Environmental Processes Related to Soil Temperature: Problems and Analysis Methodologies

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Abstract. This article investigates specific environmental degradation processes driven by climate and land use changes. These changes significantly influence the surface energy balance, leading to increased aridity in rural environments and the urban heat island (UHI) effect in urban areas. Land Surface Temperature (LST), a key variable influencing the surface energy balance, serves as a crucial indicator for monitoring these degradation phenomena.

Aridity represents a significant risk in Italy, with the National Atlas of areas at risk of desertification reporting 51.8% of the territory as potentially vulnerable, particularly the Southern and Central Italian regions. A primary consequence is reduced soil fertility due to the loss of organic matter and carbon. This degradation can lead to desertification, consequently increasing the demand for nutrients and irrigation to sustain agricultural productivity, thus exerting greater pressure on natural resources.

The UHI effect is a major challenge in contemporary urban planning, negatively affecting the comfort and health of city dwellers. Since LST is a key indicator for both aridity/desertification and UHI, this article focuses on methods for its estimation and application. A significant advantage of LST is its relatively inexpensive determination over vast areas (land-scape scale) using remote sensing. The article provides a critical review of methodologies for LST retrieval from satellite data. The contribution of this paper is twofold: it underscores the importance of the integrated analysis of urban and rural landscapes through climate-related processes, unified by the LST indicator, which can be determined efficiently via remote sensing, particularly using imagery from Landsat Thematic Mapper (TM) and Moderate Resolution Imaging Spectroradiometer (MODIS).

Furthermore, while the scientific literature offers numerous solutions addressing the impacts of climate change on soils or urban climates separately, the potential for integrated analysis of these interconnected processes is less investigated. This paper aims to contribute to filling this gap.

Consequently, the research seeks to advance the integrated and holistic planning of urban and rural landscapes.

Keywords: Land Surface Temperature (LST) · Climate change and aridity · Remote Sensing

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1 Introduction

The topics addressed in this paper are the risk of desertification of most of the soils of arid climates and the phenomenon of the urban heat island. These two processes are usually studied separately, but they have in common the climate issue, exacerbated by global change and the increase, both in air and surface land temperatures.

Land Surface Temperature (LST), which derives from the energy balance at the Earth's surface (absorption and partitioning of solar radiation), is strongly correlated with land use. This correlation makes LST analysis a crucial component for sustainable land planning. LST influences numerous environmental processes and reflects significant environmental impacts related to land use. Considering the two main macro-categories of land use (rural and urban), the key environmental processes influenced by LST or which LST itself can indicate include:

a. Soil aridity and desertification risk in rural environments.
b. The urban heat island (UHI) affects urban environments.

These two phenomena, although manifesting in different contexts and ways, share the commonality of unsustainable land management, the effects of which are exacerbated by global warming. Such management includes both soil artificialization and sealing linked to urban development, and unsustainable agricultural practices leading to the degradation of rural lands. In both cases, the analysis of LST distribution serves as a fundamental parameter for understanding and monitoring both processes [1, 2].

The scientific literature is very rich on both processes, while a lack has been found in their integrated analysis, which is instead important, especially for planning. This paper wants to give a contribution to this last aspect, for a more holistic approach.

The bibliography has been selected based on the specific contents regarding the desertification risk and the urban heat island, with particular attention to the influence of land use on them and their integrated treatment. In the face of the enormous cases on the two separate processes, the lack in their integration has emerged. In the face of the enormous case history of the two separation processes, the lack of their integration emerged. Consequently, this paper has drawn from the consulted bibliography what was the most effective approach, which turned out to be the assessment of the LST indicator.

1.1 Aridity and Soil Desertification Risk in Rural Environments

Desertification, defined as land degradation in arid, semi-arid, and dry sub-humid areas, results from factors including climate variations and human activities, particularly land use. The Intergovernmental Panel on Climate Change (IPCC) reports that desertification has intensified in some dryland areas in recent decades, posing significant threats to food security and ecosystem services [3].

This phenomenon is expanding, now covering approximately 40% of the planet's land surface and contributing to reduced agricultural productivity. This change has caused significant economic losses, particularly in Africa, where GDP decreased by 12% from 1990 to 2015 due to increased aridity [4].

In Europe, Italy is significantly affected by these problems, as can be observed in the National Atlas of areas at risk of desertification, the map of which is shown in

Fig. 1[1]. Based on climatic and soil analyses, 51.8% of Italian territory has been considered potentially at risk, particularly the entire southern region and parts of the regions of Central Italy. Specifically, within these potentially at-risk areas: 4.3% (1.3 million hectares) exhibit characteristics of functional sterility; 4.7% (1.4 million hectares) are susceptible to desertification processes; and 12.3% (3.7 million hectares) are considered vulnerable [5].

