Evaluating the influence of temperature fluctuations on soil state in the Maltese Islands using remote sensing techniques

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~~FACULTY/~~INSTITUTE/~~CENTRE/SCHOOL~~ of Earth Systems

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Abstract

Increasing temperatures and droughts present growing environmental challenges in the Mediterranean region, particularly for small island environments like the Maltese Islands where water resources are limited and climate pressures are intensifying. This study examined the spatial and temporal variability of soil surface temperature and soil dryness across the Maltese Islands over a ten-year period (2015–2024) using remote sensing techniques. The analysis focused on seasonal and interannual changes in Land Surface Temperature (LST) and the Temperature Vegetation Shortwave Dryness Index (TVSDI), and on evaluating the relationship between surface temperature and soil dryness under semi-arid conditions. Wet and dry seasons were analysed separately to capture the strong seasonal contrasts characteristic of the Mediterranean climate. Statistical analyses, including correlation and regression tests were applied to assess relationships between LST and TVSDI across districts and seasons. The results revealed a clear seasonal contrast, with dry-season LST values consistently exceeding wet-season values across all districts. While district-level differences in LST were not statistically significant once seasonality was considered, spatial patterns showed persistently higher temperatures in urbanised districts and cooler conditions in rural districts and hydrologically active areas. TVSDI values remained relatively uniform during the wet season, reflecting the homogenising effect of winter rainfall, but exhibited pronounced spatial and temporal variability during the dry season. The South Eastern, Western and Gozo districts consistently recorded the highest dryness levels, with extreme conditions observed in 2016, 2020 and particularly 2024. A strong and statistically significant positive relationship between LST and TVSDI was identified during the dry season, indicating that surface temperature is the dominant driver of soil dryness under moisture-limited conditions. In contrast, weak wet-season relationships highlighted the moderating role of rainfall. Overall, the findings demonstrated the effectiveness of LST-based remote sensing indices for monitoring soil dryness in semi-arid island environments and provided insight into emerging drought trends under ongoing climate change.

Keywords: climate change, surface temperature, soil dryness, Maltese Islands, semi-arid climate, remote sensing

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Chapter 1: Introduction

Climate has had a significant impact on human life since the beginning of time, impacting their way of life and their daily activities (Gambin et al., 2016). Over time, several climatic changes occurred, most of which were caused by anthropogenic activities. As a result, humanity had to adapt to these changes to lessen their impact on human lives (Diodato & Bellocchi, 2012). One of the most critical consequences of climate change is the increased frequency and intensity of droughts, which pose a significant threat to agriculture, soil, ecosystems and water resources in a water-scarce country like Malta (Hartfiel et al., 2020). Effective drought monitoring has become essential to mitigate these effects, enabling early detection, preparation and response to potential drought conditions. By closely tracking changes in temperature, precipitation and soil moisture, scientists can better predict and manage drought events, minimising the environmental, economic and social impacts. Timely information also supports decision-making for water conservation, agriculture management and drought preparedness, ensuring more resilient communities in the face of ongoing climate change (West et al., 2019).

1.1 | Purpose of the study

The objective of this study is to evaluate the 10-year changes in soil dryness across the Maltese Islands from a seasonal perspective. Additionally, it aims to analyse the correlation between temperature changes and dryness across the islands through statistical tests. The impact of changing soil temperature and soil moisture on dryness will be examined through a dryness index.

1.2 | Research questions

This research aims to address the following research questions: "What are the spatial and temporal distributions and changes in dryness across the Maltese Islands?" and "How does the remote sensing index perform under local conditions?". The null hypothesis affirms that there is no significant trend in Land Surface Temperature (LST) and Temperature Vegetation Shortwave Dryness Index (TVSDI) across the Maltese Islands. The alternative hypothesis asserts that there is a significant trend in LST and TVSDI across the Maltese Islands. This study will test whether to accept or reject the null hypothesis based on the statistical results.

1.3 | Aims and Objectives

The aim of this study will be achieved by

- Assessing Malta's changes in soil dryness conditions from a seasonal perspective
- Looking at the correlation between temperature changes and soil dryness across the Maltese Islands
- Looking at the correlation between soil temperature, soil moisture and soil texture across the Maltese Islands
- Examining the impact of changing temperatures on soil dryness conditions using the TVSDI index

The ultimate aim of the study is to enhance our understanding of Malta's soil state in the face of shifting temperatures by illustrating dryness over the Maltese Islands and documenting their spatial and temporal fluctuations through time by producing dryness maps using a remote sensing index. This will shed light on conserving the crucial soil and water resources in Malta.

1.4 | Project overview

This study began with an introduction to the topic. Chapter 2 will provide a literature review, discussing previous research on drought monitoring using remote sensing, including vegetation indices and a dryness index. It will also explore various soil properties in Malta and the impact of droughts on them. Chapter 3 will outline the methodology employed in the study. The results will be presented in Chapter 4, followed by a discussion of these outcomes in Chapter 5. Finally, Chapter 6 will conclude the study by summarising the key findings and suggesting future research.

Chapter 2: Literature Review

2.1 | Introduction

The increased occurrence of extreme weather events such as higher temperatures and extended periods of severe drought has become a worldwide concern. The central Mediterranean area, identified as a prominent climatic hotspot (*Figure 2.1*), has especially captured attention (Skuras & Psaltopoulos, n.d.). The changing weather patterns, including temperature variations, significantly impact soil conditions and various physical soil processes. The subsequent segments of this chapter will delve deeper into an extensive exploration of the effects of temperature changes on the soil in the Maltese Islands. This exploration will emphasise the significance of monitoring dryness, evaluating different dryness measures and their practical uses.

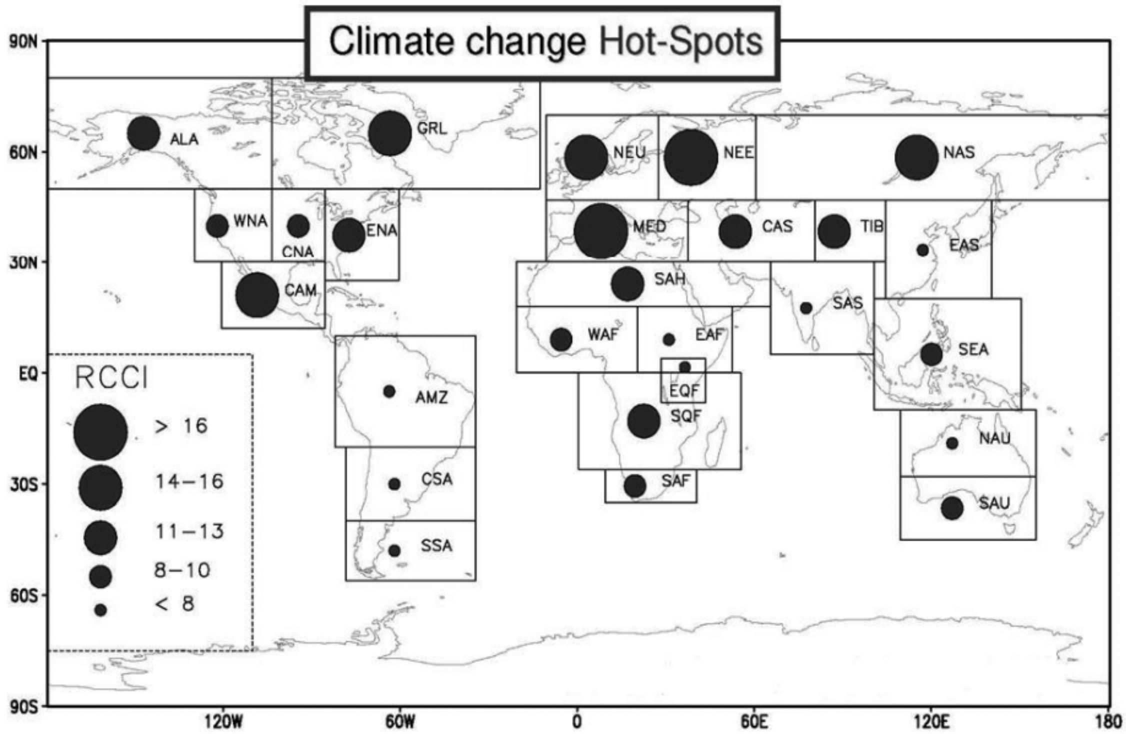


Figure 2.1 | Climate change hotspots of the world using the Regional Climate Change Index (RCCI) (Giorgi 2006)

2.2 | Geographical area and climatic characteristics

The Maltese archipelago, located in the central Mediterranean region, comprises a set of islands lying at 35.8816° N and 14.4490° E between Sicily and the North African coast.

The Mediterranean climate is found between 30 - 45° latitude and shares characteristics with California, central Chile, the western cape of South Africa and the south-west of Australia (Schembri, 1997; Seager et al., 2019). These areas exhibit similar survival strategies owing to their semi-arid climate conditions (Sultana, 2015), characterised by winter precipitation and extended dry spells during summer. Despite these commonalities, they differ significantly in their plant and animal life, setting them apart from one another.

The Mediterranean climate follows the Köppen climate classification, featuring mild, wet winters and two distinct types of summers: hot summers; Csa and warm summers; Csb (Seager et al., 2019). The central Mediterranean region is characterised by hot, dry summers; Csa, caused by the Azores high-pressure system while mild, wet winters are caused by the Icelandic low-pressure system (Galdies, 2012; Longobardi et al., 2016).

The formation of mountains in the Mediterranean basin is predominantly attributed to the northward movement of the African plate toward the Eurasian plate. Almost encircling the Mediterranean basin are mountain ranges, with the exception being the southeastern part (Bravo et al., 2008). Short-range climatic shifts primarily stem from alterations in the landscape (Crouch, 2015). These

Mediterranean mountains receive increased rainfall compared to the surrounding lowlands due to distinctive wind patterns (UNEP, n.d.). Landmasses and mountains notably shape the weather in the central Mediterranean region, primarily through orographic lifting and forced convection (Davolio et al., 2020). Moreover, these mountains act as a natural barrier against cold northerly winds. The Maltese Islands, positioned near substantial water bodies, experience relatively more humid weather patterns (Galdies, 2022a).

2.3 | Introduction to soil physical properties

In 2016, the World Soil Information Network labelled soil as "our life support system," echoing Charles Kellogg's belief that life and soil are inherently intertwined, evolving together (Hatfield et al., 2017). Kellogg's perspective underscores the profound interconnection between soil and humanity, emphasising the pivotal importance of soil. Therefore, humans carry a significant responsibility to conserve soil and enhance its biodiversity, a duty emphasised by Bhaduri et al. (2022).

Comprehending the soil's physical properties is essential for acknowledging its intricate role as the Earth's vital life support system. Attributes like soil texture, colour, structure and density significantly influence its functionality and applicability for different needs. These characteristics offer essential understanding of soil composition and behaviour, impacting its capacity to nurture plant growth, regulate water and nutrient cycles and maintain diverse ecosystems. Exploring the complexities of the soil's physical traits reveals a deeper understanding of its dynamic nature and highlights the importance of implementing responsible soil management practices.

2.3.1 | Soil composition

Soil formation is a result of the chemical, biological and physical breakdown of rocks, sedimentation and the breakdown of organic matter facilitated by diverse organisms. Over time, influenced by organisms, topography, climate and time, the original material evolves into soil. Soil stands as an intricate living system, encompassing air, water, organic matter, diverse organisms and mineral components (Parikh & James, 2012). This complex soil system plays a pivotal role in numerous biogeochemical cycles and serves as a foundation for essential ecosystem services, including the provision of food, water and regulation of climate (Nielsen et al., 2010). In essence, it is the fundamental support for life on Earth (Tecon & Or, 2017).

Soil consists primarily of mineral matter, air, water and organic matter. The mineral fraction, essentially the soil's framework, comprises various rock types. As soil forms, gravel, sand, silt and clay particles remain, defining the soil type and its qualities. Air and water occupy the soil's pore spaces. Water serves as the primary carrier of substances within the soil and the soil's capacity to retain water relies on its mineral components. Clay-rich soils, with their small pores retain more water compared to sandy soils, which have larger voids between particles and therefore do not hold water effectively. The organic fraction, composed mainly of plant roots, plant and animal residues and animal waste, is a crucial aspect of soil. Organic matter influences the soil's capacity to retain nutrients and water. Additionally, it significantly contributes to determining soil structure (Patil & Lamnganbi, 2018).

2.3.2 | Soil characteristics

Soil serves as a crucial medium supporting plant growth and hosting diverse living organisms. In certain regions, it has historically been and continues to be used as a construction material. Additionally, soil acts as a natural regulator for floods by managing water flow through infiltration. As water passes through the soil, it undergoes purification and detoxification. Agriculture, encompassing farming practices and soil cultivation for crop growth, stands as a cornerstone of economic growth. It fulfils fundamental human needs, provides materials for fabrics and significantly contributes to the economy by generating income and employment opportunities (Sishodia et al., 2020). Over 97.5% of the world's food requirements are met through land-based sources, highlighting the critical role of soils in ensuring food security (Brevik, 2013).

Soil stands as the second-largest carbon sink on Earth, possessing a significant capacity to absorb carbon dioxide from the atmosphere, thereby playing a key role in climate regulation. This terrestrial carbon sink can absorb an estimated 2 billion tonnes of organic carbon (Naddaf, 2023). Through the soil-plant system, plants photosynthesise and contribute dead organic matter to the soil, aiding in the reduction of greenhouse gases (Brevik, 2013). This underscores the critical role of soil in mitigating the effects of climate change, as enhancing this capacity could notably counterbalance the rapid increase of carbon dioxide in the atmosphere (EEA, 2023; FAO, 2017).

The Intergovernmental Panel on Climate Change (IPCC) has highlighted that human-induced greenhouse gas (GHG) emissions, encompassing carbon dioxide, methane and nitrous oxide, significantly impact the environment (Brevik, 2012). Activities like burning fossil fuels and soil tilling have disrupted the natural balance, resulting in more GHGs being released into the atmosphere than can be absorbed by global sinks (Brevik, 2012). Soil management plays a crucial role in managing GHG emissions, offering the potential to reduce these emissions by implementing appropriate soil management techniques.

2.3.2.1 | Soils and nutrient cycles

Soils play a vital role in the atmospheric climate system by actively participating in various nutrient cycles, particularly the carbon and nitrogen cycles. Before the Industrial Revolution, these cycles remained relatively balanced as human-generated GHGs were minimal. However, with increased human activities, especially the excessive emission of GHGs, the natural equilibrium of these nutrient cycles has been disrupted. This disruption has intensified the natural greenhouse effect, contributing to a warmer climate (Brevik, 2013).

2.3.3 | Soil development and profile

The formation of soil in a specific region is influenced by multiple factors, including local climate, existing biota, parent material, topography and time (Bockheim et al., 2014). Climate stands out as the primary driver of soil formation. Within Soil Taxonomy, climate plays a key role in distinguishing different soil orders. Various climatic elements like hot and dry conditions, the duration of dry spells, seasonal moisture patterns and consistently moist conditions help categorise soils developed under specific climatic regimes. Parameters such as mean annual temperature, precipitation levels and the rate of evapotranspiration significantly impact the processes involved in soil formation (Bockheim et al., 2014; Lamb & Rehm, 2018). These climatic factors play a crucial role in shaping the characteristics and properties of soils found in different regions.

Parent material is a crucial factor in distinguishing among different soil taxa. There are three primary types of parent materials: those derived from rock, including weathered minerals, those derived from organic materials like decomposed plant matter and transported sedimentary deposits such as colluvial and aeolian deposits. Additionally, the environment in which soils develop determines other parent materials. For instance, lacustrine parent materials consist of sediments formed by lakes, while alluvial parent materials originate from river deposits, among other variations (Alnaimy et al., 2023).

Moisture availability is another critical factor influencing soil development, closely tied to the prevailing climate. The amount of moisture a soil receives significantly impacts the type of soil that forms in a particular area (Costa et al., 2023). Soils of the rainforest are strongly leached acid soils due to the huge amount of rainwater they get all year round. Contrastingly, soils of desert and arid regions do not have a fully developed soil profile as they are dry for more than half of the growing season.

Living organisms, particularly certain groups like worms, are recognised for their influence on soil development. These organisms can facilitate chemical reactions and the breakdown of organic materials, contributing to the formation of soil structures and compositions. While worms are notable, various other organisms also play significant roles in soil formation (Patil & Lamnganbi, 2018).

Human activities have increasingly been recognised as a significant factor influencing soil formation, particularly in specific soil orders like Inceptisols and Aridisols. Human intervention, such as land use changes, agricultural practices and urbanisation can significantly alter soil properties and composition (Bockheim et al., 2014; Lamb & Rehm, 2018).

Topography stands as another crucial soil-forming factor. The slope of the land dictates the amount of material that gets deposited or eroded, impacting soil development. Additionally, aspect, which refers to the direction a slope faces to the sun, influences soil formation. For instance, the north-facing slopes tend to retain more moisture and vegetation as they receive less direct sunlight as opposed to south-facing slopes (Bockheim et al., 2014; Lamb & Rehm, 2018).

Lastly, time is a fundamental factor in soil development. Soil formation, known as soil pedogenesis, occurs over extended periods. The intricate processes involved in transforming parent materials into fully developed soils take considerable time, often spanning thousands to millions of years (Bockheim et al., 2014; Lamb & Rehm, 2018). Time, therefore, plays a critical role in the evolution and maturation of soils.

The soil profile, which is an important feature of soil morphology, explains how the several soil layers are developed. Different soils that developed under different climatologies have different soil profiles. The soil profile is made up of several soil horizons, all distinctive of each other. The top-most O horizon consists mainly of organic matter that falls on the soil and is further subdivided into the fibric, hemic and sapric horizons, based on the different decomposition levels. The topsoil A horizon is the most fertile layer, rich in nutrients and organic material and highly active with microorganisms. The E horizon, which is not present in all soils, results from leaching materials from the A horizon, showing a paler colour due to the eluviation of clay and iron oxides. The B horizon is a zone of illuviation, where materials leached from the A horizon accumulate. The C horizon primarily consists of the parent material from which the soil formed while the R horizon represents the bedrock layer.

This soil profile is heavily influenced by the region's climate. For instance, Entisols, found in desert regions, often lack distinct horizons, typically possessing only an A horizon due to limited rainfall and minimal organic matter. In contrast, Alfisols found in temperate and humid regions tend to have well-developed profiles as they receive ample rainfall, making them relatively fertile and supporting the development of distinct horizons (Lamb & Rehm, 2018). The differences in these soil profiles highlight the impact of climate on soil development and composition in various regions.

In the Mediterranean region, soil is indeed a limited resource, facing challenges both in quantity and quality. The management of soil resources in this area has often been inadequate, leading to threats such as accelerated erosion rates. Mismanagement practices, including improper land use, deforestation, overgrazing and unsustainable agricultural practices contribute to soil degradation and erosion. The Mediterranean region's unique climate, characterised by hot and dry summers, exacerbates these challenges. With limited water resources and susceptible soil conditions, erosion becomes a significant concern, leading to the loss of valuable topsoil and reduced soil fertility (Sultana, 2015).

2.3.4 | Soil texture

Soil is composed of sand, silt and clay particles, forming the three primary soil types. Sand is predominantly composed of quartz and similar primary minerals, while silt and clay consist mainly of secondary minerals.

Sandy soils have a gritty texture due to distinct sand grains and tend to be non-cohesive unless very wet. These soils possess large voids between particles, aiding in drainage and air penetration. However, their high permeability results in lower water and nutrient retention, making them prone to quick drying and susceptibility to droughts (RHS, 2023).

Silty soils have a texture that feels more floury than gritty. Unlike sandy soils, the voids in silty soils are smaller due to the smaller size of silt particles. This characteristic enables silty soils to retain more water and exhibit slower drainage compared to sandy soils. Similar to sand, silt particles do not adhere well unless thoroughly wet, making these soils susceptible to erosion (RHS, 2023).

Clay soils primarily consist of tiny clay particles, known as colloids. When wet, these soils become exceptionally sticky and their drainage is notably slow. This is attributed to the small pore spaces, causing slow movement of air and water within the soil. Consequently, clay soils possess a high capacity for holding water. However, this characteristic can lead to issues like waterlogging due to the reduced rate of water movement through the soil (RHS, 2023).

2.3.5 | Soil classification in Malta

While the USDA Soil Taxonomy system is widely used in soil science for classification, the FAO's World Reference Base for Soil Resources (WRBS) is commonly used in Europe for soil classification. The WRBS classification system offers an approach to categorising soils, encompassing several soil types found in the Maltese Islands. These include Calcisols, which prevail as the predominant soil type since the parent material is rich in calcium carbonate. Arenosols, identified as sandy soils, are primarily located in Ramla Bay, Gozo. Leptosols are the shallow soils that characterise the garrigue environment. Luvisols represent the red Terra Rossa soils while Vertisols are the clay-rich soils of Malta (ERA, n.d.).

Although modern soil classification in Europe commonly follows the WRBS, the Kubiena classification system is relevant to the Maltese Islands since it was historically used in early soil studies, including the work of Lang (1960). The Kubiena classification system identifies three primary categories of soils in Malta, as outlined by Lang (1960). These categories include Terra soils, Xerorendzinas and Carbonate raw soils. Terra soils are considered mature and extensively weathered, characterised by low levels of calcium carbonate and relatively higher organic matter content. The parent material of these soils is the Lower Coralline Limestone and Lower Globigerina Limestone. Xerorendzinas, on the other hand, are classified as immature soils with a high calcium carbonate content and low organic matter. They develop on valley deposits and weathered Globigerina limestone. The third category, Carbonate raw soils, is also classified as immature, with sand, clay and additions from the Upper Coralline Limestone, Upper Globigerina Limestone and Greensand being the parent material (Lang, 1960).

The three primary categories of the soils of Malta - Carbonate raw soils, Xerorendzina, and Terra soils - are further classified into series, as detailed by the Environment and Resources Authority (n.d.) and by the map created by Lang & Osmond (1960) (*Figure 2.2*). Under Carbonate raw soils, the Ramla series encompasses sandy soils classified as Arenosols. The Nadur series develops from a thin greensand layer and are classified as Regosols. The Fiddien series represents clay soils falling into the Vertisols and Regosols category, while the San Lawrenz series comprises clayey and sandy soils falling under Regosols. Within the Xerorendzina category, the San Biagio series comprises white soils classified as Calcisols (*Figure 2.3*). The Tal-Barrani series consists of brown soils classified as Calcisols or Luvisols, while the Alcol series is a mix of Regosols, Cambisols and Luvisols. Lastly, within the Terra Rossa soil classification, the Tas-Siġra series is categorised as Luvisols (*Figure 2.4*) and the Tax-Xagħra series (*Figure 2.5*) represents soils found in garrigue environments classified as Leptosols (Dr. A. Sacco, pers. comm., December 2023).

In addition to the soil categories and series, the soils of Malta are further delineated into complexes, each with distinct characteristics and locations, according to Lang's study (1960). The Iklin complex is prevalent and describes man-made soils formed during the construction of terraces. The Rdum complex is typically found on cliffs, notably on the Dingli cliffs. The Armier complex is composed of sandy soils located around the Armier area on the northern side of Malta. Lastly, the Tad-Dawl complex comprises soils found within disused quarries, a common feature across the Maltese Islands (Lang, 1960). These complexes represent specific soil formations based on their unique locations and the processes that shape them.

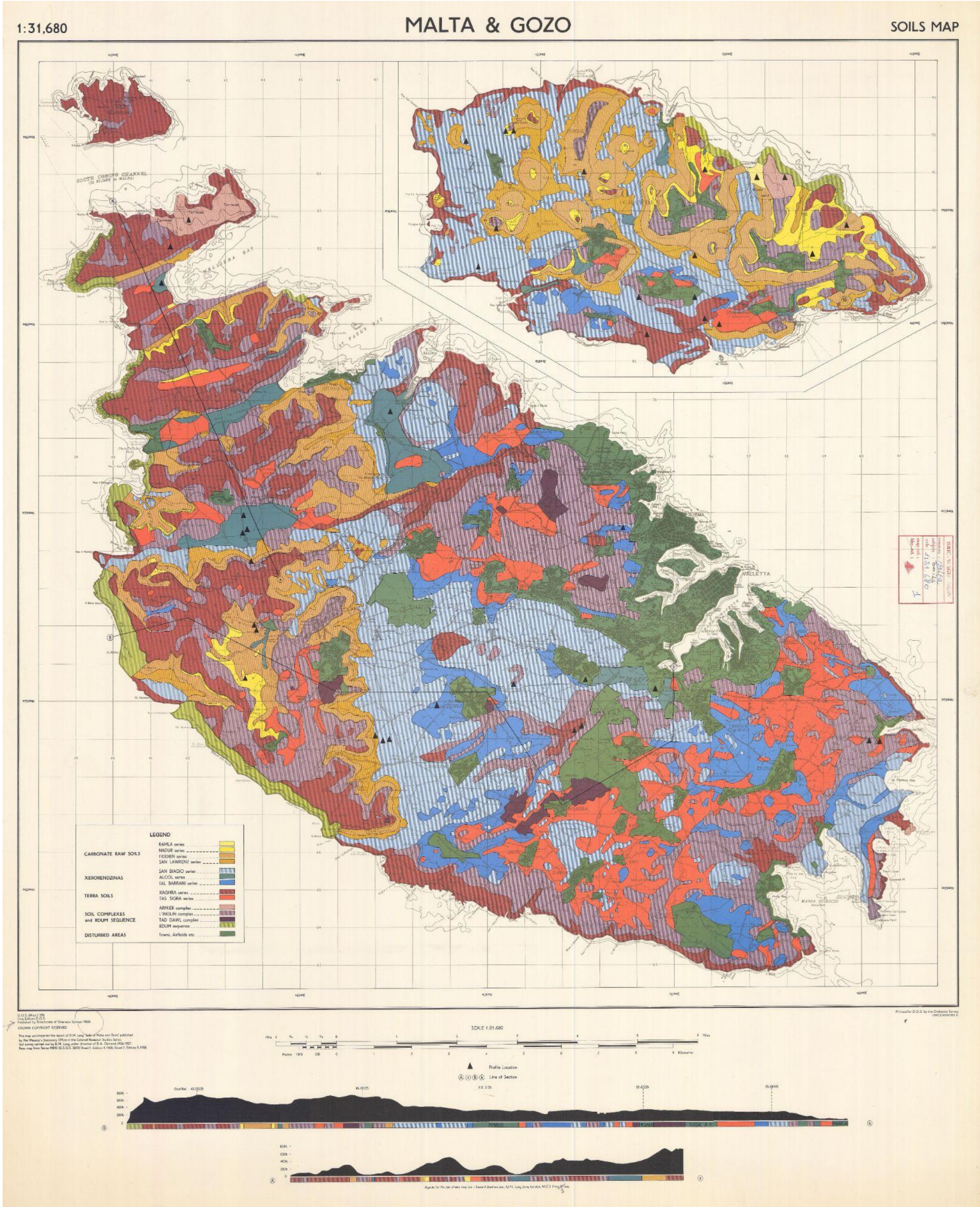


Figure 2.2 | The different soil types found in the Maltese Islands (Lang & Osmond, 1960)

Figure 2.3 | San Biagio series (Calcisol) with some San Lawrenz series (Regosol) in the foreground (Sacco, n.d.)

Figure 2.4 | Terra soils: Tas-Siġra series (Luvisol) (Sacco, n.d.)

Figure 2.5 | Terra soils: Xagħra series (Leptosol) found in the garrigue environment (Sacco, n.d.)

2.3.6 | Soils of the Maltese Islands

The variability of soils across regions is heavily influenced by the prevailing climate in each area (Balestrini et al., 2015). In the case of the Maltese Islands, the climate characterised by high temperatures and limited annual rainfall significantly impacts soil formation (Schembri, 1997). Consequently, the process of soil development is slow, resulting in soils that are relatively young and immature, thus lacking complete development. Furthermore, extensive agricultural cultivation has altered the natural state of soils on the Maltese Islands, rendering them shallow and not fully representative of their natural condition. Being predominantly derived from limestone material, the soils of Malta are highly calcareous, containing abundant quantities of calcium carbonate. This abundance of calcium carbonate contributes to the alkalinity and high buffering capacity of these soils (Vella, 2001).

The predominant textural classes of the soils of Malta include clay loams and clays, primarily observed in soil types such as 'Ħamri' and 'Tafli'. On the other hand, sandy soils, sandy loams and silty loams are also present in the 'Bajjad' and 'Ramli' soil types. These soil types exhibit lighter textures compared to the clay-dominated 'Ħamri' and 'Tafli' soils, as can be seen from Figures 2.3 and 2.5.

2.3.7 | Soil state in the Maltese Islands

Maltese society tends to undervalue the significance of its soil resources, especially their crucial role in supporting life. Despite being vulnerable to damage if not properly treated, soil has the potential to sustain human and ecological needs as a renewable asset if managed correctly. The distribution of different types of soils in Malta is highly complex, found in both natural and agricultural areas. The soils of Malta typically have a slightly to moderately alkaline pH. With a clay content exceeding 48%, approximately two-thirds of these soils are challenging to cultivate, yet they exhibit strong nutrient retention and water filtration capabilities. Agricultural suitability is limited due to factors such as unfavourable alkalinity levels, shallow soil depths in around 60% of areas, low organic matter content, significant stoniness and the arid climate (MEPA, 2006).

In Malta, a significant portion of arable soils is left exposed, devoid of any vegetation cover and subjected to deep ploughing in anticipation of the initial heavy September rains. This agricultural approach significantly exacerbates water erosion in these areas. In 2015, a study across Europe found that Malta's average soil loss rate surpassed that of the entire continent (Galdies, 2022b). Soil erosion research in the Maltese Islands has been previously neglected, with only a basic soil erosion map recently released by ERA (Galdies, Azzopardi & Sacco, 2022). Given the climatic sensitivity of the Maltese Islands, integrating climate projections into local soil erosion studies could be opportune for implementing soil conservation practices effectively.

Field observations highlight the importance of retaining rubble walls in agricultural regions with steep inclines as a crucial method to control soil erosion. These walls serve as a practical measure to mitigate erosion caused by agricultural practices in such areas (Sultana, 2015). Reducing water flow velocity by terracing fields located on slopes and cultivating the land using contour tillage are also measures utilised by Maltese farmers to combat water erosion. Farmers in the area can opt to plant specific trees or shrubs on their land to assist in retaining soil. However, it is crucial to seek expert guidance due to the fragile ecological equilibrium of erosion-prone areas. Additionally, farmers should be cautious not to plough too close to the field's edge as this can exacerbate erosion compared to ploughing further away. Galdies (2022b) emphasised the necessity of implementing comprehensive conservation initiatives in Malta to safeguard its precious natural resources.

2.4 | Soil physical properties and the effects of changing temperatures

Several physical soil parameters may be influenced by changing temperatures. Increasing temperatures alter the soil’s moisture content, which in turn changes soil colour, soil structure and leads to more evaporation. However, soil texture is an inherent property determined by the proportion of sand, silt and clay particles and it generally remains unchanged by short-term environmental fluctuations.

The following paragraphs will delve into the several physical soil properties and how changing temperatures are affecting these physical parameters.

2.4.1 | Soil texture and the effect of temperature

Soil texture refers to the proportional composition of sand, silt and clay particles in the mineral component of soil (Costa et al., 2023; Patil & Lamnganbi, 2018). The soil texture is commonly determined using the soil texture triangle, which presents various combinations of sand, silt, and clay percentages, categorising soils into twelve distinct textural classes.

The texture of soil significantly impacts its thermal behaviour and surface temperature. Sandy soils tend to heat more rapidly compared to clay soils because of their lower heat capacity, reduced thermal conductivity and diminished evaporative cooling capabilities. Clay soils tend to retain more water and since water has a higher heat capacity, more energy is required to increase its temperature, resulting in slower heating rates (Costa et al., 2023).

