Vegetation Cover and Tumuli’s Shape as Affecting Factors of Microclimate and Biodeterioration Risk for the Conservation of Etruscan Tombs (Tarquinia, Italy)

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Abstract: The conservation of underground tombs is affected by several physical-chemical and biological factors, which could be reduced by insulating systems able to maintain the microclimatic stability also decreasing the biodeterioration risk. In Mediterranean areas, wild ephemeral plants, which reduce their cover during the hot season, seem unsuitable for reducing summer overheating. In this study, we wish to assess the influence of vegetation cover and of overlaying soil, after the establishment of an evergreen turf of a cultivar of Cynodon dactylon, on two tombs in the Etruscan Necropolis of Monterozzi, covered by linear-shaped tumuli. Therefore, we evaluated for 10 months the thermo-hygrometric values of these tombs, together with two tombs as controls. We also evaluated the different tumuli’s morphologies and the related received solar radiation. Results confirmed that late summer and early autumn as critical microclimatic periods for the risk factors of hypogeal paintings when peaks of superficial temperature occur. A positive influence of vegetation cover on maintaining constant humidity and internal temperatures was detected, but the mounds orientation, as well as soil depth, seems to have a relevant role. Considering the naturalistic features of the area and the related cultural ecosystem services, a careful selection of wild plants is suggested.

Keywords: archaeological parks; biodeterioration prevention; cultural ecosystem services; hypogea microclimate; hypogea conservation; Monterozzi Necropolis; plant cover effects; UNESCO site; wall paintings conservation

1. Introduction

Underground (hypogeal) monuments, such as tombs, catacombs, caves, and sepulchers, are often enriched with wall paintings and stuccoes, which can be affected by several physical-chemical and biological deteriorative factors [1–6]. Considering their placements, their environmental conditions are characterized by high water content of the surfaces and rocks, whereas ventilation, lighting conditions, and temperatures are usually relatively low [7,8].

Humidity and temperatures (T) are the most important factors affecting both physical-chemical and biological deterioration [9–12]. In particular, the associated high values of water content and low temperatures give rise to a high level of relative humidity (RH > 70% and often greater than 90%), which increases in the case of the presence of visitors [13–15]. At high RH levels, condensation can occur, even if a small decrease of the superficial temperature is reached. When percolation also occurs, pigments of mural paintings are washed away from the walls, and chemical lithic effects seriously weather the rocks and mortars [16,17]. Moreover, the high water content creates a suitable environment for bacteria, fungi, and algae, and for roots penetration of plants, responsible for hypogea’s biodeterioration [11,18–21]. Furthermore, lighting systems can favor the
growth of cyanobacteria and algae [18,22,23], whereas low values of lighting combined
with the low ventilation explain the lichens’ absence [9].

Hypogea are not isolated systems, and they are susceptible to heat, water, and salts
coming from the outside, which can give rise to different weathering processes. For instance,
fluctuations of T and RH cause expansion and shrinkage of the materials, which can lead
to fragmentation, cracking, and detachment of mural paintings [2,10,11]. In addition,
salt crystallization, which can take place on the surface of a wall painting (efflorescence)
or beneath it (sub-florescence), leads to surface blooms, and the associated volumetric
expansion also gives rise to cracking and detachments of painted layers [1,16,24]. When
temperatures increase in the hottest season, a higher risk for biological colonization has
been detected, as observed in several sites, such as in ancient Korean tombs [6,25–28]. In
fact, for such tombs, three levels of risk for colonization of microorganisms were established,
using a scale that follows increasing temperature values [29,30].

Therefore, accurate monitoring of humidity and temperatures is needed to maintain
the maximum stability of internal microclimatic conditions in order to avoid the warming
that follows the hottest season. This topic has great relevance in particular in the case
of fragile environments, such as the hypogoeal Etruscan tombs of the Monterozzi area in
Tarquinia, which, together with Cerveteri tombs, are part of the UNESCO World Heritage
List (WHL) since 2004 [6]. Here, different biodeterioration phenomena are recurrently
detected, due to the growth of different bacterial and fungal strains, as well as to root
development [31–33], and for such reasons, we selected the site within an international
bilateral project (Italy and South-Korea) focused on the conservation of hypogea and their
protection against biodeterioration processes [6,34,35].

The practices of building hypogaeal tombs and decorating them with mural paintings
developed in several Etruscan cities, in a wide region of Etruria, during a period from the
7th to the 3rd century B.C. Their painted tombs have an extraordinary cultural and artistic
relevance because they reflect the life, the funeral rites, and the concept of the afterlife of
the Etruscans aristocracy [36,37]. In this necropolis, the sepulchral chambers often lie at a
variable depth from the surface (from 2 m to 8 m), under variable soil and bedrock types,
which have been excavated to obtain them. The original tumuli, which covered the tombs,
were often dismantled and only partially rebuilt [38]. The building of mounds as burial
marks, a sign that appears from a long distance, has a long tradition, which can be dated
even from the last millennium B.C. in the area of the ancient Thracia, Illyria, and Greece,
and similar buildings can be found all over the world [39].