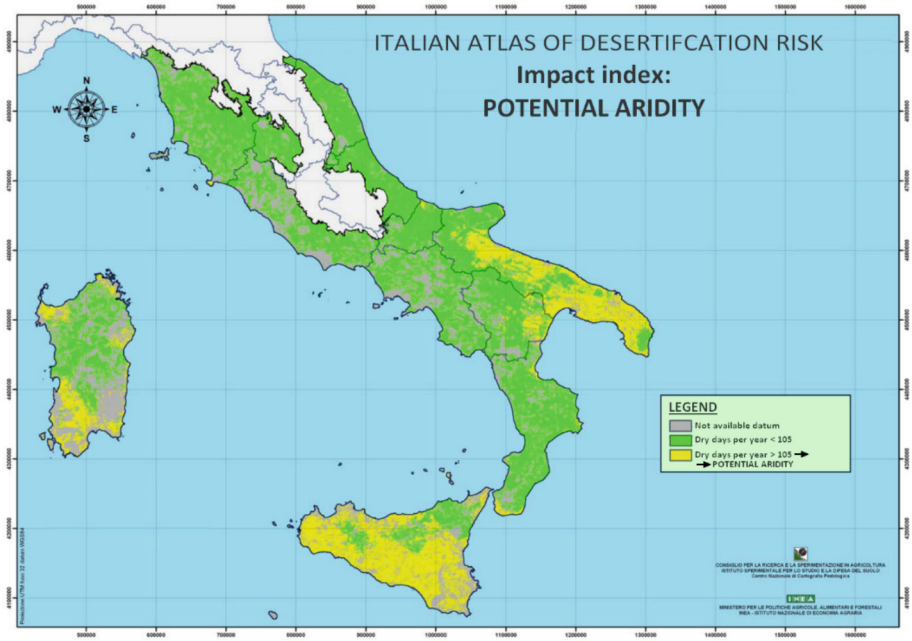

Fig. 1. Desertification risk for Italy (from Costantini et al., 2007).

Although direct measurement of the complex dynamics of desertification on a large scale presents challenges, LST serves as a valuable indirect indicator for monitoring land surface conditions related to aridity and degradation. Indeed, several scientific studies have explored the relationship between LST and desertification, focusing particularly on the degradation of soil organic matter and its impact on agricultural productivity.

Yuan et al. highlight that rising temperatures disturb soil organic carbon stocks, which poses threats to fertility and biodiversity and can exacerbate soil salinization problems [4]. Similarly, Peplau et al. indicate that deforestation for agriculture leads to soil warming, which increases organic matter decomposition [6]. This suggests that land use changes contributing to increased soil temperatures can accelerate the degradation of soil organic matter [4].

Soil degradation represents one of the main threats to environmental sustainability, negatively impacting not only agricultural productivity but also the balance of natural

[1] The desertification index used is the number of days of "dry soil". A soil is "dry" when water is absent in the layer between the level reached by a rainfall of 25 mm and one of 75 mm.

ecosystems. The loss of fertility, caused by phenomena such as erosion, salinization, and depletion of organic matter, increases dependence on chemical fertilizers to ensure adequate agricultural yields. However, the intensive use of such products generates a significant environmental impact, risking the contamination of surface and groundwater resources through leaching and runoff processes. Nitrates and phosphates, in particular, can cause eutrophication of water bodies, compromising aquatic biodiversity and water potability. Furthermore, the high sensitivity of groundwater bodies to nitrate contamination resulting from leaching from agricultural soils is well-known [7].

Soil health, the reduction of fertilizer and pesticide use, and the adoption of microbiome-based solutions are fundamental elements for promoting sustainable agriculture, essential for the production of quality food and other resources for a circular bioeconomy. The One Health concept is linked to these needs, representing a collaborative, multisectoral, and transdisciplinary approach operating at local, regional, national, and global levels. The goal is to achieve optimal health outcomes by recognizing the interconnection between people, animals, plants, and their shared environment [8].

Concurrently, in agricultural contexts with degraded soils, maintaining economically sustainable production levels increasingly requires irrigation, due to the increased frequency and intensity of arid periods. Indeed, higher temperatures intensify evapotranspiration.

Phenomena such as aridity and floods are consequences of natural climate cycles, while the intrinsic environmental impact of climate change is responsible for profound alterations in rainfall regimes, characterized by long periods of drought alternating with torrential rains.

The described phenomena represent the main drivers of transformation in agricultural systems. Associated with them is a risk of negative feedback: the growing water demand for irrigation contributes to the further depletion of water resources and soil deterioration. Thus, a vicious cycle of degradation is triggered, as irrigation itself increases the risk of uncontrolled runoff, soil erosion (including organic matter), and the leaching of agrochemicals.

