momentum and heat transfer ( $\psi_m$  and  $\psi_h$ ), friction velocity ( $u^*$ ), and aerodynamic resistance ( $r_a$ ). These variables are corrected until convergence is reached according to predefined tolerances for changes in  $u^*$  and sensible heat flux ( $H$ ).

Once the corrected  $r_a$  is obtained, sensible heat flux ( $H$ ) is calculated using  $\rho$ ,  $C_p$ ,  $T_s$ ,  $T_a$ , and  $r_a$ . Latent heat flux ( $LE$ ) is then estimated as the residual of the energy balance and evapotranspiration ( $ET$ ) is finally calculated from  $LE$  using  $\lambda$  and expressed in  $\text{mm h}^{-1}$ . Additionally, a parallel calculation under neutral atmospheric conditions is included to compare the effect of atmospheric stability corrections. This comparison includes neutral aerodynamic resistance ( $r_{a\_neutral}$ ), neutral sensible heat flux ( $H\_neutral$ ), neutral latent heat flux ( $LE\_neutral$ ), and neutral evapotranspiration ( $ET\_neutral$ ).



**Figure 1.** Methodological framework for evapotranspiration estimation using a surface energy balance approach coupled with Monin–Obukhov similarity theory, including iterative atmospheric stability corrections, aerodynamic resistance estimation, and turbulent flux calculations.

## Calibration and performance analysis

The EB monitoring system was calibrated to ensure the reliability, comparability, and applicability of the results. First, both Eddy Covariance (EC) and EB datasets were subjected to quality control and environmental filtering procedures that excluded nighttime data with friction velocity below a critical threshold, as well as periods with precipitation or extremely low wind speeds that could compromise measurement validity. Subsequently, the internal energy balance closure of the EC system was verified ( $R^2=0.85$ ,  $p\text{-value}=1.2\text{e-}262$ ). The  $LE$  and  $H$  fluxes estimated using the EB approach were then compared against EC measurements. The comparison was based on a quantitative framework combining classical statistical metrics and magnitude errors diagnostics. The statistical metrics included the Nash–Sutcliffe Efficiency (NSE), Mean Bias Error (MBE), Root Mean Square Error (RMSE), and the coefficient of determination ( $R^2$ ). Magnitude corrections were applied due to the

systematic underestimation of H and overestimation of LE. For H, a sensitivity analysis based on multiplicative correction factors was implemented. Subsequently, the presence of temporal lag between observed and simulated signals was evaluated.

For LE flux, a calibration procedure using correction factors ranging from 0.20 to 1 was applied. Additionally, a nighttime constraint based on low net radiation conditions ( $R_n < 10 \text{ W m}^{-2}$ ) was incorporated, reducing LE estimates during periods of minimal energy availability. Finally, a light temporal smoothing procedure was applied to reduce high-frequency fluctuations and improve the temporal coherence of the simulated signal. Model performance after calibration was reassessed using NSE,  $R^2$ , RMSE, and MBE.

### Normalization with remote sensing data

Evapotranspiration normalization using a vegetation index was performed to reduce the effect associated with differences in vegetation cover and canopy density among gardens. For this purpose, the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) were used. Daily NDVI and EVI records were obtained from Climate Engine platform using Sentinel-2 SR datasets.

## Results and discussion

### Energy balance system calibration

Magnitude and temporal lag corrections revealed important differences in turbulent flux representation among gardens (Table 2). In AEC1, H flux required amplification by 50%, whereas the Exotic garden required reduction to 64% of its original magnitude. Likewise, all gardens required substantial reduction factors for LE (0.32–0.40).

**Table 2.** Results of the magnitude and temporal lag factors applied to the data for each garden

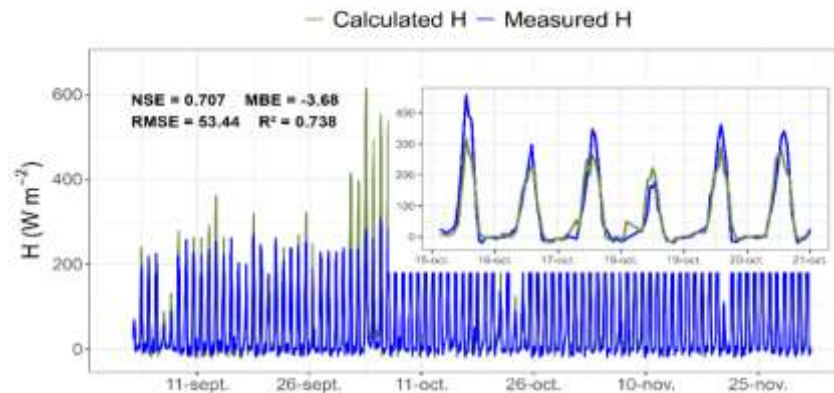
| Garden | Magnitude factor |      | Lag factor |      |
|--------|------------------|------|------------|------|
|        | H                | LE   | H          | LE   |
| AEC1   | 1.5              | 0.40 | -3         | 0.15 |
| AEC2   | -                | 0.32 | -1         | 0.40 |
| Exotic | 0.64             | 0.40 | -          | -    |

The EB system showed moderate to high performance in reproducing turbulent fluxes measured by the EC system (Table 3, Figure 2 and Figure 3). In general, H flux presented better agreement than LE flux, with NSE values ranging from 0.542 to 0.777 and  $R^2$  values between 0.63 and 0.82. The Exotic garden showed the best performance for H, while AEC1 presented the best performance for LE. Despite the lower statistical performance observed for LE, all gardens showed a consistent trend of moderate flux underestimation reflected by negative MBE values.