2.4.2 | Soil colour and its relationship with temperature

The colouration of soil primarily stems from the minerals it contains. Aerobic soils rich in iron typically display an orange-brownish hue, while those abundant in organic matter tend to appear dark brown to black. Additionally, soil colour can vary based on its moisture content. Saturated soils under anaerobic conditions might exhibit blue patches and often feature grey mottles (Lindbo et al., 2012).

Dark-coloured soils tend to have higher temperatures compared to light-coloured soils because they absorb more radiant heat. However, the presence of substantial organic matter in dark-coloured soils can enhance their water retention capacity. This capacity helps counterbalance the heightened heat absorption caused by their dark colouration (Costa et al., 2023).

2.4.3 | The effect of temperature on soil structure

The soil structure denotes the organisation of soil particles, known as peds, and their tendency to merge into aggregates (Costa et al., 2023; Lindbo et al., 2012). The primary structural types of soil include granular, platy, prismatic, blocky and columnar formations. Among these, the granular structure is deemed optimal due to its excellent porosity, ease of tillage, favourable root development and efficient air and water movement facilitated by loosely arranged granules. In contrast, platy, prismatic, blocky and columnar structures are more compacted to varying degrees, restricting plant root penetration and impeding efficient drainage as they hinder water percolation (Dr A Sacco, pers. comm., October 2023).

The arrangement of soil particles impacts soil temperature and governs pore distribution. Soils exhibiting a more rounded structure experience quicker warming owing to increased aeration and reduced waterlogging. Conversely, compaction detrimentally affects soil structure by elevating soil density and thermal conductivity. This results in swifter alterations in soil temperature and influences root growth and morphology (Costa et al., 2023). Soil's aggregate stability rises with increased soil temperatures. This occurs due to the thermal alteration of iron and aluminium oxides, causing them to function as binding agents for clay particles (Onwuka & Mang, 2018).

Soil structure regulates the presence of water and air within the soil (Patil & Lamnganbi, 2018). Its role is crucial as it facilitates water infiltration, movement and storage and enables root and tuber development. Factors influencing structure encompass the quantity of organic matter, constituents composing soil minerals as well as cultivation and tillage practices (Patil & Lamnganbi, 2018). Notably, an elevation in soil organic carbon contributes to enhancing soil structure, including its aggregate stability (Feng et al., 2022). A well-aggregated soil fosters improved water entry at the surface, enhanced aeration, increased water-holding capacity and resists surface crusting, thereby augmenting water flow into the soil (Patil & Lamnganbi, 2018).

2.4.4 | Soil density in relation to temperature

Soil density serves as a standard measure for assessing the degree of soil looseness or compactness. García-Fayos & Bochet's research (2009), cited in Brevik (2013), highlighted significant correlations between climate change and detrimental effects on bulk density and aggregate stability within semi-arid Mediterranean ecosystems. The level of aggregation significantly impacts the movement of water and air within the soil (Costa et al., 2023).

Clay content significantly contributes to bulk density, as higher clay concentrations correlate with increased bulk density values (Patil & Lamnganbi, 2018). Numerous factors, such as soil organic matter, primary soil minerals and land management practices influence bulk density. Bulk density, in turn, impacts soil infiltration, root growth, water availability, porosity and aeration (USDA, 2014).

Elevated bulk density values indicate significant soil compaction issues. The soils of the Mediterranean usually have a bulk density of 1.04 g cm^{-3}, depending on the land use and soil management practices (Panagos et al., 2024). Rising temperatures cause organic carbon depletion, consequently elevating bulk density and rendering the soil more susceptible to compaction (Patil & Lamnganbi, 2018). Elevated bulk density values range from 1.3 to 1.6 g cm^{-3} and these enhance heat dissipation from the soil surface by accelerating the rate of heat energy transfer through the soil (Onwuka & Mang, 2018).

2.5 | Soil water content and soil moisture

Soil water plays a central role in the hydrological cycle by capturing, storing and filtering water, thereby supporting global agricultural production that provide the world's food (FAO, 2017). The soil water content is primarily dependent on the amount of water present and the force holding the water in the soil. The amount of rainfall, the texture of the soil, evapotranspiration and vegetation cover all influence soil water content. Water is not always available for plant roots even though it can be present in soil. Field capacity is the amount of water held in the soil after excess water has drained away and the rate of downward movement has decreased. Soils reach field capacity typically following rainfall or irrigation. Plant-available soil water refers to the water accessible for plants to absorb. Once the permanent wilting point is attained, plants can no longer draw water to satisfy their physiological needs. At this stage, water is retained and firmly held in the capillaries, leading to irreversible wilting and plant death.

Available water capacity denotes the quantity of soil moisture accessible to plants (USDA, 2014). Soil moisture present on the surface and below plays a role in moderating the daily fluctuations in soil temperature (Costa et al., 2023). It serves as a direct indicator of land surface dryness, influenced by factors such as precipitation levels, vegetation health and land surface temperature, collectively determining the degree of aridity (Wei et al., 2020). Notably, there has been a significant decline in soil moisture within the Mediterranean region (EEA, 2023). This reduction occurs as heightened soil temperatures diminish water viscosity, permitting increased water percolation through the soil profile (Onwuka & Mang, 2018).

Soils with higher moisture levels possess a higher specific heat compared to dry soils due to water's greater specific heat compared to soil. Consequently, moist soils exhibit lower temperature fluctuations. Higher soil water content slows down changes in soil temperature compared to drier soils. Reduced moisture content causes more solar energy to transform into sensible heat, contrasting high soil moisture where solar energy primarily evaporates water. Evaporation of soil water leads to decreased soil temperature. The contrast in temperature between soil and the atmosphere is tied to the rate of evaporation, resulting in an inverse relationship between soil surface temperature and soil water content (Costa et al., 2023).

The moisture content in topsoil plays a crucial role in various hydrologic processes, including rainfall. Soil moisture patterns, both in terms of space and time, are influenced by factors like precipitation variability, evapotranspiration and runoff. Higher soil moisture can contribute ample moisture to the atmosphere, elevating humidity levels and consequently boosting precipitation. From an energy balance perspective, increased soil moisture reduces surface albedo, allowing for greater absorption of solar and terrestrial radiation and promoting moisture convergence, potentially leading to increased precipitation. Research by Sehler et al. (2020) indicated a general association between higher precipitation and increased soil moisture levels. They also found a moderate to very strong correlation between precipitation and soil moisture across various land cover types, with the strongest correlations observed in arid regions with limited vegetation.

Additionally, findings from Al-Kayassi et al. (1990) demonstrated that higher moisture content in soil reduces temperature variations between day and night, offering protection against abrupt temperature changes. Moreover, they observed that solar energy absorption increases with higher moisture content, leading to greater heat storage capacity. Furthermore, higher moisture content was found to enhance plant climate conditions, consequently improving plant growth rates and yields.

2.5.1 | Evaporation

The process of water evaporation from the soil demands a significant amount of energy. This energy, sourced from solar radiation, is utilised by soil water during evaporation, consequently restricting its availability for heating the soil. As a result, higher rates of evaporation lead to soil cooling, contributing to a reduction in its temperature (Onwuka & Mang, 2018). Warmer air, due to climate change, can hold more moisture, resulting in enhanced evaporation and the ramifications associated with this such as drier, harder and less permeable soils and reduced hydraulic conductivity in soils. Furthermore, enhanced evaporation leads to soil salinisation since when water is evaporated, the salts are left behind.

2.6 | The effect of climate change on soil temperatures

According to the IPCC's sixth assessment report, global temperatures are anticipated to rise between 1.1ºC and 6.4ºC throughout the 21st century. This increase is expected to accompany shifts in precipitation patterns worldwide. Climate change will not only impact the total amount of precipitation received but will also disrupt how and where precipitation is distributed in numerous locations (Brevik, 2012; Feng et al., 2022).

The relationship between soil and atmospheric temperatures is crucial within the context of climate change (Costa et al., 2023). Soil temperature is regulated by the balance between solar radiation absorbed and emitted (Onwuka & Mang, 2018; Patil & Lamnganbi, 2018). This temperature significantly impacts the exchange of energy and substances with the atmosphere, affecting evaporation, aeration and the speed and nature of chemical reactions in the soil. Various factors, including soil characteristics like colour, texture and structure, along with atmospheric elements such as air temperature and solar radiation, collectively impact soil and water movement. Additionally, they influence key soil temperature factors such as thermal conductivity and extreme temperatures. Features like slope and sunlight exposure also play a role, with higher slopes correlating with reduced soil temperatures due to the scattering angle (Onwuka & Mang, 2018).

In the Mediterranean region, the soil experiences xeric conditions with dry summers. The highest soil temperatures occur during the summer months in the northern hemisphere, correlating with maximum incident global radiation. Researchers like Costa et al. (2023) have identified an increasing trend in soil temperature across southern Europe. This, in conjunction with the warm Mediterranean climate, is projected to lead to decreased soil moisture, intensifying heat anomalies and extremes. Such dry conditions exacerbate heat stress effects as the absence of moisture prevents evaporative cooling, resulting in higher and more severe temperatures, which can significantly impact crop growth and yield (Costa et al., 2023).

In the Anthropocene era, the overall rise in atmospheric temperatures has likely caused an increase in soil temperatures, as suggested by Biswas et al. (2018). According to the findings of Crowther et al. (2016), referenced in Biswas et al. (2018), even a 1ºC increase in soil surface temperature could result in carbon loss from the upper soil horizon. Predictive models indicate that elevated temperatures are anticipated to cause a decrease in carbon content within agricultural soils (Biswas et al., 2018).

Surface soil albedo denotes the Earth's surface reflectivity concerning incoming solar radiation (Evett, 2000 as cited in Costa et al., 2023). The reflected radiation amount and type are influenced by factors like vegetation cover, underlying mulch and soil surface attributes. Ground vegetation plays a role in modulating the sunlight reaching the ground, with bare soils heating and cooling more rapidly than those covered by vegetation. Management practices, such as employing mulches and conservation tillage can impact soil albedo. Mulch materials used in soil management restrict evaporation, enhance soil moisture and consequently lower the soil surface temperature (Onwuka & Mang, 2018).

The most recent study by Huang et al. (2023) highlights that plant diversity serves as a natural regulator, mitigating soil heating during hot weather and cooling during cold periods. This diversity exerts a consistent influence throughout the year, particularly under extreme climatic conditions like droughts, effectively impeding the pace of global warming. This stabilising effect on soil temperature is attributed to the heightened concentrations of soil organic carbon due to increased plant diversity (Huang et al., 2023).

2.6.1 | Effect of changing temperatures on society, the environment and the economy

The repercussions of increasing temperatures extend beyond environmental concerns, significantly affecting societal and economic progress. There is an elevated risk of conflicts over natural resources, particularly in developing nations relying heavily on agriculture (EEA, 2023).

Dry spells contribute to various environmental challenges and give rise to natural disasters like prolonged droughts and desertification, particularly in arid and semi-arid regions globally. The fluctuation in temperatures significantly impacts crop yields by changing flowering times and increasing susceptibility to pests and diseases. This poses a threat to both global food production and food security. These natural disasters have a great economic burden on the affected countries, especially developing countries. The hydrological cycle will be altered as climate change influences precipitation patterns which, in turn, affects soil moisture and water availability for agriculture (Hatfield, 1990).

Malta grapples with water scarcity, primarily attributed to issues like the depletion of groundwater and the intrusion of seawater caused by extensive groundwater extraction. While registered groundwater sources used for agricultural and commercial purposes are metered, effective monitoring and management of groundwater resources remain important challenges, especially considering the limited rainfall experienced in the Maltese Islands. The forthcoming climate changes are projected to have adverse effects on Malta's natural freshwater reservoirs and crop viability, exacerbating the existing strain on local arable land and altering production patterns and the economy accordingly (Galdies & Vella, 2019). Regardless of the specific Representative Concentration Pathway (RCP) scenario, agricultural productivity and food quality in the Maltese Islands are expected to decline, as highlighted by Galdies and Vella (2019). Confirming these findings, Galdies and Meli (2022) conducted a study indicating that southern European countries, including Malta, are likely to witness a 10% decrease in agricultural productivity due to climate change. Moreover, the study suggests that approximately 54% of Malta's usable agricultural land may become unsustainable due to declining productivity, posing significant challenges for farmers reliant on this sector for their livelihoods. Supporting these projections, data indicates that Malta has experienced a rise in mean annual air temperature by +$0.17℃$, coupled with a reduction of 6 mm in rainfall (Galdies & Meli, 2022). To address these challenges, adopting sustainable water practices is crucial, such as utilising harvested rainwater for irrigation and incorporating reclaimed water from the Sant' Antnin Sewage Treatment Plant with Malta's New Water Programme and its distribution networks (Agricultural Services and Rural Development Division, n.d.).

Bare soils generally exhibit higher land surface temperatures than vegetated surfaces due to lower evaporative cooling and greater absorption of solar radiation (Duveiller et al., 2018). Therefore, seasonal increases in LST and reductions in soil moisture may reflect not only climatic warming and altered precipitation patterns but also changes in land cover associated with agricultural practices (Duveiller et al., 2018). Consequently, distinguishing between the effects of climate change and those arising from land management practices is important when assessing trends in soil dryness and thermal conditions, as observed increases may result from the combined influence of climate variability and land management.

Forecasts by the IPCC indicate an anticipated surge in severely arid lands in the coming years. A comprehensive global and national approach to assessing the consequences of droughts is pivotal for implementing effective drought risk management strategies and sustainable development policies to minimise the effects on society, the environment and the economy at an early stage (Zhang et al., 2019).

2.6.2 | Soil management strategies in central Mediterranean countries

Climate change is reshaping agricultural practices (McDaniel et al., 2023). Implementing sustainable soil management techniques can mitigate the adverse impacts of intensified droughts and heat waves resulting from shifts in climate. This approach involves integrating efficient soil management methods with more efficient use of irrigation. In the Mediterranean region, irrigation stands out as a crucial short-term strategy to counter the effects of climate change, notably in moderating extreme thermal conditions within the soil and the atmosphere. However, despite its effectiveness in promoting transpiration and higher soil moisture, water resources are dwindling in central Mediterranean countries (Costa et al., 2023).

Precision agriculture encompasses technology applications that promise enhanced agricultural productivity while minimising environmental impact. Novel farming methodologies empower farmers to make data-driven decisions, meeting the demands of a growing population while curbing losses in yield, nutrients and water. The rapid advancements in remote sensing technologies have been instrumental in this field, allowing for efficient monitoring of crops, nutrient distribution, disease and pest management, weed control, irrigation practices and estimation of evapotranspiration. These remote sensing tools enable the collection of site-specific data, facilitating the targeted application of agricultural strategies tailored to specific areas of interest (Sishodia et al., 2020).

Soil temperature regulation under warmer, drier conditions can be achieved through various practices like soil-cover vegetation, cover crops and mulching. These methods act as protective layers, curbing soil erosion, enhancing water retention and infiltration and reducing evaporation. Mulching not only assists in weed and pest control but also aids in sustaining yields during challenging climatic situations. Employing sustainable soil management practices such as no-tillage proves crucial in minimising soil erosion, reducing compaction and preventing the formation of impermeable layers that impact soil's thermal and water characteristics. Tillage practices must be based on good spatial characterisation of the soil profile and properties. Additionally, the installation of photovoltaic panels over crops has emerged as an innovative solution that can simultaneously support climate adaptation and renewable energy production. However, the effectiveness of agri-photovoltaic systems depends on several factors, including crop type, shading intensity, panel design, irrigation regime and local climatic conditions. While partial shading may reduce crop water stress and soil evaporation under hot and dry conditions, excessive shading can negatively affect crop growth and yields. Therefore, agri-photovoltaic systems should be carefully designed and adapted to local environmental and agricultural requirements to maximise their benefits (Costa et al., 2023).

Managing soil compaction is indeed a global concern, and one effective solution involves utilising agricultural machinery with wider tires and lower pressure. This strategy helps distribute the machinery's weight more evenly, reducing the impact and potential for soil compaction (Hamidov et al., 2018).

The National Agricultural Policy for the Maltese Islands 2018-2028, formulated by the Ministry for the Environment, Sustainable Development, and Climate Change (MESDC) in 2018, outlined various measures and objectives spanning economic, social, resource and governance aspects for the advancement of the Maltese Agricultural Sector. To address economic concerns, the policy emphasised the crucial role of developing smart technologies to tackle present and future challenges in agriculture. On the social front, the focus is on integrating cultural and social activities to promote local products and preserving Maltese agricultural heritage through the promotion and dissemination of traditional indigenous knowledge and skills. In terms of resources, there was a significant emphasis on encouraging farmers to reduce reliance on groundwater. From a governance perspective, the policy underscored the importance of maintaining coherence and consistency among different policies, along with ensuring effective communication (MESDC, 2018).

The MESDC is the main authority responsible for the implementation and monitoring of such measures in collaboration with other entities such as the Agriculture Consultative Council, the Agricultural Directorate, the Plant Protection Directorate, the Rural Development Department, the Lands Authority, the Environmental Resource Authority and the Energy and Water Agency (MESDC, 2018).

2.7 | The use of remote sensing in the climate change context

The use of remote sensing methods for monitoring soil conditions has become a vital tool in modern environmental studies and resource management. Remote sensing provides a unique perspective, allowing for non-intrusive and frequent evaluations of soil conditions across vast geographical regions. This capability is especially crucial in addressing and managing the challenges brought by shifting climate patterns. The combination of satellite imagery, aerial photography and ground-based sensors has transformed our ability to continuously monitor soil conditions across different spatial scales, enabling more informed decision-making in the conservation of natural resources. The role of remote sensing in assessing soil conditions is increasingly significant, solidifying its place as an essential tool in the field of environmental science (Ghauri & Zaidi, 2011).

Remote sensing is advantageous due to its extensive coverage across geographical areas and frequent monitoring intervals, particularly beneficial in regions where data and measurement sources are limited (Wei et al., 2020). It serves as an efficient tool for monitoring drought, especially in countries lacking consistent in-situ datasets (Mehravar et al., 2021). Remote sensing accurately measures crucial drought indicators like rainfall and temperature. Nonetheless, issues like data gaps and discontinuities persist, resulting in uneven data quality (Mehravar et al., 2021; Zhang et al., 2019).

Despite its advantages, the suitability of remote sensing data depends largely on the spatial resolution of the sensors employed. Landsat 8 and Landsat 9 provide imagery at a spatial resolution of 30 m, which offers a useful balance between spatial detail, temporal coverage and long-term data availability for environmental monitoring. However, the fragmented nature of Malta's agricultural landscape, characterised by small and heterogeneous fields, presents challenges for the use of moderate-resolution imagery. Individual pixels may encompass multiple land-cover types, resulting in mixed-pixel effects that can reduce the accuracy of soil and vegetation assessments at the field scale. Consequently, when interpreting remotely sensed indicators in Malta, it is important to consider that observed patterns may reflect a combination of agricultural parcels, natural vegetation and other surrounding land uses.

2.7.1 | Water management

Remote sensing data, employing optical, thermal and microwave bands, enables farmers to determine crop water needs for effective irrigation planning, reducing water loss and mitigating water stress. Compared to conventional evapotranspiration measurements, remote sensing offers superior capabilities and cost-efficiency. However, despite its advantages, improving remote sensing-based evapotranspiration estimates requires continued research and advancements due to existing errors and limitations (Sishodia et al., 2020).

2.8 | Remote sensing as a tool for monitoring soil moisture

Drought, as described by the World Meteorological Organisation (WMO), characterises a prolonged and abnormal shortage of precipitation (Wei et al., 2022). It is a hydrometeorological occurrence influenced by various environmental factors (Mehravar et al., 2021; Sreekesh et al., 2019). This phenomenon signifies a deficit in water across soil, atmosphere and vegetation in natural ecosystems, reflecting conditions of water scarcity. Land aridity stems from multiple factors like limited rainfall, elevated land surface temperatures, increased evapotranspiration and amplified surface reflectivity (Wei et al., 2022;

Xu et al., 2022). In agriculture, dryness signifies insufficient water supply to meet crop water needs (Sreekesh et al., 2019; Wang et al., 2022). Drought instances have amplified in recent years and are anticipated to intensify further in the future (Mehravar et al., 2021).

Droughts encompass five primary classifications: meteorological droughts, indicating precipitation deficits; agricultural droughts, characterised by insufficient soil moisture; hydrological droughts, representing shortages in runoff, groundwater or overall water storage; socio-economic droughts, denoting a scarcity in water supply concerning societal needs and physiological droughts, referring to water that is present in soil but cannot be absorbed by plants (Mehravar et al., 2021; Sreekesh et al., 2019). These conditions impact surface vegetation growth, diminish crop yields, contribute to vegetation degradation and decrease surface water levels. In semi-arid environments like Malta where rainfall is limited and highly variable, drought conditions are particularly significant due to the strong dependence on episodic precipitation for both runoff generation and groundwater recharge. Prolonged droughts may further exacerbate water scarcity by reducing aquifer replenishments, lowering groundwater levels and increasing the risk of land desertification and soil salinisation (Wei et al., 2022). Additionally, they perpetuate environmental, social and economic challenges, often amplified by a rise in extreme heatwave occurrences (Xu et al., 2022).

Monitoring aridity has become increasingly crucial due to the extensive impact of climate change on various aspects of society, especially agriculture and the economy and given the sensitivity of semi-arid systems like Malta to changes in rainfall patterns and evapotranspiration. Therefore monitoring is essential for preventing and mitigating losses caused by droughts (Xu et al., 2022). Meteorological drought monitoring relies on precipitation deficits and evapotranspiration relationships derived from weather stations whereas remote sensing-based monitoring combines various methods like vegetation status, thermal inertia and soil moisture from satellite data products (Mehravar et al., 2021; Wei et al., 2022). While meteorological monitoring depends on ground-based stations, which can be unevenly distributed and time-sensitive, remote sensing offers higher resolutions and cost-effective data from satellite instruments (Wei et al., 2022).

Despite their widespread application, remote-sensing-based evapotranspiration estimates are associated with several sources of uncertainty. The accuracy of these estimates depends on the quality of the input data, including land surface characteristics and meteorological variables, as well as the assumptions embedded within the models used to calculate evapotranspiration. Measurement errors, spatial variability in surface conditions and limitations in data acquisition can all influence the reliability of evapotranspiration estimates. Furthermore, uncertainties may arise when scaling observations across different spatial and temporal resolutions. Consequently, evapotranspiration estimates derived from remote sensing should be interpreted with caution and, where possible, validated using ground-based observations (Allen et al., 2011).

The IPCC's fifth assessment report highlighted a concerning trend of increased aridity in various countries, a trend expected to persist in the coming decades.

Presently, around 41% of the global land area faces drought disasters and this figure is projected to escalate due to rising temperatures. Future estimations suggest that more than half of the world's land area could experience drought conditions by the end of the 21st century. Understanding and monitoring these aridity fluctuations have become crucial across environmental and agricultural domains to develop proactive measures for sustainable global development (Wei et al., 2022).

For several decades, tools like the vegetation index, land surface temperature (LST) and Normalised Difference Vegetation Index (NDVI) have been utilised to track and assess drought conditions (Liu & Yue, 2018). Guillevic et al. (2018) characterised LST as an indicator of the Earth's surface temperature, indicating its hotness or coldness. This metric varies based on the geographical region being observed as it measures the temperature of anything beneath the satellite. Conversely, NDVI is a remote sensing tool employed to gauge the presence and extent of vegetation on the Earth's surface. By assessing whether vegetation is present or absent, NDVI is capable of distinguishing between areas of green vegetation and bare soil (Gupta et al., 2021).

2.8.1 | Land Surface Temperature

Land Surface Temperature (LST) has become an essential remote sensing tool for monitoring droughts as it reflects the thermal properties of the Earth's surface and is sensitive to changes in moisture levels. During periods of drought, reduced soil moisture and increased evaporation lead to higher surface temperatures, making LST a valuable indicator for assessing drought conditions (Zhou et al., 2019). Remote sensing satellites such as MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat provide continuous, high-resolution LST data, enabling the identification and monitoring of drought over large areas. Research has shown a strong correlation between LST and other drought indicators, including vegetation indices and precipitation, confirming its reliability as a tool for drought assessment (Lian et al., 2017). By combining LST with additional remote sensing data, the early identification of droughts can be enhanced, supporting more effective response and mitigation efforts. Additionally, LST data play a crucial role in refining drought models and advancing the understanding of both the spatial and temporal patterns of drought (Yang et al., 2020; Zhang et al., 2017).

2.8.2 | Normalised Difference Vegetation Index

NDVI has long been a fundamental remote sensing tool in drought monitoring due to its ability to capture changes in vegetation health, a key indicator of water stress. NDVI is derived from the difference in reflectance between the near-infrared and visible red bands of satellite imagery, allowing for an effective measurement of vegetation cover and biomass. As vegetation responds to changing water availability, NDVI provides valuable insights into plant health, where low NDVI values typically indicate stressed or sparse vegetation, often associated with drought conditions, while high values correspond to healthier, well-watered vegetation (Rabin et al., 2014). Its widespread use in assessing drought has made NDVI an indispensable tool in monitoring the spatial and temporal distribution of drought impacts. However, NDVI does have limitations, especially in regions with sparse vegetation or where the soil background influences reflectance, making it less reliable in certain environments (Guo et al., 2023). Relying solely on LST and NDVI might not comprehensively capture drought conditions. To enhance drought assessment accuracy, scholars have introduced additional parameters like precipitation and evapotranspiration. NDVI remains valuable in pinpointing changes in vegetative cover across regions, especially when combined with other indices and environmental data for more robust drought monitoring (Wei et al., 2022).

2.8.3 | Enhanced Vegetation Index

The Enhanced Vegetation Index (EVI) is a widely used remote sensing tool for drought monitoring, as it provides a more accurate and sensitive measure of vegetation health compared to other vegetation indices like the NDVI. EVI is less affected by atmospheric conditions and soil background, making it particularly useful in regions where these factors can influence vegetation readings. During droughts, reduced water availability leads to stress on vegetation, causing a decrease in EVI values, which can be used to assess the severity and extent of drought impacts on vegetation. Satellites such as MODIS and Landsat provide continuous, high-resolution EVI data, allowing for spatially and temporally detailed monitoring of drought effects on vegetation over large areas (Harbowo & Muliawati, 2023). Several studies have demonstrated that EVI is closely related to drought conditions and can effectively monitor the progression of drought, even in semi-arid regions like Malta. By integrating EVI with other remote sensing data, such as precipitation and temperature, it is possible to enhance drought monitoring, providing early warnings and supporting more effective drought management strategies (Sangpradid et al., 2021).

2.8.4 | Temperature Vegetation Shortwave Infrared Reflectance Dryness Index

The precise evaluation of surface dryness is crucial in mitigating drought-related losses and has been made more achievable through remote sensing methodologies. An amalgamated satellite-driven dryness index, termed TVSDI, was innovated by Xu et al. (2022). This index incorporates three key variables- LST, EVI and Shortwave Infrared Reflectance (SWIR). Moreover, these remote sensing variables can also be independently employed to assess dryness characteristics (Xu et al., 2022).

Dryness indices have been extensively utilised in China and similar investigations employing these indices have been conducted in regions like Southern Spain, Iran, Taiwan and the United States of America. However, such studies are notably absent in many other parts of the world, including Malta. These diverse indices characterise dryness conditions differently, leading to varied interpretations across regions. Moreover, the availability of satellite data, particularly precipitation data from reliable online sources is inconsistent, posing a significant challenge for conducting such studies, as precipitation data is essential for generating meaningful results. Additionally, limitations such as cloud cover and other atmospheric interference can hinder satellite observations, consequently impacting the quality of the final analysis and introducing uncertainties in the indices. Furthermore, the dryness indices often rely on surface indicators, which may not fully capture subsurface moisture conditions.

Research on dryness indices such as the Temperature Vegetation Dryness Index, the Temperature Vegetation Precipitation Dryness Index and the TVSDI has yielded valuable insights into environmental conditions. By examining alterations in vegetation and moisture levels indicated by these metrics, policymakers gain a deeper understanding of drought severity and its fluctuations. These indicators also aid in water resource management by offering perspectives on water availability for diverse purposes like agriculture, urban water provision and ecosystem upkeep. Understanding patterns of dryness informs decisions regarding water distribution, irrigation scheduling and conservation actions. Scientists utilise dryness indicators to explore ecological phenomena associated with drought stress and its repercussions on ecosystems. This encompasses assessing the ability of plant communities to endure drought, investigating shifts in species distribution in response to evolving dryness conditions and evaluating the enduring impacts of drought on biodiversity.

Insights gleaned from dryness indicators inform decisions pertaining to land use planning and the management of natural resources. Areas prone to drought or enduring prolonged dry spells may be earmarked for particular land uses or conservation endeavours to alleviate potential impacts on ecosystems and human activities. Dryness indicators also serve as valuable tools for examining the effects of climate change on vegetation and water resources. Through the examination of trends in dryness indicators over time, researchers can gauge how climate change is impacting the occurrence, severity and duration of drought events across various regions. Overall, the information derived from studies on dryness indicators has proven highly beneficial for implementing diverse management practices aimed at mitigating drought, managing water resources, planning land use and conserving ecosystems. By furnishing timely and spatially explicit data on dryness conditions, these indicators facilitate informed decision-making to bolster resilience to drought and foster sustainable resource management strategies.

2.9 | Soil legislations

Malta currently lacks dedicated legislation concerning soil conservation, highlighting the urgent need for the development of policies and laws in this regard. Presently, soil protection in Malta is addressed solely through the Fertile Soil (Preservation) Act 236 (Galdies, Azzopardi & Sacco, 2022). However, at the European level, recent policy developments such as the EU Soil Monitoring and Resilience Directive under the EU Soil Strategy for 2030 aim to establish a common framework for soil health monitoring, sustainable soil management and the restoration of degraded soils across Member States (European Commission, 2023). The implementation of such directives is expected to support national efforts in addressing soil degradation and improving soil resilience. Updating national legislation in alignment with these EU policy initiatives is therefore critically needed to alleviate the negative impacts of socio-economic pressures on agricultural practices. By improving the net income of Mediterranean farmers, there is a direct potential to reverse the ongoing trend of agricultural land abandonment (Sultana, 2015).

Creating resilience strategies is crucial in addressing the anticipated impacts of climate change in the Mediterranean region. The Institute for European

Environmental Policy has categorised adaptation efforts into behavioural, technological and management-based actions, stressing the need for solutions in each category to tackle diverse climate challenges. In addition to immediate responses, long-term adaptations such as crop substitution and biotechnology are gaining traction. It is essential to coordinate these resilience measures at both regional and national levels to ensure coherence and effectiveness (Skuras & Psaltopoulos, n.d.).

2.9.1 | European and National Legislation

It is concerning that despite European Union (EU) member states acknowledging the impact of desertification, efforts to combat it lack coherence, as highlighted in a report by the European Court of Auditors. There is an imperative to improve understanding of land degradation and desertification within the EU, evaluate the adequacy of the existing legal framework for soil and intensify actions to fulfil the commitment of achieving land degradation neutrality by 2030, a pledge made by the EU and its member states (EEA, 2023; European Court of Auditors, 2018).

The EU implemented various measures at the farm level to enhance resilience against climate change. In the EU, climate change became a part of the Common Agricultural Policy (CAP), with a greater focus on sustainable development and strategies for both adapting to and mitigating climate change after 2013. This shift was realised through the six priorities of the EU Rural Development Policy. These priorities encompass improving water and energy efficiency, promoting carbon capture, decreasing nitrous oxide and methane emissions and supporting the adoption and utilisation of renewable energy sources within the agricultural sector (Skuras & Psaltopoulos, n.d.).

There are several Council Directives that protect the soils of EU member states, some of these being Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources and Council Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances (Agricultural Services and Rural Development Division, n.d.). In Malta, we have the Environment Protection Act of 2001 and Legal Notice 426 of 2007 to protect the Maltese environment (Leġiżlazzjoni Malta, 2005).