In light of these challenges to sustainability, integrating advanced technologies into agricultural systems is fundamental. In particular, the adoption of machine learning techniques, combined with the analysis of high-resolution satellite imagery, allows for real-time monitoring of crop health status, early detection of water stress, and optimization of irrigation practices. Such tools support informed decisions based on objective data, improving water use efficiency and contributing to food security within the framework of sustainability and climate change adaptation.

1.2 The Urban Heat Island (UHI)

The urban heat island (UHI) is characterized by significantly higher temperatures in urban areas compared to surrounding rural zones, a phenomenon particularly pronounced during the night, whereas during the day the difference may be less marked. In urban areas, inadequately planned urbanization processes induce significant changes in land cover, replacing natural permeable and vegetated surfaces with predominantly impermeable artificial materials. Such surfaces, besides reducing rainwater absorption capacity,

possess a high capacity to retain heat from solar radiation, contributing to the effect known as UHI.

In summary, two main phenomena contribute to the intensification of the UHI: the increase in temperatures due to the absorption of solar radiation and, indirectly, the reduced heat dissipation through evaporation (latent heat of evaporation) owing to the lower presence of vegetated and evaporating surfaces [9].

This phenomenon has significant implications for public health, exposing the urban population to a greater risk of heatstroke. Concurrently, it increases the energy demand for building cooling, which contributes to further greenhouse gas emissions and intensifies the UHI itself through anthropogenic heat release from buildings into the external environment.

Land cover and land use play a key role in influencing the intensity and distribution of the UHI effect; it is therefore essential that urban planners consider this factor. Numerous studies show that anthropogenic activities have modified between one-third and one-half of the global land surfaces, with significant impacts on local and global climate [10].

The UHI phenomenon is a central topic in urban climatology studies. Its considerable complexity derives from the multiple interacting processes that contribute to it, often characterized by complex feedback dynamics that can amplify its effects. Consequently, it is necessary to employ synthetic indicators capable of effectively representing the entirety of these processes. Land Surface Temperature (LST) proves to be a suitable indicator for this purpose, as it reflects the spatio-temporal variations associated with these dynamics [11]. Land use significantly influences the UHI through variations in surface cover and materials, leading to higher land surface temperatures (LST) in urban areas compared to surrounding rural areas [12].

The study of UHI requires a multitude of processes to be analysed, first of all land use/land cover change, which can increase the extent of impermeable surfaces, thus intensifying the UHI effect and the consequent higher temperatures in cities compared to surrounding rural areas. The UHI effect has significant implications, including contributing to increased energy demand (e.g. for air conditioning), which in turn increases greenhouse gas emissions in urban centers, already hubs for major emissive activities [13]. For example, the summer UHI drives air conditioning use in buildings, leading to approximately 12% higher energy consumption [14].

2 Materials and Methods

In line with the objectives stated so far, remote sensing has been considered to increase knowledge of aridity and UHI.

In the analysis, preference was given to other review articles because they allow access to “third-party” analyses by other authors and are therefore themselves a demonstration of the thesis underlying this paper: the notable quantity of studies on individual topics, compared to the limitations of integrated analyses.

Aridity and Desertification

Drought and water stress significantly affect plant physiology, leading to changes aimed at improving water efficiency and survival. To combat soil degradation, sustainable land management practices are essential. For example, bare soils exacerbate the tendency



Fig. 2. Evaluation of the maximum urban heat island according to the Oke model (from Leone et al., 2020).

towards desertification due to the loss of organic matter [6]. At the same time, irrigation is now almost structural, in order to support agricultural production and its economic return [18].

The reviewed literature suggests a strong interest in utilizing satellite-based spectral information to update soil maps, particularly for soils that are bare during satellite image acquisition. Satellite imagery contributes to improving the management of cultivated areas in the following ways [16]:

- Need for Updated Soil Mapping: for monitoring Soil Organic Carbon (SOC) within the upper soil horizons across both temporal and spatial dimensions. Such initiatives are essential to underpin sustainable land management practices, aligning with global policy frameworks including the United Nations Sustainable Development Goals and the European Commission's "Caring for Soil" mission.
- Digital Soil Mapping (DSM): over recent decades, the practice of DSM has conventionally relied upon georeferenced soil samples subjected to laboratory chemical analysis. These techniques integrate morphometric data and indices derived from Earth observation, such as the Normalized Difference Vegetation Index (NDVI).
- Challenges of soil sampling: the direct collection of soil samples is difficult and expensive; therefore, data acquired via Earth observation platforms is strategic.
- Spectral characteristics of SOC: SOC exhibits specific spectral features across various wavelength bands. These spectral signatures enable the development of predictive models that correlate soil reflectance data with SOC content.
- Historical context: since the early stages of satellite remote sensing, pedologists began establishing correlations between Landsat Thematic Mapper (TM) radiance values

and soil properties. However, the direct linkage between image reflectance and surface soil SOC content remained less prevalent until the advent of satellite time series offering high revisit frequency (e.g., weekly). Consequently, this research domain has witnessed a significant increase in attention over the past decade.