These monumental tombs could, however, have a protective reason for the sepulchral
chambers. The effects of tumuli on the stability of microclimate were investigated for three
Macedonian tombs, showing that the tumulus protects the tomb against the deterioration
processes, maintaining the stability of the hydrothermal values thanks to the soil layers [39].
Moreover, the vegetation cover, as a waterproof and insulating system, seems to have a role
in the regulation and maintenance of the microclimatic conditions [40]. As a waterproof
system, vegetation absorbs part of the rainwater, which is partly retained by the soil
layers, contributing to keeping moisture at a suitable level and avoiding percolation [40].
As an insulating system, both vegetation and soil layers seem able to absorb and reflect
part of the light radiation, reducing the intensity of thermal waves, which spread to the
hypogeum, contributing to keeping the temperature at a suitable level [40]. Moreover,
during the penetration through the soil, these thermal waves delay their effects on hypogaeal
environments for some months [2].

Indeed, the vegetation cover often varies during the seasons, following the climatic
variations. In Mediterranean areas, which have hot, dry summers, most species are
herbaceous ephemeral plants (Therophytes), which die during summer, surviving as
seeds [41]. To improve the stabilization of microclimatic parameters through a better
insulation during the hottest season, the perennial plants seem more suitable than the
ephemeral ones. In particular, perennial herbaceous plants (Hemicryptophytes) [42] seem
optimal for this purpose, because they can maintain the cover without creating high
risk of root penetration, such as can occur in the case of wooden plants. Therefore, an experimental evergreen turf of a warm-grass *Cynodon dactylon* (L.) Pers. (Bermudagrass, in the American cultivar ‘Premier’) was previously selected. *Cynodon dactylon*, which has a wide sub-cosmopolitan distribution, is a macro-thermal plant, which can grow in xeric conditions (low water availability in the hottest season). It is widely adapted to a wide climatic range and to trampling, which justifies its use for sports courses [43,44]. A new turf with this American cultivar, which forms a thin and dense perennial cover [45], was installed in August 2017 on two selected tombs of the Necropolis, thanks to the support of the Hidrowatt Society. To set up such new covers, structured herbal rolls were layered on the tumuli after the scraping of natural plants, but without removing roots, seeds or propagules, and without further irrigation after the initial stages (Barbato, unpublished report). The effectiveness of this green solution, such as the protective effects of the tumuli themselves, still needs to be evaluated.

Therefore, we selected the tombs of the Monterozzi Necropolis where the artificial turf was employed, and others having a wild ephemeral cover, to test the influence of the upper vegetation on the microclimatic conditions of the hypogea. Here, we also wish to evaluate the influence of tumuli characteristics on underground temperatures and establish the most critical conditions for the conservation of tombs, as well as for the biodeterioration risk.

2. Materials and Methods

2.1. Study Area

The Monterozzi Necropolis, which covers an area of about 9.40 ha, is one of the most important Etruscan funerary complexes. It is located on a hill near the city of Tarquinia, in northern Latium, about 70 km N-W from Rome, close to the Tyrrhenian sea (Figure 1). This site is included in a protected zone (SCI/SAC-IT6010028- of the European Directive 92/43/CEE “Habitat”) for its naturalistic features. The area falls in the Mediterranean macroclimate (in particular with a lower Mesomediterranean thermotype and an upper dry ombrotype) [46]. Meteorological data on temperature, rainfall, and humidity were taken from the public archive database, showing an average annual rainfall of 648.2 mm, with an average monthly value of 55.0 mm, among which July is the driest one (20.7 mm) and November is the wettest one (102.5 mm) (http://www.idrografico.regione.lazio.it/annali/index.htm, accessed on 18 March 2021). In the 2019–2020 studied period, the average temperature was 16.9 °C, whereas the average minimum and maximum temperature values were, respectively, 5 °C and 31 °C. Late December 2019 to early January 2020 is the coldest period (average value of 7.7 °C, with minimum values around 5 °C), and late June to early August corresponds to the hottest period (average value 27 °C, with maximum temperatures around 31 °C).

The geological substrate of the necropolis, dated back to Pliocene, is composed of marls and clays, sometimes with olistostromes, in the northern parts and detritic and organogenic limestones in the southern one [47]. The rock tombs are cut into a very porous (among 30% and 43% of porosity) and brittle yellowish limestone, locally named Macco, which is also influenced by some risks of instabilities and detachments [48,49].

The necropolis consists of more than 6000 hypogeal tombs cut into the rock and covered by soil mounds, spanning a chronological period from the 7th to 2nd century BC, and about 3% of them are painted, comprising the only great evidence of pre-Roman painting in the Mediterranean basin [38]. Paintings, which were made using soil oxide and mineral pigments on rock or plaster, accurately portray Etruscan civilization, its customs, beliefs, and everyday life of its people (Figure 1) [36]. Most of the original tumuli were probably visible during the 19th century when the area was used for animal grazing, and this explains the toponym “Monterozzi” (in local Italian dialect, it means “small hills”). Their dismantlement was linked to the development of agricultural activities, in the search for increasing the cultivable areas. Few tumuli still maintain the original shape, whereas, in most of them, the present morphology is the result of their partial rebuilding. This partial
rebuilding was done during the 1980s, using the soil resulting from the tomb excavations, which was accumulated with a linear orientation to cover the sepulchral chambers [38].

The examined tombs were the two where the experimented turf has been laid on (Fiore di Loto—FdL*—and Leonesse—L*—Tombs) and the other two tombs whose natural cover has been maintained (Cacciatore—C—and Caccia e Pesca—CeP—Tombs). These last ones were selected as controls, considering their proximity and a certain similitude. The tombs are dated between the 6th and 5th centuries BC, and they were discovered between 1873–1874 (CeP and L* Tombs) and 1962 (FdL* and C Tombs). All tombs have one subterranean sepulchral chamber (two in the case of CeP Tomb), accessible through a downhill corridor, called dromos. The sepulchral chambers are closed by a thermic door with glass, and visitors can enjoy the pictures, but they are not allowed to enter inside. All the tombs are covered by a non-circular mound, so the sides and the prevailing orientations are also quite different, and the depth of bedrocks varies from 3.27 m (CeP) to 4.33 m (C). A small building, made by a small chamber closed with a metal door, was also settled to protect the entrance to the dromos (Figure 2).

