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Sustainable Cultural Development through a Theoretical Interpretive Approach in the Context of the Climate Crisis: A Mathematical Model - The Case of Delphi

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Abstract

This study explores sustainable cultural development in the context of the climate crisis, using Delphi as a representative case of a cultural landscape increasingly exposed to environmental pressures. It develops a theoretical and interpretive framework supported by a simplified mathematical model that links visitor capacity, climate stress, and management resources. The model is applied using empirical data in order to examine how changing climatic conditions may influence the site's carrying capacity. The findings suggest that climate stress can significantly affect the number of visitors that can be safely accommodated, while improvements in management resources may help mitigate part of this effect. These results highlight the importance of adopting adaptive and climate-responsive management strategies. Overall, the study aims to contribute both to the theoretical discussion and to the practical management of cultural heritage sites facing growing climate-related challenges.

Keywords: Sustainable Cultural Development , Climate Change , Adaptive Carrying Capacity , Mathematical Modeling , Cultural Heritage Resilience , Delphi.

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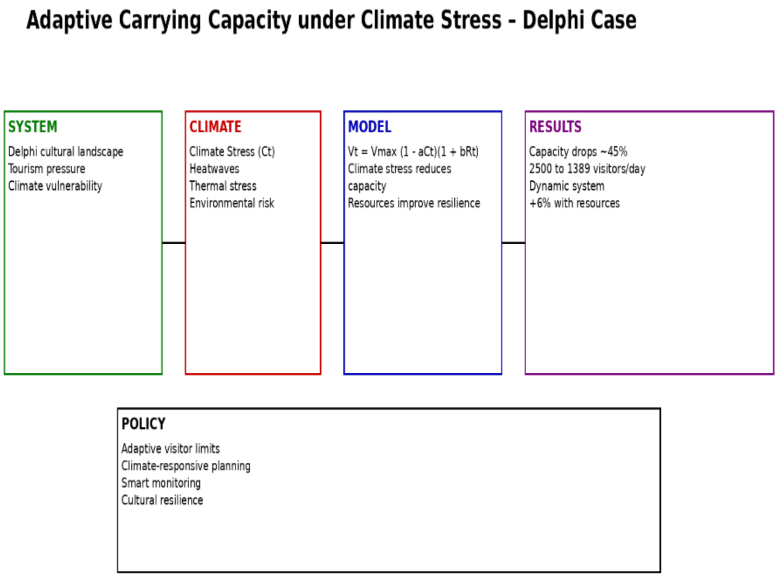
Graphical abstract



1. Introduction

Sustainable cultural development is one of the most dynamic and demanding areas of contemporary scientific research. At a time when the climate crisis is shaping new conditions for both the natural environment and society, this paper explores the interaction between culture, sustainability, and climate, decoding the parameters, cultural resources and archaeological sites of global significance face challenges that are not limited to the preservation of monuments, but extend to the management of visitor numbers, social cohesion, and the integration of new practices for their protection and promotion. The archaeological site of Delphi is home to a rich intangible and tangible cultural heritage, as evidenced by its well-known monuments, including the ruins of the ancient city of Delphi, cemeteries, fortifications, and the archaeological site of Kirra. There is also the Corycian Cave, a sacred site dedicated to the god Pan. Everyone believed that the god "Panas" was the protector of sheep and goats and of nature, known for his love of the outdoors and his ability to cause panic with his terrifying cries. Panhellenic athletic competitions were established in Delphi, according to tradition, in honor of Apollo's victory over Python and acquired equal importance with those of the Olympic Games. The games in Delphi were held every four years and included athletic and musical competitions, battle reenactments, hymns, and sacrifices (Evdokia, 2023). The ancient Greeks relied on divination and sought advice on both public and private matters. Herodotus reports that there were at least 18 shrines that included oracles and 96 missions for the purpose of seeking advice from an oracle, and of course, 53 of them were addressed to the Oracle of Delphi. The same source states that, among all the oracles, the most reliable prophecy was that given to King Croesus by the Oracle of Delphi (Tzirivilas 2015). It is now clear that the Oracle of Delphi was one of the greatest attractions in the region, as its power was so great that even kings from Persia and many other distant places visited it in order to be informed by the seer about what the gods were planning. It should be noted that each visit came at a high price and payment was made in gold, precious metals, or any expensive or artistic objects. Over the centuries, Delphi became an extremely wealthy and powerful city. In fact, the narrative references do not highlight specific individuals but refer abstractly to the priesthood of the Oracle involved in divination (Asimakopoulos, 2012). The search for an interpretative framework that links the concept of sustainable cultural development with the contemporary conditions of the climate crisis, with the present approach, also includes the methodological tool of the mathematical model, which provides an understanding of the cultural landscape, not as a static object, but as an "object" that is interpreted through social and environmental conditions. Thus, we are not limited to the management of our archaeological site, but also open up a field of understanding of the relationship between culture, society, and nature, with the contribution and quantitative analysis of the relationship between the site's visit ability, climate stress, and the carrying capacity of the landscape, useful conclusions and proposals emerge. This study contributes to the growing body of research on sustainable cultural development by introducing an integrative framework that explicitly links cultural heritage management with climate stress dynamics through a simplified mathematical modeling approach. Unlike existing studies that primarily focus on qualitative assessments or isolated indicators of tourism pressure, this paper proposes a quantifiable and adaptable model that captures the interaction between environmental constraints and management capacity. The innovation of the study lies in the operationalization of the concept of adaptive carrying capacity, allowing for dynamic adjustment of visitor limits in response to climate conditions. Furthermore, the empirical application to the case of Delphi provides a context-specific demonstration of how climate-responsive management strategies can be implemented in practice. By combining theoretical interpretation with quantitative modeling, the study offers both conceptual advancement and practical policy relevance, supporting more resilient and data-driven decision-making for cultural heritage sites under climate change pressures. This study contributes to the existing literature on sustainable regional development in several important ways. First, it provides updated and policy-relevant empirical evidence on the relationship between economic growth and labor market performance at the regional level in Greece, focusing on the post-crisis and post-pandemic period (2015–2024), which remains relatively underexplored in the literature. Second, the study employs panel data econometric techniques that explicitly control for unobserved regional heterogeneity, thereby offering more reliable and robust estimates compared to cross-sectional approaches commonly used in earlier studies. Third, the analysis integrates economic growth and unemployment within a unified empirical framework to explain employment outcomes, highlighting the dual role of income dynamics and labor market conditions in shaping sustainable development trajectories. Fourth, by focusing on NUTS-2 regional disparities, the study provides a spatially disaggregated perspective that allows for a better understanding of structural inequalities within the Greek economy. Finally, the findings offer clear policy implications by demonstrating that sustainable regional development requires not only economic expansion but also effective labor market functioning, thereby supporting the design of targeted and region-specific development strategies. Overall, the study contributes to bridging the gap between macroeconomic performance and social sustainability by empirically linking growth dynamics to employment outcomes at the regional level.