Irrigation is essential for achieving sufficient yields and quality in agricultural products, especially in semi-arid environments like the Mediterranean basin, which faces growing water scarcity. Efficient irrigation scheduling requires determining the water and physiological status of plants to prevent water stress and water waste. Traditional methods for monitoring plant status are often burdensome in terms of time and cost for field operations. Remote sensing is an efficient technology and is therefore increasingly employed to supplement traditional monitoring methods [17].

Remote sensing technologies offer detailed and high-frequency information on crop water status. This allows for the identification of areas subject to water stress and the optimization of irrigation both temporally and spatially.

A further technological advantage lies in the possibility of integrating remote sensing data with Geographic Information Systems (GIS). This approach, for example, supports precision irrigation, enabling the delivery of water to different field zones based on their specific needs, potentially modulated via local sensors that complement satellite data. Furthermore, machine learning algorithms and IoT solutions applied to remote sensing data have recently been tested with the aim of predicting irrigation needs based on current crop conditions and weather forecasts [18].

Urban Heat Island

Urban heat islands (UHIs) are characterized by higher surface and atmospheric temperatures compared to surrounding rural areas, resulting primarily from the alteration of the land surface energy balance in densely built environments. UHI research utilizes remote sensing data to monitor land cover changes and quantify key UHI characteristics, such as intensity and spatial extent, often derived from Land Surface Temperature (LST). Studies demonstrate that urbanization significantly affects the local climate, influencing surface temperature and energy exchange with the atmosphere. The literature highlights the importance of developing methods to assess the physical and spatial indicators of urban heat islands [9].

Land Surface Temperatures

The processes described so far are significantly different, as are the territories involved: the rural one in the first case, the urban one in the second. But the analysis carried out shows that they have in the LST the fundamental common thread, with the further advantage of the relative ease of surveying the LST. Consequently, it satisfies the objective of carrying out the integrated analysis of the territories, being, moreover, modified by land use.

LST is commonly measured using remote sensing techniques, particularly through the acquisition of satellite thermal imagery. Several satellite sensors acquire data in the thermal infrared range, which are subsequently processed to estimate LST over broad spatial coverage. Among the sensors employed are:

- Landsat TM/ETM+ (Thematic Mapper/Enhanced Thematic Mapper Plus): widely used for detailed spatial analyses of LST.

- MODIS (Moderate Resolution Imaging Spectroradiometer): provides data with high temporal resolution, suitable for global and daily LST analyses.
- ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer): acquires both daytime and nighttime thermal data.

The following sections will discuss the main physical parameters influencing LST and the advantages offered by Landsat 8 data, as an illustration of techniques possible through remote sensing; however, this does not diminish the importance of other satellites. LST corresponds to the radiative temperature emitted by the land surface, distinguishing it from the air temperature measured at standard height, and is influenced by multiple factors, such as land use, vegetation cover, intrinsic soil properties, and atmospheric conditions [19].

The Landsat program, jointly managed by NASA and the U.S. Geological Survey (USGS), offers a historical archive of multispectral data spanning over four decades, specifically in terms of temporal coverage, spatial resolution, sensor quality, and data accessibility. In particular, the Landsat 8 satellite is equipped with two main sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These instruments acquire data in various spectral bands, including those in the thermal infrared necessary for LST estimation. This estimation typically relies on determining three key parameters: surface emissivity, atmospheric transmittance, and effective mean atmospheric temperature [20].

The main advantages offered by Landsat data include the relatively high spatial resolution, free accessibility (open access), temporal continuity of the archive, and high radiometric quality of the sensors. The Landsat program thus constitutes a fundamental tool for environmental monitoring and the study of climatic and territorial dynamics, holding particular importance for LST estimation. Indeed, an accurate estimation of the mentioned parameters (emissivity, transmittance, atmospheric temperature) allows for deriving LST.