2.2. Analysis of Vegetation Changes in Composition and Cover during the Seasons

The analysis of the vegetation growing on the mounds was carried out twice in summer and autumn 2019 to assess the floristic pattern of the different tumuli and their changes in composition and in cover during such seasons, when the overheating of the underground can occur. For such surveys, we followed the Zurich-Montpellier phytosociological method [50], using the coverage index of plants of the Braun-Blanquet scale: + = 0.5%; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%. As is usually done, we adopted the average values of such a scale (+ = 0.5%; 1 = 3%; 2 = 15%; 3 = 37.5%; 4 = 62.5%; 5 = 87.5%) to calculate the total cover percentage of each plant, making the sum of them to assess the total cover of the plants in the whole mound. Considering that the vegetation can be stratified according to the different heights of plants, the total value could be higher than 100%. The plants were mostly identified on the field, and the collected samples were later identified in the Herbarium of Roma Tre, following the analytical keys of Pignatti [51]. The nomenclature was finally updated according to Bartolucci et al. [52]. On the field, we also defined the life forms of the plants, considering the usual categories, which are based on their life cycle and the position of buds: Therophytes—T, ephemeral herbs; Hemicryptophytes—H, perennial herbs with buds at soil level; Geophytes—G, perennial herbs with underground storage organs; Chamaephytes—Ch, woody plants with buds at no more than 25 cm above the soil surface; Phanerophytes—P, trees and shrubs with buds over 25 cm above the soil surface [42].
more than 25 cm above the soil surface; Phanerophytes—P, trees and shrubs with buds over 25 cm above the soil surface [42].

2.3. Analysis of Tumuli’s Shapes and the Solar Radiation Inputs as Related to Microclimatic Influences

Two drone surveys, with APR filming in full HD, were later carried out in autumn 2019 (November) and summer 2020 (July) to characterize the changes in vegetation covers and phenologies (yellowing and death of Therophytes) and for the analysis of the tumuli’s shapes. A general model was obtained, using the Autocad software, through the level’s curves and the inclination at the soil angle. Then, using the maps of Marzullo [37] (Figure 2) we overlapped the tumuli with the underground structures (Figure 3). From the Marzullo data [37], which contain the dimension of the tombs, we also obtained an approximative evaluation of the volumes of the different sepulchral chambers.

Using the data of tumuli, we also calculated for each tomb the incident solar radiation by the Solarity software (http://www.solaritaly.enea.it/CalcRggmmIncl/Calcola1.php, accessed on 18 March 2021). The calculation was carried out at an assigned location and considering a surface of known geographic orientation. The procedure complies with the requirements of the standard UNI 8477/1 and requires Azimuth and incident at soil angles. Because of the vegetation cover, we calculated the incident solar radiation considering the months with different reflection coefficients, using 0.20 (dry grass) for July, August, and September and 0.26 (green grass) for the remaining months. These data were also used for

Figure 2. Internal structure of the tombs (tumuli are not enhanced in the drawings Fiore di Loto (FdL*); Leonesse (L*); Cacciatore (C); Caccia e Pesca (CeP) (from Marzullo, 2017).
information on the differential energy input, which can influence the microclimate inside the tombs.

Figure 3. Vegetation cover changes and tumuli shapes, as collected by drone aerial views (by Simone Gianolio, Archeo-Digital® S.r.l.s.) in different seasons: (a) topography of the tombs and overlapping of tumuli morphologies, enhanced by level curves and inclination angles; (b) vegetation cover in summer; (c) vegetation cover in autumn (credits by the authors).
2.4. Collection and Analysis of Microclimatic Data

Data related to the hypogean environment’s microclimate were collected from 29 April 2019 to 21 January 2020, waiting 14 days between each sampling session. Further measurements were not possible due to COVID-19 restrictions. Considering that the relevant seasons for such Mediterranean area are summer, when overheating occurs, and autumn, when the thermal heating is transferred underground, the lack of two months among winter and spring are irrelevant to this study.

Microclimatic data were collected inside the sepulchral chambers behind closed doors through two devices: Flash, an infrared-thermometer (error ±2.5%) used to measure inner surfaces’ temperature right wall (W_{fr}), left wall (W_{fl}), front wall (W_{f}), vault (V), and floor (F) 1 m from them. A thermo-hygrometer (Hygrometer PCE-555) was used to measure the air relative humidity RH (error ±2.5%) and the dew point at the center of the chamber, and the air temperature in the dromos, just outside the door of the tomb (Air). In the case of the two-room CeP Tomb, air RH and inner surface temperatures (V, F, W_{fr}, W_{fl}) were measured inside the first room, only the front wall’s temperature (W_{f}) was measured in the second one. An example of data set is presented in Figure 4.

![Figure 4](image_url)

**Figure 4.** Example of microclimate data (line-points) measured in the FdL* tomb: the air temperature just outside the entrance (Air) and the temperatures measured on the right (W_{fr}), left (W_{fl}), and front (W_{f}) wall, on the floor (F), on the vault (V) and the dew point temperature (DwP). Below are reported the relative humidity (RH) data. The best fit to Air and RH data is shown for sake of example.

