Investigating Biomass and Water Productivity in the United Arab Emirates: A Case Study of Al Ain Oases

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Abstract

This study examines the productivity, water dynamics, and environmental factors of oasis ecosystems in Al Ain City, United Arab Emirates. It analyzes Total Biomass Production (TBP), Evapotranspiration (ET), and Net Primary Production (NPP) across different oases and over different seasons. The results reveal significant variations in these parameters, influenced by factors such as oasis size and climatic conditions. Al Ain Oasis exhibited the highest productivity, while smaller oases like Jahili tended to have the lowest TBP and NPP, suggesting potential environmental stresses and lower vegetation density. The study shows seasonal patterns in water demand and ecosystem productivity, with peak ET during summer and higher NPP in winter. These findings underscore the need for adaptive management strategies tailored to each oasis's unique characteristics. The research provides valuable insights for sustainable practices to enhance oasis resilience and productivity amid limited water resources and climate variability, contributing to the understanding of arid ecosystem dynamics and evidence-based oasis management strategies.

1. Introduction

Biomass evaluation is essential for assessing ecosystem health and carbon storage in arid regions (Liang and Liu, 2017), making it particularly relevant in the United Arab Emirates (UAE), which contains multiple oases. Effective monitoring of biomass and carbon storage within these ecosystems is critical not only for optimizing date palm cultivation but also for enhancing carbon sequestration, supporting both agricultural sustainability and climate change mitigation. Moreover, conducting biomass assessments in arid regions like the UAE provides valuable insights into ecological resilience, aiding in the development of long-term environmental sustainability strategies (Ben Salem et al., 2021).

In these semi-arid regions, date palms are a critical component of the ecosystem, especially in areas with scarce water resources. Biomass evaluation in oases involves assessing key metrics such as Evapotranspiration (ET), Net Primary Productivity (NPP), and Total Biomass Production (TBP), which are fundamental for analyzing biomass production and guiding water management strategies (Montazar et al., 2020).

Groundwater is the primary water source for agriculture across the Arabian Peninsula, including Saudi Arabia and the UAE. However, the uneven distribution of these resources, coupled with limited rainfall, necessitates the use of supplementary water sources (Odhiambo, 2017). Precipitation levels play a vital role in influencing key ecological processes, such as evapotranspiration (ET) and Net Primary Productivity (NPP). Furthermore, irrigation practices in the region exhibit seasonal variability, with distinct operational strategies employed during the hot and cold seasons (El Amrousi et al., 2018).

Given the challenges in managing water resources within these ecosystems, satellite remote sensing has become an invaluable tool for monitoring and evaluating key ecological processes. This technology allows for the observation and measurement of parameters such as ET and NPP from space, providing both high spatial and temporal resolution. When integrated with in situ measurements, satellite data offers a more precise and comprehensive understanding of ecosystem dynamics.

The WaPOR (Water Productivity through Open-access Remote-sensed Data) database, developed by the Food and Agriculture Organization (FAO) of the United Nations, provides comprehensive datasets for monitoring agricultural water productivity across various spatial and temporal scales. These datasets have been utilized in studies assessing irrigation performance and developing indicators for different irrigation schemes (e.g., Blatchford et al., 2020; Chukalla et al., 2022). This study utilizes WaPOR data to evaluate water productivity and biomass in the oases of Al Ain City.

Al Ain City is located in the eastern part of the Abu Dhabi Emirate, at the international border with the Sultanate of Oman, spanning latitudes 24.1° to 24.3° North and longitudes 55.6° to 55.8° East. The city contains seven oases, distributed across its central and northern parts (Figure 1). Table 1 presents the areas of these oases.

Oasis Name	Area (m^2)
Al-Ain	1186362.1070
Mutared	264677.6108
Muwaiji	414837.5210
Al-Jimi	615716.6646
Hili	604708.0959
Al-Qattara	385710.8340
Jahili	209432.7045

Table 1. Areas of the Al Ain Oases.

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Understanding how these oases influence ecological processes and contribute to carbon sequestration is fundamental for effective environmental management. This knowledge is vital for implementing sustainable water management practices, enhancing agricultural productivity, and ensuring the resilience of the region's ecosystems. By examining key ecological parameters such as evapotranspiration (ET) and Net Primary Productivity (NPP), this study seeks to deepen our understanding of ecosystem dynamics within the Al Ain Oases. The findings are expected to support more informed decision-making in managing natural resources, promoting sustainability, and addressing challenges in semi-arid environments, with potential applications extending beyond the immediate region.