2.9.2 | Sustainable Development Goals

The 2015 United Nations 2030 Agenda for Sustainable Development urges global collaboration to achieve all 17 Sustainable Development Goals (SDGs) by 2030 (UNDP, 2015). Agriculture and soils are at the heart of the SDGs and they are fundamental towards achieving the targets that promote sustainable soil management and food production and eradicating poverty. SDGs 2 and 3, aiming for zero hunger and good health respectively, rely on healthy soils to produce nourishing food. They endorse sustainable agriculture to ensure food security, boost agricultural productivity and eradicate hunger. SDG 6, focusing on clean water and sanitation, highlights the soil's role as a natural water purifier as water percolates through it. SDG 13 underscores the significance of soil in carbon sequestration and its crucial role in addressing climate change. Additionally, SDG 15 emphasises the necessity of safeguarding, reviving and endorsing sustainable land usage, which encompasses responsible soil use and management to counteract biodiversity loss and mitigate the harmful impacts of climate change (Lal et al., 2021; United Nations, 2015). Achieving a harmonious balance between society, the environment and the economy requires a holistic approach (Keesstra et al., 2018).

2.10 | Conclusion

The issue of dryness carries significant implications for agriculture, society and the economy, presenting irreversible consequences (Wei et al., 2020). This heightened importance has led to increased attention and comprehensive study of droughts, especially in small island environments like Malta where little research was conducted on local soil properties. Further exploration of this factor is imperative to comprehend its environmental, societal and economic impacts and devise strategies to mitigate these effects amid ongoing changes. Leveraging remote sensing data together with in situ soil data can significantly enhance our understanding and provide more definitive insights for ongoing research questions.

Chapter 3: Methodology

This chapter will delve into the methodologies employed for gathering and assessing satellite data, deriving equation values and their subsequent mapping of LST and the dryness index. A detailed description of the procedures conducted in the laboratory will be comprehensively outlined to compare in-situ data with satellite data and to obtain soil temperature, soil moisture, soil colour and soil texture data. The statistical tests used to analyse the data will also be outlined.

3.1 | Geographical location and timeframe

The Maltese Islands, located at 35.8816° N and 14.4490° E in the central Mediterranean region, form the geographical focus of this research (*Figure 3.1*). The Maltese Islands are three habitable islands with several other small uninhabitable rocks along the coastline. Their small size and insular setting make them an ideal case for studying spatial variability in land surface dryness. Visual representations of data pertaining to the Maltese Islands will cover the period from 2015 to 2024, encompassing a time frame of 10 years. The Maltese Islands will be further divided into districts since statistical data conducted by Malta's National Statistics Office is always represented into the six districts.

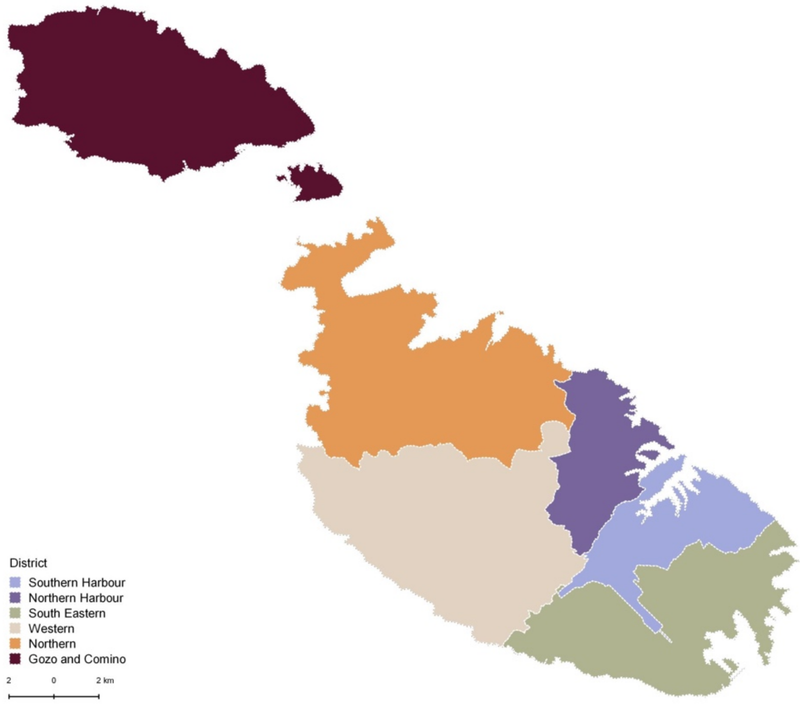


Figure 3.1 | The study area comprised of the Maltese Islands' districts (NSO, n.d.)

3.2 | Climatology of study area

Under the Köppen climate classification, the Maltese Islands exhibit mild, wet winters caused by the Icelandic low-pressure system and hot; Csa, dry summers caused by the Azores high-pressure system. The semi-arid climate in the Maltese Islands is typified by winter rainfall and extended periods of dryness throughout the summer (Galdies, 2012).

Since 1952, the average yearly temperature has risen by 1.5ºC, while rainfall in Malta has seen a decline of 10.3 mm per decade, leading to more prolonged periods of consecutive droughts since the year 2000. Notably, the climate norm for total annual rainfall has reduced by 9.7mm from the period of 1961-1990 to 1991-2020 (Galdies, 2022a). Sea temperatures in Maltese waters have progressively increased by 0.4ºC per decade since 1978. Furthermore, climate models (CMIP5) foresee further impacts of climate change in Malta, including heightened air and sea temperatures, increased occurrences of heatwaves and droughts and reduced precipitation, alongside an increase in heavy rainfall, flooding and severe storms (Galdies, 2022a). In fact, the year 2024, together with 2007, recorded the hottest mean meteorological winter temperature in Malta, measuring 14.8ºC since the 1900s (Malta Meteorological Office, 2025). Understanding these long-term climatic trends is essential for interpreting remote sensing-derived parameters such as temperature, which are highly sensitive to seasonal and interannual variability.

3.3 | Data collection

To quantify land surface temperature and surface dryness, this study integrated multiple remote sensing datasets derived from both Landsat and MODIS platforms. The following sections describe the data sources and satellite systems used.

3.3.1 | Satellites used for data collection

Landsat 8 provides essential high-resolution data for monitoring environmental parameters. Launched by NASA in 2013, Landsat 8 is part of a series of satellites that have revolutionised the ability to study land cover changes and environmental trends over time. Equipped with advanced sensors capable of capturing detailed imagery across multiple spectral bands, Landsat 8 provides scientists, policymakers and the public with valuable data on everything from deforestation and urbanisation to agricultural patterns (Omran, 2012). In today's era of rapid climate change, Landsat 8's continuous stream of high-quality data is indispensable for tracking environmental shifts, assessing the impact of human activities on ecosystems and informing strategies for sustainable resource management and adaptation efforts. Its detailed imagery is very important in monitoring the Earth's changing climate and cannot be overstated. This high-resolution satellite serves as a vital tool in our collective efforts to safeguard the planet.

Landsat 9, launched in late 2021 to replace Landsat 7, is a continuation of Landsat 8, having the same resolutions and the same remote sensors: Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Landsat 8 and 9 satellites image the Earth every 16 days in an 8-day offset. They pass over the Maltese Islands at 09:36 GMT, meaning that they pass over the Maltese Islands at 11:36 summer local time. Landsat 8 and 9 products contain surface reflectance and surface temperature. Landsat surface reflectance measures the fraction of incoming solar radiation that is reflected from the Earth’s surface to the Landsat sensor (USGS, n.d.A). Landsat 8 and 9 have a 15 metre resolution for the panchromatic band, a 100 metre resolution for the two thermal infrared bands and a 30 metre resolution for the remaining eight spectral bands (*Figure 3.2*).

Landsat Collection 1 and Collection 2 represent different iterations of data products derived from the Landsat satellites, each offering distinct improvements and advancements. Collection 2 Level-2 offers enhanced data quality and usability when compared to Collection 1, featuring enhancements such as updated digital elevation model sources, improved geolocation accuracy and enhanced quality assessment bands. Level-2 was chosen for its atmospherically corrected surface reflectance data, eliminating the need for additional corrections, unlike Level-1 (USGS, 2024). Thus, Landsat Collection 2 Level-2 was selected for this study, from 2015 to 2023. Together, Landsat 8 and 9 provided the primary remote sensing datasets for 2015 - 2023 while MODIS data complemented these observations for 2024, ensuring consistent temporal coverage (*Step 1 - Figure 3.3*).

Bands	**Wavelength (micrometers)**	**Resolution (meters)**
Band 1 – Coastal aerosol	0.43–0.45	30
Band 2 – Blue	0.45–0.51	30
Band 3 – Green	0.53–0.59	30
Band 4 – Red	0.64–0.67	30
Band 5 – Near Infrared (NIR)	0.85–0.88	30
Band 6 – Shortwave Infrared (SWIR) 1	1.57–1.65	30
Band 7 – Shortwave Infrared (SWIR) 2	2.11–2.29	30
Band 8 – Panchromatic	0.50–0.68	15
Band 9 – Cirrus	1.36–1.38	30
Band 10 – Thermal Infrared (TIRS) 1	10.6–11.19	100 (resampled to 30)
Band 11 – Thermal Infrared (TIRS) 2	11.50–12.51	100 (resampled to 30)

Figure 3.2 | Landsat 8 and 9 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) bands, wavelengths and resolutions (ESRI, 2022 & USGS, n.d.A)

The MODIS tool on the Terra satellite of the Earth Observing System was employed to gather Land Surface Temperature (LST) data, offering daily coverage and consequently, daily LST data for the Maltese Islands. MODIS data was used for the year 2024. LST data was acquired through the NASA Earth Data AppEEARS website by selecting the MOD11A1 dataset. To synchronise with the chosen soil sample collection dates, MODIS LST data was collected for those particular days only for 2024 (Earth Data, 2024). MODIS bands 2, 4, 5 and 7 (MOD09GA) were also collected for selected days in 2024 to keep a 1km resolution standard for the whole year. Bands 2, 4 and 5 were used to calculate the Enhanced Vegetation Index (EVI). Then, the EVI, LST and band 7 were used to calculate the final dryness index equation.

Satellite overpass dates spanning from April to September 2024 (*Table 3.1*) were acquired to schedule soil sample collection days (*Step 2 – Figure 3.3*). A standardised template was developed for the collection of soil samples, detailing the date and time of collection, sampling locations and the parameters of temperature, colour and moisture to be recorded. This template was consistently utilised for all soil sample collection days (*Appendix 1*). This was done to allow for a comparison between the LST satellite data and the actual soil temperature measurements taken on-site.

Table 3.1 | Landsat 9 satellite overpass dates April - September 2024

Date	Season	Local Time
Sunday 7 April 2024	SPRING	11:36 L.T.
Tuesday 23 April 2024	SPRING	11:36 L.T.
Thursday 9 May 2024	SPRING	11:36 L.T.
Saturday 25 May 2024	SPRING	11:36 L.T.
Monday 10 June 2024	SPRING	11:36 L.T.
Wednesday 26 June 2024	SUMMER	11:36 L.T.
Friday 12 July 2024	SUMMER	11:36 L.T.
Sunday 28 July 2024	SUMMER	11:36 L.T.
Tuesday 13 August 2024	SUMMER	11:36 L.T.
Thursday 29 August 2024	SUMMER	11:36 L.T.
Saturday 14 September 2024	SUMMER	11:36 L.T.
Monday 30 September 2024	AUTUMN	11:36 L.T.

3.3.2 | Sourcing of satellite data

After describing the satellites, the following section outlines how data were sourced and processed. The satellite data for this research was acquired for free through the open-access USGS Earth Explorer and NASA Earth Data websites (*Table 3.2*). Landsat 8 Collection 2 Level-2 was selected for the majority of the study, from 2015 to 2023. For 2024, MODIS data was used since this satellite provided LST, band 2, 4, 5 and 7 data that was consistent with the soil sample collection dates (*Step 3 - Figure 3.3*).

Satellite electromagnetic band data was atmospherically corrected using software in QGIS. The thermal bands were converted from digital numbers to top-of-atmosphere radiance and then to brightness temperatures in Celsius (USGS, 2024). Datasets for the chosen satellite overpasses were eliminated if either the MODIS MOD11A1 LST dataset was not available or if the cloud cover of the band dataset was higher than 30%. This threshold ensured adequate data quality and minimised cloud cover. The final selection of overpass dates is presented in table 3.3. The seasons were divided into two; the wet season, encompassing the months of December till May, and the dry season, encompassing the months of June till November. This approach, as used by Silvestri et al. (2025) and Dang et al. (2020), was chosen to obtain more representative imagery for both seasons, rather than attempting to represent all four seasons, which would have been less effective due to limited satellite overpass dates and increased cloud cover.

Table 3.2 | Datasets used in this study

Data type	Source	Period	Spatial Resolution	Temporal Resolution	Description
MOD11A1 LST	Earth Data AppEEARS	2024	1000 m	Daily	Used to visualise LST maps
MOD09GA bands 2,4,5 & 7	Earth Data AppEEARS	2024	1000 m	Daily	Used to calculate EVI & TVSDI equations
Landsat 8 visible, near-infrared & thermal bands	USGS Earth Explorer	2015 – 2023	30 m	16-day	Used to calculate LST, EVI and TVSDI

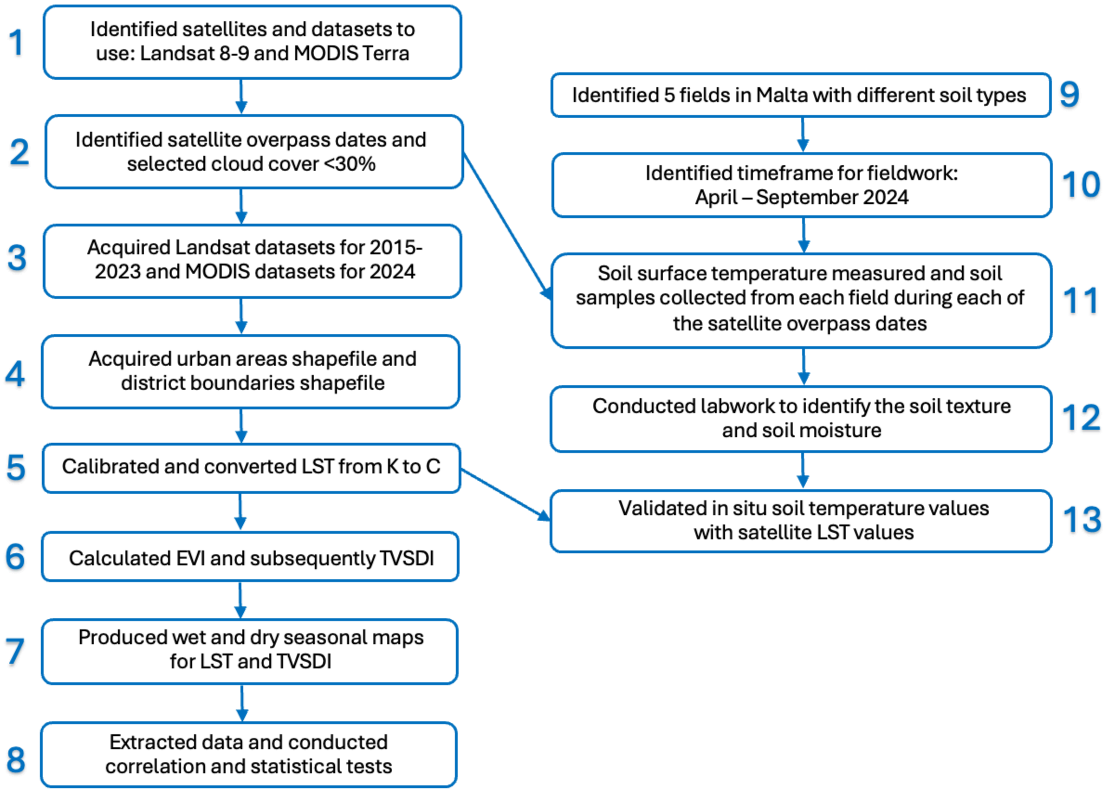


Figure 3.3 | Flow chart depicting the methodology for the study

Table 3.3 | Satellite overpass dates used for each season during the study period

Year	Wet	Dry
2015	17/01/2015, 06/03/2015, 22/03/2015, 07/04/2015, 23/04/2015, 09/05/2015, 25/05/2015	10/06/2015, 26/06/2015, 12/07/2015, 28/07/2015, 29/08/2015, 14/09/2015, 16/10/2015, 17/11/2015
2016	05/02/2016, 21/02/2016, 09/04/2016, 25/04/2016, 27/05/2016, 21/12/2016	28/06/2016, 14/07/2016, 30/07/2016, 15/08/2016, 31/08/2016, 16/09/2016, 02/10/2016, 03/11/2016
2017	06/01/2017, 23/02/2017, 11/03/2017, 27/03/2017, 12/04/2017, 30/05/2017	15/06/2017, 01/07/2017, 17/07/2017, 02/08/2017, 18/08/2017, 03/09/2017, 19/09/2017, 06/11/2017, 22/11/2017
2018	09/01/2018, 14/03/2018, 30/03/2018, 15/04/2018, 01/05/2018, 11/12/2018, 27/12/2018	02/06/2018, 18/06/2018, 04/07/2018, 20/07/2018, 21/08/2018, 06/09/2018, 24/10/2018, 09/11/2018
2019	28/01/2019, 13/02/2019, 17/03/2019, 02/04/2019, 18/04/2019, 20/05/2019	05/06/2019, 21/06/2019, 07/07/2019, 23/07/2019, 08/08/2019, 24/08/2019, 25/09/2019, 11/10/2019, 28/11/2019
2020	15/01/2020, 16/02/2020, 19/03/2020, 04/04/2020, 06/05/2020, 22/05/2020	23/06/2020, 09/07/2020, 25/07/2020, 10/08/2020, 26/08/2020, 29/10/2020, 14/11/2020, 30/11/2020
2021	01/01/2021, 18/02/2021, 06/03/2021, 07/04/2021, 09/05/2021, 25/05/2021, 19/12/2021	12/07/2021, 28/07/2021, 13/08/2021, 29/08/2021
2022	04/01/2022, 05/02/2022, 25/03/2022, 10/04/2022, 26/04/2022, 12/05/2022, 28/05/2022	13/06/2022, 15/07/2022, 31/07/2022, 16/08/2022, 17/09/2022, 03/10/2022, 04/11/2022
2023	23/01/2023, 24/02/2023, 28/03/2023, 13/04/2023, 29/04/2023, 31/05/2023	16/06/2023, 02/07/2023, 18/07/2023, 03/08/2023, 19/08/2023, 06/10/2023, 22/10/2023, 07/11/2023
2024	03/02/2024, 06/03/2024, 07/04/2024, 23/04/2024, 10/06/2024, 03/12/2024	26/06/2024, 12/07/2024, 28/07/2024, 29/08/2024, 14/09/2024, 30/09/2024, 01/11/2024

Following the acquisition and quality control of satellite datasets (*Step 5 – Figure 3.3*), several derived parameters were computed to generate the Temperature Vegetation Shortwave Dryness Index (TVSDI).

3.3.3 | Derivatives used to calculate TVSDI

The calculation of the TVSDI required three key input parameters - LST, EVI and short-wave infrared (SWIR) reflectance - each of which captures different aspects of land surface and vegetation conditions. Once these variables were computed, they were integrated into the TVSDI equation to produce dryness maps for each year of the study period (*Steps 6 & 7 – Figure 3.3*).

3.3.3.1 | Land Surface Temperature

LST is a parameter that differs from air temperature because from a satellite perspective, it represents the temperature of whatever surface the satellite observes from the atmosphere down to the ground surface (Li & Duan, 2018). LST was needed to calculate values for the dryness index. LST data for 2024 corresponding to the Landsat 9 satellite overpasses was acquired through the MOD11A1 version 6.1 dataset, which provided 1km resolution data (*Figure 3.4*). LST data from 2015 to 2023 was extracted using a software tool in QGIS, resulting in calibrated data with an improved 30m resolution (NASA, n.d. c). This data was then converted from Kelvin to Celsius in QGIS to obtain the final LST map. A colour ramp, ranging from dark blue to dark red, was selected to effectively represent temperature variations. The LST maps were interpreted to highlight their contribution to a better understanding of local climatic systems. Through such LST analysis, changes were revealed, showcasing the potential of satellite imagery to address pressing environmental challenges.

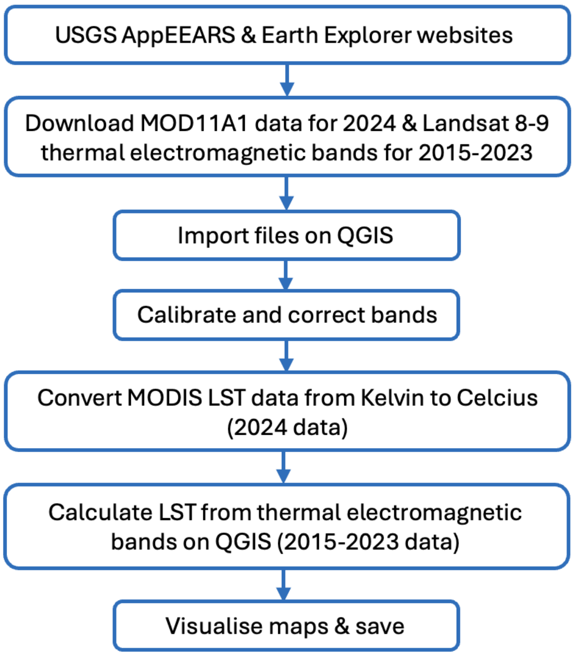


Figure 3.4 | Flow chart depicting the acquisition of LST maps

3.3.3.2 | Enhanced Vegetation Index

EVI is a vegetation index that was developed to optimise vegetation health and cover measurement, improving on the previous limitations of the NDVI. EVI was designed to correct for atmospheric conditions, such as aerosol scattering and haze, therefore providing more accurate measurements in areas with highly dense vegetation. It was also developed to optimise vegetation signals, particularly in regions with high biomass and thick canopies (Huete et al., 2002). EVI also minimises issues such as background and atmospheric noise, making it better suited to capture vegetation variations. Furthermore, studies comparing NDVI with EVI showed that EVI captured more strong correlations in soil moisture and droughts (Krishnan & Indu, 2023).

This index uses the near-infrared, red and blue reflectances. The values range from -1 to 1, with the lower values indicating that bare soil or stressed vegetation is present, while higher values representing areas with lush and healthy vegetation. Moderate EVI values close to 0 suggest the presence of less dense but still healthy vegetation, such as those found in semi-arid regions (Didan, 2021). The process of acquiring EVI values is depicted in figure 3.5. The following equation was used on QGIS to derive EVI values, the same that was used by Xu et al. (2022):

$$EVI = 2.5 \, x \, \frac{NIR - Red}{1 + NIR + 6 \, x \, Red - 7.5 \, x \, Blue}$$

band 2; blue, band 4; red and band 5; near infrared were collected from Landsat 8 for 2015 - 2023 and from MODIS for 2024. These were used to calculate the EVI equation and obtain EVI values (USGS, n.d.B).

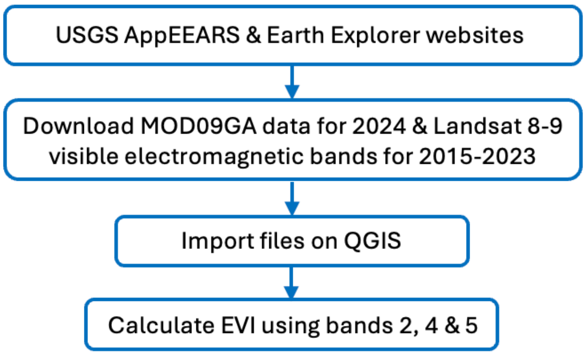


Figure 3.5 | Flow chart depicting the acquisition of EVI data

3.3.3.3 | Short-wave Infrared

Short-wave infrared typically encompasses wavelengths ranging from 1.57µm to 1.65µm and from 2.11µm to 2.29µm. These possess the ability to penetrate thin clouds and haze while also detecting heat through high-heat thermal emissions (European Space Imaging, n.d.). It offers crucial insights into the health of vegetation and the moisture content of soil, which is why it is especially utilised in vegetation assessments. In general, SWIR is pivotal in remote sensing applications, supplying essential data for numerous scientific, environmental and resource management objectives (Manxar, n.d.).

3.3.4 | Temperature Vegetation Shortwave Dryness Index

In this study, a dryness index was deployed to assess the dryness of the land surface throughout the Maltese Islands. This index, widely adopted for monitoring droughts on both a global and regional scale, offers robust capabilities in drought monitoring and is known for its straightforward implementation, as highlighted by Guo et al. (2023). Through a comprehensive analysis, the study aims to evaluate this index in the context of the Maltese Islands. Researchers can then enhance the accuracy and reliability of dryness assessments, thereby contributing to more informed decision-making processes regarding land management and resource allocation in the area.

To acquire TVSDI values, LST, EVI and SWIR values were obtained (*Figure 3.6*). Subsequently, the TVSDI equation below was utilised to calculate the respective TVSDI values:

$$TVSDI = \sqrt{LST^2 + SWIR^2 + (\frac{\sqrt{3}}{3} - EVI)^2}$$

The degrees of dryness used in this study were the same used by Xu et al. (2022), which is a standard classification for measuring dryness. A specific colour ramp was created and utilised for all the TVSDI maps to create the best contrast between near normal dryness and extreme dryness areas (*Figure 3.7*). The higher the TVSDI value, the lower the EVI, the higher the SWIR reflectance and the higher the LST value and vice versa (Xu et al., 2022). The last part of the equation was developed to enhance the sensitivity to vegetation related soil moisture. These values were then used to generate seasonal wet and dry maps depicting changes in dryness from 2015 till 2024 using QGIS.

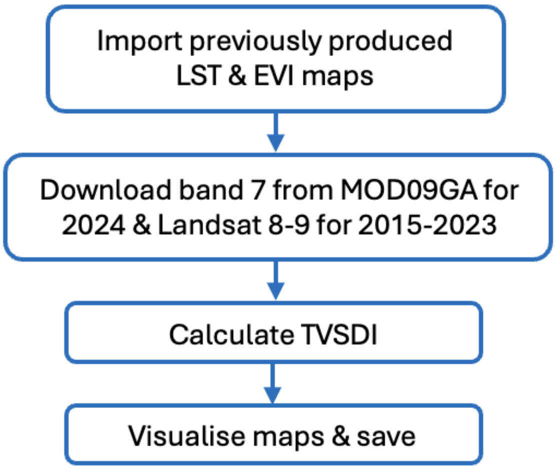


Figure 3.6 | Flow chart depicting the acquisition of TVSDI maps

Colour	Degree of dryness	Value of dryness
	Near Normal Dryness	0 – 0.45
	Mild Dryness	0.45 – 0.55
	Moderate Dryness	0.55 – 0.65
	Severe Dryness	0.65 – 0.85
	Extreme Dryness	0.85 – 1

Figure 3.7 | The legend used to classify dryness for TVSDI maps

3.4 | Data visualisation using GIS software

The processed datasets and computed indices were subsequently visualised and analysed using Geographic Information System (GIS) software to facilitate spatial interpretation of the results. GIS is a spatial system that facilitates the creation, management, analysis and mapping of data. It offers various capabilities to scientists and researchers. QGIS software is open-source and enables the visualisation of many different types of information. It allows for the overlaying of diverse data, regardless of their original format or source, onto a single map. Key to QGIS is its utilisation of location as the primary index variable which enables the integration of seemingly unrelated data. In this study, QGIS was used to examine changes in dryness over time. QGIS facilitated the visualisation and interpretation of spatial and temporal variations in dryness across the Maltese Islands.

An urban areas shapefile provided by Malta's Planning Authority was used to mask urban areas, quarries and industrial areas so that these do not influence the interpretation of the mapped results (*Step 4 – Figure 3.3*). These areas were excluded from the analysis because the study focused on soil temperature and soil dryness patterns within natural and agricultural environments. Built-up and industrial areas typically exhibit higher land surface temperatures due to the urban heat island effect and the thermal properties of impervious materials such as concrete and asphalt. Similarly, quarries often contain exposed rock and bare surfaces that can generate elevated surface temperatures. Including these land-cover classes could have therefore introduced bias into the interpretation of LST and soil dryness patterns by reflecting anthropogenic surface characteristics rather than environmental or agricultural soil conditions. Consequently, masking these areas enabled a more representative assessment of soil thermal and moisture dynamics across the study area.

3.5 | Soil sample collection, selected locations and lab work

To validate the satellite-derived data and strengthen the reliability of the remote sensing analysis, field and laboratory measurements were conducted across representative soil sites in southern Malta. Data validation is crucial as it ensures the quality and accuracy of the collected data.

Soil sampling was conducted twice monthly over a six-month period, beginning in April and continuing through September 2024 (*Step 10 – Figure 3.3*). These months were selected because they typically represent the driest conditions in the Maltese Islands. This approach allowed for the collection of soil samples under conditions that are most conducive to assessing dryness levels. Furthermore, the hydrological year of 2023-2024 was the driest year on record since 2008 according to the Energy and Water Agency (2025) since 220.3mm of rainfall were recorded. This made it ideal for monitoring soil parameters in 2024 and correlating them with satellite data.

The five soil sites (*Step 9 – Figure 3.3*), located in the south of Malta, were selected based on the soil map created by Lang & Osmond in 1960 (*Figure 3.8*). These sites (*Figure 3.9*) correspond to the following five soil types under the Kubiëna classification system:

- Terra soils - Xaghra series (Equivalent to Leptosols)
- Terra soils - Tas-Sigra series (Equivalent to Luvisols)
- L'Inglin complex (Equivalent to Luvisols)
- Xerorendzinas - San Biagio series (Equivalent to Calcisols)
- Carbonate Raw soils - Fiddien series (Equivalent to Vertisols)

The site of the Terra soils - Xaghra series is situated in the exposed coralline limestone garrigue, characterised by stony parent material rich in calcium carbonate. According to the WRBS, the soil at this location is classified as a Leptosol, which denotes shallow soils with limited horizon development and falls within the loamy clay textural class. Conversely, the Terra soils - Tas-Sigra series are predominantly found in the southern region of Malta and are classified as Luvisols under the WRBS system. Both types of Terra soils exhibit a reddish hue and were formed during a period of wetter climate in Malta's past. The L-Iklin complex is primarily found in areas where the Terra soils - Xaghra series occur, also classified as Luvisols under the WRBS system, with significant clay movement from the upper soil profile to the B horizon (Stellini et al., 2023). The Xerorendzinas, San Biagio series is categorised as a Calcisol and is primarily located in the central region of the Maltese Islands. These soils derive from the upper and middle Globigerina limestone as their parent material and typically exhibit a greyish colouration. They form through the primary and secondary accumulation of calcium carbonate due to evaporation in semi-arid conditions, resulting in high calcium carbonate content. The Carbonate raw soils - San Lawrenz series, predominantly found in the northwestern region of Malta and throughout Gozo, are classified as Regosols according to the WRBS system. These soils contain clay minerals with a significant swelling capacity, causing them to develop deep, wide cracks when dry and expand when wet (Lang & Osmond, 1960).