To quantify the microclimate behavior in the tombs, the data were fitted to a sinusoidal function with 365 days:

\[
f(t) = T_{ave} + \frac{\Delta T}{2} \sin \left( \frac{2\pi}{365} (t - t_0) \right)
\]

in which \( T_{ave} (°C) \) is the average temperature in the measurement period and \( \Delta T (°C) \) is the maximum temperature difference along the seasonal cycle. Equation (1) reaches a maximum \( t = \frac{365}{4} + t_0 \) (days) after the start of measurements (29 April 2019). The same model is used to fit the meteorological data. For humidity data, \( RH_{ave} \) is the average
relative humidity and $\Delta(RH)$ the amplitude of RH variation along the seasonal cycle (Figure 4). In each tomb, the wall temperatures (front, right, left walls) had very similar values, with no significant differences, and therefore, they were averaged in a single dataset labeled as W in the relevant figures and discussion.

3. Results

3.1. Changes in Vegetation Cover during the Analysed Seasons

In the archaeological site, the vegetation is mainly constituted of herbaceous species, with just a few trees and shrubs, usually growing far from the tombs. In the limited areas of the four tumuli, a total of 39 different species (and 17 Families) was detected. This floristic pattern mainly belongs to the Thero-Brachypodietea and Festuco-Brometea phytosociological classes, which describe ephemeral and perennial grasses in the Mediterranean areas [53]. Most plants also show and Euromediterranean chorotype, followed by those with wide distribution or Stenomediterranean ones (Table 1). Indeed, a higher number of plant species was detected in the archaeological site, and the highest number was detectable during Spring (unpublished data). Since most of the ephemeral herbaceous species (Therophytes) die during Summer, in this season, the plants’ cover is reduced and mainly constituted by perennial herbaceous plants (Hemicryptophytes, 25 species, and Geophytes, 2 species) and in limited parts by plants of other life forms (Chamaephytes, 2 species, and Therophytes 10 species). The collected plants often had relevant changes in their presence and cover during the seasons. In autumn, when the annual plants grow back, an increase in both the number of species and the plant cover was detected (Tables 1 and 2). On the tumuli covered by the artificial cover of Cynodon dactylon, a not negligible regrowth of spontaneous species was detected. This fact proves the ability of both seeds and vegetative parts, which remained underground, to recolonize the natural spaces. C. dactylon showed its maximum cover in Summer and a reduction of it in Autumn.

Table 1. Variations of plant composition and cover (in Braun-Blanquet scale) from summer to autumn on the tumuli of the four analyzed tombs. Acronyms: FdL* = Fiore di Loto; L* = Leonesse; C = Cacciatore; CeP = Caccia e Pesca. Ch suffr: Chamaephytes suffruticoso; G rhiz: Geophytes rhizomatoso; H bienn: Hemicryptophyte biennial; H caesp: Hemicryptophyte caespitose; H ros: Hemicryptophyte rosalate; H scap: Hemicryptophyte scapose; T caesp: Therophytes caespitose; T scap: Therophytes scapose. Eurimedit: Eurimediterranean; Steno-medit: Stenomediterranean; Eurasiat: Eurasitarian; Circumbor: Circumboreal; Endem: Endemic; Wide distr: wide distribution; Europ: European; Euro-Cauc: Eurocaucasian; Silv-cult: agronomic origin; Submedit: Submediterranean; Paleotemp: Paleotemperate; Subcosmol: Subcosmopolite; Eurosiber: Eurosiberian.

| Family     | Chorotype | Species                    | Life Form | Cover Values Summer | Cover Values Autumn |
|------------|-----------|----------------------------|-----------|---------------------|---------------------|
| Lamiaceae  | Steno-medit. | Clinopodium nepeta (L.) Kuntze | Ch suffr  | +                   | 1                   |
| Lamiaceae  | Euri-Medit. | Teucrium chamaedrys L.     | Ch suffr  | +                   |                     |
| Asphodelaceae | Steno-medit. | Asphodelus ramosus L.     | G rhiz    | 1 1                 |                     |
| Poaceae    | Silv-cult  | Cynodon dactylon (L.) Pers. var. Premier | G rhiz | 5 5 4 4 |                     |
| Asteraceae | Submedit  | Crepis vesicaria L.       | H bienn  | 1                   | 1                   |
| Boraginaceae | Euri-medit. | Echium plantagineum L. | H bienn  | +                   | +                   |
| Apiaceae   | Steno-medit. | Seseli tortuosum L.      | H bienn  | + + + + + 1 1 1 1 1 |                     |
| Caprifoliaceae | Steno-medit. | Sisaxis atropurpurea (L.) Greuter & Burdet | H bienn | +                   |                     |
Table 1. Cont.