2. Data & Methods

2.1 Data

The data for this study were obtained from the Water Productivity through Open-access Remotely Sensed Derived Data (WaPOR) portal (https://data.apps.fao.org/wapor/, last accessed October 20, 2024). The study employed evapotranspiration (ET), net primary production (NPP), and total biomass production (TBP) from WaPOR Version 2, Level 1, with a spatial resolution of 250 m. ET and NPP were analyzed at a monthly temporal resolution, while TBP was assessed on an annual basis. These datasets provided essential insights into water use efficiency and biomass dynamics across the study area.

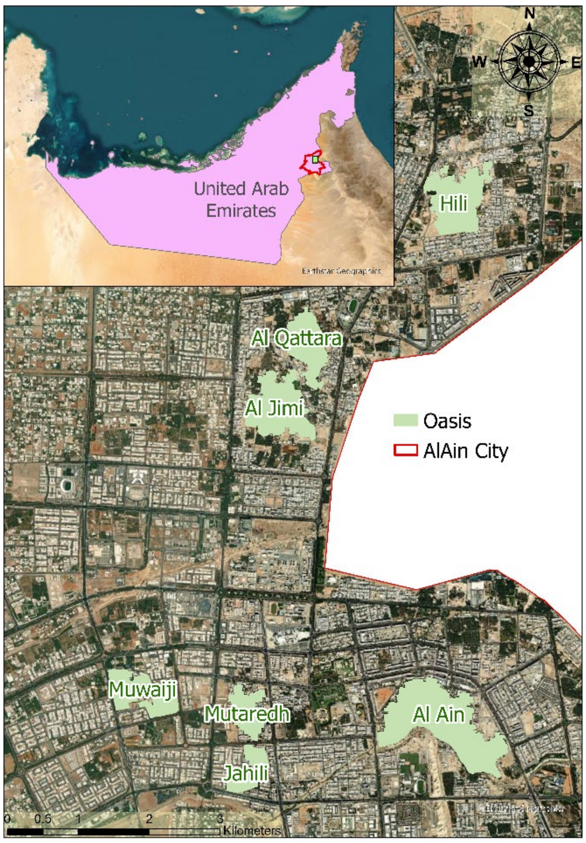

Figure 1. Location of the study area and the seven oases.

2.2 Methods

Evapotranspiration in the WaPOR datasets was calculated using the ETLook model, developed by eLEAF. This model separately calculates evaporation and transpiration, then combines the two to derive actual evapotranspiration. The ETLook model incorporates multiple input data, including temperature, relative humidity, solar radiation, wind speed at a 2-meter height, and both optical and radar satellite imagery (Pelgrum et al., 2012).

The NPP in WaPOR was calculated using the following equation:

$$NPP = S_C \times R_S \times \varepsilon_P \times fPAR \times SM \times \varepsilon_{lue} \times \varepsilon_T \times \varepsilon_{CO_2} \times \varepsilon_{AR} \times [\varepsilon RES] \quad (1)$$

Where *Sc* represents the scaling factor used to convert dry matter productivity to NPP, Rs is the total incoming shortwave radiation, ε_P is the fraction of PAR (Photosynthetically Active Radiation) in total shortwave radiation, fPAR is the fraction of PAR absorbed by green vegetation, SM is the soil moisture stress reduction factor, ε_{lue} is the light use efficiency at optimum conditions, ε_T is the normalized temperature effect, ε_{CO_2} is the normalized carbon dioxide fertilization effect, is the ε_{AR} fraction retained after autotrophic respiration, and $[\varepsilon RES]$ is the fraction retained after residual effects (Er, 2024).

The TBP was calculated using the NPP derived from Equation 1, with the following equation:

$$TBP = 22.22 \times NPP \quad (2)$$

The contribution of the seven oases listed in Table 1 was assessed by aggregating the values of each parameter studied for each oasis. For annual total biomass production (TBP), the values were averaged across each oasis. Similarly, the monthly evapotranspiration (ET) values were aggregated and converted into cubic meters using the area data provided in Table 1. To assess the accuracy and reliability of the ET data, both the standard deviation and standard error of the mean were calculated. For Net Primary Productivity (NPP), the values were first aggregated by calculating the monthly average for each oasis, then the total NPP for each oasis was computed. Finally, the annual NPP values were derived by summing the monthly NPP values for each oasis. The flowchart in Figure 2 illustrates the methods used in this study.