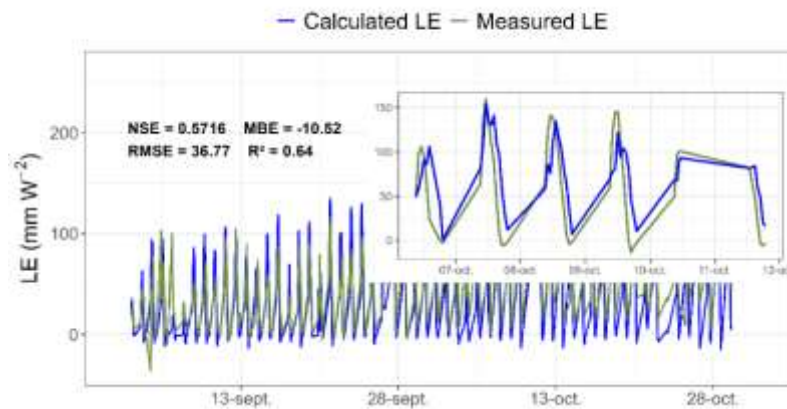
**Table 3.** Results of the calibration of the energy balance systems for each garden

| Flux | Garden | NSE   | MBE    | RMSE  | $R^2$ |
|------|--------|-------|--------|-------|-------|
| H    | AEC 1  | 0.542 | -3.46  | 67.23 | 0.63  |
|      | AEC 2  | 0.707 | -3.68  | 53.44 | 0.738 |
|      | EXOTIC | 0.777 | -7.21  | 46.08 | 0.82  |
| LE   | AEC 1  | 0.679 | -10.38 | 37.23 | 0.72  |
|      | AEC 2  | 0.571 | -10.52 | 36.77 | 0.64  |
|      | EXOTIC | 0.407 | -9.55  | 51.86 | 0.47  |

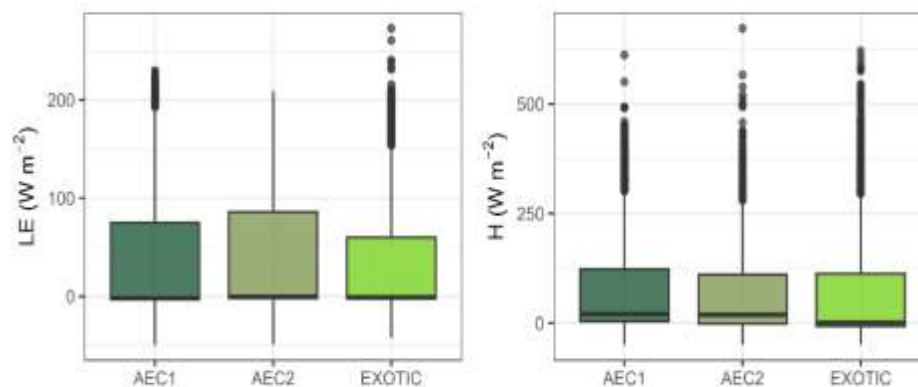
The statistical distribution of turbulent fluxes showed that H reached substantially higher maximum values than LE, with peaks close to  $673 \text{ W m}^{-2}$  in AEC2 (Figure 4).



**Figure 2.** Temporal comparison between the H flux estimated through the energy balance approach and measured by EC system for the AEC2 garden.



**Figure 3.** Temporal comparison between the LE flux estimated through the energy balance approach and measured by the EC system for the AEC2 garden.



**Figure 4.** Distribution of H flux and LE flux obtained for the gardens after calibration of the EB system.

The magnitude differences observed between the EB approach and EC measurements can be partially explained by the conceptual differences between both methods. While the residual energy balance approach forces energy closure, EC systems commonly present imbalances associated with advection, energy storage, and secondary circulations (Mauder and Foken, 2020; Mauder et al., 2017). Likewise, temporal lag corrections applied to H and LE suggest differences in synchronization between available energy and turbulent response, particularly under heterogeneous surface conditions (Reed et al., 2018; Xu et al., 2017). Despite these limitations, the calibrated model showed moderate to high performance, especially for H, indicating that the coupled energy balance and Monin–Obukhov approach was capable of reproducing the main temporal dynamics of turbulent fluxes.