| Family                  | Chorotype | Species                                      | Life Form | Cover Values Summer | Cover Values Autumn |
|-------------------------|-----------|----------------------------------------------|-----------|---------------------|---------------------|
|                         |           |                                              |           | FdL* L* C CeP       | FdL* L* C CeP       |
| Scrophulariaceae        | Euri-medit.| *Verbascum sinuatum* L.                     | H bienn   | 1 + + + + 1 1 1 2 2 |
| Poaceae                 | Euroasiat.| *Dactylis glomerata* L.                     | H caesp   | +                   | 2                   |
| Asteraceae              | Euro-Cauc.| *Bellis perennis* L.                        | H ros     | +                   | +                   |
| Asteraceae              | Steno-medit.| *Hyoseris radiata* L.                     | H ros     | + + + + 1 1 1 2 2  |
| Plantaginaceae          | Euroasiat.| *Plantago lanceolata* L.                   | H ros     | + +                 | 1 1 2 2             |
| Asteraceae              | Steno-medit.| *Centaurea aspera* L.                     | H scap    | + + + + 1 1 1 1 1 1 |
| Convolvulaceae          | Euri-medit.| *Convolvulus cantabrica* L.                  | H scap    | 1 2 + + + 1 1 1 1 1 |
| Asteraceae              | Euri-medit.| *Crepis bursifolia* L.                    | H scap    | +                   |
| Brassicaceae            | Euri-medit.| *Diplotaxis tenuifolia* (L.) DC.          | H scap    | + + + + 1 1 1 1 1 1 |
| Apiaceae                | Euri-medit.| *Ferula communis* L.                       | H scap    | 1 1 1 1 1 1 1 1 1 1 |
| Apiaceae                | Steno-medit.| *Foeniculum vulgare* Mill.             | H scap    | 2 1 1 5 1 1 + 2 2  |
| Lamiaceae               | Eurosiber.| *Linaria purpurea* (L.) Mill.             | H scap    | + +                 |
| Malvaceae               | Wide distr.| *Malva sylvestris* L.                    | H scap    | + + 1 + 2 + 2 + 2  |
| Fabaceae                | Subcosmop.| *Medicago sativa* L.                      | H scap    | 1                   |
| Asteraceae              | Eurosiber.| *Picris hieracioides* L.                   | H scap    | 1 1 1 1 1 1 3 3 3 3 |
| Asteraceae              | Steno-medit.| *Reichardia picroidea* (L.) Roth   | H scap    | + + + + 2 2 2 2 3 3 |
| Polygonaceae            | Euroasiat.| *Rumex acetosa* L.                       | H scap    | + +                 | 2 + + + +          |
| Lamiaceae               | Euro-medit.| *Salvia verbenaca* L.                    | H scap    | + + 1 1 1 1 1 3 3 3 |
| Caryophyllaceae         | Euroasiat.| *Silene vulgaris* (Moench) Garcke       | H scap    | 1 + + 2 2 1 + +     |
| Asteraceae              | Euri-medit.| *Urospermum dalechampii* (L.) F.W. Schmidt | H scap    | + +                 |
| Geraniaceae             | Subcosmop.| *Erodium cicutarium* (L.) L’Hér.       | T caesp   | +                   |
| Asteraceae              | Steno-medit.| *Anthemis arvensis* L.                  | T caesp   | +                   |
| Poaceae                 | Euroasiat.| *Avena fatua* L.                        | T caesp   | 1                   |
| Asteraceae              | Euro-medit.| *Calendula arvensis* (Vaill.) L.        | T caesp   | 2 3 2 2 2 2 2 2 2 2 2 |
| Asteraceae              | C-Europ.| *Crepis capillaris* (L.) Wallr.       | T caesp   | 1 +                 |
| Poaceae                 | Euri-medit-Turan.| *Dasypyrum villosum* (L.) P. Candargy | T caesp   | + + + + 1 1 1 1 1 2  |
| Asteraceae              | Subcosmop.| *Erigeron canadensis* L.                  | T caesp   | 1                   |
Table 1. Cont.

| Family       | Chorotype | Species                  | Life Form | Cover Values Summer | Cover Values Autumn |
|--------------|-----------|--------------------------|-----------|---------------------|---------------------|
| Euphorbiaceae| Subcosmop.| *Euphorbia helioscopia* L.| T scap    | FdL* 123% (100)     | L* 132% (100)       |
| Geraniaceae  | Subcosmop.| *Geranium molle* L.       | T scap    | C 19% (20)          | CeP 101% (65)       |
| Asteraceae   | Stenomedit.| *Sonchus tenerrimus* L. | T scap    | FdL* 165% (100)     | L* 183% (100)       |
|              |           |                          |           | C 112% (70)         | CeP 182% (100)      |

Table 2. Changes in plant cover (%) from summer to autumn on the tumuli of the four analyzed tombs. (Values in brackets represent the total cover on the surface without considering the plant stratification).

|          | FdL*   | L*    | C      | CeP    |
|----------|--------|-------|--------|--------|
| Summer   | 123%   | 132%  | 19%    | 101%   |
|          | (100)  | (100) | (20)   | (65)   |
| Autumn   | 165%   | 183%  | 112%   | 182%   |
|          | (100)  | (100) | (70)   | (100)  |
| Difference: D = A - S | 42% | 50.5% | 92.5% | 81.5% |
|          | 0.74   | 0.72  | 0.17   | 0.55   |

In particular, significantly lower values of plant richness (from 12–13 species to 22–17 species) were observed in summer compared to autumn in tombs with natural covers. The highest number of species (from 16–17 species to 20–24 species) was observed in summer in comparison with Autumn in tombs with the turf of *Cynodon dactylon* ‘Premier’ (Table 1).

More important, significantly lower values of plant cover were observed in summer than in autumn for the tombs with the turf of *Cynodon dactylon* (FdL* and L*) (Tables 1 and 2). These values of plant cover increase from 2 to 5 times in the case of the tombs with natural covers (CeP and C, relative values in Table 2). The collected data also show that even the tombs covered by the *Cynodon dactylon* mat do not reach a total cover of the surfaces (values in brackets), despite a coverage value exceeding 100%, due to the underlined stratification of herbaceous plants with different heights. The FdL* and L* Tombs present a lower difference in the plant cover compared to the C and CeP Tombs, where we observe high changes between summer and autumn (ε in Table 2), which can be estimated as 93%.