2. Theoretical framework

The theoretical framework of this study draws on interdisciplinary literature on cultural heritage, sustainable development, tourism carrying capacity, and climate change.

2.1. *Delphi as a UNESCO World Heritage Site*

In 1987, Delphi was added to the World Heritage List based on the following criteria: Masterpiece of human creative genius, Exchange of values, Testimony to cultural tradition, Exceptional architectural ensemble, and Connection with ideas and traditions of global significance (UNESCO, 2016). This inclusion demonstrates the uniqueness of Delphi as a meeting place of natural and cultural environments, as well as a cradle of religious, spiritual, and artistic creation. Inclusion in UNESCO recognizes both the monument's archaeological significance and its unique integration into the natural landscape (UNESCO, 2016; Perry, 2020). However, this inclusion is accompanied by international obligations, including protecting and maintaining the monument, managing visitor numbers in line with carrying capacity, ensuring the authenticity and integrity of the site, and involving the local community in management strategies (UNESCO, 2016). In support of this, a program entitled "Works for the care, configuration, beautification, and cleaning of archaeological sites" was recently made public (Hellenic Ministry of Culture, 2023).

2.2. *Delphi as a Representative Case Study*

Delphi constitutes an exceptionally suitable case study for examining the interaction between sustainable cultural development and climate change adaptation. As a UNESCO World Heritage Site of Outstanding Universal Value, Delphi combines exceptional archaeological significance with a unique integration of natural and cultural landscapes (UNESCO, 2016; Perry, 2020). Historically regarded as one of the most influential religious and cultural centers of the ancient world, Delphi continues to represent a powerful symbol of cultural identity and collective memory (Tzirivilas, 2015; Asimakopoulos, 2012).

At the same time, the site is increasingly exposed to environmental pressures associated with climate change, including thermal stress, erosion, drought, and wildfire risk (Fatorić & Seekamp, 2017; IPCC, 2022; Sesana *et al*., 2023).. These characteristics make Delphi an ideal setting for exploring how cultural heritage sites can balance conservation objectives, visitor management, and sustainable development under conditions of environmental uncertainty. Consequently, Delphi serves not only as a local case study but also as a representative example of the broader challenges currently faced by cultural heritage sites worldwide.

2.3. *Historical and cultural significance of Delphi*

Delphi is widely recognized as one of the most iconic archaeological sites in Greece and worldwide (UNESCO, 2016). In ancient times, the Oracle of Delphi was also considered the "center of the world" (the navel of the earth), while Apollo's presence in Delphi made the site a meeting point for political, religious, and cultural forces (Tzirivilas, 2015). The religious, political, and artistic activity that developed in Delphi made the site a symbol of Greek identity and cultural memory (Asimakopoulos, 2012). It is worth noting that the archaeological site includes: the Temple of Apollo, the Theater, the Stadium, the treasures of various cities, and important monuments such as the Omphalos (Karapatoucha,2021). The existence of the Delphic Oracle influenced the decisions of city-states, determined colonization's, and profoundly affected the development of the ancient Mediterranean (Tzirivilas,2015). Finally, there is the Archaeological Museum of Delphi, located right next to the archaeological site, with the most important and well-known exhibit being the Iniochos, while the archaeological site is known for the Temple of Apollo and the Tholos (Karapatoucha, 2021).