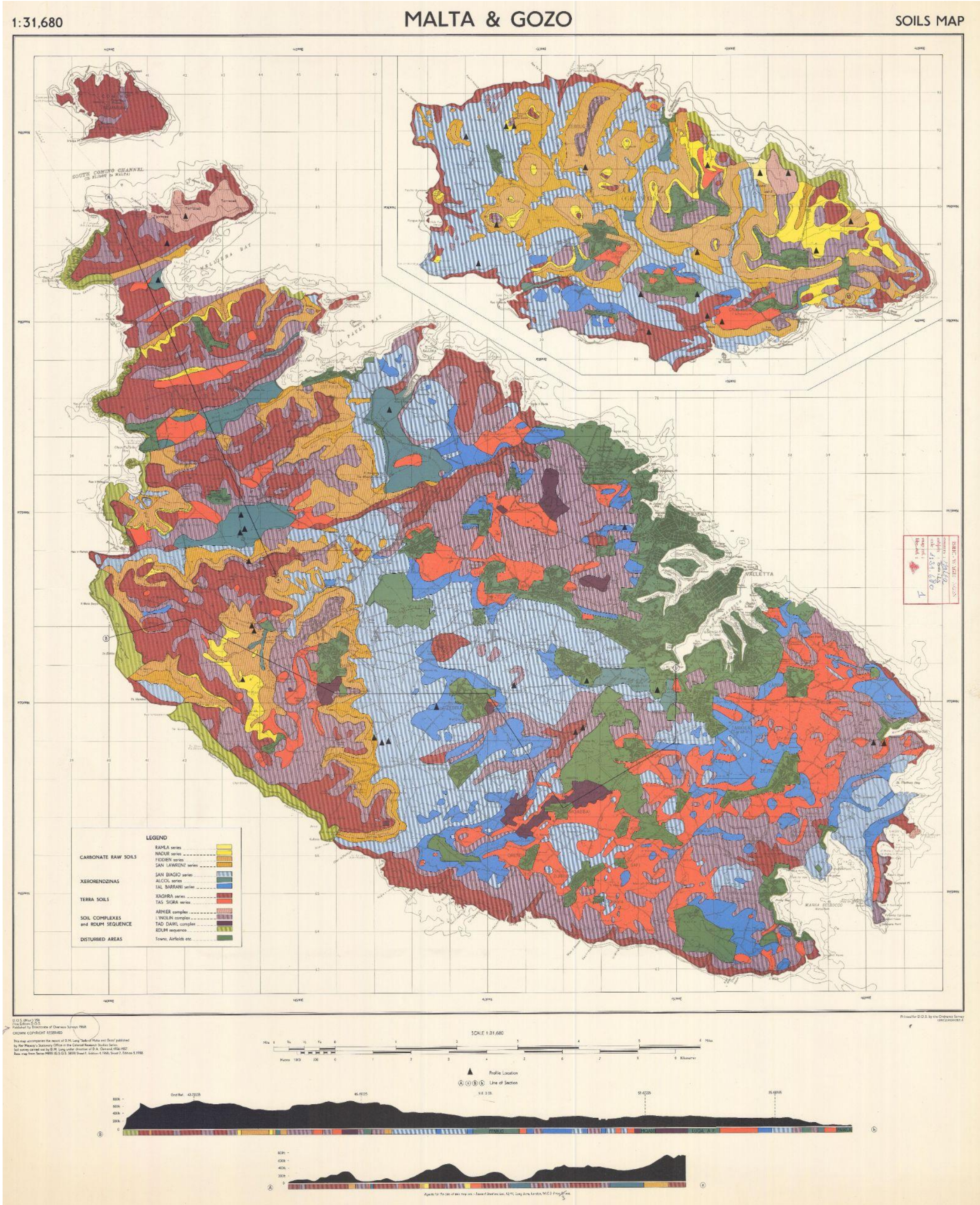


Figure 3.8 | Maltese Islands soil map with different soil types (Lang & Osmond, 1960)

Figure 3.9 | The five soil sample collection sites in the south of Malta

Local farmers were consulted to obtain access and contextual information regarding the selected fields. The study was designed to assess soil temperature, moisture, colour and texture, aiming to investigate the relationship between soil temperature and moisture and various physical soil parameters (*Steps 11 & 12 – Figure 3.3*). Soil temperature was measured on-site using a thermometer (*Appendix 2*), while soil colour was assessed using the Munsell chart (*Figure 3.10*).

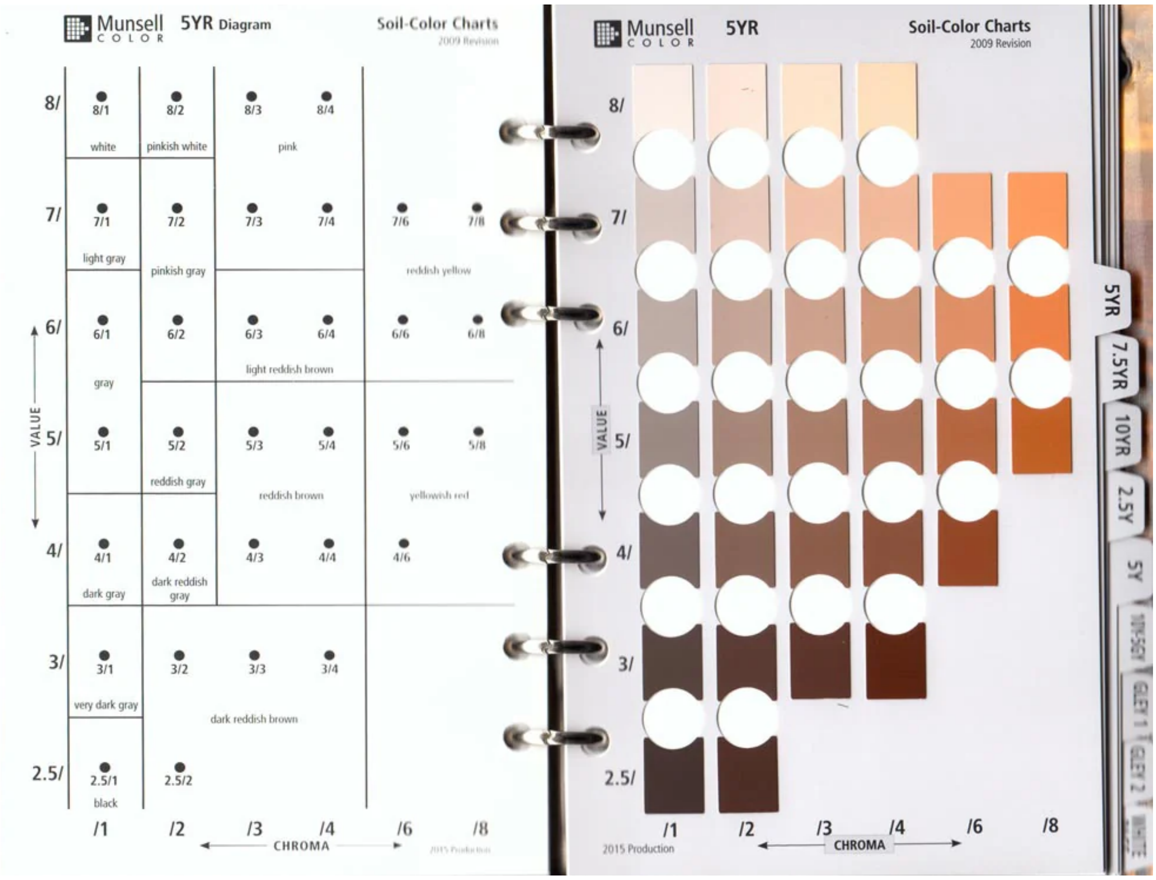


Figure 3.10 | Munsell chart in the soil colour book (NZ Soils, n.d.)

Three soil samples were obtained from each field for laboratory analysis to determine soil texture and moisture (*Figure 3.11*). The procedure for calculating soil moisture involved weighing the collected wet soil sample using a balance, heating it at 105°C for 2 h in an oven, re-weighing the sample to obtain its dry mass and then using the equation $\frac{wet\ mass - dry\ mass}{wet\ mass}\ x\ 100$ to obtain the moisture percentage in the soil. The average of the three soil samples (*Figure 3.16*) from each field was then calculated to determine the final moisture value (*Appendix 2*).

Figure 3.11 | The three soil samples for the five selected fields after weighing

Soil texture was assessed for the sampled sites using the hydrometer method (Van Reeuwijk, 2002), a reliable technique in laboratory settings commonly employed in soil science research. The process began by sieving and weighing the soil sample. A mixture of 20g of soil, 400ml of water and 20ml of sodium hexametaphosphate, which is the dispersing agent, was shaken at 80 rpm for 16 h. The resulting suspension was poured through a 62 μm sieve, separating the sand fraction, which was collected in a separate dish and dried in an oven. The percentage of sand was then calculated. The remaining silt-clay suspension that passed through the sieve was transferred to a measuring cylinder filled with water up to 1000 ml and placed in a water bath. Hydrometer and temperature readings were taken at intervals of 1 min, 5 min, 2 h and 16 h. After 2 h, the silt particles had settled out of suspension and what was left were the clay particles. According to Stoke's Law, sand particles quickly settle out of suspension, silt particles stay suspended longer before eventually settling and clay particles remain suspended indefinitely. The percentages of sand, silt and clay were then calculated, allowing for soil classification using the textural triangle (Bowen, n.d.).

The soil texture for the rest of the Maltese Islands was obtained from Lang & Osmond's (1960) soil survey, based on their detailed soil classification map. This data was further validated by the findings of Spiteri & Sacco (2024). This soil texture data was used to assess how it affects LST and TVSDI patterns across the islands. The field and laboratory analyses provided ground-truth data that supported the statistical validation of satellite-derived parameters, as outlined in this section (*Step 13 – Figure 3.3*).

3.6 | Statistical tests

Statistical analysis plays a crucial role in scientific studies as it unveils research findings and lends meaning to raw data and numerical information. It is through statistical analysis that researchers can accurately interpret and understand the results of their studies. Utilising appropriate statistical tests ensured the accuracy and reliability of research findings (Ali & Bhaskar, 2016). Statistical analyses were performed to evaluate the relationships between the remotely sensed variables of LST and TVSDI and in-situ soil measurements, thereby addressing the study's research objectives.

The Pearson correlation coefficient was used in this study to look at the correlation between temperature changes using LST, and dryness using the TVSDI index across the Maltese Islands. A linear and multiple regression analysis was performed for LST and TVSDI as well to test whether LST affected TVSDI and vice versa and to test if these parameters change seasonally. The two-way ANOVA is a parametric statistical test used to determine whether there are significant differences in the mean values of a continuous dependent variable across the levels of two categorical independent variables, as well as to identify any interaction between these factors (Sueriman & Mangera, 2020). Regression modelling extends beyond correlation by estimating how changes in an independent variable influence a dependent variable, allowing for the prediction of one variable from another (Ali & Younas, 2021).

Spatial and temporal analysis of the data was conducted using the Moran's I and Mann-Kendall test respectively. Moran's I, a widely used measure of spatial autocorrelation, was applied to quantify the degree to which similar values cluster spatially across the raster grid (Vazquez-Luna et al., 2025). The analysis was conducted by defining a neighbourhood search radius around each raster cell, allowing the computation of local and global Moran's I statistics. Positive values of Moran's I indicate clustering of similar values, negative values indicate spatial dispersion and values near zero indicate random spatial patterns. The significance of the observed autocorrelation was assessed using the corresponding z-scores and p-values (Yamada, 2024). The Mann-Kendall test was used to determine the presence of trends and their magnitude. The null hypothesis specified that there is no trend in LST and TVSDI data from 2015 to 2024 and was accepted if the p-value exceeded the 0.05 level of significance. The alternative hypothesis specified that there is a trend present in LST and TVSDI from 2015 to 2024 and was accepted if the p-value was less than the 0.05 level of significance.

Finally, the impact of changing soil temperatures and soil moisture on the TVSDI index during the 2024 study period was examined through statistical correlation tests and regression analyses.

This approach enabled a detailed exploration of the interdependencies among the different soil properties, thereby contributing valuable insights into the dynamics of soil behaviour and its potential environmental implications in the Maltese Islands. The statistical tests also provided insights into spatial and temporal variability across the datasets. However, several methodological limitations were encountered during the process, as discussed in the next section.

3.7 | Limitations

Several constraints were inherent to the methodology of this study. Variability in the availability and quality of satellite data occurred due to factors like cloud cover, sensor resolution and temporal coverage. Some dates had to be eliminated due to this. Furthermore, data gaps were also present in some maps due to some cloud cover.

Since the satellite overpass dates for 2024 were selected using Landsat 9 at the start of the study, Landsat 8 data could not be used for 2024 due to software limitations. The program used to calculate LST at 30 m resolution in Celsius was compatible only with Landsat 8 or earlier satellites, making it unusable for the 2024 maps. Consequently, the MODIS dataset had to be selected for 2024, which had a coarser 1 km resolution. This lower resolution limited the ability to capture fine-scale spatial patterns for that year.

Additionally, processing satellite data was labour-intensive, demanding significant time investment. Proficiency in remote sensing, GIS and image calibration and processing techniques was required for effectively utilising GIS software and processing satellite data, as lacking expertise in these areas might have led to errors in data processing or misinterpretation of data.

Despite these constraints, the adopted methodology provided reliable and consistent datasets for analysis. The following chapter presents the results derived from the application of these methods, highlighting spatial and temporal trends in surface temperature and dryness across the Maltese Islands.

Chapter 4: Results

Following the description of the methodological framework and data acquisition processes in Chapter 3, this chapter presents and interprets the key results derived from the analysis. The findings were organised thematically, covering spatial and temporal patterns of LST and TVSDI across the Maltese Islands between 2015 and 2024. Statistical analyses were also performed to explore relationships among soil temperature, soil moisture and the dryness index. The Maltese Islands were divided into districts and the maps were masked out to eliminate urban areas, ensuring more precise analysis. Furthermore, some maps contained data gaps due to extensive cloud cover in the data, since remotely sensed optical data is not achievable whenever extensive cloud cover is present on the ground. Together, these results provided a comprehensive overview of the land surface temperature and the resultant soil moisture characterising the Maltese landscape, which comprises agricultural sites, semi-natural and garrigue areas as well as exposed rocky areas.

4.1 | Land Surface Temperature maps

The spatial and temporal variations of LST across the Maltese Islands were analysed for both wet and dry seasons between 2015 and 2024 (*Figure 4.1*). Variations in LST are evident across the Maltese Islands throughout the 2015–2024 study period. Wet-season LST values were consistently lower than dry-season LST values, reflecting expected climatic seasonality. Despite this overall pattern, the magnitude of warming differed between districts.

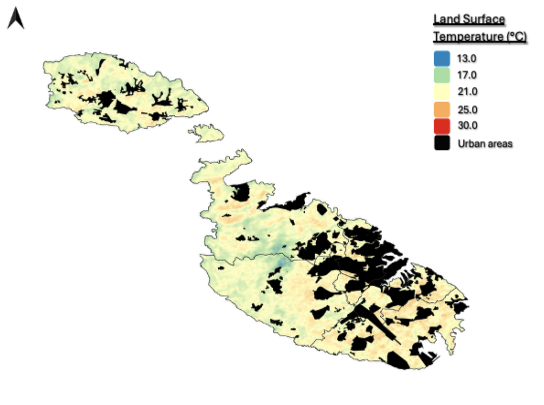
In most years, the Southern Harbour, South Eastern and Northern Harbour districts showed the highest wet-season LST values, frequently exceeding those of the Gozo, Western and Northern districts (*Appendix 3*). For example, in 2015, wet-season LST peaked at 21.9°C in the South Eastern and Southern Harbour districts, while the Western district recorded a lower mean of 20.1°C (*Figure 4.1 - a & b*). Conversely, Gozo and the Western district generally exhibited cooler wet-season values, reflecting their relative rural character, the presence of clayey soils and underlying perched aquifers.

Across all study years, Comino consistently registered lower LST values relative to the main islands, maintaining cool to moderate temperatures throughout both wet and dry seasons. This stability is likely due to its limited built-up extent and the cooling influence of surrounding maritime conditions.

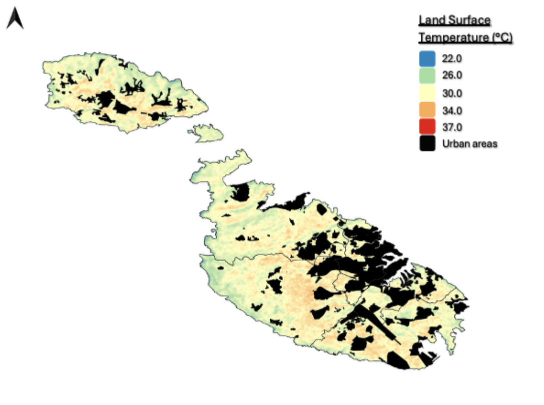
During the dry season, district-level disparities were more pronounced. The South Eastern, Western and Southern Harbour districts recorded the highest dry-season LST values when compared with the districts of Gozo, Northern and Northern Harbour. In 2019, dry-season LST peaked in the Southern Harbour district at 31°C, exceeding Gozo's 30.1°C (*Figure 4.1 - j*). These findings demonstrate that urban districts experience amplified warming during the dry months. These findings were consistent across all years except for 2016, 2019, 2020, 2023 and 2024 (*Figure 4.1 - b, f, h, n* & *p*).

Marked interannual variability was also observed. Years such as 2015 and 2022 were notably warmer, with wet-season LST values reaching 21.9°C and 23.1°C respectively (*Figure 4.1 - a & o*) across several mainland districts and dry-season temperatures exceeding 33°C in 2021 for almost all districts (*Figure 4.1 - n*). This suggests that even wetter years may experience thermal anomalies under specific atmospheric and land cover conditions, therefore leading to reduced soil moisture retention. The 2024 dry season stands out as one of the warmest, with LST values exceeding 33°C in Gozo, Northern Harbour, South Eastern, Southern Harbour and Western districts, with a peak of 34°C recorded in the South Eastern district (*Figure 4.1 - t*). These exceptionally high values indicate strong warming trends consistent with regional heatwave activity.

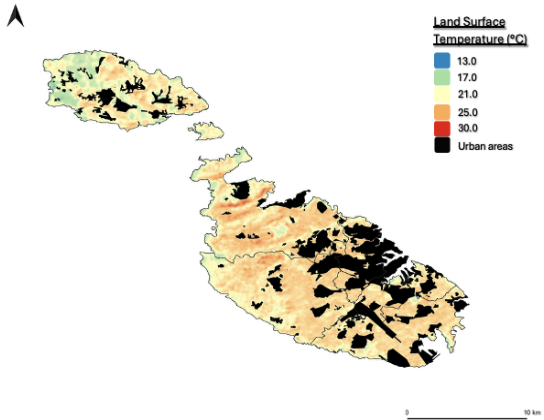
Overall, the district-level analysis reveals a clear spatial pattern. Gozo and the Western district remain comparatively cooler, especially in the wet season, while Southern and South-Eastern districts consistently exhibit the highest temperatures, particularly during the dry season (*Appendix 3*). This spatial consistency suggests that coastal heat dynamics, hydrologically active and clay-rich zones and land surface vegetative cover strongly modulate LST across the Maltese Islands.



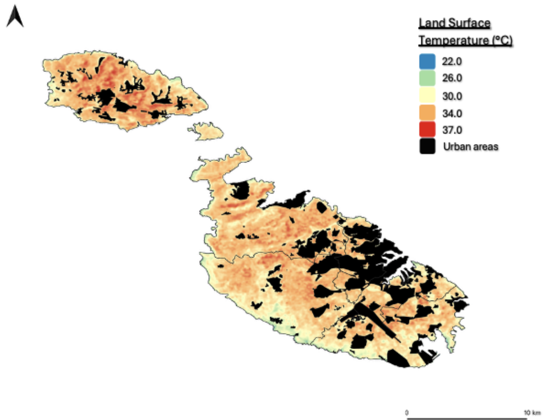
(a)
Wet 2015 LST map



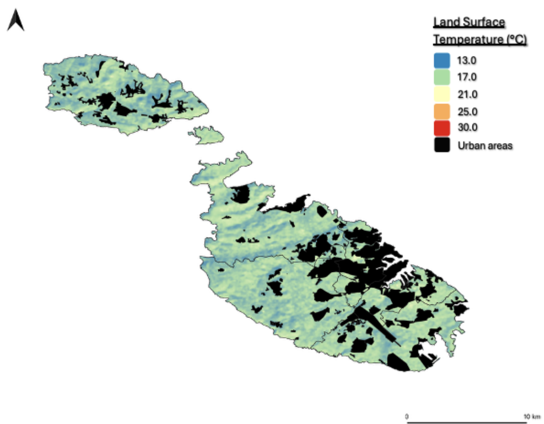
(b)
Dry 2015 LST map



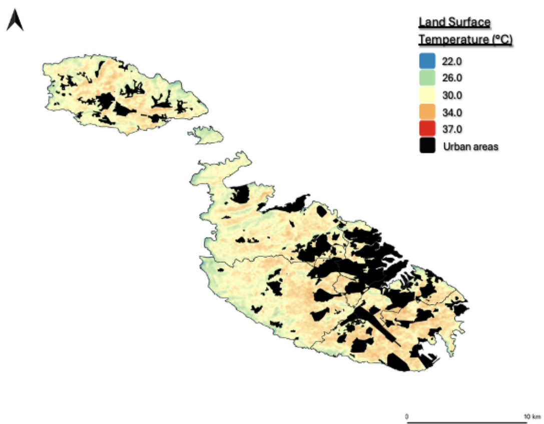
(c)
Wet 2016 LST map



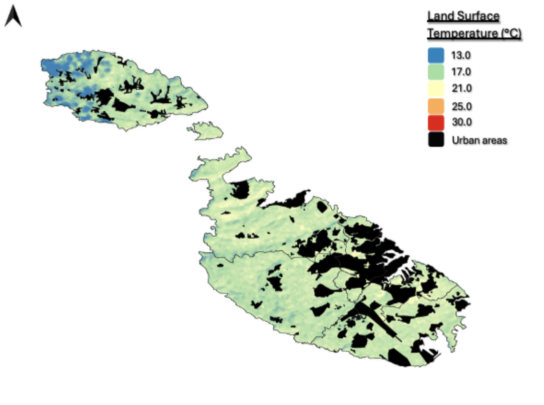
(d)
Dry 2016 LST map



(e)
Wet 2017 LST map

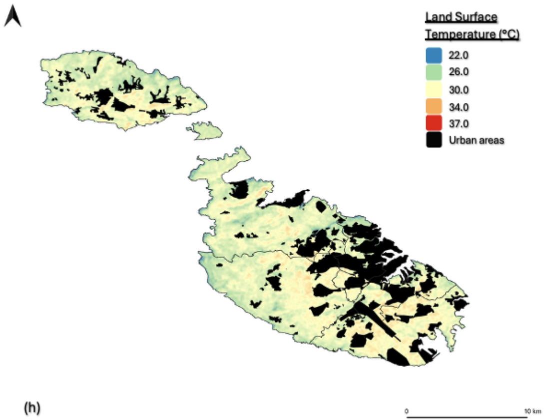


(f)
Dry 2017 LST map



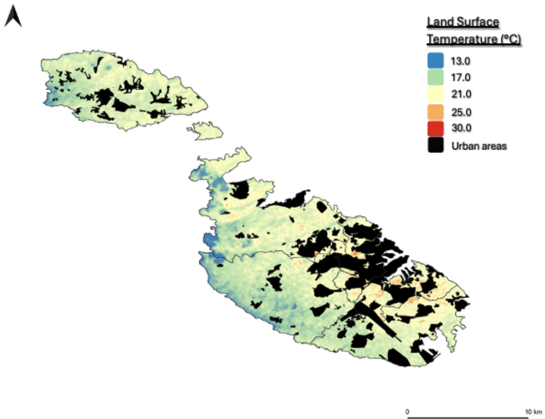
(g)

Wet 2018 LST map



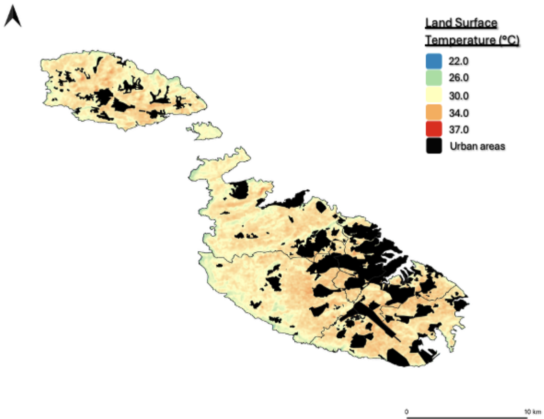
(h)

Dry 2018 LST map



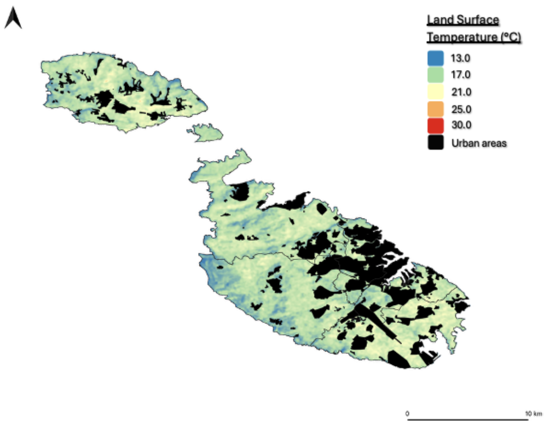
(i)

Wet 2019 LST map



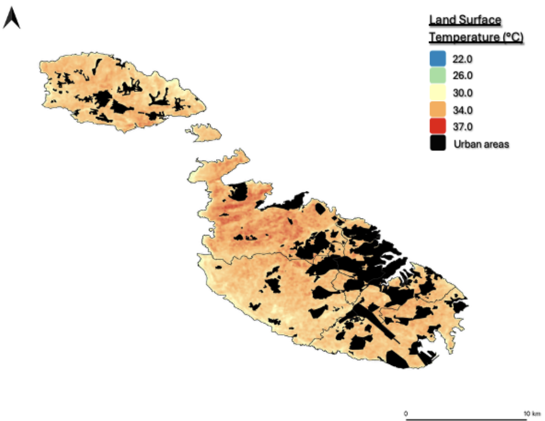
(j)

Dry 2019 LST map



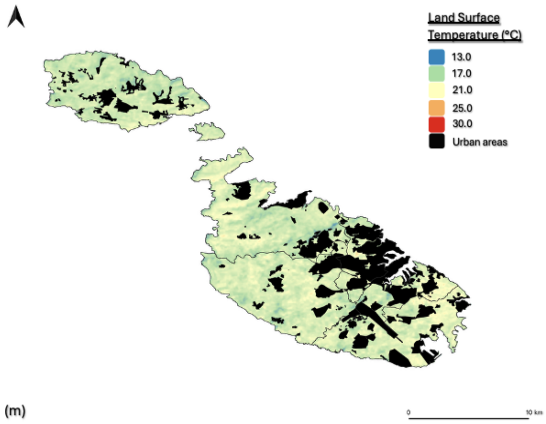
(k)

Wet 2020 LST map



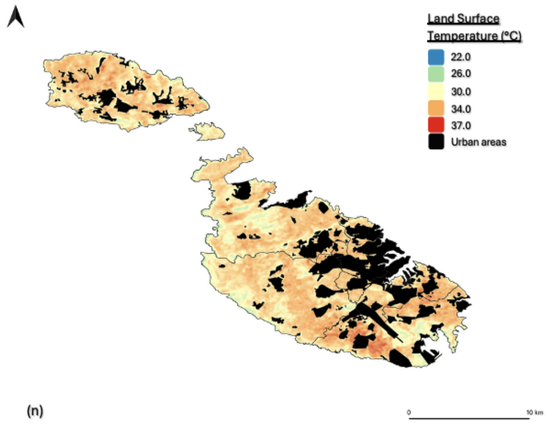
(l)

Dry 2020 LST map



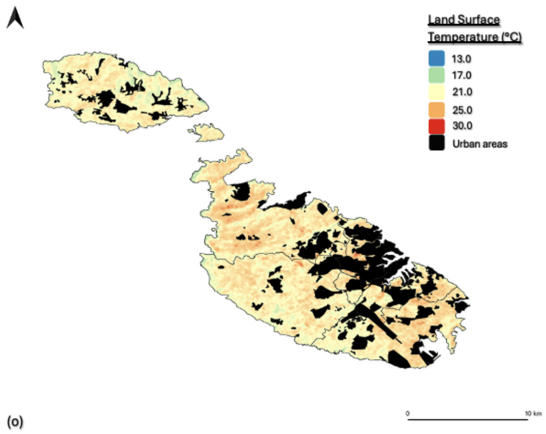
(m)

Wet 2021 LST map



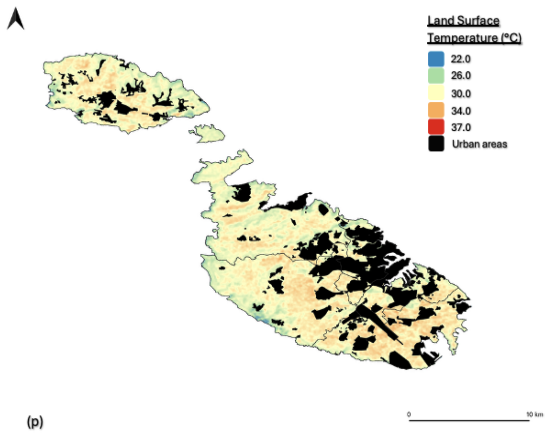
(n)

Dry 2021 LST map



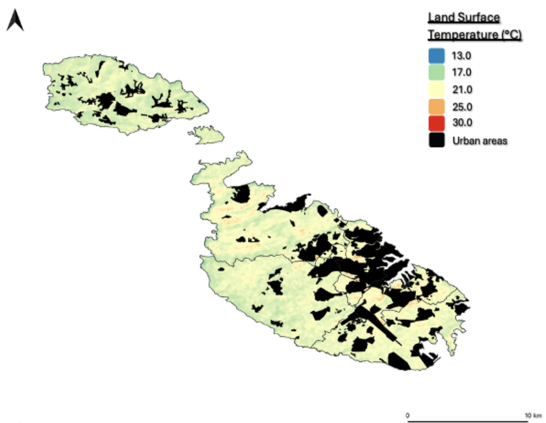
(o)

Wet 2022 LST map



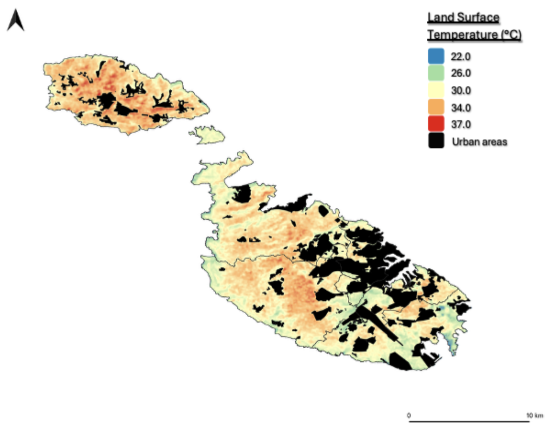
(p)

Dry 2022 LST map



(q)

Wet 2023 LST map



(r)

Dry 2023 LST map

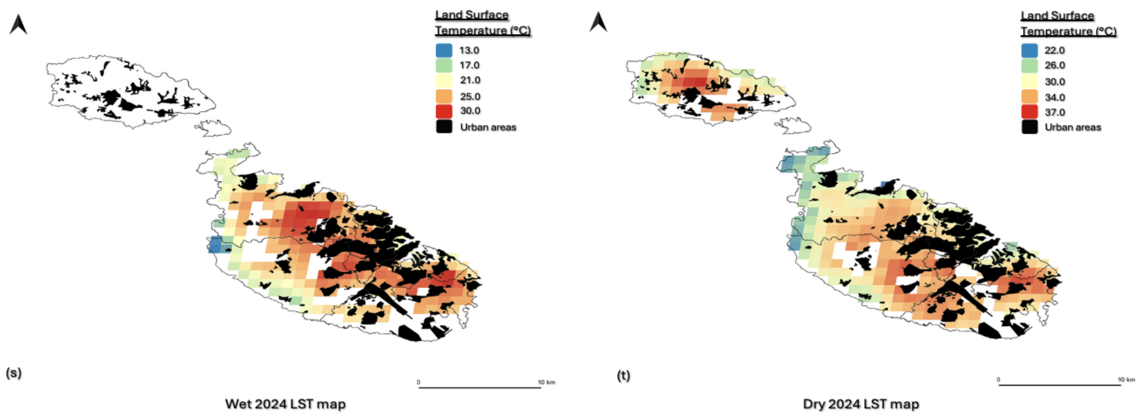


Figure 4.1 | LST maps illustrating spatial distribution of LST during the wet and dry seasons across the Maltese Islands from 2015 to 2024

4.2 | Temperature Vegetation Shortwave Dryness Index maps

In the following section, TVSDI maps for the wet and dry seasons of the Maltese Islands from 2015 to 2024 were presented (*Figure 4.2*). TVSDI values ranged from 0 (near-normal soil conditions) to 1 (extreme soil dryness), following the classification by Xu et al. (2022). The index was calculated using three key variables: LST, EVI and SWIR. A green to red colour gradient was chosen, with dark green representing areas of normal soil dryness, yellow signifying areas of moderate soil dryness and bright red representing extreme dryness, typically characterised by high gravel content.