The essential characteristics of Landsat 8 include [21, 22]:

- Accessibility: Landsat 8 adheres to an open access policy, allowing researchers and public and private entities free access to the data. This availability promotes the replicability of studies, supports environmental planning, and informs management decisions in urban and natural contexts.
- Temporal Coverage: The satellite ensures global coverage with a 16-day revisit cycle. This permits the analysis of LST variations on both seasonal and multi-year time scales, useful for monitoring phenomena such as urban heat islands or the effects of land use changes.
- Spatial Resolution: The Visible and Near-Infrared (VNIR) bands acquired by the OLI sensor possess a native spatial resolution of 30 m. The thermal bands of the TIRS sensor have a native resolution of 100 m, but LST products are commonly made available at 30 m through resampling. Such resolution proves adequate for detailed analyses, such as mapping soil organic carbon (SOC) content or urban thermal zoning.
- Data Quality: The OLI and TIRS sensors ensure high radiometric performance and superior data quality compared to previous Landsat missions, factors that contribute to improving accuracy in LST estimation.

Overall, Landsat 8's advanced features and data quality significantly contribute to the effectiveness and accuracy of the research on surface urban heat island intensity and land cover changes.

Deriving Land Surface Temperature (LST) from thermal sensor data, such as that acquired by Landsat satellites or comparable instruments, necessitates a multi-stage computational procedure. This process begins with the conversion of raw digital numbers (DN) into at-satellite brightness temperatures, followed by the estimation of the actual land surface temperature. The principal stages involved in this calculation, drawing upon methodologies outlined by researchers like Liu and Zhang [23],Convert the digital number (DN) into spectral radiance:

1. Transformation of Digital Numbers (DN) to spectral radiance

The initial computational step involves converting the sensor-recorded digital numbers (DN) for each pixel into at-sensor spectral radiance (L_i). This transformation utilizes sensor-specific parameters representing maximum and minimum radiance and DN values, as expressed in Eq. (1):

$$L_i = (L_{max} - L_{min})\, Q_{dn} / Q_{max} \tag{1}$$

where L_i denotes the at-sensor spectral radiance ($MW \times cm^{-2} \times sr^{-1} \times \mu m^{-1}$); L_{max} is the maximum at-sensor spectral radiance; L_{min} is the minimum at-sensor spectral radiance; Q_{max} represents the maximum DN value of pixels and Q_{dn} represents the DN value of pixel.

Frequently, particularly for sensors like Landsat, this relationship is simplified in metadata or technical documentation to a linear equation involving sensor- and band-dependent coefficients (a, b), as shown in Eq. (2):

$$L_i = a + b\, Q_{dn} \tag{2}$$

2. Conversion of the spectral radiance to at-sensor brightness temperature

Following the calculation of spectral radiance, the next stage converts this value into an equivalent at-sensor brightness temperature (T_i). This conversion is typically achieved by inverting Planck's radiation law, using established physical constants (C_1, C_2) and the central wavelength (λ_i) of the specific thermal band, as formulated in Eq. (3):

$$T_i = C_2 / \{\lambda_i \times \ln[1 + C_1/(\lambda_i^5 \times L_i)]\} \tag{3}$$

$$C_1 = 1.19104356 \times 10^{-16} W \cdot m^2 \tag{4}$$

$$C_2 = 1.4387685 \times 10^4 \mu m \cdot K \tag{5}$$

where T_i represents the at-sensor brightness temperature in Kelvin (K); C_1 and C_2 are Plank constants; λ_i is the central wavelength and L_i is the previously calculated at-sensor spectral radiance (from Eq. 1).

3. Estimation of Land Surface Emissivity

Determining the land surface emissivity (ε_i), a crucial parameter representing the efficiency of thermal energy emission by the surface, is often accomplished indirectly. A common approach utilizes the Normalized Difference Vegetation Index (NDVI), a widely adopted indicator derived from the contrast between near-infrared (NIR) and red (R) reflectance measurements (Eq. 6), which enhances the vegetation signal [24]:

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}) \tag{6}$$

The calculated NDVI value is then employed to estimate emissivity. For instance, Van De Griend and Owe [24] proposed an empirical relationship applicable within a specific NDVI range (0.157 to 0.727), as shown in Eq. (7):

$$\varepsilon = 1.0094 + 0.047 \ln (\text{NDVI}) \tag{7}$$

Comprehensive formulas for estimating land surface emissivity based on different NDVI value ranges, adapted from Liu and Zhang [23], are presented in Table 1.