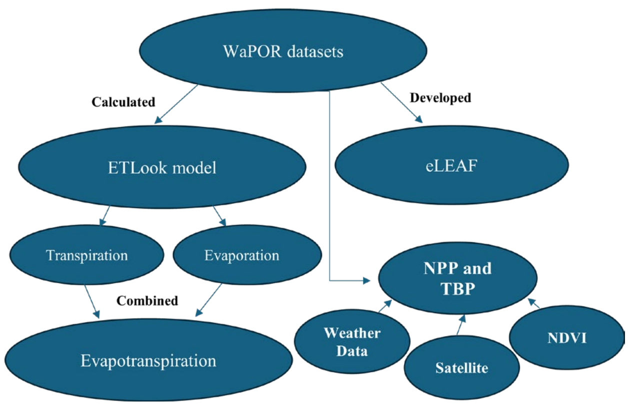

Figure 2. Study Methods Flowchart.

3. Results

The results are presented in three subsections. The first subsection presents the annual average total biomass production (TBP). The second subsection focuses on the average monthly evapotranspiration (ET). The final subsection provides an analysis of both monthly and annual net primary productivity (NPP).

3.1 Total Biomass Production (TBP)

As shown in Figure 3, TBP was highest in the Al Ain Oasis, reaching 6,000 kg/ha during the study period, followed by Al Jimi, Muwaiji, and Mutaredh Oases. In contrast, the Jahili Oasis exhibited the lowest TBP, consistently remaining below 1,000 kg/ha. A decline in TBP was observed in 2012, followed by an increase in 2020 across all oases. However, interannual variability was evident between 2016 and 2018 in the Mutaredh and Muwaiji Oases.

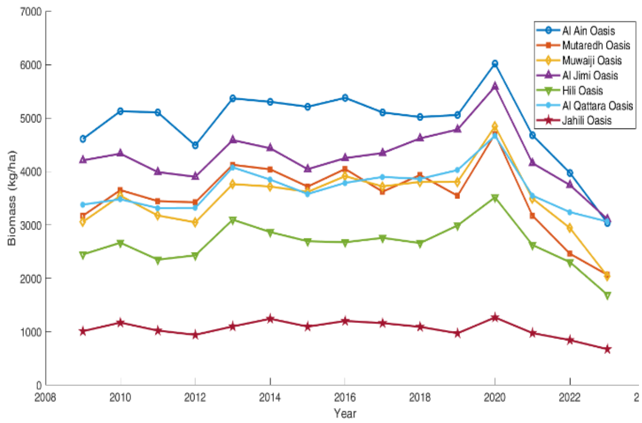

Figure 3. Average total biomass production from 2009 to 2023

3.2 Evapotranspiration

The ET gradually increases from May, reaching its peak in June and July (summer), before decreasing to its lowest levels in December and January (winter), as depicted in Figures 3 and 4.
In August, the Al Ain Oases exhibited the highest evapotranspiration, reaching approximately 600.02 mm. Al Jimi and Muwaiji Oases followed, with mean ET values of 540.50 mm and 529.68 mm, respectively. In contrast, the Jahili Oases had the lowest mean ET at 309.82 mm (Figure 4).

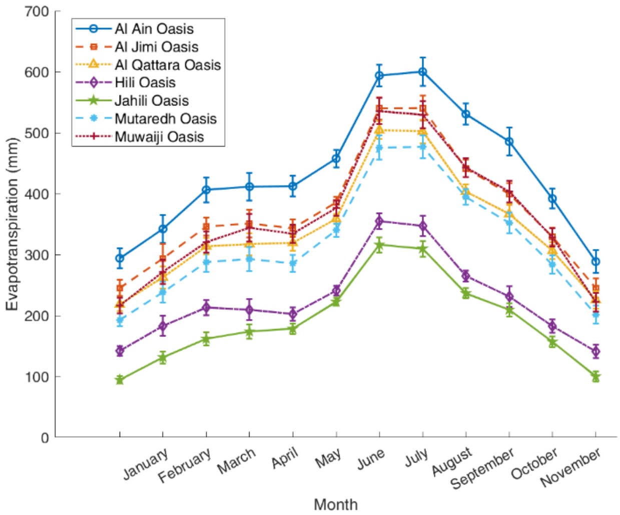

Figure 4. Average monthly evapotranspiration in millimetres

Figure 5 shows that average monthly ET peaks in all oases during July and August, with the highest values recorded in the Al Ain Oasis, reaching approximately 711,842 and 704,520 m³, respectively. In contrast, the lowest values occur in December and January, at around 342,380 and 348,711 m³. Among the oases, Jahili Oasis exhibits the lowest average ET, with 66,212 and 64,886 m³ in July and August, respectively, and 20,964 and 19,791 m³ in December and January, respectively.