TVSDI values across the Maltese Islands show relatively limited district variability during the wet seasons but noticeably greater differences during the dry seasons. In the wet season, TVSDI values remained consistently within a narrow range (typically 0.52–0.55), demonstrating uniform soil moisture conditions across districts despite differences in land cover (*Figure 4.2 – a, c, e, g, i, k, m, o, q & s*). Even in years with unusually warm wet seasons, such as 2020 (*Figure 4.2 – k*), TVSDI values remained tightly clustered, indicating that winter rainfall effectively homogenises soil moisture conditions across the islands.

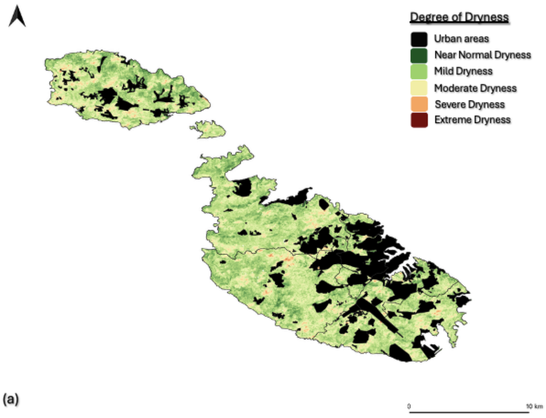
In general, dry season maps displayed a wider extent of moderate to severe soil dryness, while wet season maps were dominated by near-normal to mild soil dryness levels. Nonetheless, certain locations repeatedly stood out as dryness hotspots, including the Marsa and Gozo horse tracks and barren coastal terrains in Qala, southwestern Gozo and Marfa Ridge in Armier (*Figure 4.2 - b*). These areas correspond closely with low-vegetation and high-exposure environments, often composed of bare rock or disturbed soil.

Dry-season TVSDI values reveal more visible spatial gradients (Figure 4.2 – b, d, f, h, j, l, n, p, r & t). Districts such as South Eastern, Western and Gozo regularly exhibited the highest dryness values. For instance, in 2016, both the South Eastern and Western districts recorded higher TVSDI values, indicating drier soil conditions relative to Northern Harbour and Southern Harbour (Figure 4.2 - d). This pattern is likely driven by the more agricultural and semi-natural land uses in the South Eastern and Western regions, which expose soils to direct solar radiation, as well as the karstic geomorphology that reduces moisture retention.

The Northern Harbour and Southern Harbour districts tended to display slightly lower TVSDI values in most dry seasons, corresponding to near-normal soil dryness conditions (Appendix 3). This suggests shaded areas and mixed land-use mosaic, such as urban gardens, which may help moderate soil dryness during summer months. This also confirms the link between surface temperature moderation and soil moisture retention.

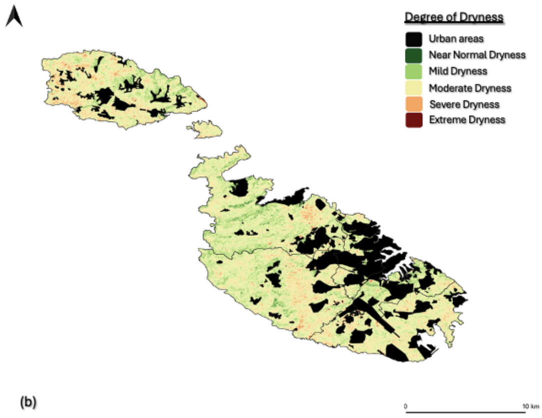
Notably, the 2024 dry season showed the highest TVSDI values across the entire dataset (Figure 4.2 – t), with Gozo, Northern and South Eastern districts all reaching 0.65, and other districts ranging from 0.62–0.65. This indicates the driest conditions recorded in the study period and aligns with the exceptionally high LST values detected during the same season. The strong concurrence of high LST and high TVSDI in 2024 suggests an intensified summer drought in line with ongoing climate warming trends.

Overall, TVSDI spatial patterns demonstrate that while wet-season moisture conditions remain relatively uniform, dry-season dryness was consistently highest in the South Eastern, Western and Gozo districts and lowest in the more urbanised harbour districts. This indicates that land cover and exposure play a critical role in shaping soil and vegetation moisture stress during the warm season.



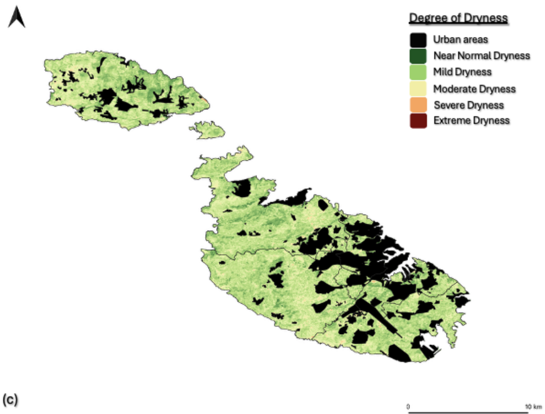
(a)

Wet 2015 TVSDI map



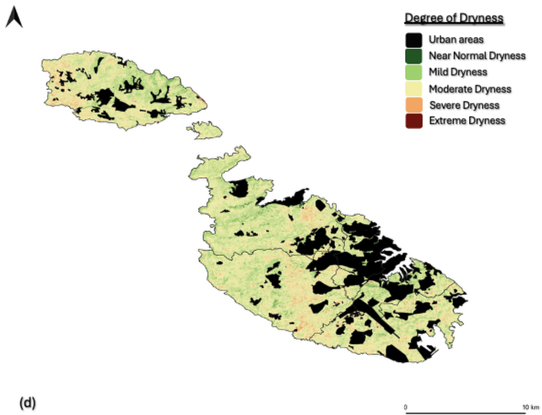
(b)

Dry 2015 TVSDI map



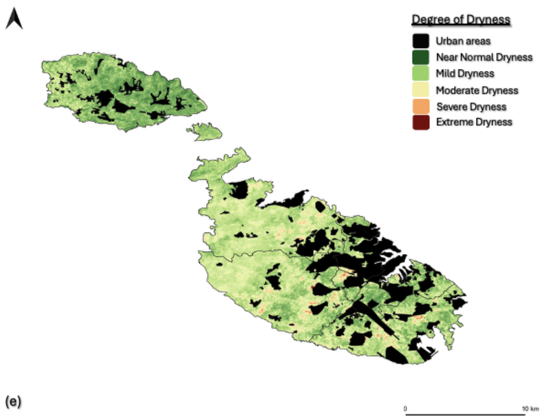
(c)

Wet 2016 TVSDI map



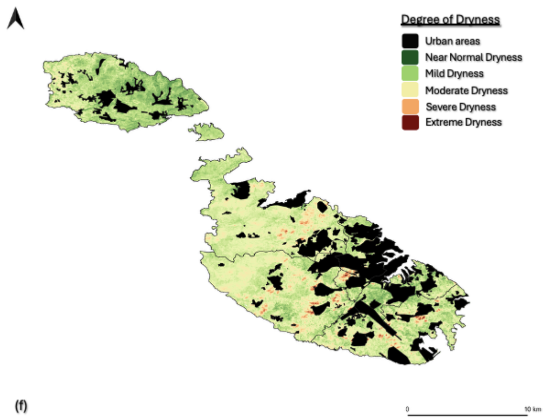
(d)

Dry 2016 TVSDI map



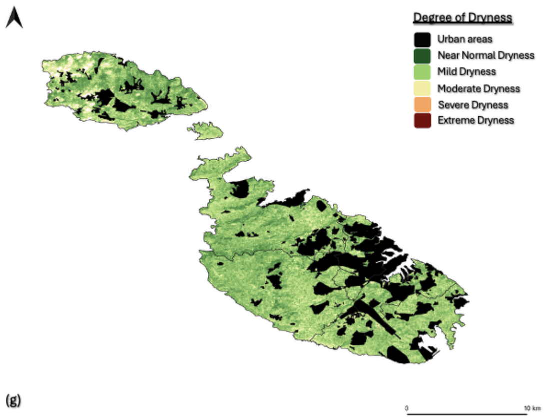
(e)

Wet 2017 TVSDI map



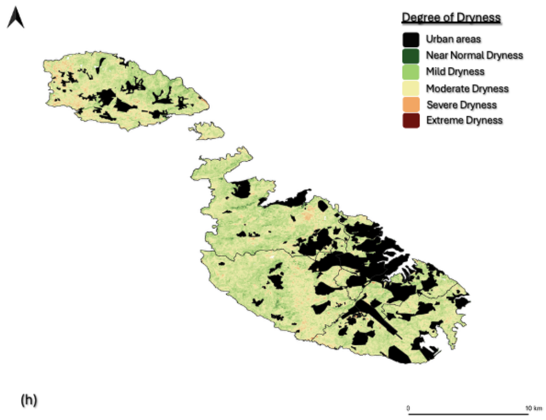
(f)

Dry 2017 TVSDI map



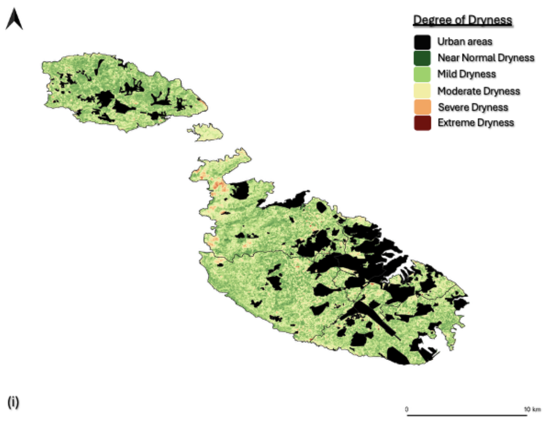
(g)

Wet 2018 TVSDI map



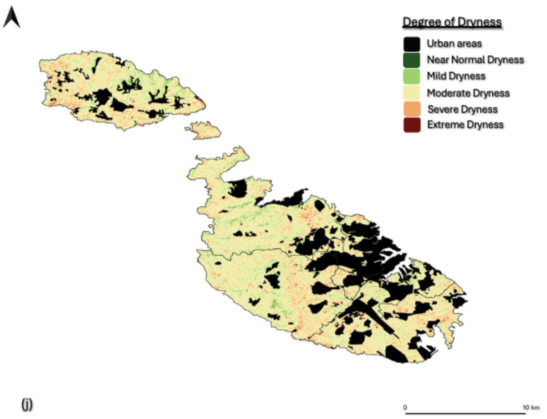
(h)

Dry 2018 TVSDI map



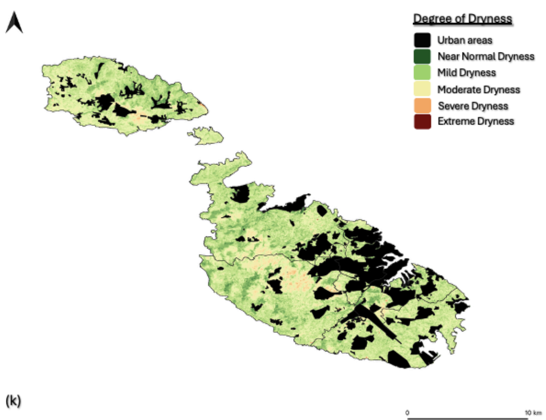
(i)

Wet 2019 TVSDI map



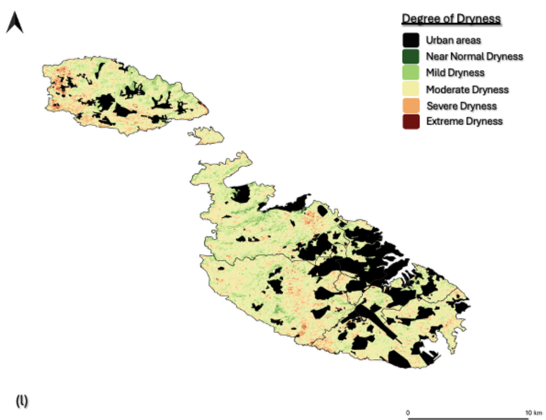
(j)

Dry 2019 TVSDI map



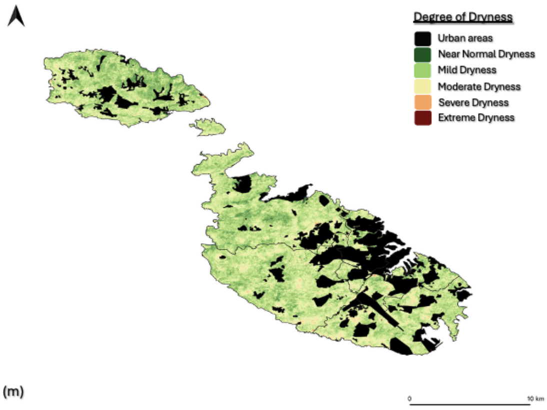
(k)

Wet 2020 TVSDI map

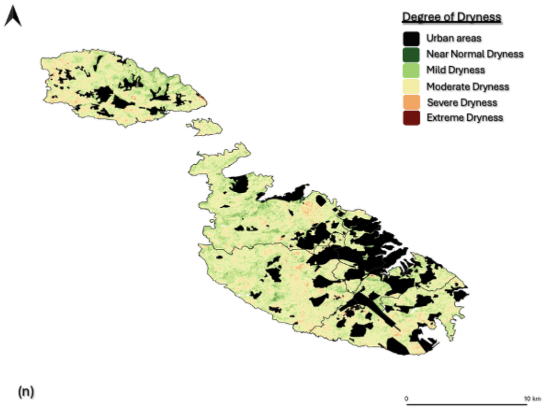


(l)

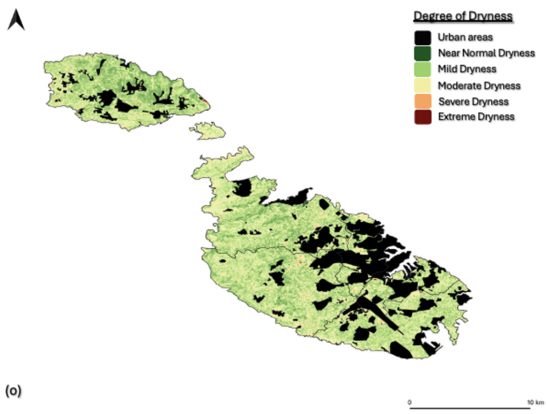
Dry 2020 TVSDI map



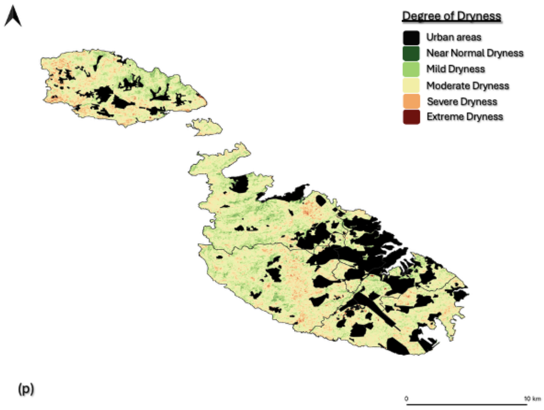
Wet 2021 TVSDI map



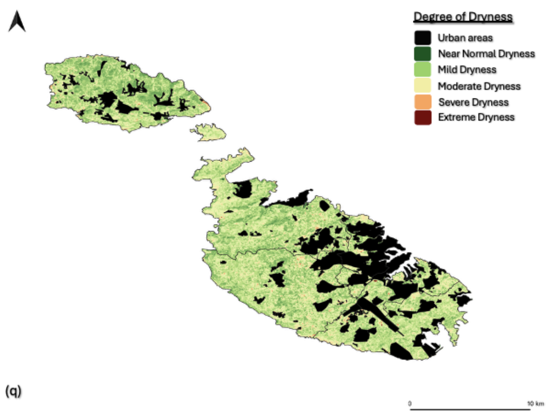
Dry 2021 TVSDI map



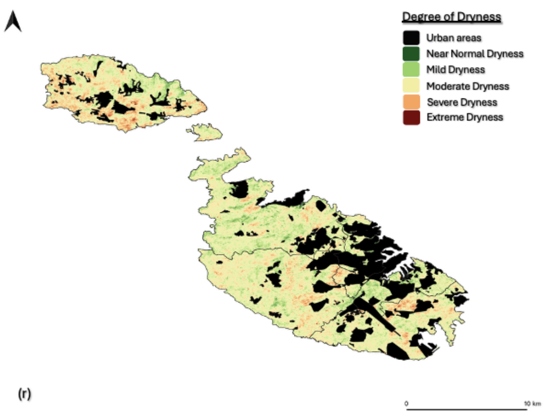
Wet 2022 TVSDI map



Dry 2022 TVSDI map



Wet 2023 TVSDI map



Dry 2023 TVSDI map

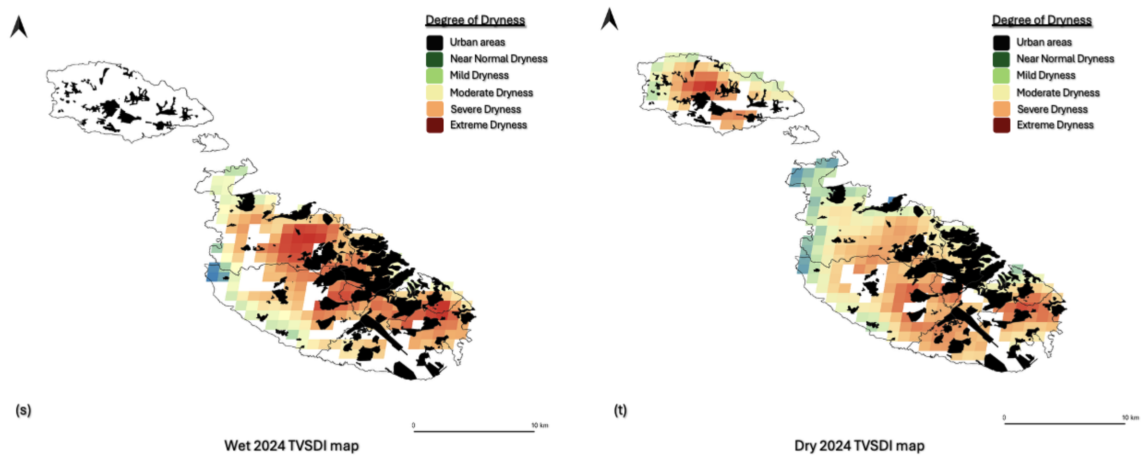


Figure 4.2 | TVSDI maps illustrating spatial patterns of wet and dry season dryness conditions across the Maltese Islands for each year from 2015 to 2024

Taken together, the LST and TVSDI patterns reflected an increasingly complex interaction between climatic variability, land cover and geomorphology across the Maltese Islands. Across all districts, higher LST values in the dry season consistently coincided with elevated TVSDI, indicating that temperature increases contributed to, and likely accelerated, soil moisture depletion. The relationship between incoming radiation, the thermal capacity and conductivity of soil also influenced how quickly soil surfaces heat and cool, thereby intensifying local thermal gradients and amplifying LST contrasts. The observed peaks in 2016, 2020 and 2022 (*Figure 4.1 - c, d, k, o & p*), where anomalously warm dry seasons aligned with highest TVSDI values, coincided with years of regional heatwaves and prolonged dry spells, suggesting that climate-driven anomalies were superimposed on enduring landscape controls. Conversely, the resilience of cooler, moister regions underscored the importance of soil texture, aquifer recharge zones and vegetation density in mitigating thermal extremes. These spatial and temporal trends highlighted a gradual shift toward greater surface temperature variability and episodic dryness, consistent with Mediterranean climate intensification and heightened drought frequency projected under ongoing climate change scenarios.

Spatially, the interaction between LST and TVSDI varied across districts. The South Eastern, Western and Gozo districts routinely exhibited both high dry-season LST and high TVSDI values, marking them as hotspots of surface drying and thermal stress. These areas were characterised by extensive agricultural land, exposed soils and open terrain, all of which enhanced surface heat absorption and promoted moisture loss. In contrast, the Northern Harbour and Southern Harbour districts typically experienced the highest LST values due to dense urbanisation but displayed slightly lower TVSDI values than more rural districts. This suggests that while urban surfaces heat more intensely, factors such as vegetation pockets, water-retentive landscaping and reduced exposed soil may moderate soil dryness.

2024 stood out as a year of amplified thermal and moisture stress, with dry-season LST values surpassing 33°C in several districts and TVSDI values representing severe dryness. This convergence of high temperature and dryness in the same year indicated heightened sensitivity of Maltese soils to warming trends. Conversely, cooler and wetter years demonstrated uniformly lower LST and TVSDI values, illustrating the responsiveness of soil moisture to comparatively mild conditions. Therefore, the combined results showed that temperature fluctuations exerted a direct influence on soil moisture, with the

Maltese Islands exhibiting interdependence between thermal conditions and soil dryness, particularly when climatic stressors are strongest.

To validate these satellite-derived indices and better understand their relationship with physical soil parameters, complementary field and laboratory analyses were undertaken, as discussed in the last section.

4.3 | Statistical tests

4.3.1 | Correlation between LST and TVSDI

To examine the relationship between LST and TVSDI in the different districts, a Pearson correlation analysis was conducted. This test quantified the strength and direction of association between temperature and dryness and provided a correlation coefficient ranging from –1 to +1, where values closer to either extreme indicate stronger linear relationships. By applying Pearson's correlation separately for the wet and dry seasons, temporal variations in the LST - TVSDI relationship were also explored.

The correlation results indicated that the relationship between LST and TVSDI varied in strength across districts but was consistently positive and statistically significant (*Table 4.1*). The Gozo, South Eastern and Western districts exhibited the strongest correlations, suggesting that increases in LST were closely associated with increases in soil dryness as captured by TVSDI in these areas. This implied that these districts are more sensitive to temperature-driven changes in soil dryness conditions. The Northern and Northern Harbour districts showed moderate correlations, indicating a meaningful but less pronounced linkage between LST and soil dryness, potentially reflecting differences in soil characteristics. The Southern Harbour district displayed the weakest correlation, though the relationship remained statistically significant, suggesting that additional environmental, hydrological or anthropogenic factors might have influenced soil dryness in this district and how it responds to temperature increases. Overall, the results highlighted district-level variability but confirmed a clear and significant association between rising surface temperatures and increasing soil dryness throughout the study area.

Table 4.1 | Correlation between LST and TVSDI

District	LST-TVSDI correlation	Significance level	p-value
Gozo	0.866	0.05	<0.001
Northern	0.568	0.05	0.009
Northern Harbour	0.551	0.05	0.012
South Eastern	0.803	0.05	<0.001
Southern Harbour	0.468	0.05	0.037
Western	0.763	0.05	<0.001

The correlation between LST and TVSDI was further analysed for both the wet and dry seasons. Correlation analysis for the wet season (*Table 4.2*) indicated that the relationship between LST and TVSDI across districts was generally weak, with Gozo being the only district exhibiting a statistically significant correlation. Gozo showed a strong positive correlation, suggesting that even during the wet season, when moisture conditions are typically uniform, higher surface temperatures in Gozo were still associated with increased dryness. This implied that Gozo's soil moisture conditions remained sensitive to temperature fluctuations throughout the year, likely reflecting the district's more exposed rural landscapes, less urban interference and greater agricultural continuity. All other districts displayed very weak and statistically insignificant correlations. The Northern district recorded a slightly negative relationship, indicating no meaningful association between temperature and dryness during the wet season. Similarly, the Northern Harbour and Southern Harbour districts showed minimal correlations, suggesting that factors other than temperature, such as rocky limestone substrates, shallow soils or higher soil sealing dominate moisture dynamics in the more urbanised areas. The South Eastern and Western districts displayed moderate but non-significant positive correlations, implying a tendency for LST increases to align with higher dryness, though not strongly enough to be statistically reliable.

Overall, the wet-season correlations demonstrated that temperature has limited influence on soil–vegetation dryness during winter, except in Gozo where the relationship remained pronounced. This supports the earlier finding that wet season moisture conditions across the Maltese Islands are largely homogeneous and driven primarily by rainfall rather than thermal variability.

Table 4.2 | Correlation between LST and TVSDI for the wet season

District	LST-TVSDI correlation for the wet season	Significance level	p-value
Gozo	0.704	0.05	0.034
Northern	-0.101	0.05	0.780
Northern Harbour	0.115	0.05	0.751
South Eastern	0.366	0.05	0.298
Southern Harbour	0.100	0.05	0.783
Western	0.259	0.05	0.470

Correlation results for the dry season (*Table 4.3*) revealed a consistently strong and predominantly significant positive relationship between LST and TVSDI across the districts of the Maltese Islands, indicating that higher surface temperatures were closely linked to increased soil dryness during the dry season. This represented a clear contrast to the weak and mostly non-significant correlations observed during the wet season, demonstrating that temperature exerted a much stronger influence on soil moisture under dry-season conditions. All districts exhibited moderate to strong positive correlations, with several having a statistical significance at the 0.05 level. The strongest significant correlation was in the Southern Harbour district, indicating that as surface temperatures rose in this highly urbanised region, soil dryness intensified markedly. Similarly strong and significant correlations occurred in the Gozo, Western, South Eastern and Northern Harbour districts. These results showed that the relationship between thermal conditions and moisture was robust across both rural and urban districts during the dry season. Only the Northern district exhibited a moderate but statistically non-significant correlation, suggesting that although higher temperatures were still associated with increased dryness, the relationship was less consistent. This weaker response may reflect higher vegetation cover relative to other regions.

Table 4.3 | Correlation between LST and TVSDI for the dry season

District	LST-TVSDI correlation for the dry season	Significance level	p-value
Gozo	0.767	0.05	0.010
Northern	0.525	0.05	0.119
Northern Harbour	0.696	0.05	0.025
South Eastern	0.713	0.05	0..021
Southern Harbour	0.779	0.05	0.008
Western	0.739	0.05	0.015

Taken together, these results demonstrated that temperature became a dominant driver of soil dryness during the dry season, with most districts showing a strong and statistically significant LST-TVSDI association. The widespread increase in correlation strength from wet to dry season highlighted the heightened vulnerability of Maltese soils to warming during summer, when reduced rainfall and stronger solar radiation amplify the drying effect of elevated surface temperatures.

While the correlation analysis provided preliminary evidence of the temperature - dryness association, a two-way ANOVA test was subsequently applied to explore whether these relationships varied by district and season.

<u>4.3.2 | Influence of season on LST and TVSDI</u>

To assess the combined influence of spatial and seasonal factors on LST and the TVSDI, a two-way analysis of variance (ANOVA) was employed. In this study, the two-way ANOVA was chosen since it allows for the simultaneous examination of both district and seasonal effects on LST and TVSDI. This method was particularly suitable for evaluating environmental datasets where multiple categorical factors may influence a continuous outcome. By applying this test, it was possible to determine whether surface temperature and dryness varied significantly between seasons, among districts and whether the effect of one factor depended on the other.

An R squared of 0.839 indicated that the two-way ANOVA model explained 83.9% of the variation in LST (*Table 4.4*). Since the p-value of the model was <0.001, this meant that the model was overall highly significant. District recorded a p-value of 0.934, indicating that there was no significant difference in LST between the districts. Season, however, recorded a p-value of <0.001, indicating that LST differed significantly between the wet and the dry seasons since the p-value was less than the 0.05 level of significance. District and season had no significant correlation, meaning that they did not have an influence on each other. From this, one can conclude that seasonality, not the districts, drive temperature differences across the Maltese Islands, since LST values are much higher in the dry season than in the wet season.

Table 4.4 | Two-way ANOVA test results for LST

Source	F	Significance
District	0.259	0.934
Season	556.908	**<0.001**
District x Season	0.321	0.899

R squared = 0.839 (Adjusted R squared = 0.823)

An R squared of 0.436 indicated that the two-way ANOVA model explained 43.6% of the variation in TVSDI (*Table 4.5*). Since the p-value of the model was <0.001, this meant that the model was overall highly significant. Since the p-value of the district was greater than the 0.05 level of significance, this meant that there was no significant difference in TVSDI between the different districts. Season recorded a p-value of <0.001, suggesting that TVSDI had a statistically significant relationship with season. In fact, TVSDI was significantly higher in the dry season. District did not have a significant relationship that affected TVSDI. In conclusion, TVSDI was significantly higher in the dry season but did not differ meaningfully between the districts, therefore suggesting that dryness was mainly influenced by seasonal changes not by location. To further quantify these relationships and assess predictive capabilities, regression models were developed.

Table 4.5 | Two-way ANOVA test results for TVSDI

Source	F	Significance
District	1.685	0.144
Season	65.968	**<0.001**
District x Season	1.770	0.125

R squared = 0.436 (Adjusted R squared = 0.378)

4.3.3 | Regression model

To quantify the predictive relationship between variables such as LST, TVSDI, district and season, simple and multiple linear regression analyses were performed. A multiple regression model was developed to assess the combined effects of LST, district and season, as well as potential interaction effects between these factors. This approach enabled the identification of both spatial and seasonal influences on surface dryness while isolating the contribution of temperature. Collectively, these statistical tests provided a robust framework for quantifying and interpreting the spatial-temporal dynamics between land surface temperature and vegetation-soil dryness across Malta.

An R square value of 0.449 indicated that LST explained about 44.9% of the variation in TVSDI (*Table 4.6*). The remaining 55.1% must be explained by other factors, such as vegetation, soil type and soil moisture. The model was also significant since the p-value was less than the 0.05 level of significance (<0.001).

Based on the parameter estimates obtained from the simple linear regression, the relationship between LST and TVSDI can be expressed as:

$$\boldsymbol{TVSDI = 0.474 + 0.004(LST)}$$

This indicates that for every 1°C increase in LST, the predicted TVSDI increases by 0.004 units. The intercept represents the expected TVSDI when LST is equal to 0. From this, one can conclude that there was a significant positive linear relationship between LST and TVSDI, meaning that higher land surface temperatures correspond to higher surface dryness. Higher temperatures accelerate evapotranspiration and reduce soil moisture, which increases TVSDI. However, the moderate R^2 value indicates that other environmental variables, such as vegetation density and irrigation, also influence surface dryness.

Table 4.6 | Simple linear regression between LST and TVSDI

R square	F	Significance	Constant	b
0.449	95.309	**<0.001**	0.474	0.004

The statistically significant model explained 53.6% of the variation in TVSDI (*Table 4.7*). LST was a strong, statistically significant positive predictor of TVSDI since its p-value was less than the 0.05 level of significance (<0.001). District and season did not have a significant effect on TVSDI since their p-values exceeded the 0.05 level of significance. Although seasonal differences in environmental conditions would be expected to influence dryness levels, season was not a significant predictor in this regression model. This may be because LST already captured most of the seasonal variability in soil dryness, leaving little variation for season to explain. Additionally, potential lagged response to soil moisture might have also weakened the direct seasonal effect on TVSDI.