### ET and remote sensing normalization

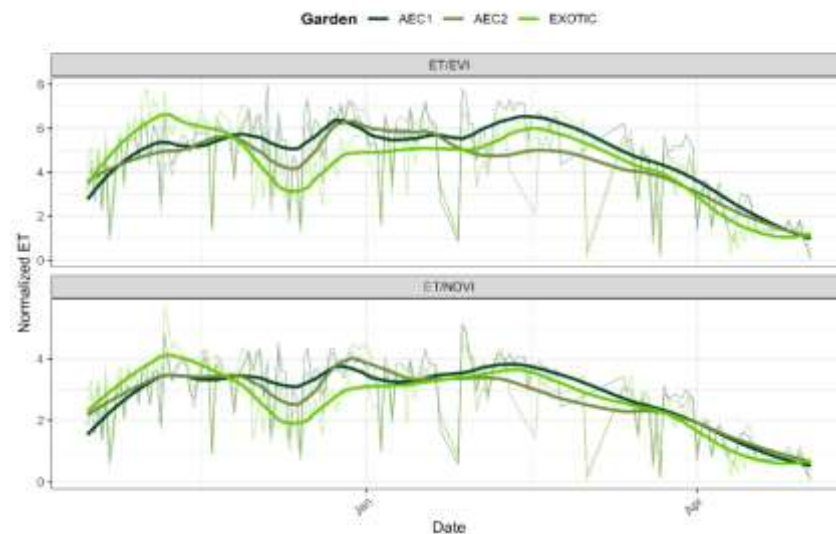
Mean ET from 17<sup>th</sup> October 2025 to 30<sup>th</sup> April 2026 was 1.31 mm day<sup>-1</sup> in AEC1, 1.33 mm day<sup>-1</sup> in AEC2, and 1.17 mm day<sup>-1</sup> in EXOTIC, showing higher values in AEC1 and AEC2 and lower ET in EXOTIC. However, after normalizing ET using vegetation indices, the interpretation changed (Table 4). AEC1 showed the highest normalized ET, both with EVI and NDVI, indicating greater relative water use in relation to its vegetation level. In contrast, AEC2, despite maintaining high absolute ET, decreased its relative position after normalization due to its higher vegetation vigor. EXOTIC showed the lowest absolute ET and, when normalized with EVI, also showed the lowest relative ET.

**Table 4.** Statistical description of vegetation index values and normalized ET

| Index | Garden | Index mean | ET normalized mean (ET/NDVI or ET/EVI) | ET normalized min | ET normalized max |
|-------|--------|------------|----------------------------------------|-------------------|-------------------|
| NDVI  | AEC1   | 0.45       | 2.93                                   | 0.06              | 5.14              |
|       | AEC2   | 0.48       | 2.84                                   | 0.04              | 4.98              |
|       | EXOTIC | 0.43       | 2.76                                   | 0.08              | 5.69              |
| EVI   | AEC1   | 0.26       | 4.95                                   | 0.12              | 7.96              |
|       | AEC2   | 0.30       | 4.55                                   | 0.06              | 7.12              |
|       | EXOTIC | 0.26       | 4.52                                   | 0.14              | 7.80              |

During the evaluation period, irrigation was applied at low frequency, once or twice per week depending on the season, until soil saturation, with water replenished whenever 40 to 50% of the readily available water had been depleted. Under these comparable irrigation conditions, the observed differences in absolute and normalized ET are therefore more likely associated with differences in vegetation structure, canopy development, physiological regulation, and surface–atmosphere water exchange rather than contrasting irrigation inputs. Although the temporal dynamics of normalized ET, illustrated in Figure 5, showed differences among gardens, AEC1 presented the highest mean normalized ET values, indicating greater water use relative to its vegetation level. This suggests that AEC1 may have exhibited higher water consumption per unit of active vegetation, while differences among gardens may also reflect variations in canopy architecture, vigor, and direct soil evaporation.

These results indicate that absolute ET alone was not sufficient to distinguish differences in relative water use among gardens. The EVI-based normalization provided a clearer interpretation of vegetation-adjusted water consumption, particularly because AEC1 showed the highest ET/EVI values despite having the lowest average EVI. This suggests greater water use per unit of active vegetation, which may be related to differences in canopy structure, physiological regulation, or direct soil evaporation. The combined use of vegetation indices and evapotranspiration measurements has been widely applied to assess vegetation functioning and water-use dynamics in heterogeneous systems (Reyes-González et al., 2018; Herman et al., 2018).



**Figure 5.** Smoothed temporal dynamics of daily evapotranspiration normalized by NDVI and EVI in AEC1, AEC2, and EXOTIC gardens.

## Conclusions

The preliminary results demonstrated that the energy balance approach coupled with Monin–Obukhov similarity was capable of adequately reproducing the main temporal dynamics of turbulent fluxes in heterogeneous ornamental vegetation systems. Although absolute evapotranspiration differences among vegetation covers were relatively small during the first year of evaluation, normalization using EVI revealed differences in relative water consumption among the experimental gardens. Overall, these findings provide a robust basis for the future development of Native Landscaping Coefficients (Knl) and for improving irrigation management strategies in Mediterranean urban landscapes under increasing water scarcity conditions. Nevertheless, continued evaluation over subsequent growing seasons remains essential, as vegetation structure and canopy development are expected to evolve over time, potentially modifying both the magnitude and trends of water use as plant communities reach a more fully established state.

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