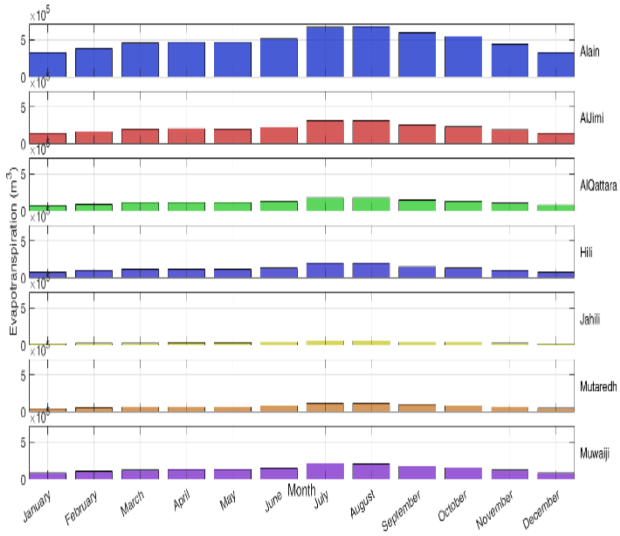

Figure 5. Average monthly evapotranspiration in cubic meter.

3.3 Evapotranspiration Uncertainty

Uncertainty quantifies the precision and reliability of the data. The vertical bars in Figure 4 represent the Standard Error of the Mean (SEM), highlighting monthly ET variability across the oases. The highest SEM values typically occurred in February, April, and August, while the lowest were observed in June and January. These variations reflect the influence of seasonal changes, temperature fluctuations, and precipitation on ET rates. For instance, high temperatures in August increase both soil moisture evaporation and plant transpiration, leading to elevated SEM values. In contrast, June’s stable temperatures and consistent solar radiation promote a more uniform ET rate, resulting in lower SEM values. Irrigation practices in each oasis further contribute to these fluctuations. Mutaredh and Muwaiji Oases exhibited similar SEM patterns, with the highest values in April (5,237.85 m³ and 9,518.68 m³, respectively) and the lowest in January (2,691.89 m³ and 5,180.99 m³, respectively). In Al Ain and Hili Oases, SEM peaked in April and was lowest in June. Jahili and Al Qattara recorded their highest SEM in August and lowest in June, while Al Jimi had the highest in February and the lowest in June. Table 2 summarizes the maximum and minimum SEM values for each oasis.

Oasis Name	Maximum SEM (m^3)	Minimum SEM (m^3)
Al Ain	27104.3788	16785.6223
Mutaredh	5237.8496	2691.891
Muwaiji	9518.6828	5180.9903
Al Jimi	14521.2197	5367.434
Hili	10384.6268	4779.396
Al Qattara	7287.7422	3163.1573
Jahili	2683.9325	1414.6093

Table 2: Standard Error of the Mean (SEM) of Evapotranspiration

3.4 Net Primary Productivity for Al Ain Oases

NPP serves as a key indicator of ecosystem health, biomass productivity, carbon sequestration, and environmental conditions. Figure 6 presents the annual NPP for the study period. Al Ain Oasis exhibited the highest NPP, exceeding 2.5×10^{11} gC/m², reflecting a high photosynthetic rate, substantial carbon sequestration capacity, and abundant water resources. In contrast, Jahili Oasis had the lowest NPP, below 0.5×10^{11} gC/m².