Table 4.7 | Multiple regression model explaining TVSDI

Source	F	Significance
LST	22.777	**<0.001**
District	2.234	0.056
Season	0.630	0.429
District x Season	1.553	0.180

R squared = 0.536 (Adjusted R squared = 0.483)

From the table in Appendix 4, one can again conclude that TVSDI increased by 0.004 units for every 1°C increase in LST. The p-values of district and season were not statistically significant since their p-values all exceeded the 0.05 level of significance. Therefore, LST was the only significant predictor of TVSDI. The parameter season no longer mattered once LST was included since LST already captured seasonal differences in temperature. In conclusion, TVSDI variation across the Maltese Islands was mainly driven by LST.

This test predicted LST using TVSDI (*Table 4.8*). The highly statistically significant model explained 86.8% of LST variation. TVSDI statistically significantly predicted LST since its p-value was less than the 0.05 level of significance. LST was statistically significantly higher in the dry season. Season had a very strong impact on LST, indicating that LST values differ significantly between the seasons. There was also no significant difference among the districts and no interaction between the districts and season.

Table 4.8 | Multiple regression model explaining LST

Source	F	Significance
TVSDI	22.777	**<0.001**
District	0.787	0.561
Season	303.283	**<0.001**
District x Season	0.131	0.985

R squared = 0.868 (Adjusted R squared = 0.853)

From the table in Appendix 5, it can be stated that for every 0.1 increase in TVSDI, LST increased by about 4.1°C. One can also state that the dry season was statistically significantly 8.3°C warmer than the wet season. Overall, LST was strongly predicted by TVSDI and season but not by district. Beyond spatial and seasonal effects, long-term temporal trends were also assessed using non-parametric tests.

Multiple linear regression was also performed to evaluate the influence of topographic and radiative variables on TVSDI. Initially, regressions were conducted using topographic aspect and insolation as predictors (*Table 4.9*). In the dry season model, the regression was not statistically significant ($R^2 = 0.074$, p-value = 0.112), indicating that these variables explained only a small proportion of the TVSDI variability. Similarly, the wet season model showed a very weak relationship ($R^2 = 0.036$, p-value = 0.349), suggesting that topographic aspect and insolation alone have limited predictive power for TVSDI. These results indicate that terrain orientation and solar radiation on their own are insufficient to explain the spatial variability of soil dryness represented by the TVSDI.

When LST was included in the regression analysis together with aspect and insolation, the model performance improved substantially (*Table 4.9*). The dry season model became highly significant, explaining approximately 47.2% of the variation in TVSDI. LST emerged as the strongest predictor, indicating a strong positive relationship between surface temperature and soil dryness, although not statistically significant. Insolation showed a weak positive relationship although not statistically significant and topographic aspect remained non-significant. A similar pattern was observed in the wet season, where the regression model explained 55.7% of the TVSDI variability. LST was again the dominant predictor, indicating that higher surface temperatures are associated with increased soil dryness.

Table 4.9 | Summary of multiple regression models predicting TVSDI from topographic aspect, insolation and LST

Period	Season	Predictors	R squared	Significance	Test interpretation	Equation
2015 - 2024	Dry	Aspect & Insolation	0.074	0.112	Not significant	TVSDI = 0.633 + 0.056(Aspect) + 0.000(Insolation)
2015 - 2024	Wet	Aspect & Insolation	0.036	0.349	Not significant	TVSDI = 0.391 – 0.189(Aspect) – 0.00003947(Insolation)
2015 - 2024	Dry	LST, Aspect & Insolation	**0.472**	**<0.001**	Significant	TVSDI = 0.330 + 0.046(Aspect) + 0.010(LST) + 0.000(Insolation)
2015 - 2024	Wet	LST, Aspect & Insolation	**0.557**	**<0.001**	Significant	TVSDI = 0.224 – 0.018(Aspect) + 0.015(LST) + 0.000003548(Insolation)

The standardised regression coefficients for the predictors of TVSDI are presented in Table 4.10. In the models including only topographic aspect and insolation, neither of these variables showed a statistically significant relationship with TVSDI in either season. In the dry season, topographic aspect and insolation were both non-significant predictors. Similarly, in the wet season, topographic aspect and insolation showed no significant influence on TVSDI.

When LST was included in the regression models, it was the only statistically significant predictor of TVSDI in both seasons, showing a strong positive relationship in the dry season and an even stronger relationship in the wet season. This outcome is expected, as TVSDI is derived from LST and therefore inherently reflects the index’s dependence on surface thermal conditions.

The reliability of the regression relationships can also be evaluated using the comparison between satellite-derived TVSDI and in situ soil moisture values. As shown in Figure 4.8, TVSDI exhibits a negative relationship with measured soil moisture, confirming that higher TVSDI values correspond to drier soil conditions. This agreement between remotely sensed TVSDI and ground measurements provides additional support for the validity of the regression models derived in this study.

Table 4.10 | Standardised regression coefficients and their significance levels for the predictors of TVSDI across the dry and wet seasons

Period	Season	Variable	Beta	Significance	Test interpretation
2015 - 2024	Dry	Aspect	0.153	0.285	Not significant
2015 - 2024	Dry	Insolation	0.169	0.238	Not significant
2015 - 2024	Wet	Aspect	-0.180	0.216	Not significant
2015 - 2024	Wet	Insolation	-0.021	0.882	Not significant
2015 - 2024	Dry	LST	**0.632**	**<0.001**	Significant
2015 - 2024	Dry	Aspect	0.125	0.251	Not significant
2015 - 2024	Dry	Insolation	0.210	0.057	Not significant
2015 - 2024	Wet	LST	**0.742**	**<0.001**	Significant
2015 - 2024	Wet	Aspect	-0.017	0.869	Not significant
2015 - 2024	Wet	Insolation	0.002	0.984	Not significant

4.3.4 | Statistical trends for LST and TVSDI

Following the regression analysis, trend detection tests were used to evaluate temporal changes over the 10-year period. The Mann-Kendall, non-parametric test is widely used for detecting trends and their magnitude in climate data without the need for linearity in the data. The Sen's slope estimator was employed to estimate the trend's magnitude. Together, these methods offered a comprehensive assessment of both the direction and strength of temporal trends across the decade-long dataset.

The Mann-Kendall test was applied to mean LST and TVSDI district data for the wet and dry seasons between 2015 and 2024 to identify trends (*Table 4.9*). The test results showed positive LST Sen's slope values for all districts and seasons, meaning a warming LST over time, even if not statistically significant for some of the districts. Significant increasing trends in LST were observed in the Northern, Northern Harbour, Southern Harbour and Western districts during the wet season. These findings suggest that surface soil dryness has intensified during the wet season over the past decade for some of the districts. No dry season LST trends were significant in any district at the 0.05 level of significance. TVSDI results showed non-statistically significant trends for all seasons and across all districts. No district showed any measurable trend, matching the Mann-Kendall test results, which showed no significant trends in TVSDI.

Table 4.11 | Mann-Kendall and Sen's slope tests for LST and TVSDI district-based data for both the wet and dry seasons

District	Parameter	p-value	Sen's slope	Significance level	Test interpretation
Gozo	LST - wet season	0.052	0.279	0.05	non-significant trend
Northern	LST - wet season	**0.037**	0.243	0.05	significant increasing trend
Northern Harbour	LST - wet season	**0.037**	0.15	0.05	significant increasing trend
South Eastern	LST - wet season	0.052	0.225	0.05	non-significant trend
Southern Harbour	LST - wet season	**0.037**	0.121	0.05	significant increasing trend
Western	LST - wet season	**0.037**	0.396	0.05	significant increasing trend
Gozo	LST - dry season	0.107	0.35	0.05	non-significant trend
Northern	LST - dry season	0.245	0.175	0.05	non-significant trend
Northern Harbour	LST - dry season	0.474	0.225	0.05	non-significant trend
South Eastern	LST - dry season	0.531	0.25	0.05	non-significant trend
Southern Harbour	LST - dry season	0.474	0.2	0.05	non-significant trend
Western	LST - dry season	0.245	0.25	0.05	non-significant trend
Gozo	TVSDI - wet season	0.835	0	0.05	non-significant trend
Northern	TVSDI - wet season	1	0	0.05	non-significant trend
Northern Harbour	TVSDI - wet season	0.371	0	0.05	non-significant trend
South Eastern	TVSDI - wet season	0.421	0	0.05	non-significant trend
Southern Harbour	TVSDI - wet season	0.371	0	0.05	non-significant trend
Western	TVSDI - wet season	0.858	0	0.05	non-significant trend
Gozo	TVSDI - dry season	0.107	0.004	0.05	non-significant trend
Northern	TVSDI - dry season	0.371	0.00375	0.05	non-significant trend
Northern Harbour	TVSDI - dry season	0.283	0	0.05	non-significant trend
South Eastern	TVSDI - dry season	0.474	0	0.05	non-significant trend
Southern Harbour	TVSDI - dry season	0.474	0	0.05	non-significant trend
Western	TVSDI - dry season	0.531	0	0.05	non-significant trend

4.3.5 | Geo-statistical test

Spatial autocorrelation was examined because environmental variables such as LST and TVSDI typically form spatial clusters rather than behaving independently (Gaspard, Kim & Chun, 2019). Since standard regression techniques assume independence among observations, failing to account for spatial autocorrelation can result in biased coefficients and inflated significance levels (Dale & Fortin, 2025). Assessing spatial autocorrelation therefore helps validate the reliability of the regression results and reveals the spatial patterns underlying the relationship between LST and TVSDI.

To examine the spatial autocorrelation, Moran's I was calculated to evaluate the degree of clustering or dispersion in the observed patterns. The LST and TVSDI raster layers were first exported from QGIS and projected to an appropriate coordinate system to ensure accurate spatial analysis.

Moran's I values ranged between 0.77 and 0.96 (*Appendix 6*), indicating strong positive spatial autocorrelation. Both temperature and dryness exhibited strong spatial clustering, reflecting the influence of stable geographic and climatic factors. These findings, when combined with the preceding statistical analyses, highlight the persistent and spatially coherent nature of temperature - dryness interactions across the Maltese Islands.

Wet season values were consistently slightly higher than dry season values for both LST and TVSDI, suggesting that during the wet season, spatial patterns are more homogeneous. The dry season shows slightly lower Moran's I values, indicating more spatial variability. Moran's I values for LST were consistently higher than those of TVSDI, implying stronger clustering of temperature values. This means that nearby areas tend to have similar temperatures. Overall, these values remained consistent across the 10-year period, suggesting that the spatial structure of LST and TVSDI has remained persistent over time, with no major shifts in spatial patterns.

4.4 | Fieldwork and labwork results for the 2024 data across southern Malta

To enable the comparison between the in-situ measurements and the satellite-derived observations, the discussion now shifts from the broader district-level analysis to specific locations in the southern part of the Maltese Islands (*Figure 4.3*). Focusing on individual locations allowed the field-based soil temperature and soil moisture to be directly matched with their corresponding satellite pixels, ensuring a more accurate validation of the remotely sensed LST data and a clearer understanding of local thermal and soil conditions. For this evaluation, averages for the wet and dry seasons for both LST and TVSDI were derived from the processed satellite imagery. These indices were used to assess surface temperature fluctuations and potential drought conditions across the study area.

Figure 4.3 | The five soil sampling sites across the southern part of Malta, as used in this study

A comparison between satellite-derived LST and in-situ soil temperature readings showed a very close correspondence between the two datasets (*Figure 4.4*). Across all sampling dates and locations, the mean difference between LST and in situ soil temperature was effectively 0°C, indicating no systematic bias (*Table 4.10*). The variability of the difference was ±3.1°C, with values ranging from -4.6°C to 3.9°C. This confirms that the satellite-derived LST reliably represents near-surface thermal conditions at the locations of this study.

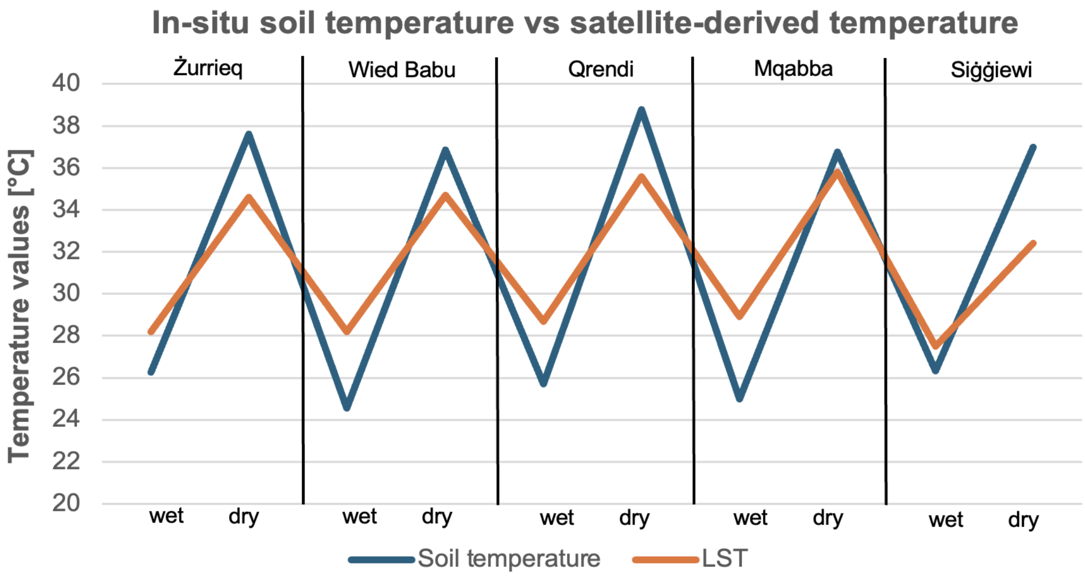


Figure 4.4 | Seasonal variation in in-situ soil temperature and satellite-derived LST for the sampled sites, illustrating the differences between the wet and dry seasons

Table 4.12 | Differences between satellite-derived LST and in-situ soil temperature measurements, showing mean bias, variability and minimum and maximum differences across all sampled dates and locations

Mean difference	Standard deviation	Minimum difference	Maximum difference
0.0	3.1	-4.6	3.9

The highest in situ soil temperatures were observed at Qrendi whereas Wied Babu consistently recorded the lowest temperature values (*Figure 4.5*). Among the sampled months, April exhibited the lowest soil temperatures at all locations while June registered the highest overall temperatures.

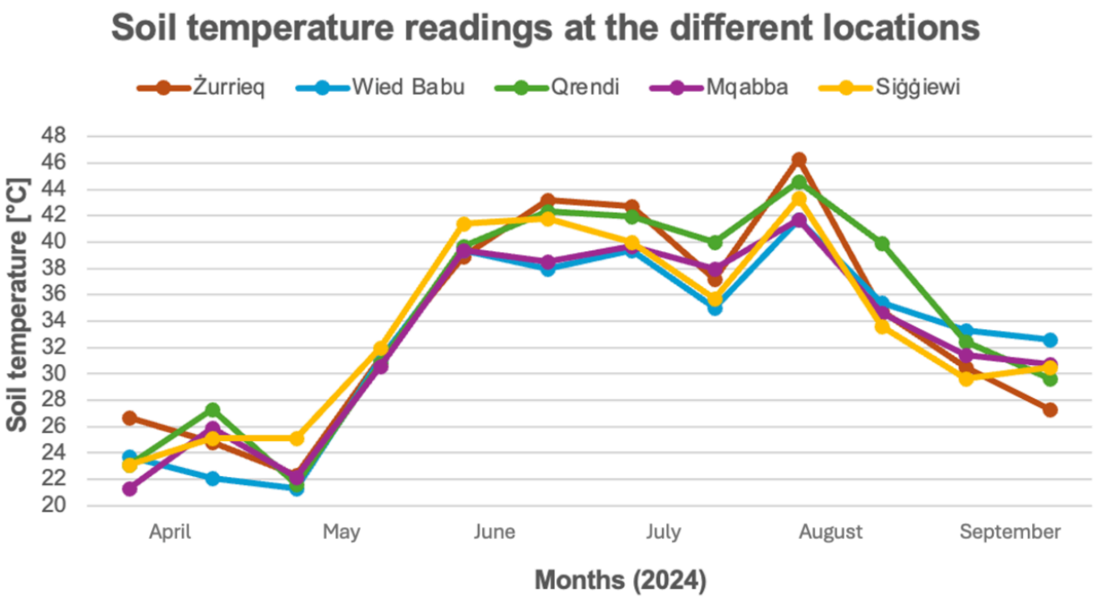


Figure 4.5 | In situ soil temperature readings recorded at each sampling site during the study period

Alongside temperature measurements, soil samples were collected from the top of the soil at each location. These samples were then transported to the laboratory, where soil moisture content was determined for each overpass date. Soil moisture values peaked in May due to rainfall on the previous day of the soil sample collection day, whereas consistently low values below 10% characterised the rest of the period, indicating generally dry conditions throughout the remainder of the study period (*Figure 4.6*). Similar though higher moisture results were obtained by Mifsud (2002), where soil moisture content did not exceed 14% during the dry summer season.

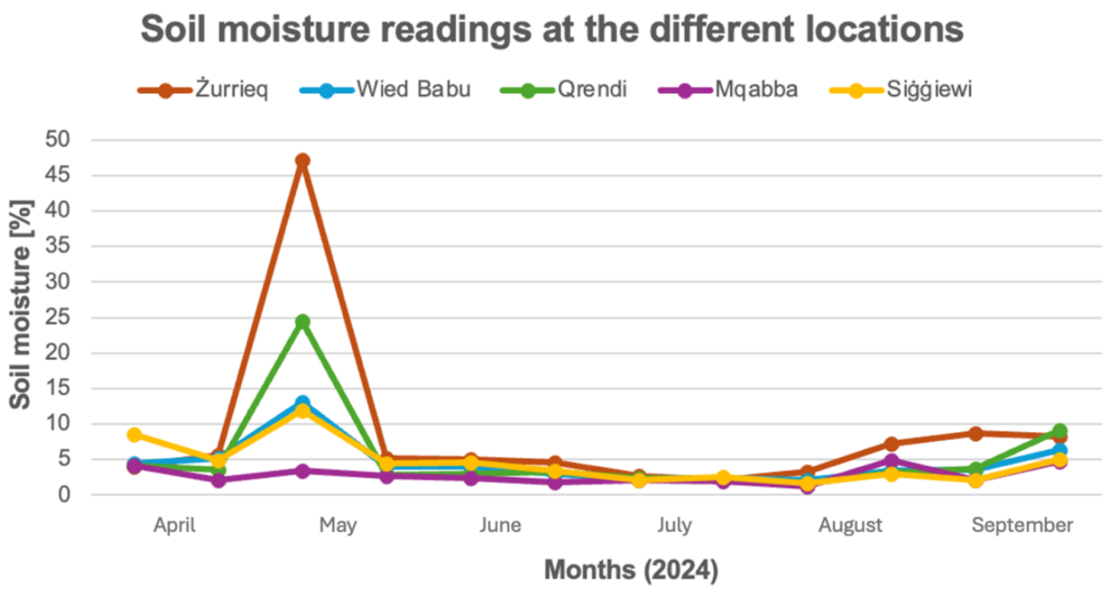


Figure 4.6 | In situ soil moisture values recorded at each sampling site during the study period

This sampling and measurement process was repeated during each satellite overpass date from April to September 2024, resulting in a comprehensive dataset that captured variations in soil temperature and moisture mainly during the dry season of the Maltese Islands (*Figure 4.7)*. These data supported a detailed assessment of spatiotemporal patterns across the different locations represented in the study. The wet season across all locations always recorded lower soil temperatures and higher soil moisture when compared to the dry season. In fact, low moisture content was associated with higher recorded soil temperature, as seen in all the sampling sites during the dry season (second bar).

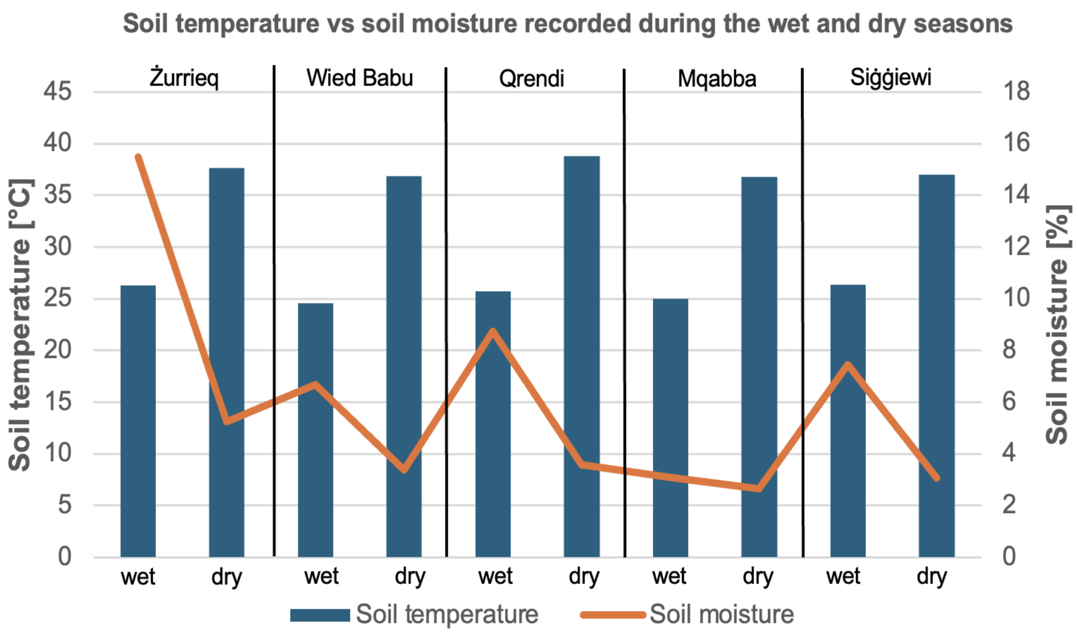


Figure 4.7 | Seasonal comparison of soil temperature and soil moisture across the sampled sites, highlighting the differences between the wet and dry seasons

In the field, soil colour was assessed visually using the Munsell soil colour chart. Soil texture classification was based on Lang & Osmond's (1960) soil map of the Maltese Islands, which offers a detailed and regionally relevant categorisation of local soil.

Soil texture was determined in the laboratory using the hydrometer method and using the USDA soil texture classification, with results presented in Table 4.11. Although the soil colour varied among the five selected sites, the soil texture was consistent across all locations except for Wied Babu, which exhibited a slightly different texture compared to the others.

Table 4.13 | Soil texture class identified for each sampling site

Soil sample location	Sand %	Silt %	Clay %	Texture
Qrendi	35	40	25	Loam
Mqabba	32	47	21	Loam
Wied Babu	38	33	29	Clay Loam
Żurrieq	35	44	21	Loam
Siġġiewi	40	34	26	Loam

Overall, the integration of in-situ measurements with satellite-derived data provided a coherent and quantitative picture of soil-atmosphere interactions across the sampled sites in southern Malta. The close alignment between ground-based and remotely sensed temperatures, together with the clear seasonal contrasts in soil moisture, strengthened the reliability of the LST observations. Laboratory analyses further contextualised these patterns by characterising the physical properties of the soils, allowing the subsequent sections of the results to build on a well-validated and site-specific foundation for interpreting spatial variations in LST and TVSDI.

4.4.1 | Statistical tests for the 2024 data across southern Malta

The 2024 data were further analysed to include soil temperature, soil moisture and soil texture measurements obtained during each soil sampling collection. Corresponding mean TVSDI values were also retrieved from the same locations using the previously generated maps. This analysis aimed to better understand how the recorded soil temperature and moisture levels influence dryness conditions across southern Malta.

A Pearson correlation analysis was conducted to examine the relationship between TVSDI and soil moisture. The results (*Table 4.12*) indicated a moderate negative correlation between TVSDI and soil moisture. This suggests that higher soil moisture levels are generally associated with lower TVSDI values. However, the relationship was not statistically significant at the 0.05 level of significance, indicating that the observed correlation may have occurred by chance due to the limited sample size.

Table 4.14 | Correlation between TVSDI and soil moisture

Variables	r	Significance	n
TVSDI – soil moisture	-0.537	0.110	10

A Pearson correlation analysis revealed a very strong positive relationship between TVSDI and soil temperature (*Table 4.13*). This indicates that higher soil temperatures are strongly associated with higher TVSDI values. The correlation was statistically significant at the 0.01 level of significance, suggesting that the relationship is unlikely to have occurred by chance. These results imply that soil temperature plays a major role in influencing TVSDI, with warmer soil conditions corresponding to increased surface dryness as reflected by higher TVSDI values.

Table 4.15 | Correlation between TVSDI and soil temperature

Variables	r	Significance	n
TVSDI – soil temperature	0.895	**<0.001**	10

A one-way ANOVA test was conducted to examine the effect of soil texture on TVSDI (*Table 4.14*). The results indicated that there was no statistically significant difference in TVSDI among the different soil texture groups. This suggests that soil texture had no significant influence on TVSDI in the study area.

Table 4.16 | One-way ANOVA test for TVSDI vs soil texture

Variable	F	Significance
Soil texture	0.035	0.857

A simple linear regression was performed to assess the influence of soil moisture on TVSDI (*Appendix 7*). The model explained 28.8% of the variance in TVSDI, with a moderate negative relationship between the two variables. Although the negative coefficient indicates that TVSDI tends to decrease as soil moisture increases (*Figure 4.8*), this relationship was not statistically significant. Therefore, soil moisture does not significantly predict TVSDI within the study area, though the trend suggests that drier conditions and, therefore lower soil moisture, are generally associated with higher TVSDI values.

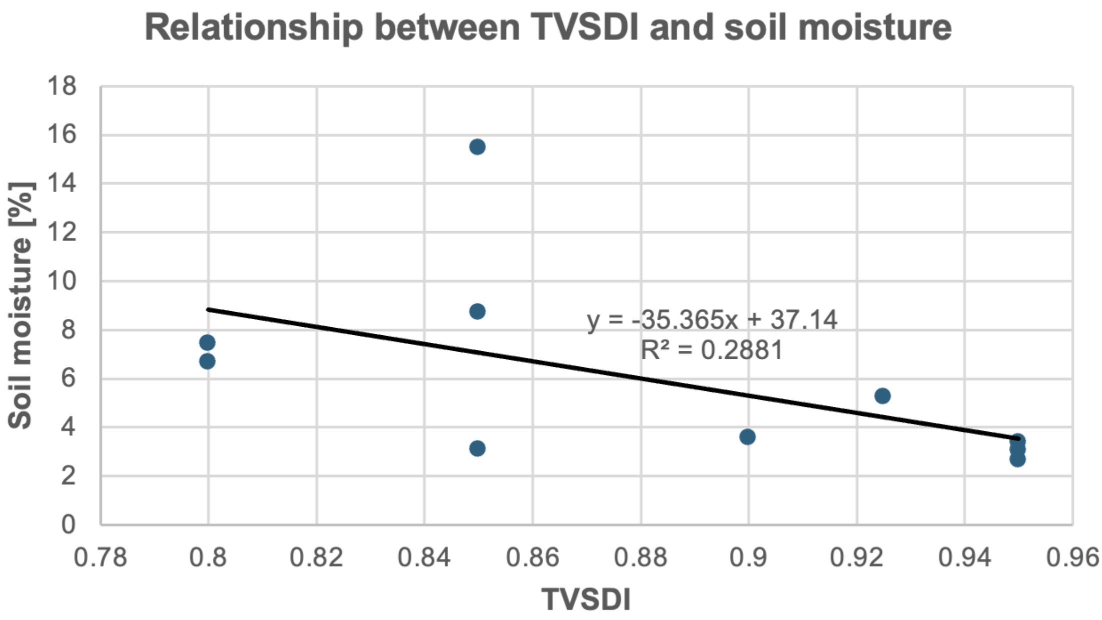


Figure 4.8 | The effect of soil moisture on TVSDI in the study area of southern Malta

A simple linear regression analysis was conducted to assess the effect of soil temperature on TVSDI (*Appendix 8*). The results showed a very strong positive and statistically significant relationship between soil temperature and TVSDI (*Figure 4.9*). An increase in soil temperature leads to a corresponding increase in TVSDI. This suggests that higher soil temperatures are associated with drier soil conditions. Overall, soil temperature explained approximately 80% of the variance in TVSDI, making it a strong predictor of surface soil dryness.

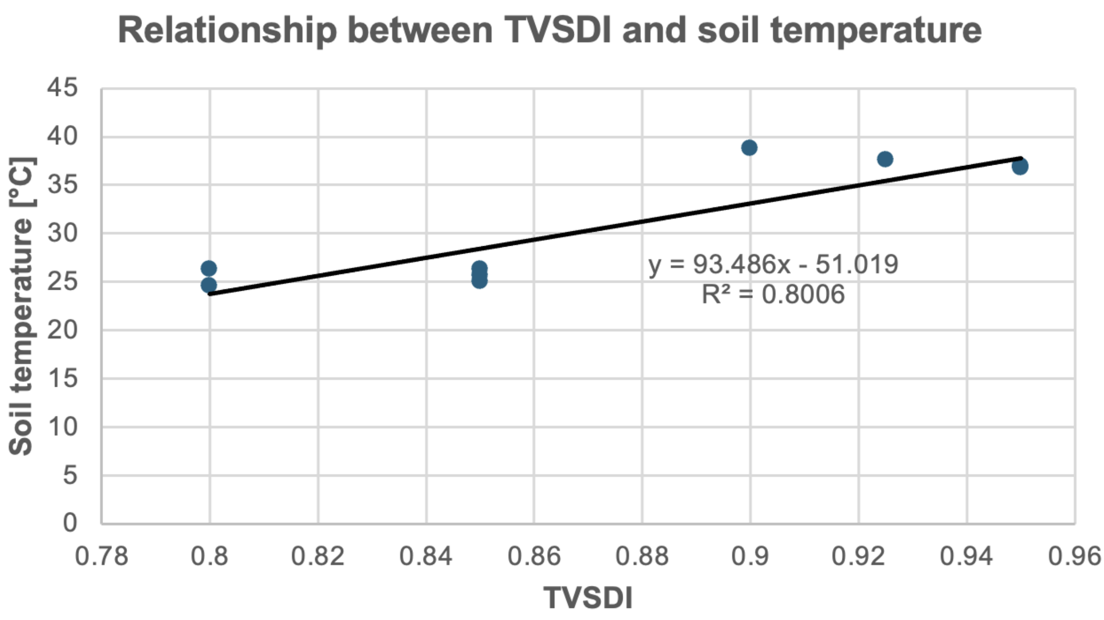


Figure 4.9 | The effect of soil temperature on TVSDI in the study area of southern Malta

A multiple linear regression analysis was performed to evaluate the combined effect of soil temperature and soil moisture on TVSDI (*Appendix 9*). The overall model was statistically significant, explaining approximately 80.1% of the variance in TVSDI. Among the predictors, soil temperature had a strong and statistically significant positive influence on TVSDI, indicating that higher soil temperatures are associated with higher surface dryness. In contrast, soil moisture had a weak and non-significant effect. This suggests that, within the study area, soil temperature is the primary driver of variations in TVSDI, while soil moisture plays a minor role when both variables are considered together.

In summary, the results reveal that both land surface temperature and dryness across the Maltese Islands exhibit clear seasonal differentiation, with significantly higher values during the dry season. While local geographical differences were minor, seasonality emerged as the dominant control on surface thermal and dryness patterns. These findings provide an essential basis for the discussion in the next chapter, which explores the implications of these patterns in the context of climate change and land management.

Chapter 5: Discussion

This chapter interprets and contextualises the results presented in Chapter 4, examining the spatial and temporal dynamics of LST and TVSDI across the Maltese Islands between 2015 and 2024, with the focus being on non-urban, agricultural areas. The discussion contextualises the findings into the broader picture of Mediterranean climatic variability, land-atmosphere interactions and remote sensing-based drought monitoring. The implications of seasonal effects on soil surface temperature and soil dryness are given particular attention, especially with ongoing climatic changes. The integration of field and laboratory data further enabled a critical evaluation of the reliability of remote sensing and satellite-derived indices in a small island like Malta with a semi-arid climate.