2.4. *Elements of cultural heritage*

Cultural heritage includes tangible elements (monuments, archaeological sites, landscapes) and intangible expressions (traditions, rituals, languages) (UNESCO, 2015). In the context of sustainable cultural development, cultural resources function as economic capital through cultural tourism, the creative cultural industry, and local production. As social capital, it strengthens collective identity and social cohesion, and as environmental capital, especially when cultural heritage is integrated into natural landscapes (Throsby, 2001; Koumoutsea, 2022). However, integrating cultural heritage into development strategies requires balance. Excessive commercialization can lead to overtourism, with well-known consequences for cultural areas, which are negatively affected and where locals respond accordingly (Butler, 1999; McCool & Lime, 2001). On the other hand, the goal of sustainable tourism development is to protect the positive economic and social impacts while minimizing the consequences on the natural, cultural, and social environment of a tourist destination. Sustainable tourism requires significant and well-coordinated efforts from all parties involved (UNWTO, 2020). The phenomenon of overtourism, in terms of its sustainability impacts, has been a major issue for many organizations and countries (Kouvaras,2023). The challenge lies in developing a model that enables the dynamic use of cultural resources while respecting their limits.

2.5. *Axes of sustainable cultural development framework*

With a focus on Delphi, the exploration of sustainable cultural development in relation to the climate crisis is an important field of research (UNESCO, 2015; IPCC, 2022). Because the Delphi sanctuary interacts directly with the wider natural environment, the site is a unique example of a cultural landscape where natural and artificial elements coexist in a timeless interdependence (Perry, 2020). It is precisely this interdependence that is now under serious threat due to the climate crisis, with extreme weather events, soil erosion, fire risk, and thermal stress (IPCC, 2022). In fact, these phenomena threaten not only the monuments themselves, but also the sustainability of the local community, which depends heavily on cultural tourism (Fatorić & Seekamp, 2017). Sustainable cultural development, in relation to the climate crisis, considers culture to be a fundamental pillar of sustainable development (UNESCO, 2015). Cultural heritage as a dynamic resource is intertwined with social, economic, and environmental dimensions, as well as a complex landscape of relationships and meanings (Throsby, 2001). On the other hand, the climate crisis creates an urgent need for new resilience strategies that incorporate both technical and social parameters (Fatorić & Seekamp, 2017). Based on the above, although the analysis draws on theoretical tools specific to the cultural landscape, it highlights the challenges and opportunities for sustainable cultural development.

2.6. *Setting the Goals of the Study – Cultural landscape – climate*

Cultural landscapes should not be understood as static, but as "non-static" variables that acquire meaning through their social perception (UNESCO, 2015; Perry, 2020). Every society and every era "reads" historical sites and monuments differently (Throsby, 2001). In the case of Delphi, a simple interpretative analysis sees the landscape not only as an archaeological monument or a tourist economic resource, but also as a vulnerable component of its ecosystems, subject to climatic pressures (Fatorić & Seekamp, 2017; IPCC, 2022). In this paper, the monument is placed within a climate framework and is transformed into a sum of social, economic, and environmental relationships.

2.7. *Cultural heritage - Climate crisis*

Climate change currently poses the greatest threat to the preservation of cultural heritage (IPCC, 2022; UNESCO, 2021), highlighting risks that directly affect monuments and cultural landscapes, including extreme weather events such as floods, storms, and heatwaves. Also, soil erosion and destabilization, with a focus on archaeological sites in sloping areas, such as Delphi (Fatorić & Seekamp, 2017). Furthermore, rising temperatures cause thermal stress on marble, stone, and other materials, as well as increasing the risk of fires, droughts, and extreme heat (IPCC, 2022). UNESCO (2021) reported that over 70% of World Heritage Sites are at immediate risk from climate change. As for Greece, data show that almost all outdoor archaeological sites will face increased erosion, thermal stress, and fire risk (IPCC, 2022). This is why responsible organizations are calling for resilience and adaptation strategies, proposing a series of strategies to strengthen the resilience of cultural resources, integrate risk management, and support prediction, prevention, preparedness, and response (UNESCO, 2021). They also call for infrastructure adaptation, with shading, drainage systems, and anti-corrosion works. Moreover, the active participation of local communities is essential to all of this, as it will contribute positively to the joint management of cultural heritage (Perry, 2020). Digital documentation is also necessary, including three-dimensional images and digital archives in the event of disasters (UNESCO, 2021). Green tourism practices are also important, including reducing pollutants, promoting sustainable mobility, and diversifying visitor flows (UNWTO, 2020). The use of these strategies certainly aims at sustainable cultural development, leading to a comprehensive framework for heritage protection, but also a social and political challenge (Popidou, 2022; Climate Academy, 2025).