These changes in cover, as well as in the phenology of the plants, are stressed by the aerial photographs. Whereas Therophytes die, Hemicryptophytes (and *Cynodon dactylon* too) show yellowing and a reduction of their life activities during summer (Figure 3). Few of them, such as *Foeniculum vulgare*, *Ferula communis*, *Convolvulus cantabrica*, *Salvia verbenaca*, *Picris hieracioides*, and *Clematis cirrhosa*, which were found in other parts of the site, remain fully active during summer.

3.2. Seasonal Trends of Microclimatic Data and Related Risks for Weathering and Biodeterioration Phenomena

The trends of microclimatic data are presented in Figure 4, with the best fits to air temperature and RH data obtained using the Equation (1) and with the FdL* Tomb as example. In fact, the behavior of the microclimatic data is visually very similar in all the
tombs, and, to quantitatively compare the microclimatic data of the different tombs, the best-fit parameters are presented in Figure 5a–c.

The microclimatic data depict an evident swinging trend related to the seasonal periodicity (Figure 4), and it is evident that the temperature variation measured in the dromos is anticipated compared to those measured inside the sepulchral chambers of the tombs, because it is not completely isolated from the outside. The interiors of the tombs are isolated from the dromos by a tight door; therefore, they are less influenced by external temperature variations.

In the investigated period, the average external temperature (meteorological data) was 16.9 °C, varying by ±9.5 °C between the maximum average temperature in the period late June to early August (60–110 days after 29th April) and the minimum temperature in late December 2019 to early January 2020.

The parameters presented in Figure 5a show that the average air temperature ($T_{ave}$) and the amplitude of temperature variation along the seasonal cycle ($\Delta T$) in the dromos were systematically higher than those measured on the tombs’ surfaces. The average air temperature here varied between 18.2 ± 1 °C (FdL*) and 19.4 ± 2 °C (CeP). In all the tombs, the $T_{ave}$ of the surfaces ranged from 17 °C to 18 °C. The average seasonal temperature variation $\Delta T$ of the surfaces was around 6–7 °C for FdL* and L* tombs and significantly lower, around 4 °C, for the CeP. The $\Delta T$ of the dromos Air is also noticeably reduced in the CeP Tomb compared to the other tombs. This could be due to the longer and deeper tunnel at the entrance of the dromos of this tomb, which stabilizes the values. Furthermore, we notice that in all the tombs, the $\Delta T$ of the floor (F) is systematically the lowest one and that of the vault (V) the highest, whereas the walls (W) have intermediate values. The $T_{ave}$ and $\Delta T$ values obtained fitting the dew point temperature data appear very similar without significant differences in all the tombs.

The temperature oscillations in both conditions followed the external changes with a delay: the air temperature in each dromos reached the maximum in late August to early September (around 120 days after the 29th April), about one month after the external meteorological temperatures. Inside the tombs, the temperatures reached the maximum in early/late October 2019, with a delay of more than one month after the dromos’ behavior. Such a trend is likely due to the dromos not being completely isolated from the outside, whereas the interiors of the tombs are isolated by tight doors. Such a delay between dromos and the interior of the tombs was the least for the L* and FdL* Tombs (30–40 days) and the greatest (50–60 days) for the C and CeP Tombs.

The relative humidity (RH) data were fitted to Equation (1), and the best-fit parameters are reported in Figure 5c. The $RH_{ave}$ was the highest for FdL* Tomb (82%) and the most constant one, presenting the lowest variability $\Delta (RH) \approx 6\%$, in the measured period. The $RH_{ave}$ decreased to around 78% for the CeP Tomb, which, together with the C Tombs, had the greatest humidity variation $\Delta (RH) \approx 10\%$, along the measured period. The minimum RH was found between late June and early July in all the tombs, except for CeP, which the minimum RH around the 20th of July.

Considering the risks for the hypogean conservation, we can observe that in every hypogeeum, the temperature variation is attenuated and delayed compared to the outside. In addition, the tight doors protect the tomb interiors.

The microclimatic data in FdL* and L* Tombs behave noticeably differently from C and CeP Tombs: $\Delta T$ of vaults and walls is greater for FdL* and L*, which also have the least delay concerning external temperature variation, suggesting a reduced thermal screening. As shown by the humidity data, also in this case the FdL* and L* humidity of vaults and walls is systematically higher with less variability than C and CeP Tombs.
These changes in cover, as well as in the phenology of the plants, are stressed by the aerial photographs. Whereas Therophytes die, Hemicryptophytes (and Cynodon dactylon too) show yellowing and a reduction of their life activities during summer (Figure 3). Few of them, such as Foeniculum vulgare, Ferula communis, Convolvulus cantabrica, Salvia verbenaca Picris hieracioides, and Clematis cirrhosa, which were found in other parts of the site, remain fully active during summer.

3.2. Seasonal Trends of Microclimatic Data and Related Risks for Weathering and Biodeterioration Phenomena

The trends of microclimatic data are presented in Figure 4, with the best fits to air temperature and RH data obtained using the Equation (1) and with the FdL* Tomb as example. In fact, the behavior of the microclimatic data is visually very similar in all the tombs, and, to quantitatively compare the microclimatic data of the different tombs, the best-fit parameters are presented in Figure 5a–c.