5.1 | Overview of key findings

Wet season LST values across all districts and years were lower than dry season LST values. The highest LST values for the wet season were recorded in 2020, peaking at 26.7°C, while the highest LST values for the dry season were recorded in 2024, peaking at 34°C. The warmest districts were the Southern Harbour, South Eastern and the Northern Harbour districts while Gozo, Northern and Western districts were the coolest. Progressive warming of these districts was visible across both the wet and dry seasons, with post-2020 years consistently being warmer than pre-2019. From 2020 onwards, the presence of hotter and less dense vegetation was more common, as stated in the 2022 NSO climate report, where consecutive drought years became more noticeable. In fact, in this study, post-2020 years were about 1.5°C hotter when compared to pre-2020 years. Extreme dry-season temperature values were recorded in 2020 in the

Northern district with 32.5°C, in 2021 in the Southern Harbour district with 33.5°C and in 2024, with 34°C in the South Eastern district, indicating significant thermal anomalies, with 2020 being the warmest year overall.

TVSDI values across all districts during the wet season had a very narrow range, indicating homogeneous soil moisture conditions. In fact, in the 2024 wet season, TVSDI values ranged only from 0.48 to 0.50, with a range of 0.02 and in 2018, the range was of 0.03. A broader range of TVSDI values was detected during the dry season, demonstrating stronger spatial differences in soil dryness, with the highest values occurring in 2024. In fact, 2016 and 2020 wet season TVSDI values had a range of 0.04. Soil dryness was highest in 2016 (0.62) and 2024 (0.65), with lower dryness years being 2018 and 2019, matching with the cooler temperature conditions. From the geostatistical analysis, a gradual increase in dryness was detected during the dry season from 2015 to 2024, with soil dryness ranges of 0.55-0.58 from 2015 to 2018 and then to 0.62-0.65 in 2024, indicating intensifying dryness.

5.2 | The influence of seasonal variability on LST

5.2.1 | Contrasts in LST between the wet and dry seasons

One of the most robust findings of this study was the strong seasonal contrast in LST across all of Malta’s districts. Wet season LST values were consistently lower than dry season LST values throughout the study period. The two-way ANOVA test demonstrated that seasonality was the only statistically significant factor influencing LST. In fact, the highest wet season LST value reached up to 26.7°C in 2020 while the lowest dry season LST value recorded was that of

27.6°C in 2018. This result was consistent with patterns dominating the Mediterranean climate, where solar radiation intensity, atmospheric circulation and soil moisture availability differ significantly between the wet and dry seasons (Yuan et al., 2020). Similar seasonal effects have been reported in other Mediterranean and semi-arid regions (Andronis et al., 2022; Lai et al., 2020). From the regression analyses performed, it was found that the dry season was statistically significant 8.3°C warmer than the wet season. This further confirms the clear seasonal difference in LST.

5.2.2 | Seasonal LST variations at the district level

During the wet season, the lowest LST values were recorded in the Gozo, Northern and Western districts while the highest values were recorded in the Northern Harbour, South Eastern and Southern Harbour districts. The same can be said for the dry season, where the highest LST values were also recorded in the South Eastern district. Gozo and the northwestern coast of Malta are characterised by clay and clayey soils which retain more moisture and therefore warm more slowly due to their higher water holding capacity, resulting in this difference when compared to the other southern districts. Furthermore, the northwestern coast of Malta is north-facing and being oriented away from the sun's direct solar radiation and sunlight results in lower temperature values when compared to the other districts.

Despite the clear mapped differences between districts, especially between the eastern harbour districts and the northwestern rural districts, district-level differences in LST were not statistically significant once season was accounted for. This meant that during the study period, seasonality drove temperature differences across the Maltese Islands. This apparent contradiction underscores the distinction between visually observable spatial patterns depicted in the maps and the outcomes of the statistical tests. Although local land cover types and soil properties may influence LST at finer spatial scales, these localised effects are often masked by the magnitude of seasonal temperature variations. This is reflected in the generally weak and non-statistically significant LST-TVSDI relationships observed during the wet season across most districts, with the exception of Gozo, where a stronger positive relationship was detected. This finding aligns with studies from other small Mediterranean islands like Greece, where regional-scale seasonal variations were found to dominate over local land-use effects in driving LST variability (Eleftheriou et al., 2018).

5.3 | Spatial and temporal variability of LST across the Maltese Islands

Although district-level statistical differences were not significant, spatial analysis revealed consistent patterns where the Southern Harbour, South Eastern and Northern Harbour districts exhibited higher LST values, particularly during the dry season. These districts are characterised by urbanisation and therefore reduced vegetation cover, which enhance sensible heat storage and reduce evaporative cooling (Sandoval et al., 2023; Scicluna, 2016). The presence of elevated dry season LST in urbanised districts reflects classic urban heat island effect dynamics, even though urban areas were masked in the maps. Residual effects from adjacent built-up zones and road networks likely contributed to elevated temperatures in surrounding non-urban pixels (Scicluna, 2016).

Although urban, industrial and quarry areas were masked from the analysis, it is important to acknowledge that the exclusion of these land-cover classes does not entirely remove their influence on the observed LST patterns. Due to the 30 m spatial resolution of Landsat imagery, mixed-pixel effects may occur along the boundaries between urban and non-urban land uses, particularly in Malta's highly fragmented landscape. Furthermore, built-up surfaces store and re-radiate heat, creating localised thermal gradients that can extend beyond the masked urban areas. Consequently, agricultural and semi-natural areas located adjacent to urban centres, major road networks and industrial zones may still exhibit elevated surface temperatures resulting from the indirect influence of the urban heat island effect. Therefore, some of the higher LST values observed within non-urban pixels, especially in the Southern Harbour, Northern Harbour and South Eastern districts, may partly reflect the thermal influence of nearby urban surfaces rather than solely the characteristics of the local soil, vegetation or topography.

Gozo and the Western district consistently exhibited lower LST values, especially during the wet season. This pattern is likely linked to several factors, including higher topographical areas of agricultural and semi-natural land, clay-rich soils which are prevalent in Gozo and the presence of perched aquifers, especially in the Western district. Clay soils have higher water-holding capacity, which moderates surface temperature fluctuations. The cooling influence of soil moisture and subsurface hydrology has been widely documented. Moist soils reduce surface temperatures by enhancing latent heat flux, especially during the transitional seasons (Liu et al., 2025; Mimeau et al., 2021). In Gozo, the persistence of cooler wet season LST values suggests that hydrologically active zones play a key role in buffering thermal extremes. This effect may be further reinforced by the relatively higher clay content of soils, which enhances soil moisture retention and promotes evaporative cooling, therefore contributing to lower surface temperatures.

Beyond land cover and soil properties, the topographical configuration of Malta and Gozo exerts an important control on spatial variations in LST. The Maltese archipelago is characterised by a sequence of limestone plateaus, ridges and deeply incised valleys with elevation generally increasing from the north-east towards the south-west. Although absolute elevation differences are modest, even small topographic gradients can significantly influence surface energy balances in semi-arid environments. Elevated plateau areas tend to experience greater exposure to solar radiation and wind, which can enhance daytime heating and accelerate soil moisture loss, particularly during the dry season (Bennie et al., 2008; Filho et al., 2025). In contrast, valley bottoms often retain higher moisture levels and experience reduced wind speeds (Dirmeyer, 2011), promoting lower LST values relative to surrounding uplands.

Valley systems play an important role in moderating surface temperatures across both Malta and Gozo. These geomorphological features act as natural drainage pathways that concentrate runoff and promote infiltration following rainfall events. As a result, soils within valley bottoms often retain higher moisture levels than surrounding upland areas, particularly during the wet season and transitional periods. Higher soil moisture availability increases latent heat flux through evaporation and transpiration, thereby reducing the proportion of incoming energy converted into sensible heat and leading to lower LST values (Dirmeyer, 2011; Khamidov et al., 2023). In addition, valley environments frequently support denser vegetation cover due to greater water availability, which further enhances evaporative cooling and shading effects. However, the magnitude of this cooling influence may vary depending on valley morphology, soil characteristics, land use and seasonal moisture conditions. Nevertheless, the persistent occurrence of lower LST values in several Maltese valley systems suggests that topographically controlled moisture accumulation is an important factor influencing local thermal patterns.

Slope orientation further modulates LST variability by influencing solar exposure (Bennie et al., 2008). South-facing slopes in Malta and Gozo receive higher incoming solar radiation throughout the year, particularly during summer, leading to higher surface temperatures and faster soil drying. Conversely, north-facing slopes experience reduced insolation, allowing soils to remain cooler and retain moisture for longer durations. Although slope angles in the Maltese Islands are generally gentle, the cumulative effect of aspect becomes significant during prolonged dry periods when thermal contrasts are amplified. This contributes to localised LST heterogeneity that may not be captured by district-scale statistics but is evident in spatial analyses. This is apparent in the produced LST maps where the northwestern coast of Malta always records lower LST values due to the cliffs and slopes located there being north-facing and therefore receiving less solar radiation. Contrastingly, south-facing slopes, such as those found in ix-Xatt l-Aħmar in Għajnsielem Gozo, in Għadira beneath The Red Tower and the slope crossing from Xemxija to Golden Bay, receive more direct solar radiation due to the orientation toward the sun's path in the Northern Hemisphere, resulting in increased surface heating and consequently higher LST values, as they are clearly visualised in the LST maps.

The presence of terraced slopes, shallow depressions and small-scale elevation changes promotes heterogeneity in soil depth, vegetation density and moisture availability. Terraced agricultural landscapes and rubble walls reduce runoff velocity and enhance infiltration, thereby maintaining cooler surface conditions (ERC, 2025; Pedroli et al., 2007; Vella & Garrido, n.d.). In contrast, Malta's more extensive urban expansion across relatively flat plateaus limits such buffering processes, reinforcing higher LST values, particularly during the dry season.

Additionally, coastal topography influences LST through land-sea interactions. Low-lying coastal areas are subject to cooling sea breezes that can moderate surface temperatures during daytime hours. Inland areas, particularly enclosed valleys and urban-adjacent plateaus, are less affected by these cooling mechanisms, allowing heat to accumulate more (Ali et al., 2022; Scicluna, 2016). This pattern is consistently reflected in the generated LST maps, where coastal zones appear cooler relative to the mainland. This effect is even more pronounced along the northwestern and southwestern coastline of Malta and along the northern coast of Gozo. An illustrative example case is Babu Valley within the South Eastern district, which consistently registers lower LST compared to its surrounding landscape.

Overall, the observed LST patterns across Malta and Gozo reflect a complex interplay between topography, hydrology and coastal influences. The spatial analysis consistently demonstrated that the Southern Harbour, South Eastern and Northern Harbour districts exhibited higher LST values, particularly during the dry season. Contrastingly, Gozo and the Western district persistently recorded lower LST values, especially during the wet season, highlighting the moderating role of clay-rich soils and perched aquifers. The higher moisture retention capacity of these soils enhances evaporative cooling and buffers thermal extremes, demonstrating the strong coupling between hydrological processes and surface energy balance (Barcikowska et al., 2020). Topography further shapes these spatial patterns, with valleys and north-facing slopes promoting moisture retention and reducing solar exposure, resulting in consistently cooler LST values. South-facing slopes, on the contrary, experienced greater solar radiation and accelerated drying, leading to elevated temperatures. Similar results that topography and slopes influence solar exposure and energy balance have been found by Adeyeri et al. (2024). Coastal zones benefitted from sea-breeze cooling effects, further reinforcing lower surface temperatures (Ali et al., 2022). Together, these findings demonstrated that geomorphological and hydrological factors act as significant local-scale moderators of surface temperature.

5.4 | Spatial distribution and variability of the TVSDI across the Maltese Islands

Understanding the spatial and temporal distribution of dryness is essential for assessing the variability and intensity of drought conditions across the Maltese

Islands for the last 10 years. Dryness, often quantified using indices, is influenced by a range of climatic and environmental factors including precipitation patterns, temperature trends and land use changes, while variables such as soil moisture provide a direct indication of drought conditions. The following paragraphs explore how soil dryness manifests across spatial scales and how its occurrence and severity fluctuate over time. By examining both the spatial and the temporal changes in soil dryness, this section aims to provide a discussion of drought dynamics, which are crucial for effective soil and water resource management, agricultural planning and climate adaptation strategies.

TVSDI values during the wet season were remarkably uniform across all districts and throughout all study years, suggesting relatively stable moisture conditions across the Maltese Islands during this study. This suggests that rainfall replenishment reduces variability in vegetation water stress. The weak and mostly non-significant correlations between LST and TVSDI during the wet season further reinforces this finding. When water availability is sufficient, evapotranspiration increases and latent heat flux dominates the surface energy balance, thereby buffering temperature fluctuations and diminishing the sensitivity of temperature-based drought indicators (Xue et al., 2025).

In contrast, dry season TVSDI values displayed pronounced spatial gradients, with higher dryness consistently observed in the South Eastern and Western districts. These areas, which are mostly characterised by agricultural land, exposed soils and karstic geomorphology, experience rapid soil moisture loss with the intense solar radiation during the dry season. Karstic landscapes are known for limited soil depth as well as rapid drainage, thereby reducing water retention during the dry season. The recurrent identification of these districts as dryness hotspots aligns with studies where shallow soils and open terrain were associated with higher dryness (Wang et al., 2022).

Specific locations, such as garrigue environments and barren coastal areas repeatedly exhibited high TVSDI values since these areas were typified by sparse vegetation and shallow soils and are exposed to sea salt spray and wind exposure. Xu et al. (2022), who developed the TVSDI, noted that such surface conditions amplify surface temperature signals, leading to elevated dryness index values. In this study, TVSDI had a statistically significant relationship with season since its recorded p-value was <0.001, suggesting that the temperature differences experienced during the different seasons influence this dryness index.

Topographically driven LST patterns help to explain the spatial variability observed in the LST-TVSDI relationship across the Maltese Islands. Valleys, clay-rich areas and hydrologically active zones tend to exhibit lower LST values and correspondingly lower TVSDI, particularly during the wet season when soil moisture availability moderates thermal stress. In this study, such conditions were observed in Babu valley in the South Eastern district, where valley morphology contributed to greater moisture retention and lower LSTs when compared to surrounding plateau areas. In contrast, elevated plateaus, south-facing slopes and urban-adjacent plateaus experience higher surface temperatures, accelerating evapotranspiration and promoting increased soil dryness during the dry season. This reinforces the strong positive LST–TVSDI correlations identified in several districts, where topography amplifies temperature-driven soil moisture depletion. In Gozo and parts of the Western district, the prevalence of valleys, terraced landscapes and moisture-retaining soils weakens this coupling, resulting in lower LST values and a more buffered TVSDI response. These findings highlight that while LST is a key driver of soil dryness, its influence is spatially modulated by topography through its control on moisture redistribution and exposure to solar radiation (Bennie et al., 2008).

5.4.1 | Environmental predictors of TVSDI

The first regression analysis demonstrated that LST was the only strong statistically significant predictor of TVSDI. Once LST was included in the model, season was no longer a significant predictor of TVSDI. Since LST strongly reflects seasonal thermal conditions, it effectively integrates the seasonal signal within the regression model, leaving little additional explanatory power for season itself. Additionally, potential lagged response to soil moisture might have also weakened the direct seasonal effect on TVSDI. Similar results were reported by Sandholt et al. (2002), who found that temperature-based indices often outperform precipitation-only indices in semi-arid regions.

Since TVSDI is directly derived from LST, a strong relationship between these two variables is inherent. The second regression analysis therefore aimed to assess whether the inclusion of additional terrain-related variables, namely topographic aspect and insolation, improved the explanation of TVSDI variability beyond that accounted for by LST. The inclusion of other variables, such as soil type, may have provided further insight into spatial variations in soil dryness conditions. However, such data were not available to include in the present study. In the models including only topographic aspect and insolation, the predictors showed weak explanatory power and were not statistically significant. In the dry season, topographic aspect and insolation did not significantly explain TVSDI variability. Similarly, in the wet season, topographic aspect and insolation showed no significant relationship with TVSDI. These results indicate that terrain orientation and solar radiation on their own are insufficient to explain the spatial variability of vegetation dryness represented by the TVSDI.

When LST was incorporated into the regression models together with topographic aspect and insolation, the explanatory power of the models improved substantially. In the dry season, the regression model explained approximately 47.2% of the variability in TVSDI, while in the wet season the model explained 55.7% of the variability. In both cases, LST emerged as the only statistically significant predictor, with strong positive standardised coefficients. These results indicate that higher LSTs are strongly associated with increased soil dryness.

This finding is consistent with the conceptual basis of the TVSDI, which is derived from the relationship between vegetation condition and surface temperature. Higher LST values generally reflect increased evapotranspiration and reduced soil moisture availability, leading to greater stress on soil. As surface temperatures increase, plants experience greater atmospheric demand for water, which can result in reduced vegetation greenness and increased dryness signals in remotely sensed drought indices (Xu et al., 2022). The strong relationship observed between LST and TVSDI therefore reflects the fundamental coupling between surface thermal conditions and vegetation water stress.

Although topographic aspect and insolation influence the spatial distribution of solar radiation and surface heating, their direct contribution to TVSDI variability appeared limited when considered independently. Instead, their influence may operate indirectly through their effect on surface temperature. Slope orientation affects the amount of solar radiation received at the surface, which in turn influences local temperature patterns and evapotranspiration rates. However, once LST is explicitly included in the regression models, much of the variability associated with these terrain and radiation effects is already captured by the temperature variable (Mamassis, Efstratiadis & Apostolidou, 2012). This explains why topographic aspect and insolation show weak or non-significant contributions.

The strong relationship observed between LST and TVSDI highlights the importance of surface thermal conditions in determining soil dryness in Mediterranean environments. Previous studies in Mediterranean regions have similarly reported strong relationships between LST and drought indices derived from remote sensing. Sandholt et al. (2002) demonstrated that the relationship between NDVI and LST provides an effective framework for estimating soil moisture and drought conditions using satellite data. Their work showed that surface temperature plays a central role in determining the position of vegetation within the temperature-vegetation feature space used to derive drought indices.

Similarly, Patel et al. (2013) found that LST-based drought indices provide reliable estimates of water stress in semi-arid environments, highlighting the strong link between thermal conditions and drought dynamics. Gouveia et al. (2016) also showed that remote sensing indicators combining vegetation and temperature information are effective for monitoring Mediterranean droughts.

The results of the present study therefore align with previous findings that emphasise the dominant role of surface temperature in controlling drought dynamics. While terrain orientation and solar radiation influence local microclimatic conditions, their effects appear to be largely mediated through their influence on LST. Consequently, incorporating LST into regression models significantly improved the predictive capacity for TVSDI, whereas terrain orientation and insolation alone provided only limited explanatory power.

The regression equations derived in this study highlight their potential predictive utility. TVSDI values could be estimated in locations where LST, topographic aspect and insolation values are known without the need to directly compute the index from satellite imagery. This suggests that the regression models may provide a practical framework for approximating spatial patterns of soil dryness based on surface thermal conditions and terrain characteristics. Such an approach could be particularly useful in situations where satellite-derived indices are unavailable or where assessments of drought conditions are required. Nevertheless, the applicability of these equations beyond the present study area should be treated with caution as the relationships identified are likely influenced by the specific environmental conditions of the study area.

The absence of significant district effects suggested that local geographical differences exert a secondary influence when compared to temperature. Similarly, soil texture did not significantly affect TVSDI in the southern field sites. This does not imply that soil properties are not important, but rather that their influence may be masked by strong seasonal forcing and limited sample size.

Overall, these findings highlighted the importance of integrating thermal remote sensing variables when analysing drought patterns in Mediterranean environments. Temperature-based indicators can provide valuable information for monitoring soil dryness and drought risk under current and future climatic conditions.

5.5 | The relationship between LST and TVSDI

The strong and statistically significant positive relationship between LST and TVSDI observed during the dry season indicates a tight coupling between surface temperature and soil moisture stress under conditions of limited water availability. These findings align with several other studies demonstrating that higher temperatures accelerate evapotranspiration rates, reduce soil moisture and intensify vegetation stress (Liu et al., 2025). In Mediterranean climates, where rainfall during the dry season is minimal to none, temperature becomes the dominant factor in controlling soil moisture dynamics (Mimeau et al., 2021). Under such circumstances, increases in LST directly intensify soil moisture loss through evaporation and plant transpiration, reinforcing the sensitivity of temperature-based drought indicators like TVSDI.

In contrast, the weak wet season LST - TVSDI correlations highlighted that when soils are replenished by rainfall, thermal variations exert little influence on the dryness index. This aligns with findings from other remote sensing studies, whereby temperature-based drought indices performed better during the dry period when soil moisture was limited (Zou, Cao & Sanchez-Azofeifa, 2020). This pattern may also be influenced by the presence of specific land cover types, such as garrigue environments, which typically exhibit lower near-infrared reflectance and EVI values. These can weaken the relationship between LST and TVSDI, resulting in lower correlation values at the district level. Additionally, the inclusion of land cover types that retain moisture, as well as areas dominated by soils may further dilute the strength of the observed correlations during the wet season. (Prof. C. Galdies, pers. comm., February 2026).

Taken together, these seasonal contrasts highlight how the strength of the LST - TVSDI relationship is strongly mediated by moisture availability, with temperature acting as a primary driver of surface dryness during water-limited dry periods but becoming secondary when soil moisture is replenished during the wet season. Overall, district variability was evident in the strength of the LST and TVSDI correlations. However, a clear and significant association between rising surface temperatures and increasing soil dryness was consistently observed during the dry season while this relationship weakened during the wet season when soil moisture availability reduced the influence of thermal forcing.

5.6 | Evaluation of remote sensing techniques for soil temperature and soil moisture monitoring in small island environments

The findings of this study closely align with existing literature on the application of thermal remote sensing in semi-arid and Mediterranean environments. Similar to the observations reported by Weng (2009), LST in this study served as an integrative indicator of surface conditions, reflecting not only thermal variability but also underlying moisture dynamics. The strong coupling observed between LST and TVSDI during the dry season supports the notion that, under water-limited conditions, surface temperature becomes a reliable proxy for soil moisture stress. This corresponds with the study by Xu et al. (2022), who demonstrated that temperature-based drought indices perform more effectively during dry periods. In contrast, the weakened wet-season relationships observed in this study are also consistent with previous research highlighting the reduced sensitivity of thermal indices when soils are replenished by rainfall and latent heat flux becomes the dominant energy pathway (Weng, 2009). However, this study further contributes to the literature by illustrating how these dynamics manifest at a fine spatial scale within a small island context. The clear seasonal dependence of the LST - TVSDI relationship observed across Malta's districts reinforces the argument that while thermal remote sensing is highly effective for monitoring soil moisture stress during dry periods, its performance is moderated by hydrological buffering during wetter conditions. This demonstrates that the applicability of temperature-based indices in small Mediterranean island environments is not uniform throughout the year but varies according to seasonal moisture availability and local environmental characteristics such as topography and geomorphology.

5.6.1 | Spatial autocorrelation and clustering of LST and TVSDI

Geostatistical analysis revealed that both LST and TVSDI exhibited strong positive spatial autocorrelation across the Maltese Islands, indicating that they follow clear spatial patterns and are not random. This suggests that both surface temperature and soil dryness are influenced by consistent environmental controls such as land cover, topography and geomorphology, as commonly observed in environmental variables (Zingol et al., 2025). Spatial autocorrelation was generally higher during the wet season, reflecting more uniform conditions when soil moisture is replenished. In contrast, slightly lower Moran's I values during the dry season indicate greater spatial variability, likely driven by uneven moisture depletion since different areas lose moisture at different rates due to the different soil texture. Across all seasons, LST consistently showed stronger spatial clustering than TVSDI, suggesting that thermal patterns are more spatially coherent, while soil dryness is additionally influenced by localised factors such as soil disturbance, soil type and land management practices (Zingol et al., 2025). The stability of Moran's I values throughout the 2015 - 2024 study period further indicates that the underlying spatial structure of both temperature and soil dryness remained largely unchanged over time.

5.7 | Relationship between LST, soil temperature and soil moisture in southern Malta

The following section presents the results of field-based and laboratory analyses used to measure soil temperature and soil moisture in coordination with satellite overpasses for the period April – September 2024, as well as the determination of soil texture. This period was selected because it encompasses the transition from the wet season to the drier months of the year, thereby providing conditions that are more representative of soil dryness and elevated soil temperatures. Practical considerations also influenced the selection of this period, as it allowed sufficient time for subsequent data processing, calibration and analysis. The integration of ground data with remotely sensed indices provided a comprehensive understanding of the spatio-temporal variability of soil conditions across the study area.

5.7.1 | Soil temperature measurements across the sampled sites

The sampled sites selected for this study were located in the South Eastern district and included the sites of Wied Babu, Żurrieq, Qrendi, Mqabba and Siġġiewi. These locations represent a range of environmental and topographic conditions characteristic of the Maltese landscape. Siġġiewi and Żurrieq are located on relatively elevated terrain dominated by agricultural land and garrigue vegetation. Mqabba and Qrendi, on the other hand, are located on lower terrain characterised by agricultural fields and flat surfaces while Wied Babu represents a natural valley environment. The combination of these sites provides a representative range of topographic and soil conditions across southern Malta.

The highest soil temperature was recorded in August at Qrendi, reaching 42.3°C, while the lowest soil temperature was recorded in April at Wied Babu, with a value of 22.9°C. These readings illustrate the seasonal contrast in soil temperatures, with the months of April and May generally experiencing cooler conditions compared to the significantly warmer dry season months. June, July and August consistently showed the highest soil temperatures across all sites, reflecting the intense heat and dry soil conditions typical of the Maltese summer. In contrast, April and May recorded the lowest temperatures, highlighting the cooler nature of the wet season. During the transitional period from the dry summer months to the wetter season, soil temperatures remained high, likely due to the residual heat retained by the soil from the prolonged dry summer period. This phenomenon is attributed to the high specific heat capacity of soil, which causes it to cool gradually over time (Wang et al., 2019). Across all sites, monthly soil temperature values were relatively consistent, with the variability of difference being 3.1°C, variations that may be explained by the specific environmental characteristics of each location.

Among all the sampled locations, Wied Babu exhibited the highest coefficient of determination (R^2), with a value of 0.46 in the regression analysis between month and soil temperature. This indicated that 46% of the observed variation in soil temperature at Wied Babu can be statistically attributed to monthly climatic variation. This relatively strong relationship suggests that soil temperature in this area is considerably influenced by temporal factors such as solar radiation, ambient air temperature and day length, which are variables that fluctuate throughout the year (Weng, 2009). During the summer months, increased solar insolation results in greater heat input to the ground surface, thereby elevating soil temperatures. Moreover, ambient air temperature exerts a strong influence on the surface energy balance, directly affecting heat fluxes at the soil-atmosphere interface (Khamidov et al., 2023). As air temperature rises or falls in response to seasonal changes, the soil absorbs or loses heat accordingly, contributing to the observed temporal variation (Greiser et al., 2024). During wetter months, higher soil moisture can moderate temperature fluctuations due to the high heat capacity of water (Whan et al., 2015). Day length, which determines the duration of solar heating each day, also plays a key role by regulating the amount of time available for the soil to warm up or cool down (Watson & Watson, 2011). The remaining 54% of the variation in soil temperature may be influenced by other factors such as soil moisture content, vegetation cover, soil type and soil texture. This finding highlights the strong correlation between soil temperature and month in Wied Babu, which reflects the dynamic nature of the soil-climate interaction.

5.7.2 | Soil temperature vs LST and TVSDI across the sampled sites

In-situ soil temperature readings were compared with satellite-derived LST and TVSDI values for the same satellite overpass dates. The close correspondence between satellite-driven LST and in-situ soil temperature measurements provided strong validation for remote sensing. The negligible mean bias and limited variability from the results obtained confirmed that LST accurately represents near-surface thermal conditions across southern Malta.

Field data showed a very strong positive statistically significant relationship between soil temperature and TVSDI, meaning that higher soil temperatures were associated with higher soil dryness. Contrastingly, soil moisture exhibited a weaker, non-significant negative relationship, meaning that higher soil moisture levels resulted in lower TVSDI values. These results reinforce the dominance of thermal conditions on surface dryness, particularly during the dry season. The limited predictive power of soil moisture may be partly attributed to rapid surface drying and shallow soil profiles, which are characteristic of the soils of Malta. Similar findings have been reported in semi-arid regions, where surface temperature responds more directly to atmospheric forcing than soil moisture measurements taken at limited depths (Koster et al., 2024).

5.7.3 | Soil moisture measurements across the sampled sites

Among all the sampled locations, Siġġiewi exhibited the highest R^2 value of 0.61 between month and soil moisture. This strong relationship reflects the pronounced seasonal dependency of soil moisture, which typically fluctuates in response to rainfall patterns, evapotranspiration rates and temperature, all of which are inherently tied to the month of year (Xue & Wu, 2025). During drier summer months, high temperatures and limited to no precipitation can result in significant moisture depletion, while wetter winter months may replenish soil moisture through rainfall and reduced evaporation. The remaining 39% of variation in soil moisture may be attributed to site-specific variables such as land use, soil porosity, slope, vegetation density and irrigation (Greiser et al., 2024). This result underscores the critical role of the seasons in understanding and managing soil water availability, especially in semi-arid climates where moisture is a limiting factor for both natural ecosystems and agriculture.

Throughout the duration of the study, Żurrieq consistently recorded the highest soil moisture levels among all sites, suggesting that this area may benefit from factors such as lower evapotranspiration and soil characteristics that promote water retention (Klocke & Hegert, 1990). In fact, from the lab work conducted, it was found that the predominant soil found in Żurrieq was loam. Loam soils have a good water holding capacity due to their balanced composition of sand, silt and clay particles (Klocke & Hegert, 1990). In contrast, Mqabba consistently exhibited the lowest soil moisture values, indicating poor water-holding capacity, limited vegetation and greater exposure to drying conditions such as more exposure to wind. The consistently higher soil moisture levels observed in Żurrieq, compared to the persistently lower values recorded in Mqabba, suggest that soil moisture dynamics across the study sites are influenced by local environmental controls rather than a uniform regional response. These differences likely reflect site-specific factors such as soil texture, geomorphological setting, exposure to wind and solar radiation and variations in soil depth.

Among the months, May recorded the highest soil moisture levels overall, which can be directly attributed to a rainfall event that occurred the day before measurements were taken. This clearly demonstrates the immediate impact of precipitation on soil moisture dynamics. A similar pattern was reported by Zingol et al. (2025), who found that soil moisture exhibited clear temporal variability in response to hydrological and meteorological drivers. Conversely, July emerged as the driest month across all locations, reflecting typical seasonal patterns in Mediterranean climates where hot, dry summers significantly reduce soil water content due to high temperatures and low thermal inertia (Weng, 2009). Furthermore, regression analyses confirmed that soil moisture had a weak non-significant effect on TVSDI, meaning that soil moisture did not significantly predict TVSDI within the sites across southern Malta. Such variability implies that soil moisture behaviour may follow different response patterns across sites, thereby weakening the strength of a single regression relationship between soil moisture and TVSDI.

While the present analysis identified clear temporal variations in soil moisture across the study period, further subdivision of the data by meteorological season or individual month could have provided additional insights into soil moisture dynamics. The Mediterranean climate is characterised by marked seasonal contrasts in precipitation and temperature, with rapid transitions between wetter spring conditions and the prolonged dry summer period. Analysing soil moisture at a finer temporal scale could have helped to distinguish short-term responses to individual rainfall events from broader seasonal drying trends. Such an approach might have also improved the understanding of how soil moisture responds to changing meteorological conditions throughout the year and enhance the interpretation of soil dryness patterns in the Maltese Islands.