2.8. *Cultural tourism management*

The Delphi site is considered a multidimensional area of sustainable cultural development (UNESCO, 2016; Perry, 2020). On the one hand, we have an archaeological site of global significance, with deep historical and cultural value; on the other hand, we have a local community that depends on it (UNESCO, 2016). However, the threat of the climate crisis requires a review of all traditional models of cultural tourism management (IPCC, 2022; Wall, 2021). Thus, Delphi is not only a "case study" but also a field of conflict between environmental threats and local needs. This complexity is now the subject of interpretative, quantitative, and empirical methods of analysis for the following reasons. The archaeological site of Delphi attracts hundreds of thousands of visitors annually, most of whom are international tourists (ELSTAT, 2024). The intense mobility (especially during the summer months) creates concentrations that exceed the site's capacity (McCool &

Lime, 2001). This is due to the concentration of visitors at specific times because of organized tours. The infrastructure is largely inadequate for managing mass flows. The environmental burden stems from increased mobility (buses and private vehicles) (UNWTO, 2020). The local economy is almost entirely dependent on cultural tourism, making it vulnerable to crises (e.g., the COVID-19 pandemic and extreme weather events) (Butler, 1999). To this end, visitor management is required, which to date has not fully incorporated smart management practices (e.g., digital timetable booking, flow dispersion, diversification of cultural experiences) (Wall, 2021).

2.9. *Delphi in the context of the climate crisis*

The Delphic landscape is vulnerable to the effects of climate change (IPCC, 2022; Fatorić & Seekamp, 2017). The geomorphology of the area (mountainous, sloping, with forest vegetation) and the nature of the monuments are subject to multiple environmental risks, including erosion and landslides, as soil instability increases with rainfall intensity and extreme weather events (Iliadis, 2022; IPCC, 2022). Landslides have already been recorded that threaten parts of the archaeological site. The wider area is characterized by a high risk of forest fires, which can destroy both the natural environment and the site's protective infrastructure (IPCC, 2022). Thermal stress is a fact of life for marble and stone on the site, as they are exposed to rising temperatures and hot-cold cycles that accelerate their deterioration (Fatorić & Seekamp, 2017). At the same time, drought affects not only vegetation but also the wider stability of the landscape (IPCC, 2022). The consequences are not limited to the area itself but also spread threateningly to the local community (Perry, 2020).

2.10. *Conflict situations*

The Municipality of Delphi relies heavily on cultural tourism (UNESCO, 2016; Butler, 1999). This creates a relationship of dependency between the archaeological sites and the local community. At the same time, tensions are observed: Residents seek greater participation in the management and benefits of tourism. Cultural management bodies (the Ministry of Culture and the Ephorate of Antiquities) focus mainly on the protection of monuments, leaving less room for social co-decision. Businesses (hotels, restaurants) often prioritize increasing visitor numbers without always accounting for the site's carrying capacity (McCool & Lime, 2001). Consequently, a triangle of interests emerges: monument protection, economic benefits, and social participation. The climate crisis is intensifying this triangle, requiring additional resources and new strategic plans (Soroli,2024; IPCC,2022). The current situation in Delphi shows that we are facing critical conflicts between tourism development and the preservation of authenticity, between the local community and central management bodies, and between direct economic interests and long-term sustainable development (Wall, 2021). There is also an optimistic scenario: the possibility of integrating smart technologies into visitor management. At the same time, the development of sustainable forms of tourism (e.g., hiking, educational, and small-scale cultural tourism) (UNWTO, 2020). Strengthening the local community through cooperative initiatives and the creation of adaptive projects to protect the area from climate risks (Perry, 2020). Sustainable development, as it was first formulated, refers to meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (WCED, 1987). In the triple distinction—economy, society, environment—culture was considered a peripheral element. Today, however, there is a strong scientific and institutional argument for recognizing culture as the "fourth pillar" of sustainable development (UNESCO, 2015). This means that cultural resources should no longer be treated exclusively as remnants of the past, but as active elements that can contribute to the creation of a sustainable cultural identity of development, social cohesion, and economic activity. UNESCO (2015) emphasizes that cultural heritage—both tangible and intangible—is fundamental to sustainability, as it strengthens local communities, promotes intercultural understanding, and provides resources for innovative forms of economic development (Perry, 2020). For this reason, it is considered essential to develop a relevant mathematical model to effectively investigate sustainable cultural development in relation to the climate crisis in Delphi.

3. Methods and Data

3.1. *Mathematical Model - The context*

The analysis of the work so far has followed a clear path: from theoretical documentation to theoretical analysis, in the case of Delphi. Next, it presents a methodological approach based on mathematical modeling, with results interpreted along the way, following the stages of the calculations that lead to conclusions and proposals for sustainable cultural development in Delphi. In this way, the contribution of both the theoretical approach and, mainly, the analysis of the mathematical model leads to groundbreaking proposals for sustainable cultural development, at a time when the climate crisis urgently calls for new forms of protection, promotion, and restoration of cultural heritage. The function represents the mathematical model we used:

$$V_t = V_{max}(1-\alpha C_t)(1+\beta R_t)$$

Of course, it did not emerge "from scratch", but has been detected using basic mathematical methodology, with the use of Carrying Capacity theory (Saveriades & Parpairis, 1993) and is based on: A) Mathematical ecology (Murray, 2002). Mathematical Biology I: An Introduction. Springer, Classic textbook on mathematical biology, with a complete analysis of the logistic equation and applications in ecology. B) From the alternative form of cultural tourism applied in the 1980s and 1990s, estimating the maximum number of people that an ecosystem or area can "support" without being degraded. McCool, S. F., & Lime, D. W. (2001 & Wall, G. (2021). And C) From mathematics, where it is a linearization of the view that there is a maximum value Vmax V and that pressures (e.g. climatic) reduce proportionally. the actual level (**Table 1**).