Figure 5. Best-fit parameters obtained from the analysis of the temperatures measured in the tombs. (a) In the top plots, the average temperature ($T_{ave}$) and seasonal temperature variation amplitude ($\Delta T$) are reported for the external area of dromos (Air), the vaults (V), the walls (W) and the floors (F) of the four tombs. In the lower plots, $T_{ave}$ and $\Delta T$ are reported for the dew point. Not shown error bars are smaller than the symbol sizes; (b) days after 29th April corresponding to the maximum temperature in the fit of air, vault (V), walls (W), and floor (F) data set for the four tombs. The delay (days) between the maximum temperature of air data and internal surfaces (V, W, and F) is presented in the lower panel for sake of clarity; (c) average relative humidity ($RH_{ave}$) and relative humidity variation $\Delta (RH)$ as obtained fitting the data using Equation (1). Acronyms: Fiore di Loto (FdL*); Leonesse (L*); Cacciatore (C); Caccia e Pesca (CeP).
3.3. Relationships among External Factors and Underground Microclimatic Data

The drone survey allowed us to precisely describe the shape, orientation and overlapping of the tumuli with the underground tombs. Tumuli create a partial covering of the sepulchral chambers (Figure 3a). Considering the different orientations of the tumuli and their shapes, we calculated the different incident solar radiations received by the tumuli reported in Table 3. This Table also gives information on the heights and the volumes of the internal sepulchral chambers, which were different in size, but relatively comparable. They respectively varied between 2.1 m and 2.6 m in height and from 24 m$^3$ to 40.86 m$^3$ in volume (for the CeP tomb, two chambers were present for a whole of 62.36 m$^3$).

Such data show that two tumuli (C and FdL*) receive the highest solar radiation, whereas one tumulus (L*) receives lower radiation. Such a difference is the highest during winter and autumn, but, even though it is lower during summer (especially from June to August), this value is particularly relevant for the overheating that occurs above all during this season. The variation of the total values is not negligible since it can be about 25% (145:195).

Table 3. Tumuli characteristics and monthly values of incident solar radiation (MJ/mq) received by the four tumuli (FdL* = Fiore di Loto; L* = Leonesse; C = Cacciatore; CeP = Caccia e Pesca). The yellow lines represent the summer months.

| Tumuli | FdL* | L* | C | CeP |
|--------|------|----|---|-----|
| Height (m) of sepulchral chambers | 2.15 | 2.1 | 2.61 | 2.5 (Ir$_{room}$) 2.1 (Ir$_{room}$) |
| Volumes (m$^3$) of sepulchral chambers | 40.86 | 23.94 | 38.35 | 38.4 (Ir$_{room}$) 23.9 (Ir$_{room}$) |
| Months | January | 8.44 | 3.55 | 9.94 | 4.28 |
| | February | 10.98 | 6.12 | 12.28 | 6.97 |
| | March | 15.42 | 10.54 | 16.52 | 11.42 |
| | April | 18.4 | 15.19 | 18.9 | 15.77 |
| | May | 21.72 | 20.02 | 21.69 | 20.35 |
| | June | 23.44 | 22.7 | 23.09 | 22.9 |
| | July | 23.26 | 22.06 | 23.04 | 22.34 |
| | August | 20.45 | 17.77 | 20.83 | 18.26 |
| | September | 16.39 | 12.37 | 17.39 | 13.1 |
| | October | 12.43 | 7.66 | 13.61 | 8.5 |
| | November | 8.79 | 4.27 | 10.1 | 5 |
| | December | 6.6 | 2.92 | 7.78 | 3.44 |
| | Annual | 186.32 | 145.17 | 195.17 | 152.33 |

For the analysed underground tombs, Figure 6 shows the co-occurring changes of vegetation cover during the two relevant seasons and the incident solar radiations received by their covering tumuli, as related to their potential effects on $\Delta T$ and their delays. Interestingly, analogies among the variation of $\Delta T$ and the delay can be observed for C and CeP Tombs, which also show the lowest plant cover: indeed, these tombs show a lower $\Delta T$ and the longest delay.
Figure 6. Relation among outdoor conditions with indoor microclimate of tested tombs. (a) Solar incident radiation graph; (b) photos of a sunny day on the tumulus; (c) seasonal cover vegetation changes related to the depth of tumuli; (d) graphic representation of overheating of tumulus; (e) Maximum indoor temperature of the vaults; (f) photos of the vaults of Cacciatore tomb. Acronyms: Fiore di Loto (FdL*); Leonesse (L*); Cacciatore (C); Caccia e Pesca (CeP).
4. Discussion

The different vegetation cover and depths of bedrocks, as well as the tumuli shapes and aspects, were shown to be the relevant influencing factors for the microclimatic conditions of the underground tombs. In particular, the role of the upper vegetation coverage as influencing factors of the microclimatic conditions, as suggested by previous authors [40], seems not negligible, but at the moment, we have insufficient data to quantify its weight in such a complex system. The plant cover has a clear seasonality in the Mediterranean area, and the perennial grasses can contribute to minimizing the thermal overheating.