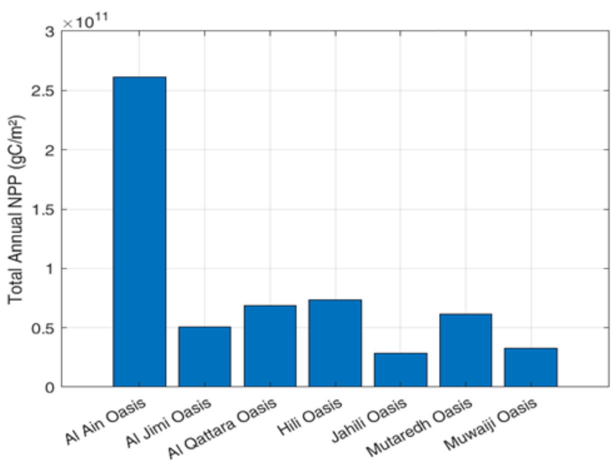

Figure 6. Average annual net primary productivity (gC/m²) for each oasis

The highest NPP values occur in winter, while the lowest are observed during the summer months. In July, all oases had NPP values below 0.5×10^4 gC/m², with Jahili Oasis having the lowest at approximately 0.1×10^4 gC/m². The highest NPP in Al Ain Oasis was observed in January, reaching around 4.0×10^4 gC/m². This seasonal trend was consistent across all oases, as shown in Figure 7.

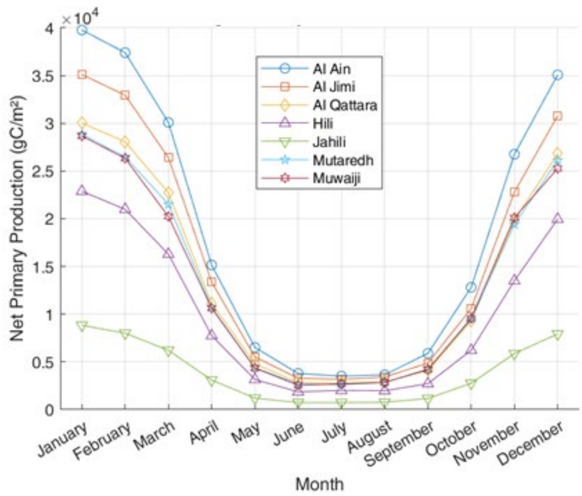

Figure 7. Average monthly NPP (gC/m²) for each oasis

Figure 8 displays the average monthly NPP across the oases. Al Ain Oasis is the most productive, with an average monthly NPP exceeding 2.0×10^{10} gC during the winter season. A similar trend is observed in the other oases during winter, but their NPP values are lower than those of Al Ain Oasis. In contrast, the lowest NPP values occur during summer across all oases, with values falling below 1.0×10^{10} gC.

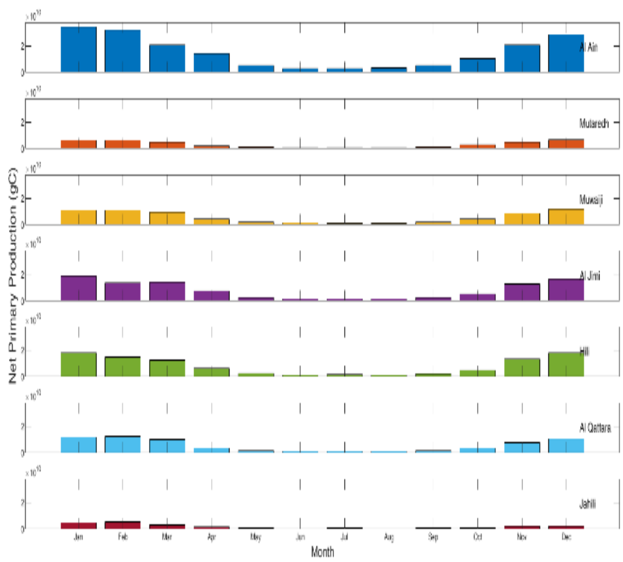

Figure 8. Average monthly NPP per oasis

4. Discussion

This study provides key insights into the productivity, water dynamics, and environmental constraints of oasis ecosystems in Al Ain City across different seasons.

4.1 Total Biomass Production (TBP)

The findings underscore the importance of biomass production, evapotranspiration patterns, and net primary productivity in shaping sustainable management strategies, particularly in response to fluctuating groundwater availability and irrigation demands (SIWI & UNICEF, 2023; Al-Muaini et al., 2019). Variations in TBP across the Al Ain Oases reflect differences in size and palm tree density. Al Ain Oasis (1,186,362 m²) exhibited the highest TBP, likely due to its larger area and denser palm cover, while Jahili Oasis (209,433 m²) had a lower TBP, possibly due to its smaller size and sparser vegetation.