Table 1. Estimation of emissivity by NDVI (from Liu and Zhang, 2011)

NDVI	Land surface emissivity (ε_i)
NDVI < −0.185	0.995
−0.185 ≤ NDVI < 0.157	0.970
0.157 ≤ NDVI < 0.727	1.0094 + 0.047ln(NDVI)
NDVI > 0.727	0.990

4. Determination of atmospheric transmittance

Accounting for the atmosphere's influence on the thermal signal requires estimating atmospheric transmittance (τ_i) for the thermal band. This typically involves two sub-steps:

a. Estimation of water vapor content (w_i)

Atmospheric water vapor content (w_i, in g/cm2) is frequently estimated using empirical equations that rely on near-surface air temperature (T_0, in K) and relative humidity (RH) data, typically sourced from local meteorological stations (Eq. 8):

$$w_i = 0.0981 \times \left\{ 10 \times 0.6108 \times exp\left[\frac{17.27 \times (T_0 - 273.15)}{237.3 \times (T_0 - 273.15)} \right] \times RH \right\} + 0.1697 \tag{8}$$

where w_i is the water vapor content (g/cm^2); T_0 is the near-surface air temperature in K and RH represents the relative humidity. The water vapor content, near-surface air temperature and relative humidity are all from local meteorological stations.

b. Calculation of atmospheric transmittance

The estimated water vapor content (w_i) is then used to calculate the atmospheric transmittance (τ_i) for the specific band 'i', often via a linear relationship with sensor- and band-dependent empirical coefficients (a, b), as shown in Eq. (9):

$$\tau_i = a - b \times w_i \tag{9}$$

5. Calculation of effective mean atmospheric temperature (T_a)

An estimate of the effective mean atmospheric temperature (T_a) is also required for atmospheric correction in some LST retrieval algorithms. This parameter can be approximated from the more readily available near-surface air temperature (T_0, in K) using empirical linear relationships that may vary depending on factors like season and latitude. Examples for mid-latitude conditions include:

- For mid-latitude summer: $T_a = 16.01 + 0.93 \times T_0$
- For mid-latitude winter: $T_a = 19.27 + 0.93 \times T_0$

6. Land Surface Temperature (LST) retrieval

The final step involves retrieving the Land Surface Temperature (LST) by integrating the previously calculated parameters. Using a mono-window algorithm as an illustrative example, LST (in Kelvin) can be computed as a function incorporating the at-sensor brightness temperature (T_i), land surface emissivity (ε_i), atmospheric transmittance (τ_i), and the effective mean atmospheric temperature (Ta). The specific formulation involves intermediate terms (a, b, C, D) as defined in Eqs. (10) through (14):

$$LST = \frac{\{a(1 - C - D) + [b(1 - C - D) + C + D]T_i - DT_a\}}{C} \tag{10}$$

$$a = -67.355351 \tag{11}$$

$$b = 0.458606 \tag{12}$$

$$C = \varepsilon_i \times \tau_i \tag{13}$$

$$D = (1 - \tau_i)[1 + (1 - \varepsilon_i) \times \tau_i] \tag{14}$$

where LST is the final Land Surface Temperature in Kelvin, T_i is the at-sensor brightness temperature, ε_i is the land surface emissivity, τ_i is the atmospheric transmittance, and Ta is the effective mean atmospheric temperature.

Figure 3 shows an application of this LST retrieval procedure to the area identified as having the highest risk in Fig. 2, adapted from Scarano [25].

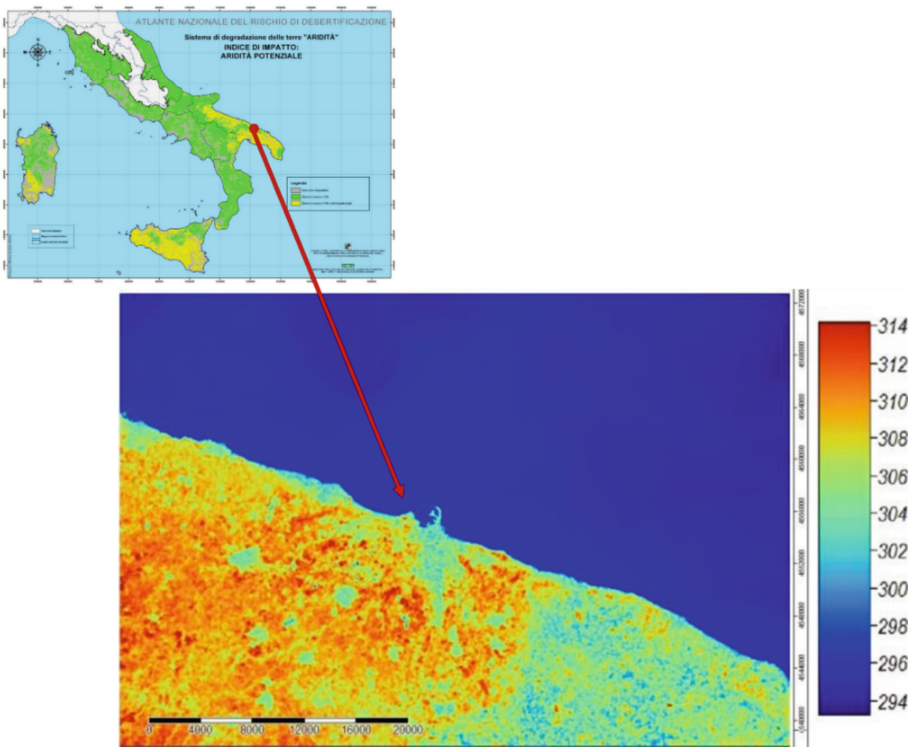

Fig. 3. Example of LST obtained using applying explained algorithms at Landsat-8 daytime image from September 24, 2013.