Mathematical modeling seeks to give a quantitative dimension to the relationship among three basic parameters: the visit ability of a cultural site, the climatic stress it undergoes due to extreme temperatures and other phenomena, and the available management resources (infrastructure, personnel, policies). Obviously, this model does not aspire to replace complex econometric or climatological approaches, but aims to be a simple yet functional tool for developing strategies to manage the climate crisis.

3.2. *Model Specification*

The proposed model determines the safe visitor capacity of a cultural heritage site as a function of environmental pressure and management support. Specifically, visitor capacity is assumed to decrease as climate stress intensifies, while the availability of management resources may partially offset this reduction. The relationship is formally expressed as:

$$Vt = Vmax\left(1-\alpha Ct\right)\left(1+\beta Rt\right)$$

where Vt represents the safe number of visitors per day at time *t*, Vmax denotes the theoretical maximum carrying capacity under ideal environmental conditions, Ct is the climate stress index ranging from 0 to 1, and Rt corresponds to the management resource index, also bounded between 0 and 1. The parameters α and β capture the sensitivity of visitor capacity to climate stress and the reinforcement effect of management resources respectively. The structure of the model reflects the interaction between environmental pressure and management capacity. The first component, (1 − αCt), represents the reduction in visitor capacity resulting from increasing climate stress. As the climate stress index rises, the effective carrying capacity of the site decreases proportionally according to the sensitivity parameter α. The second component, (1 + βRt) reflects the potential compensatory effect of management resources. Higher levels of available resources, such as shading infrastructure, staff presence, and digital visitor-management tools, may partially mitigate the negative effects of climatic stress on the site's operational capacity. For the empirical calibration of the model, visitor data from the Delphi archaeological site and museum were used. In September 2023, before the implementation of the unified ticket system, the Delphi Museum recorded 19,631 visitors, while the archaeological site received 54,658 visitors, resulting in a total of 74,289 visitors during that month. This period was selected as a reference point because it represents the last year in which visitor statistics for the museum and the archaeological site were reported separately. In September 2024, the Delphi Museum recorded 53,288 visitors, while separate statistics for the archaeological site were no longer available due to the introduction of the single ticket system that integrates access to both the museum and the archaeological site within a unified admission structure. Additional comparative national data were considered in order to place the Delphi case within the broader context of cultural tourism in Greece. According to national statistics, total visits to archaeological sites in Greece decreased by approximately 3% in August 2024 compared to August 2023, while a slight increase of 0.3% was recorded in September 2024 compared to the same month of the previous year. On an annual basis, archaeological sites recorded an overall 4.5% increase in visitor numbers during the period January–December 2024, although a temporary decline of 8.2% was observed in December 2024 compared to December 2023. Museums followed a stronger upward trend, with an overall 14.7% increase in visitors during 2024 compared to the previous year. Climate stress scenarios for 2024 were constructed using official meteorological data. June 2024 was recorded as the hottest June in Greece, corresponding to a climate stress index of C = 0.7, while July 2024 experienced the longest heatwave period since 1980, corresponding to C = 0.9. August 2024 continued to exhibit persistently high temperatures, corresponding to C = 0.8, whereas September 2024 presented milder but still elevated climatic conditions with C = 0.6. These climate stress indicators are based on reports from the National Observatory of Athens (NOA/meteo), which documented the exceptional intensity and duration of the July 2024 heatwave. Regarding management resources, the baseline scenario for 2024 assumes a management capacity index of R = 0.5, reflecting ongoing projects and operational measures implemented at the site. An improvement scenario assumes R = 0.6, representing enhanced management capacity through additional interventions such as improved visitor monitoring systems, shading infrastructure, and increased staffing during peak visitation periods. In order to estimate the theoretical maximum carrying capacity (Vmax), the visitor data from September 2023 were used as a calibration reference. The total monthly visitation of 74,289 visitors corresponds to an average of approximately 2,476 visitors per day. Using the calibration parameters Cref = 0.3, R = 0.5, α = 0.6, and β = 0.4, the coefficients of the model are calculated as follows. The climate adjustment factor is 1 − αCref = 1 − 0.6 × 0.3 = 0.82, while the resource reinforcement factor equals 1 + βR = 1 + 0.4 × 0.5 = 1.2. The product of these coefficients equals 0.984. Substituting these values into the model yields an estimated theoretical carrying capacity of approximately Vmax ≈ 2,516 visitors per day.