The selection of the best plant cover needs, however, a careful consideration of other parameters. First, this includes the potential role of the roots in penetrating underground and creating damage through physico-chemical interactions with rocks and mural paintings, as analysed in further papers (e.g., Isola et al., 2021b). Such data also show that among the 39 detected species on these tumuli, eight were able to penetrate underground. Plants also can give rise to a change in microbial biodeteriogenic communities and favor water penetration, as proven by several authors [6,54,55]. Furthermore, considering that the area is included in a naturalistic protected area of the European Habitat Directive, considering naturalistic parameters in selecting plants is required. The Mediterranean grassland should be protected if no negative interactions of some plants (e.g., root penetration underground) with the archeological structures are detectable. From this point of view, the selection of the American variety of the warm-grass cultivar of *Cynodon dactylon* is not the best fit, and it would be preferable to check the suitability of other wild perennial grasses. In fact, in order to contribute to the management plan of the site, the best selection of plants is needed, which are suitable as cover for the tombs. This selection should consider more carefully the suitability for performing the projected functions (here the potential of covering in summer, such as perennial herbaceous plants, and in particular Hemicryptophytes), their naturality and representativeness of wild communities, the absence of risk for roots penetration underground, and further naturalistic parameters [56–59]. As a preliminary list, some wild perennial herbaceous species already present in the site, could be considered, such as *Convolvulus cantabrica*, *Salvia verbenaca*, *Picris hieracioides*, and *Clematis cirrhosa*, which were not in the list of the root penetrating plants [35]. A careful evaluation of plants as elements for cultural ecosystem services suitable for the preservation of archaeological artifacts would be welcomed. Indeed, the use of natural elements for protecting cultural heritage was previously suggested, and especially the need of safeguarding both natural and cultural values [9,58,59]. As for urban community gardening, where the “cultural values” of plants were suggested as an additional ecosystem service [60], in case of archaeological areas, natural plants could have a role both in protecting and enhancing the value of the sites.

In fact, when considering the conservation problems of the tombs, this artificial turf, compared to a natural vegetation cover, seems to have some positive effects, but not enough to finally encourage it as a solution. For example, a direct correlation between solar irradiation and internal temperatures was not clearly detected, whereas the tombs with the highest plant cover showed the highest humidity with less variability in hygrometric values, but also a larger $\Delta T$ and a lesser delay concerning external temperature variation. Whereas constant induced humidity values are positive effects, the low thermal screening, also enhanced by lower thermic inertia, seems to be an effect that needs to be improved through a more efficient plant cover.

Moreover, this analysis showed the influence of the shapes and orientation of the tumuli, as well as of the soil layers and plant cover, for a better protection of the underground tombs, as observed by Kyriakou and Panoskaltsis [39]. South-facing can have a negative effect on additional thermal input, which is transferred underground, giving rise to an increase in internal temperature. In particular, when south-facing exposition occurs, an improvement in the thermal insulation system seems necessary. More importantly, tumuli rebuilding, conserving the roundish original shape and a sufficient wide size, seems necessary, not only for the philological reason in the archaeological site but also because a
roundish shape does not create a preferential exposure and because of the need to guarantee a more efficient shelter of the underground. A widening of the comparative analysis of the Etruscan tombs, having a great number of differential influencing parameters, to permit statistical elaborations, is also needed. Further efforts will be done in analyzing all the parameters that influence the thermal transmission underground, such as the depth and size of the hypogea, the length of the dromos, and the building that protects the first entrance, combining them with the transmittance of the bedrocks.

When considering the presently most critical conditions for physical-chemical damages, C and CeP tombs were shown to be at the highest risk of developing saline efflorescence and cracks of the pictured layers, due to the variability of thermohydrometric conditions. In this case, the risk due to condensation was shown to be limited.

When considering the biodeterioration risk, humidity, temperatures, lighting, and nutrients all have a relevant role. Indeed, the microflora of the hypogea is influenced by such environmental parameters, with effects due to the selective, competitive, and inhibitory processes among different microorganisms that give rise to different characteristic communities [4,12,34,61–63]. In general, fungi were found to be more resistant to dryness than bacteria [6,64]. The human influences and the opening time of the hypogea also give rise to a higher variability [4,7,65].

Some environmental factors and external influences can be more or less easily controlled and reduced, but other factors cannot reach the risky values, such as the RH, whose critical values start from 60%. Reaching stationary environmental conditions, avoiding external inputs of spores, condense, high lighting, and overheating, are very important in reducing the biological risk.

Avoiding critical values of T has a non-negligible importance for biodeterioration risk. As previously observed for the airborne microflora in other underground historical places [65–67], such as the crypt of the Anagni’s Dom (Italy) [25], or the crypt of St. Peter in Perugia (Italy) [26], a high risk for biological colonization originates from overheating, which follows the summer season. When considering data from Korean literature for hypogea conservation, three risk periods for microorganism occurrence were established as follows: (1) Safe: T < 18 °C, (2) Warning: T = 18–22 °C, (3) Risk: T > 22 °C [29,30,68]. If we apply such values to the Etruscan tombs, a safe period occurs from late autumn and winter until spring. Starting from June to July a warning period is detectable, and a risk period from August to September as well, especially when the vegetation cover is very low, and the orientation of the tumuli is south-facing (e.g., C Tomb).

5. Conclusions

The collected data show the complex network of relationships among various parameters affecting the conservation of such a subterranean cultural heritage. A positive influence of vegetation cover in maintaining higher and more constant humidity conditions was detected. Plant covers also influenced internal temperatures, but the mounds’ orientation, as well as other constructive features, also seem to have a relevant role. Data confirmed that late summer and early autumn are the most critical microclimatic periods for the hypogeal paintings and biological risks when peaks of superficial T occur. To improve the insulation systems, we suggest a careful rebuilding of tumuli over the tombs, as well as a better selection of wild plants that do not create a risk of roots penetration underground and are suitable for maintaining their covering during summer.

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