3 Discussion

The following three main key points emerge:

1. Desertification and sustainable soil management
   - Desertification affects drylands, which cover very significant areas, both globally and in Italy, impacting approximately 500 million people [3].
   - The causes of desertification include climate variability, anthropogenic climate change, and human activities such as cropland expansion and unsustainable land management practices.
   - Socio-economic responses and sustainable land management are essential to prevent degradation and restore degraded drylands. Policies include improving market access, empowering women, expanding agricultural extension services, strengthening land tenure security, payments for ecosystem services, decentralized natural resource management, and investments in modern renewable energy sources [2, 32].
   - Imperative for contemporary soil data: there exists a pressing imperative to generate contemporary soil maps and consistently track SOC levels within superficial soil layers. This effort is crucial for enhancing decision support systems in land management and ensuring alignment with major international directives, including the UN

Sustainable Development Goals and the European Commission's i.e. the 'Caring for Soil' mission [33].

- Spatio-temporal SOC assessment: the assessment of Soil Organic Carbon encompasses monitoring its variations across both geographical space and time. Initiatives like '4 per 1000' prominently highlight the significance of large-scale SOC storage quantification as a prerequisite for reliable estimation and cartographic representation of its distribution [16].
- Sampling constraints and alternatives: traditional soil sampling demands significant resources, primarily time and labour. Consequently, an alternative methodology for obtaining SOC information involves combining data from Earth observation platforms and proximal sensors, thereby reducing the reliance on extensive field sample collection [16].
- SOC spectral signatures: Soil Organic Carbon demonstrates distinct spectral responses within multiple wavelength bands spanning the Visible, Near-Infrared, and Shortwave Infrared spectrum (VNIR-SWIR; 400–2500 nm). These characteristic spectral features provide the basis for developing quantitative models designed to correlate measured soil reflectance with SOC concentrations [3].
- Historical perspective on remote SOC sensing: following the advent of satellite-based Earth observation, soil scientists established initial connections between Landsat Thematic Mapper (TM) radiance data and various soil characteristics. However, the direct quantification of surface SOC using image reflectance data remained relatively infrequent until the emergence of satellite time series offering high temporal resolution, such as weekly revisits. This technological advance has spurred a renewed and intensified research focus in this area over the last ten years [3, 16].
- Time-consuming and labour-intensive: Collecting soil samples and performing laboratory analyses are both processes that are time-consuming and labour-intensive.
- Spatial and temporal monitoring: Regular monitoring of soil properties is necessary to support decision-making and land management but requires extensive resources and coordination.
- Variability in soil properties: SOC and other soil properties exhibit spatial variability at multiple scales, from national to regional to field levels, complicating the mapping process.

These challenges highlight the need for innovative approaches and technologies to improve the accuracy and efficiency of soil map updates.

2. Impact of climate change on agricultural production

- Global warming and the increased frequency and intensity of extreme weather events negatively impact agricultural production. The increase in average temperatures has reduced the growing season duration for many crops and, together with a higher incidence of water stress, negatively affects their life cycle and nutrient assimilation [18]. More pronounced temperature fluctuations further compromise the quality and quantity of harvests.
- Increased evapotranspiration rates contribute to greater soil aridity, leading to increasing water requirements for crops and significantly reducing their yield [17].
- The increased frequency and intensity of extreme weather events, particularly floods and heatwaves, besides causing direct damage to crops, can intensify soil erosion,

compromising the SOC content, one of the main carbon storage and sequestration compartments in the biosphere.
- The destabilization of SOC, fundamental for soil fertility and biodiversity, combined with salinization problems, exacerbates difficulties for farmers, threatening the sustainability, including economic sustainability, of production [7].

These phenomena highlight the interconnections between climate change, land management, and agricultural production. It is therefore fundamental to adopt sustainable and locally adapted policies and practices such as precision agriculture, regenerative soil agriculture, crop rotation, and the use of advanced technologies, to mitigate negative impacts and ensure global food security.