Table 1. Definition of model variables

Symbol	Description	Measurement Scale
(V_t)	Safe visitor capacity at time t	Visitors/day
(V_{max})	Maximum carrying capacity under ideal conditions	Visitors/day
(C_t)	Climate stress index	0–1
(R_t)	Management resource index	0–1
α	Sensitivity to climate stress	Parameter
β	Resource reinforcement parameter	Parameter

3.3. *Empirical Application of the Model*

The proposed adaptive carrying-capacity model is empirically applied to the case of Delphi using climate and visitor data for July 2024. This period is particularly relevant due to the extreme heatwave conditions recorded in Greece during the summer of 2024. According to meteorological reports, July 2024 experienced the longest heatwave period since 1980, corresponding to a climate stress index of C = 0.9. For the purposes of the analysis, the management resource index is assumed to be R = 0.5, reflecting the baseline operational capacity of the site. Based on these parameters, the climate-adjustment factor is calculated as $1 - \alpha C = 1 - 0.6 \times 0.9 = 0.46$, while the management reinforcement factor equals $1 + \beta R = 1 + 0.4 \times 0.5 = 1.2$. The combined adjustment coefficient therefore equals $0.46 \times 1.2 = 0.552$. Using the previously estimated theoretical carrying capacity Vmax ≈ 2,516 visitors per day, the climate-adjusted visitor capacity can be calculated as:

$$Vt = Vmax \times 0.552 \text{ » } 1{,}389 \text{ visitors/day}$$

Consequently, under extreme heatwave conditions, the safe daily visitor capacity of the Delphi archaeological site decreases to approximately 1,389 visitors per day. This result illustrates the substantial influence of climate stress on the operational carrying capacity of cultural heritage sites.

3.4. *Reverse Estimation of Climate Stress (C_t)*

The proposed model also allows the reverse estimation of the climate stress index (Ct) based on observed visitor capacity levels. By algebraically rearranging the original model equation, the climate stress index can be expressed as a function of observed visitor capacity, management resources, and the theoretical maximum carrying capacity. Starting from the model specification:

$$Vt = Vmax\left(1 - \alpha Ct\right)\left(1 + \beta Rt\right)$$

the equation can be rearranged to isolate Ct as follows:

$$Ct = \left[1 - Vt / \left(Vmax\left(1 + \beta Rt\right)\right)\right] / \alpha$$

This formulation allows the estimation of the implied climate stress level when visitor capacity and management resources are known. In other words, the model can be used not only to predict visitor capacity under different climate scenarios, but also to infer the environmental pressure associated with observed visitor levels. For illustrative purposes, assuming an observed visitor capacity of Vt = 2,000 visitors per day and a management resource index R = 0.5, the denominator of the equation becomes:

$$Vmax\left(1 + \beta R\right) = 2{,}516 \times 1.2 \text{ » } 3{,}019.9$$

Dividing the observed visitor level by this value yields approximately 0.662. Subtracting this value from 1 result in 0.338, which, when divided by the sensitivity parameter $\alpha = 0.6$, produces an estimated climate stress index of approximately Ct ≈ 0.56. This result indicates moderate climatic pressure on the site. It should be emphasized that Vt represents the recommended safe visitor capacity, rather than merely observed arrivals. If actual visitor numbers exceed this safe level, the implied climate stress index may appear artificially lower because the site operates beyond its recommended resilience threshold.

3.5. *Interpretation of Results*

The findings confirm that carrying capacity is strongly climate-dependent. Extreme summer heat reduces safe capacity to approximately 1,400 visitors per day, whereas milder conditions permit levels closer to 2,500. Recorded arrivals in September 2024 (approximately 78,500 visitors) exceeded the model's estimated safe range (approximately 60,000–64,000 visitors per month), indicating measurable pressure on both monuments and the visitor experience. Furthermore, modest improvements in resource adequacy (R) yield measurable gains. Increasing R from 0.5 to 0.6 results in approximately a 6% increase in safe carrying capacity across all months. This demonstrates that targeted investments in shading infrastructure, hydration stations, staff presence, and smart monitoring systems produce tangible resilience benefits.

4. Empirical results

The empirical analysis indicates a clear relationship between climate stress and the carrying capacity of the Delphi archaeological site. Rather than being constant, carrying capacity appears to vary depending on environmental conditions. As climate stress increases, the number of visitors that can be safely accommodated tends to decline, suggesting that environmental pressure plays a critical role in shaping the operational limits of the site. A more detailed examination of the monthly estimates reveals noticeable variation across the summer period. In June (C = 0.7), the site is estimated to accommodate approximately 1,752 visitors per day. Although environmental pressure is already present, the system appears to operate within relatively manageable limits. This suggests that moderate levels of climate stress do not immediately compromise the site's functionality but may still require careful monitoring. In contrast, July (C = 0.9) represents a period of extreme climatic pressure. During this month, the estimated safe carrying capacity declines to approximately 1,389 visitors per day. This reduction is particularly significant when compared to the theoretical maximum capacity, indicating that the system approaches a critical threshold under extreme heatwave conditions. Such findings underline the importance of incorporating environmental constraints into visitor management strategies. August (C = 0.8) presents a slightly improved but still demanding scenario, with an estimated capacity of approximately 1,570 visitors per day. This suggests that prolonged exposure to high temperatures continues to affect the system, even when conditions are not as extreme as in July. In September (C = 0.6), however, a noticeable recovery is observed, with capacity increasing to approximately 1,933 visitors per day. This pattern indicates that even moderate improvements in climatic conditions may lead to substantial gains in carrying capacity (**Table 2**).