Temporal patterns indicate a decline in biomass production in 2012, followed by an increase in 2020, demonstrating the sensitivity of oasis ecosystems to climatic conditions. According to the Environmental Statistical Report (2012), average precipitation in Abu Dhabi decreased from 21.5 mm in 2011 to 12.6 mm in 2012. In the Al Ain region, most rainfall occurs over the mountains during spring and summer (Statistics Centre, 2013). After 2020, TBP declined again, suggesting that reduced rainfall constrained vegetation growth. These findings underscore the need for resource-efficient strategies tailored to each oasis to mitigate productivity losses in unfavorable years and ensure sustainable management. Dhawi and Aleidan (2024) emphasize the importance of adaptive oasis management to sustain long-term productivity and resilience amid climate variability.

4.2 Evapotranspiration (ET)

ET trends highlight seasonal water demand and stress within the oases. Peak ET values in the summer months (July and August) reflect increased water demand due to high temperatures, which can strain resources. This aligns with the physiological needs of date palms and other vegetation, particularly during the fruiting stage when water requirements are elevated to support fruit development (Elshibli et al., 2009). Mutti et al. (2019) examined daily ET rates during wet and dry years and found that, during the dry season, vegetation had higher ET rates than bare soil. In contrast, during the wet season, differences in ET rates were less pronounced due to soil saturation and the urgent need of vegetation to meet its physiological demands. Flood irrigation, commonly used in oases, can exacerbate ET through evaporation, especially in summer. In winter (December and January), lower ET values indicate reduced water demand due to cooler, less stressful conditions. These seasonal patterns, influenced by temperature and growth stages, can guide sustainable irrigation scheduling, particularly in summer when water availability is limited (Matter et al., 2021). Mahmoud and Gan (2019) found that ET in the Middle East increases during summer and declines in winter due to exposure to intense solar radiation stress.

The analysis of uncertainty in ET estimations, using the standard error of the mean (SEM), reveals increased variability in ET values, particularly during the warmer months (July and August) and peak growing periods. This variability is most probably due to seasonal and environmental factors such as temperature fluctuations, soil moisture changes, and inconsistencies in irrigation practices (Feng et al., 2020; Hussein, 2001). Such variations highlight the importance of effective water resource management, emphasizing the need for targeted irrigation strategies that account for the specific climatic and ecological conditions of each oasis.

4.3 Net Primary Production (NPP)

NPP results reveal the seasonal productivity cycles across the oases, driven by temperature, water availability, and irrigation practices. Higher NPP values during the winter months indicate that cooler temperatures and reduced evapotranspiration create optimal conditions for photosynthesis, allowing vegetation, particularly date palms, to maximize productivity (Urban et al., 2017). In contrast, lower NPP values in the summer are influenced by the combined effects of extreme heat, limited water availability, and the allocation of energy towards fruiting. During the fruiting stage, date palms prioritize energy for fruit development over vegetative growth, leading to reduced photosynthetic activity. The additional stress from high temperatures and potential water scarcity further limits NPP during the summer months.

As the largest oasis in the city, Al Ain Oasis has a higher density of date palms, contributing to increased productivity and carbon sequestration potential. The observed NPP values in Al Ain Oasis are also influenced by efficient irrigation practices, favorable soil conditions, and the presence of diverse date palm varieties. In contrast, smaller oases, such as Jahili Oasis, have lower NPP values due to their limited area, which restricts vegetation density and overall productivity. This highlights the need for seasonally adjusted irrigation strategies to optimize growth, productivity, and carbon sequestration in these ecosystems.

5. Conclusion

This study highlights the crucial role of the oasis ecosystem in local environmental dynamics and carbon storage within Al Ain City. The findings reveal significant variations in tree biomass production (TBP), ET, and NPP, primarily driven by differences in the area of the oases. Al Ain Oasis emerged as the most productive, reflecting its larger area, abundant resources, and dense vegetation, while Jahili Oasis illustrated the challenges faced by smaller oases in biomass production.

The results emphasize the necessity for an adaptive management approach tailored to the distinct characteristics of each oasis. Sustainable water use during peak demand, enhanced soil management, and optimized irrigation practices are crucial for improving productivity and resilience. The responses of evapotranspiration and NPP to climatic and environmental variations provide valuable insights into maintaining oasis ecosystems despite limited water resources and climate variability.

This study also serves as an exploration of the use of WaPOR data, which may limit certain aspects of the analysis. Future research will integrate additional data sources to enhance the robustness and comprehensiveness of the findings, providing a more detailed understanding of oasis ecosystem dynamics.

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