Challenges in Water Management in Agriculture

Water management in agriculture faces numerous challenges requiring innovative and sustainable solutions. Climate change, through rising temperatures and altered rainfall regimes (greater variability and alternation between drought and floods), makes water availability for crops increasingly unpredictable. This further complicates the management of water resources. In many agricultural regions, especially in semi-arid areas like those in Southern Italy, water scarcity is a frequent condition that also impacts the management of artificial reservoirs. A further management challenge arises from the considerable spatial heterogeneity of soils, both in terms of SOC content and regarding hydrological properties (water retention capacity, drainage). Such variability requires site-specific irrigation interventions, often over large areas. This results in operational difficulties and high costs for implementing advanced irrigation systems (e.g., precision irrigation, [18]), which can represent a significant barrier, especially for the small farms prevalent in many Italian areas. To address these issues, research has long focused on precision agriculture, an approach where satellite remote sensing represents a key enabling technology [26]. Remote sensing finds application in multiple areas related to environmental sustainability, to which the agricultural sector can provide relevant contributions. An example is represented by the emerging mechanisms of 'carbon farming', also incentivized at the European level (e.g., through the Common Agricultural Policy – CAP or other initiatives), which involve forms of remuneration for farmers adopting practices capable of increasing soil carbon sequestration, thus contributing to climate neutrality objectives. These mechanisms can foster the development of a market for agricultural carbon credits, whose effectiveness, however, requires rigorous Monitoring, Reporting, and Verification (MRV) systems. In this context, as discussed in the present work, analysis via remote sensing can assume a priority role. Carbon farming can be framed within the principles of the Circular Economy applied to agriculture [2]. Similarly, water saving represents another crucial sustainability objective, for which technologies like remote sensing provide essential information for better planning and management of irrigation interventions [17].

3. Urban Heat Island

It is clear that ground temperature measurements are a powerful indicator of UHI. Furthermore, having maps of the different thermal areas at the landscape scale is an essential tool/element for ensuring the sustainability of the urban microclimate and, therefore, for effective urban planning [13, 14].

4 Conclusion

Satellite Survey and Soil Quality in Relation to Aridity and Desertification Issues

Satellite remote sensing represents a fundamental tool for monitoring soil quality and studying the phenomena of aridity and desertification. Spectral data acquired by satellites such as Landsat, MODIS, or Sentinel allow for estimating Soil Organic Carbon (SOC) content and other fundamental soil properties. Such data are essential for updating pedological mapping, identifying areas at risk of desertification, and implementing sustainable land management practices, with particular reference to agricultural areas. Monitoring SOC levels and soil moisture via remote sensing supports decision-making processes aimed at mitigating soil degradation, optimizing irrigation, and improving agricultural productivity.

Satellite Detection of Urban Heat Islands

The urban environment significantly alters numerous natural processes, primarily the local hydrological cycle and the surface energy balance. In the former case, the cause is the substantial impermeability of urban soils; in the latter, the causes are multiple and derive from a combination of factors, including the thermal and optical properties of building materials, urban morphology (e.g., street canyons), and anthropogenic heat release.

The urban heat island (UHI) phenomenon is complex and highly site-specific; its manifestations and consequences are therefore neither unambiguous nor easily generalizable.

Given the complexity and local specificity of the UHI phenomenon, mitigation strategies require detailed case-by-case analyses. However, the integration of vegetation into urban spaces (green infrastructure) is recognized as a fundamental and effective measure to counteract the increase in temperatures. The general objective should be to integrate natural elements into the built environment in a planned manner, based on an understanding of the underlying physical processes. To this end, multi-parametric environmental analysis is crucial. In this context, Land Surface Temperature (LST), as a synthetic indicator of surface thermal conditions, assumes a fundamental role. Its availability on a large scale, thanks to satellite remote sensing, makes it a valuable tool for the diagnosis, monitoring, and evaluation of UHI mitigation strategies. These data help to understand the impact of urbanization on the local climate, identify hotspots, and develop strategies to mitigate the UHI effect. The ability to compare LST data from different times and locations improves the accuracy of UHI studies and supports urban planning efforts to enhance thermal comfort and reduce energy consumption.

Importance of measuring Land Surface Temperature

The measurement of LST is of fundamental importance as it serves as a key indicator for both aridity and desertification processes and the UHI. Elevated LST values can contribute to the degradation of soil organic matter, reducing its fertility and increasing the risk of desertification. In urban areas, the spatial distribution of LST highlights the intensity of the UHI effect, with direct implications for thermal comfort and the health of the resident population. Remote sensing techniques, predominantly based on the analysis of satellite imagery, offer wide spatial coverage and provide essential data for LST analysis. These data allow researchers and territorial planners (planners) to monitor environmental dynamics, assess the impact of land use changes, and develop sustainable strategies

aimed at mitigating the negative effects associated with both aridity/desertification in rural environments and the UHI in urban contexts.

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