Table 2. Estimated daily carrying capacity under different climate stress levels.

Month	Climate Stress (C)	Estimated Safe Capacity (visitors/day)
June	0.7	≈ 1,752
July	0.9	≈ 1,389
August	0.8	≈ 1,570
September	0.6	≈ 1,933

Table 3. Recommended visitor capacity ranges based on climate stress.

Climate Stress Range (C)	Recommended Daily Capacity (visitors/day)
$C \leq 0.4$	2,200–2,500
$0.5 \leq C < 0.7$	1,800–2,000
$0.7 \leq C < 0.85$	1,500–1,700
$C \geq 0.85$	1,350–1,450

A comparative view of the results highlights the dynamic nature of carrying capacity across different climatic conditions. The difference between the highest and lowest estimated capacity values is substantial, indicating that the system does not respond linearly to environmental stress. Instead, small increases in climate stress appear to produce disproportionately larger reductions in capacity. This dynamic behavior suggests that the site operates close to environmental thresholds. Once these thresholds are exceeded, the system's ability to accommodate visitors declines more rapidly. This observation is particularly relevant for peak summer months, during which even slight increases in temperature or duration of heatwaves may significantly affect site performance. At the same time, the results indicate that carrying capacity should be understood as a flexible and adaptive concept. Rather than being defined by a single fixed value, it varies over time and is influenced by both environmental and managerial factors. In addition to climate stress, the model highlights the role of management resources in shaping carrying capacity. Although the present analysis assumes a constant level of resources ($R = 0.5$), the structure of the model suggests that improvements in infrastructure and management practices may help mitigate part of the negative effects of climate stress. For example, the provision of shaded areas, improved visitor flow management, and the availability of staff during peak periods could contribute to maintaining higher levels of safe capacity. While such measures may not fully offset extreme environmental pressures, they may reduce their impact and enhance the overall resilience of the site. The findings of this study are broadly consistent with existing research on tourism carrying capacity and environmental stress. Previous studies have emphasized that carrying capacity should not be treated as a fixed numerical limit but rather as a context-dependent concept influenced by environmental and managerial conditions (Butler, 1999; McCool & Lime, 2001; Wall, 2021). Furthermore, the growing body of literature on climate change and cultural heritage highlights the increasing vulnerability of heritage sites to environmental pressures, particularly in regions exposed to extreme temperatures (Fatorić & Seekamp, 2017; IPCC, 2022). In this respect, the present study contributes by offering a simplified quantitative framework that helps illustrate these relationships in a practical context.

From a management perspective, the results suggest that a more adaptive approach to visitor regulation may be required. Instead of relying on fixed visitor limits, site managers could consider adjusting capacity levels in response to changing climatic conditions. Such an approach would allow for the reduction of visitor pressure during extreme periods while maintaining accessibility under more favorable conditions. In addition, the findings highlight the importance of strengthening management practices and infrastructure. Measures such as the development of shaded pathways, improved access to water, and the use of digital tools for monitoring visitor flows may contribute to enhancing site resilience. Finally, the redistribution of visitor flows across different time periods may help reduce congestion and improve sustainability outcomes. The use of time-slot systems, as well as incentives for off-peak visitation, could support a more balanced and efficient use of the site (**Table 3**).

5. Discussion

Interpreting the above framework, proactive and transparent communication with visitors emerges as a critical priority, particularly regarding risk awareness and revised carrying-capacity limits at Delphi. The adoption of off-peak pricing policies, combined with seasonal incentives for spring and autumn, as well as targeted morning and late-afternoon summer time slots, can help smooth visitor flows. The establishment of combined or staggered-entry tickets, allowing sequential visitation between the Museum and the Archaeological Site (or vice versa), would further prevent simultaneous crowd concentration at climatically exposed locations. For effective governance, systematic monitoring should include occupancy rates per time slot, cancellation and rebooking percentages during heat alerts, average length of stay, reported heat-related discomfort incidents, and waiting times at identified bottlenecks, alongside structured hydration pauses at critical circulation points. The operational objective should be to maintain occupancy levels below 85% per time slot during months when $C \geq 0.7$, thereby embedding resilience-based principles within adaptive visitor management strategies. Holistic management strategies are imperative, understood as the development of integrated planning frameworks that combine cultural heritage protection with broader objectives: sustainable cultural development, environmental protection, and social cohesion. Climate adaptation of cultural policies is equally necessary. The climate-change dimension must be systematically mainstreamed across all policy levels concerning cultural heritage ranging from conservation and restoration practices to visitor management strategies. Local communities must also be strengthened through participatory decision-making mechanisms, ensuring that they tangibly benefit from cultural development processes. Social consensus constitutes a critical precondition for cultural sustainability. Visitor management should be resilience-based through the implementation of flexible, adaptive policies that smooth visitor flows, safeguard the quality of the visitor experience, and simultaneously ensure respect for site-specific carrying capacity thresholds. For improved governance, international cooperation and the exchange of best practices are essential particularly among World Heritage cultural sites facing common climate-related challenges. Networking, knowledge exchange, and the adoption of international standards promoted by UNESCO and ICOMOS can significantly enhance adaptive capacity. Digital innovation should also be prioritized. Investment in digital tools such as virtual tours, smart visitor information systems, and big data analytics for monitoring visitation patterns can improve accessibility, reduce physical pressure on vulnerable areas, and increase transparency in management. Simultaneously, continuous education and awareness-raising initiatives are required. Targeted training programs for local communities, visitors, and heritage professionals regarding the impacts of climate change can substantially strengthen sustainable cultural management practices. The Delphi case study demonstrates that "sustainable cultural development" cannot be examined independently of the complex web of challenges posed by the climate crisis. World Heritage sites function both as sensitive indicators of human history and as fragile ecosystems, where overexposure, thermal stress, and socio-economic pressures intersect. The analysis drawing on both secondary data sources and the applied mathematical model indicates that heritage protection requires new tools, new alliances, and, above all, a renewed conceptual framework: sustainable cultural development cannot be achieved without environmental resilience, social participation, and technological innovation. The future of Delphi and of any comparable cultural site will not be determined solely within the domains of archaeology or conservation science. It will also depend on political will, local collaboration, and international solidarity. As highlighted in the recent press release of the Hellenic Ministry of Culture (30 May 2025) regarding infrastructure reinforcement and upgrading works at the archaeological site of Delphi, adaptive investment strategies are already emerging as a necessary response to escalating climate risks. In a warming world, heritage protection constitutes an act of respect for the past and a commitment to future responsibility. Delphi once a cradle of spiritual and cultural radiance in antiquity can continue to serve as a guiding reference point today. When cultural heritage is combined with vision, adaptability, and participatory governance, it can stand as a beacon of resilience and inspiration in an era defined by uncertainty.

6. Policy Implications

The findings of this study have several implications for cultural heritage management and public policy. First, the results demonstrate that carrying capacity should be treated as a dynamic rather than a fixed concept, particularly under conditions of increasing climate variability. Heritage managers may therefore benefit from adopting adaptive visitor-management systems that adjust access levels according to climatic conditions and environmental stress indicators (McCool & Lime, 2001; Wall, 2021; UNESCO, 2024).

Second, the analysis highlights the importance of investing in resilience-enhancing infrastructure, including shaded areas, water supply facilities, digital monitoring systems, and visitor-flow management technologies. Such interventions can partially mitigate the negative effects of climate stress and improve the site's operational capacity (IPCC, 2022; ICOMOS, 2024; Dastgerdi *et al*., 2023).

Third, the model may support decision-making processes by providing a simple analytical framework for evaluating alternative management scenarios. This can assist cultural authorities, local governments, and heritage organizations in designing evidence-based adaptation strategies that balance conservation priorities with visitor accessibility and local economic development. More broadly, the framework may be adapted to other archaeological sites facing similar climate-related challenges, thereby contributing to the development of climate-resilient cultural heritage policies.

7. Conclusions

This study examined the relationship between climate stress and visitor carrying capacity at the archaeological site of Delphi through the use of a simplified adaptive model. The findings suggest that carrying capacity is not constant but varies depending on environmental conditions. As climate stress increases, the number of visitors that can be safely accommodated tends to decrease, sometimes quite substantially. The empirical analysis also highlights noticeable differences across climatic scenarios. Under moderate conditions, the site appears capable of operating closer to its theoretical capacity, whereas during extreme heat events the estimated safe capacity declines significantly. At the same time, the results indicate that improvements in management resources may help to partially offset these effects, although not eliminate them entirely.

These findings point to several practical implications for cultural heritage management. One key implication is the need to move away from fixed visitor limits and towards more flexible approaches that take into account changing environmental conditions. Adjusting visitor capacity in response to climate stress could help reduce pressure on both the site and visitors during extreme periods. In addition, the results underline the importance of strengthening management practices and infrastructure. Relatively simple measures, such as increasing shaded areas, improving access to water, or enhancing visitor flow monitoring, may contribute to better site resilience under high temperatures. Another important consideration is the distribution of visitor flows over time. Encouraging visits during less crowded periods, whether within the day or across seasons, could help reduce peak pressure and improve the overall experience. In this respect, tools such as timed entry systems or targeted incentives may prove useful. Despite its contributions, the study has certain limitations that should be acknowledged. The model adopts a simplified structure and focuses primarily on the interaction between climate stress and management resources. Other potentially relevant factors, such as visitor behavior, spatial distribution within the site, or long-term environmental changes, are not explicitly included. Furthermore, the empirical application is based on aggregated data and scenario-based assumptions, particularly with regard to the climate stress index. While these assumptions are grounded in available information, they may not fully capture the complexity of real-world conditions. Future research could build on this approach by incorporating additional variables and more detailed data. For example, the integration of real-time environmental monitoring and visitor flow data could improve the model's practical relevance. It would also be useful to explore how visitor behavior and spatial patterns within the site influence carrying capacity. Applying the model to other cultural heritage sites could provide further insights and allow for comparisons across different contexts. More broadly, future work may consider combining this type of modeling approach with more advanced techniques, such as simulation methods or data-driven models, in order to support more comprehensive decision-making under conditions of climate uncertainty.

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