Soil moisture monthly values generally remained below 10%, indicating a persistent level of dryness in the soils of Malta from April through September. The same results were obtained by Mifsud (2002), where soil moisture content did not exceed 14% during the dry summer season. The only exception occurred in May at the Żurrieq and Qrendi sites, where moisture levels slightly exceeded 10% due to recorded rainfall on the previous day. This highlights the strong influence of climatic factors, particularly air temperature and precipitation on soil moisture levels. High temperatures significantly reduce soil moisture by accelerating evaporation from the soil surface, increasing plant transpiration and limiting the amount of water available for plant absorption and microbial processes.

Prolonged moisture loss associated with high temperatures also negatively affects soil fertility by reducing microbial activity, slowing nutrient cycling and limiting the availability of essential nutrients for plant growth (Abu-Hamdeh, 2003; Costa et al., 2023).

These findings align with multiple models predicting decreased rainfall and increased drying across the Mediterranean region throughout the years (Seager et al., 2024). Various models also project increased frequency and severity of droughts (Tramblay et al. 2020). The region is especially vulnerable to drying because several contributing factors are working together. Overall, projections indicate continued drying in the Mediterranean (Seager et al., 2024).

5.7.4 | Soil texture measurements across the sampled sites

Lab analysis revealed that loam was the dominant soil texture at the selected sites, with the exception of Wied Babu, which featured a clay loam texture (Hillel, 2005). High temperatures do not directly affect soil texture but they do impact how well soil retains moisture, depending on the soil's texture. Clay soils hold water for longer due to their finer particle size and strong capillary forces, thereby reducing drainage and water loss. However, they tend to compact and crack when dry (Klocke & Hergert, 1990). Further regression analyses confirmed that soil texture had no significant influence on TVSDI across southern Malta, suggesting that spatial variability in TVSDI is influenced by factors other than soil physical properties.

5.8 | Implications of rising soil temperatures on soil in the context of climate change

Against the climate change background, the rising land surface temperatures observed in this study have a direct impact and several implications on Malta's soil system. As discussed in Chapter 2, increasing climatic pressure has direct and severe implications for soil moisture dynamics. The Mann-Kendall test conducted in this study revealed positive Sen's slope values across all districts and seasons, with statistically significant increases in LST in several districts during the wet season. This suggests that seasonal cooling is becoming less effective over time, with winter and transitional seasons being expected to experience notable temperature increases (Ali et al., 2022).

Although dry season trends were not significant, the overall pattern suggests gradual warming that is consistent with regional climate projections for the Mediterranean basin (Ali et al., 2022). In semi-arid regions like Malta, higher temperatures accelerate evapotranspiration, reduce soil moisture availability and intensify dryness, leading to ecological, social and economic consequences such as agricultural losses and land degradation (Kutiel, 2019; IPCC, 2018). These reinforce soil dryness even when long-term drought indices like the TVSDI do not yet display statistically significant trends. The absence of significant trends in TVSDI may reflect the relatively short 10-year study period and the high interannual variability of drought conditions. As highlighted by Abu Arra & Sisman (2025), longer time-series are generally required to detect robust trends in drought indices.

The year 2024 emerged as an extreme case, with exceptionally high dry season LST and the highest TVSDI values recorded. This occurrence of thermal extremes highlights the vulnerability of the soils of Malta to episodic heatwaves and prolonged dry spells, which are becoming increasingly frequent. Similar extremes have been increasingly reported across the Mediterranean region, as stated in the IPCC's Sixth Assessment Report (Ali et al., 2022). Such years may become more frequent under future climate scenarios (Moran-Ordonez et al., 2020), raising concerns for soil degradation, agricultural productivity, food security and ecosystem resilience in Malta (Brevik, 2013). These episodic events can push soil systems beyond their resilience thresholds, increasing the vulnerability to degradation, even in the absence of statistically significant drought trends. These findings suggest that the soils of Malta are already responding to climatic changes.

The coupling between soil moisture and climate is especially strong in semi-arid regions where feedback loops amplify warming and drying trends (Dirmeyer, 2011). Under such conditions, soils act not only as passive recipients of climatic forcing but also as active regulators of land-atmosphere interactions.

Rising temperatures may indirectly influence soil erosion dynamics by reducing vegetation cover during prolonged periods of dryness. Galdies, Azzopardi and Sacco (2022) demonstrated that projected climate conditions are likely to decrease soil erosion rates by half in Gozo under scenarios of increased drought conditions.

Beyond soil moisture stress, rising temperatures also have profound implications for soil fertility and nutrient cycling. According to Filho et al. (2025), climate-induced warming alters soil physical, chemical and biological processes, often accelerating organic matter decomposition and disrupting nutrient availability. Higher soil temperatures increase microbial respiration rates if there is sufficient soil moisture available, leading to faster mineralisation of organic matter and also leading to the depletion of soil organic carbon over time. While short-term nutrient release may occur, prolonged warming ultimately reduces soil fertility by diminishing soil organic carbon, which is essential for nutrient retention, soil structure and water holding capacity (Mondal, 2021; Oishy et al., 2025).

5.8.1 | The effect of climate change on soil texture

The implications of prolonged dryness on soil function are particularly relevant when considered alongside the soil texture results obtained in this study. The predominance of loamy soils in Żurrieq, which consistently recorded higher soil moisture levels, suggests that its balanced particle composition enhances moisture retention even under semi-arid conditions. In contrast, sites exhibiting lower soil moisture levels reflect textures that respond more sensitively to drying processes, either through rapid moisture loss or structural limitations that restrict infiltration. As highlighted in the literature, while soil texture itself remains relatively stable, extended dry conditions can alter how soils function by reducing biological activity and weakening aggregate stability (Mao, Wei & Shao, 2022). In the shallow soils of Malta, which are already characterised by low organic matter content, these effects may be amplified. Under prolonged dryness, loamy soils may begin to behave more like coarser or finer textured soils depending on their dominant fractions, influencing water retention capacity and thermal response (Adi Associates, 2022; Chatzimpaloglou et al., 2020). This helps explain the observed variability in moisture levels between sites, as differences in texture interact with aridity-driven structural degradation to influence infiltration, storage and evaporation processes. Consequently, the soil texture results reinforce the role of pedological characteristics in moderating soil moisture dynamics and highlight how semi-arid climatic conditions can alter the functional behaviour of otherwise favourable soil types (Quintana et al., 2023).

5.8.2 | The influence of climate change on soil temperature and moisture

The interaction between solar radiation, soil moisture and soil temperature provides a useful framework for interpreting the results obtained in this study. As described in the literature, soils absorb incoming solar radiation, which raises their temperature, particularly when limited moisture is available to dissipate energy through evaporation (Al-Kayssi et al., 1990). This mechanism aligns closely with the study’s findings, where areas exhibiting higher LST corresponded with zones identified as drier in the TVSDI maps. Under low soil moisture conditions, more absorbed energy is retained as sensible heat, accelerating soil warming and further enhancing evaporation rates. This reinforces a feedback cycle in which elevated temperatures promote moisture loss, while reduced soil moisture limits thermal buffering, leading to further surface heating (Marquis, 1967). Such dynamics help explain the strong dry-season coupling observed between LST and soil dryness across several districts. Conversely, locations that retained higher moisture levels demonstrated moderate thermal responses, supporting the role of soil water content in stabilising surface temperature. These results highlight how soil moisture availability directly influences thermal behaviour in semi-arid environments like Malta, where reduced moisture not only intensifies heating but may also contribute to plant stress and reduced soil functionality under prolonged dry conditions.

5.9 | Adaptive measures

To build resilience in the face of increasing aridity and climate variability, adaptive strategies in the Maltese Islands can benefit from integrating both traditional land management practices and data-driven monitoring approaches. The results of this study demonstrated that land surface temperature plays a strong role in influencing soil dryness during the dry season, while soil moisture dynamics are strongly shaped by local environmental factors such as soil texture, topography and hydrology. These insights suggest that water management strategies, including efficient irrigation, rainwater harvesting and seasonal storage of winter rainfall, could be spatially targeted using remotely sensed indicators of thermal and moisture stress (Bezzina & Scicluna Laiviera, 2015; Kakoulas et al., 2022; Tramblay et al., 2020). For example, districts consistently exhibiting higher LST values and stronger dry-season LST–TVSDI coupling may represent priority zones for irrigation efficiency measures or soil moisture conservation practices. Similarly, areas identified as naturally moisture-retentive, such as those underlain by clay-rich soils or influenced by perched aquifers, could be managed to enhance water storage and reduce runoff losses.

An open-source tool has been developed and used in Sri Lanka and California to predict future EVI values based on satellite datasets (Nay, Burchfield & Gilligan, 2017). Public awareness and community engagement are equally important. Raising awareness and encouraging local participation in sustainable land and water use practices can significantly enhance the societal capacity to adapt to climate change (Golemi et al., 2025). These measures form a multi-layered approach to address the pressing challenges posed by climate change, especially in vulnerable regions like the Mediterranean region.

The regression analyses conducted in this study further highlight the practical value of satellite-derived indices in supporting land and water management decisions. The strong predictive relationship between LST and soil dryness during the dry season suggests that remotely sensed temperature patterns can serve as early indicators of moisture stress, allowing farmers and planners to anticipate periods of heightened evapotranspiration demand. This information could support adaptive irrigation scheduling, targeted soil conservation practices such as mulching, and the selection of drought-tolerant crops suited to specific micro-environmental conditions (El-Beltagi et al., 2022; Haruna et al., 2020; Kakoulas et al., 2022). At the same time, the weaker wet-season relationships observed in this study highlight the importance of integrating hydrological considerations into management strategies, as moisture availability during this period is influenced more by rainfall and local soil characteristics than by thermal forcing.

Vegetation restoration is globally recognised as one of the most effective adaptive responses to such challenges. It helps protect the soil surface from direct heat exchange and regulates soil temperature. China's reforestation programs have successfully curbed desertification in semi-arid regions (He et al., 2024), while European funds have supported afforestation efforts and practices, especially in Mediterranean countries (Munoz-Rojas et al., 2012).

The findings of this study also have direct applications for drought-risk assessment and climate adaptation planning in Malta. Areas that consistently exhibited high LST values and elevated TVSDI levels during the dry season may be considered potential soil vulnerability hotspots, where prolonged moisture deficits could increase the risk of land degradation, reduced agricultural productivity and heightened irrigation demand. Mapping these areas can assist policymakers and land managers in prioritising adaptation measures such as rainwater harvesting, managed aquifer recharge, soil conservation practices, mulching and the promotion of drought-tolerant crop varieties. Given Malta's limited freshwater resources and dependence on groundwater, particular emphasis should be placed on measures that improve soil moisture retention and increase the efficiency of water use within the agricultural sector. Furthermore, the integration of satellite-derived indicators such as LST, EVI and TVSDI into a GIS system could support the development of a national drought-risk mapping framework. By routinely updating these indicators using freely available satellite imagery, an operational drought-monitoring system could be established to identify emerging dryness hotspots, track seasonal changes in soil conditions and provide early warning information to farmers, water managers and policymakers.

Such a framework would support evidence-based decision-making and strengthen Malta’s capacity to respond proactively to increasing climate-related drought risks.

In small island environments such as Malta, where dense in-situ monitoring networks are limited, the combined use of regression models and satellite-derived indices such as LST, TVSDI and EVI offers a practical framework for local-scale monitoring. The spatial patterns identified in this study, including consistently warmer districts and moisture-retentive areas, demonstrate how remote sensing can support proactive soil and water management by identifying emerging dryness hotspots and areas of relative resilience. These tools provide repeatable, spatially continuous information that can inform agricultural planning, water resource allocation and land management policies. Ultimately, integrating remote sensing outputs with local environmental knowledge represents a viable approach for strengthening adaptive capacity and improving sustainable soil and water management in the Maltese Islands under future climate pressures.

5.10 | Local environmental management

5.10.1 | Soil and water governance in Malta

The need for this EU-wide framework is particularly relevant for Mediterranean regions where climate stressors interact with land pressures to accelerate degradation. The JRC reference report on the State of Soil in Europe (Jones, 2012) documents continent-wide threats such as declining organic matter, erosion, contamination, compaction and sealing, noting that low organic carbon is especially prevalent in parts of southern Europe. For Malta, these concerns are amplified by shallow soils, limited land area and a high exposure to land take and fragmentation. In such settings, policy that strengthens soil monitoring and targets prevention is critical for long-term sustainability (Jones, 2012).

At national level, Malta already has legal instruments that recognise soils as a protected resource, including the Fertile Soil (Preservation) Act (1973) which regulates the movement and mishandling of fertile soil. However, the practical challenge is ensuring that such protections operate as part of a broader, preventative soil-health framework rather than mainly as a permitting or enforcement mechanism. Aligning Malta's soil governance with EU monitoring and resilience expectations would support stronger baselines, clearer accountability and more systematic targeting of measures.

For water, the policy pathway is already strongly structured by EU obligations through the Water Framework Directive (EWA, n.d.), operationalised locally via Malta's 3rd River Basin Management Plan 2021–2027, published by ERA and EWA (2024). The RBMP explicitly frames Malta's condition as one of structural water scarcity, rather than occasional drought alone and it outlines governance roles and measures across groundwater, coastal waters and catchments. This is important for sustainability because it shifts planning from short-term supply responses to integrated demand management, catchment measures and resilience-building, especially as climate change increases pressure on recharge and quality.

5.10.2 | Way forward for the Maltese Islands

Taken together, EU soil monitoring policy and Malta's RBMP agenda point toward the same practical conclusion that soil and water resilience must be managed as one system. In Malta, drought signals detected through thermal–vegetation indices like the TVSDI can become most actionable when embedded into governance and implementation pathways. This is also consistent with Malta's increasing emphasis on non-conventional water resources, including treated water reuse, which aims to reduce pressure on groundwater while supporting agriculture. This approach can be strengthened further when linked to spatial drought-risk mapping and soil vulnerability hotspots (EWA, 2025; WSC, n.d.).

The sustainability implications extend beyond resource efficiency. Soil loss and aquifer degradation are slow to reverse and can lock future generations into higher-cost solutions. The emerging EU framework therefore matters for Malta not just as compliance, but as leverage as it can support long-term investment in monitoring, data-driven planning and targeted incentives that protect remaining soil functions and stabilise water demand. Framed this way, soil and water management becomes a central pillar of climate adaptation and sustainable development in the Maltese Islands and binding governance trajectories at EU and national levels (European Commission, n.d.).

5.11 | The importance of soil and water resource management in Malta

In addition to the climatic indicators of drought and soil moisture stress, the physical and anthropogenic pressures on soil resources in the Maltese Islands are many. Previous research on soil reveals that Malta's soils are shallow and fragile due to the underlying karstic limestone geology, which limits deep soil development and increases susceptibility to erosion under both natural climatic forces and human activities. Intense rainfall events, combined with strong winds and irregular precipitation typical of Mediterranean semi-arid climates, accelerate surface runoff and soil erosion, which are further exacerbated where vegetation cover is sparse or traditional land management practices have been abandoned. Moreover, urban expansion and land clearance for development continue to fragment and degrade productive soil landscapes, threatening soil integrity and long-term fertility (Mondal, 2021; Role & Attard, n.d.).

The strategic review of soil problems in Malta has underscored that past attitudes toward soil have been eroded by modern urbanisation and economic pressures, reducing the social valuation of soil as a finite natural capital. Despite legislative instruments such as the Fertile Soil (Preservation) Act intended to regulate soil movement and prevent soil loss, gaps remain in public awareness and integrated soil protection at the policy level. This situation has manifested not only in increased physical degradation but also in the loss of organic matter and poor soil quality across many agricultural and semi-natural areas (Role & Attard, n.d.). Climate trends documented in The State of the Climate Report issued in 2022 confirm a long-term warming and drying trajectory for the Maltese Islands, where increasing mean temperatures and reduced rainfall intensify drought frequency and severity. These climatic shifts heighten soil moisture stress, reduce infiltration and further strain limited freshwater resources that are already stressed by high demand and limited natural recharge. Water scarcity in Malta has historically driven reliance on groundwater abstraction and energy-intensive desalination, while saltwater intrusion into aquifers reduces freshwater quality, particularly near the coast and in low-lying agricultural zones

Addressing these intertwined soil and water challenges requires integrated management strategies that combine policy, technology and nature-based interventions. Policy frameworks such as Malta's National Agricultural Policy and river basin management planning emphasise sustainable use of soil and water resources, flood and drought risk management and maintaining ecological function. Sustainable agricultural practices, including conservation tillage, increased organic matter inputs and crop rotations with deep-rooted or cover crops, have been shown in local assessments to improve soil structure, enhance water retention and reduce erosion risk. These practices not only contribute to soil health but also support ecosystem services that underpin long-term agricultural productivity (Sultana, 2015).

The strong coupling between temperature and dryness highlights the importance of thermal indicators in drought monitoring frameworks for the Maltese Islands. TVSDI, when combined with LST, offers a valuable tool for identifying vulnerable areas and periods of heightened soil moisture stress. The identification of recurrent dryness hotspot areas suggests priority areas for soil conservation, irrigation planning and vegetation management. Maintaining vegetation cover and enhancing soil water retention may help mitigate surface drying and thermal extremes.

Innovation in water management also plays a crucial role. Technologies such as precision irrigation and IoT-based irrigation systems have been proposed to increase water use efficiency, reduce waste and better match supply with crop water needs, which is very important in semi-arid environments like Malta's, where freshwater resources are limited and climate change impacts are projected to intensify (Gauci, 2024).

Beyond technical solutions, nature-based solutions such as restoration of vegetative cover and green infrastructure can enhance soil and water resilience. Ecosystem services delivered by well-managed soils like water filtration and carbon sequestration contribute to landscape sustainability and support human well-being. Integrating these solutions into land-use planning, agricultural extension and climate adaptation strategies strengthens resilience to future environmental change while preserving soil and water resources for future generations (Balzan, 2021).

5.12 | Methodological limitations and data constraints

Despite yielding valuable insights, this study is not without limitations. One of the most significant constraints was the relatively small sample size of soils collected across the Maltese Islands, which may not fully represent the spatial variability of the different soil types found in the Maltese Islands and the different conditions present across the archipelago. This limitation restricts the generalisability of the findings and underscores the need for broader sampling in future research. Furthermore, the 10-year temporal window might have been insufficient to capture long-term drought trends.

Time constraints also posed a challenge, limiting the number of locations selected for the study and the ability to capture seasonal variability in temperature and soil factors, especially in the winter season. Given more time, the study could have also extended beyond soil physical properties to include the effects of temperature fluctuations on other critical aspects of soil health, such as soil chemistry and soil biology. These components, such as nutrient cycles, microbial activity and organic matter are equally influenced by temperature variations and could provide a more holistic understanding of soil responses under changing climatic conditions. However, due to time limitations, the research was necessarily focused on the physical dimension of soil state, which, while valuable, offers only a partial view of the broader soil system.

The resolution of the remote sensing data employed, even though it was suitable for regional analysis, may not have captured small changes in soil state, particularly in areas with different land covers or microclimatic conditions. Although the study focused primarily on non-urban, agricultural areas, garrigue landscapes were also mapped, which may have introduced additional variability due to their distinct spectral and moisture characteristics. The reliance on cloud-free satellite imagery further narrowed the dataset, especially during winter months when cloud cover was more prevalent. Lastly, the study primarily focused on temperature fluctuations, potentially overlooking other climatic or anthropogenic factors such as precipitation patterns, land use changes or irrigation practices that may also significantly influence soil dynamics. Addressing these limitations in future work could enhance the validity and applicability of the research outcomes.

While the district-based analysis provided a useful framework for identifying broad spatial trends, administrative boundaries did not necessarily correspond to the environmental processes controlling LST variability. Factors such as soil type, geology, topography, hydrology, land use and proximity to the coast often transcend district boundaries and may exert a stronger influence on surface temperature patterns than administrative divisions. Consequently, future studies could benefit from adopting environmental or geomorphological classifications, such as watershed boundaries, valley systems, geological units or land-cover zones, to better capture the spatial controls on LST distribution. Such an approach may provide a more process-based understanding of the interactions between soil properties, moisture availability and surface temperature across the Maltese Islands.

While the results indicate a strong influence of thermal conditions on surface dryness, this also highlights an inherent limitation of remote sensing approaches that rely on surface temperature as a proxy for soil moisture dynamics. The comparatively weaker predictive role of soil moisture in this study may be partly attributed to the shallow and rapidly drying soils characteristic of the Maltese Islands. In such environments, surface moisture conditions can fluctuate quickly following rainfall events, meaning that satellite-derived indicators may primarily capture short-term surface responses rather than deeper soil moisture storage. This limitation is particularly relevant in semi-arid settings, where land surface temperature often responds more directly to atmospheric forcing than to subsurface hydrological processes (Koster et al., 2024). Consequently, while LST-based indices such as TVSDI are effective in detecting surface moisture stress during dry periods, they may underrepresent longer-term soil moisture dynamics or deeper hydrological buffering. This suggests that temperature-driven remote sensing techniques should be interpreted cautiously, as they may reflect surface drying rather than the full complexity of soil water availability.

The index was calculated using three key variables: LST, EVI and SWIR. However, each of these variables comes with its own limitations, which, in turn, can affect the overall accuracy and reliability of the index. For instance, the use of satellite imagery to analyse surface conditions is one of the primary constraints as it cannot capture subsurface elements such as soil moisture, a crucial factor in assessing drought severity.

Despite these limitations, the TVSDI remains a valuable tool when paired with the latest high-resolution datasets. By analysing these TVSDI maps, researchers can gain insight into the impact of climate change on the Maltese Islands, providing essential information for developing drought resilience strategies and management plans, especially if longer time series are used. This data is critical in planning for future climate shifts, aiding in proactive responses to mitigate drought risks.

5.13 | Conclusion and recommendations for future research

This discussion highlighted the complex and dynamic interactions between temperature fluctuations and soil physical properties in the Maltese Islands, a region already vulnerable to climate-related stressors due to its semi-arid Mediterranean climate. By integrating remote sensing techniques, particularly the satellite-derived LST and TVSDI, this study demonstrated the utility of spatial and temporal monitoring in capturing variations in soil temperature, soil moisture and dryness, linked to thermal extremes.

Looking forward, Tramblay et al. (2020) project that ongoing human-induced climate change is expected to alter ecosystems by 2100, resulting in the spread of drylands and desert areas in southern Europe. In this context, improved drought monitoring and soil assessment tools are essential. Land surface models, which were originally developed for numerical weather prediction, could be adapted to enhance drought monitoring in semi-arid Mediterranean regions. While initiatives such as the European Drought Impact Inventory provide valuable insights on drought impacts, there is still room for improvement, particularly in expanding its coverage to better include southern European countries like Malta (Tramblay et al., 2020). Integrating remote sensing indicators such as LST and TVSDI could significantly improve early warning systems and inform sustainable soil and land management strategies under a warming climate.

The evidence suggests that increasing surface temperatures, exacerbated by regional climate trends, contribute significantly to soil dryness, especially during prolonged warm periods and during the dry season. These temperature-induced changes not only affect soil moisture retention but also impact vegetation cover, impose more water scarcity and threaten agricultural sustainability.

Moreover, the application of remote sensing has proven effective for evaluating these impacts at a local scale, offering a practical method for ongoing environmental monitoring. The insights gained here underscore the importance of incorporating adaptive strategies such as soil conservation, improved irrigation and early warning systems into land management policies to enhance the resilience against thermal and hydrological stressors.

Overall, this chapter reinforces the value of satellite-based tools in understanding climate-soil interactions and provides a scientific foundation for informed decision-making in Malta’s efforts to combat land degradation and adapt to a warming climate.

Chapter 6: Conclusion

This study set out to examine the spatial and temporal variability of soil temperature and dryness across the Maltese Islands over a ten-year period, from 2015 to 2024, using remote sensing techniques. Specifically, it aimed to assess seasonal and interannual changes in LST and the TVSDI, how these changes are impacting Malta's soil state and to evaluate the relationship between temperature and soil dryness under Malta's semi-arid Mediterranean climate. By integrating satellite-derived data with statistical analyses and supporting field observations, the study sought to enhance the understanding of drought dynamics in a small island environment and to assess the applicability of TVSDI under local conditions.

The results demonstrated a clear seasonal pattern in LST across all districts, with dry-season temperatures consistently exceeding wet-season values throughout the study period. Statistical analysis confirmed that seasonality was the dominant factor influencing LST, while district-level differences were not statistically significant once seasonal effects were accounted for. Despite this, spatial patterns revealed persistently higher LST values in the more urbanised Southern Harbour, South Eastern and Northern Harbour districts, particularly during the dry season, reflecting the influence of land cover, exposure and urban heat island effects. Conversely, Gozo and the Western district consistently exhibited cooler surface temperatures, likely linked to greater agricultural land cover, clay-rich soils, hydrologically active valleys and the moderating effects of topography and soil moisture availability.

Analysis of TVSDI revealed markedly different behaviour between seasons. During the wet season, dryness values remained within a narrow range across all districts and years, indicating that winter rainfall effectively homogenises soil moisture conditions across the islands. In contrast, dry-season TVSDI values displayed pronounced spatial and temporal variability, with the highest dryness consistently observed in the South Eastern, Western and Gozo districts. These areas are characterised by exposed agricultural soils, shallow karstic terrain and limited moisture retention, making them particularly vulnerable to summer drying. Interannually, the study identified a gradual intensification of dry-season soil dryness over the decade, with extreme dryness recorded in 2016, 2020 and especially 2024, the latter coinciding with exceptionally high surface temperatures.

A key finding of this research was the strong and statistically significant positive relationship between LST and TVSDI during the dry season across most districts. Correlation and regression analyses confirmed that increases in surface temperature are closely associated with increased soil dryness when moisture availability is limited. LST emerged as the only strong predictor of TVSDI in the regression models, while season and district effects became insignificant once temperature was accounted for. This indicated that LST captures much of the seasonal and environmental variability influencing soil dryness, reinforcing its value as a proxy for surface moisture stress in semi-arid conditions. In contrast, weak or non-significant LST-TVSDI relationships during the wet season highlighted the dominant role of rainfall in moderating soil moisture and decoupling temperature from dryness under replenished conditions.

The integration of satellite-derived indices with field and laboratory observations further demonstrated that remote sensing provides a reliable and effective framework for monitoring soil temperature and dryness in small island environments such as Malta. The ground-based soil sampling conducted during the 2024 study period provided additional validation of soil surface conditions and supported the interpretation of satellite-derived dryness patterns. Despite limitations related to spatial resolution, cloud cover and the indirect nature of soil moisture estimation, TVSDI proved particularly effective during the dry season, when thermal conditions dominate soil moisture dynamics. The findings confirm that remote sensing-based dryness indices can capture both long-term trends and episodic drought events, offering valuable insights for soil and water resource management in data-scarce regions.

Overall, this study provided clear evidence of increasing thermal stress and intensifying dry-season soil dryness across the Maltese Islands over the past decade, consistent with broader Mediterranean climate warming trends. It highlighted the sensitivity of the Maltese soils to rising temperatures and underscored the importance of seasonal context, land cover and topographic controls in shaping soil moisture dynamics.

Future research should build on this work by incorporating higher-resolution soil moisture datasets, longer time series and climate model projections to better quantify drought risk and inform targeted adaptation and land management strategies in Malta.

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Appendix

Appendix 1

Soil sample collection form used during all the fieldworks

Samples	Date	Time	Location	Temp.
1			Munqar– Żurrieq (Terra: Xagħra series) (*LEPTOSOL*)	
2				
3				
Samples	**Date**	**Time**	**Location**	**Temp.**
1			Wied Babu – Żurrieq (Iklin complex) (*LUVISOL*)	
2				
3				
Samples	**Date**	**Time**	**Location**	**Temp.**
1			Qrendi (Terra: Tas-Siġra series) (*LUVISOL*)	
2				
3				
Samples	**Date**	**Time**	**Location**	**Temp.**
1			Ħal Millieri – Mqabba (Xerorendzinas: San Biagio series) (*CALCISOL*)	
2				
3				
Samples	**Date**	**Time**	**Location**	**Temp.**
1			Girgenti – Siġġiewi (Carbonate raw: San Lawrenz series) (*VERTISOL*)	
2				
3				

Appendix 2

Soil temperature readings at every location for each satellite overpass date

Date	Żurrieq	Wied Babu	Qrendi	Mqabba	Siġġiewi
07/04/2024	26.7°C	23.7°C	23.1°C	21.3°C	23.1°C
23/04/2024	24.8°C	22.1°C	27.3°C	25.9°C	25.1°C
09/05/2024	22.3°C	21.3°C	21.6°C	22.2°C	25.1°C
25/05/2024	31.2°C	31.1°C	30.8°C	30.6°C	32.0°C
10/06/2024	38.9°C	39.4°C	39.7°C	39.4°C	41.4°C
26/06/2024	43.2°C	38°C	42.3°C	38.5°C	41.8°C
12/07/2024	42.7°C	39.4°C	41.9°C	39.7°C	40°C
28/07/2024	37.2°C	35°C	40°C	38°C	35.7°C
13/08/2024	46.3°C	41.7°C	44.6°C	41.7°C	43.3°C
29/08/2024	34.8°C	35.4°C	39.9°C	34.6°C	33.6°C
14/09/2024	30.5°C	33.3°C	32.4°C	31.4°C	29.6°C
30/09/2024	27.3°C	32.6°C	29.6°C	30.7°C	30.5°C

Soil moisture readings at every location for each satellite overpass date

Date	Żurrieq	Wied Babu	Qrendi	Mqabba	Siġġiewi
07/04/2024	3.96%	4.40%	4.17%	4.14%	8.49%
23/04/2024	5.58%	5.20%	3.53%	2.16%	4.89%
09/05/2024	47.21%	13.03%	24.42%	3.43%	11.91%
25/05/2024	5.15%	4.02%	2.80%	2.65%	4.47%
10/06/2024	5.01%	3.99%	2.95%	2.34%	4.64%
26/06/2024	4.59%	3.04%	3.24%	1.75%	3.47%
12/07/2024	2.64%	2.21%	2.35%	2.11%	2.13%
28/07/2024	2.18%	2.34%	2.25%	2.03%	2.48%
13/08/2024	3.31%	2.04%	1.72%	1.25%	1.66%
29/08/2024	7.27%	3.49%	3.09%	4.96%	3.04%
14/09/2024	8.73%	3.54%	3.73%	2.08%	2.04%
30/09/2024	8.18%	6.41%	9.16%	4.72%	5.03%

Appendix 3

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2015

Year	District	Season	Mean LST	Mean TVSDI
2015	Gozo	Wet	20.6	0.55
2015	Northern	Wet	20.6	0.55
2015	Northern Harbour	Wet	21.7	0.55
2015	South Eastern	Wet	21.9	0.55
2015	Southern Harbour	Wet	21.9	0.55
2015	Western	Wet	20.1	0.55
2015	Gozo	Dry	28.7	0.58
2015	Northern	Dry	28.7	0.55
2015	Northern Harbour	Dry	28.9	0.55
2015	South Eastern	Dry	29.1	0.58
2015	Southern Harbour	Dry	29	0.55
2015	Western	Dry	29.3	0.58

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2016

Year	District	Season	Mean LST	Mean TVSDI
2016	Gozo	Wet	21	0.55
2016	Northern	Wet	22.9	0.55
2016	Northern Harbour	Wet	22.8	0.55
2016	South Eastern	Wet	22.9	0.55
2016	Southern Harbour	Wet	22.7	0.55
2016	Western	Wet	23.1	0.55
2016	Gozo	Dry	32.1	0.6
2016	Northern	Dry	31.8	0.6
2016	Northern Harbour	Dry	31.2	0.58
2016	South Eastern	Dry	30.7	0.62
2016	Southern Harbour	Dry	31.4	0.58
2016	Western	Dry	31.4	0.62

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2017

Year	District	Season	Mean LST	Mean TVSDI
2017	Gozo	Wet	16.3	0.52
2017	Northern	Wet	16.6	0.58
2017	Northern Harbour	Wet	16.9	0.55
2017	South Eastern	Wet	16.8	0.55
2017	Southern Harbour	Wet	17	0.55
2017	Western	Wet	16.6	0.58
2017	Gozo	Dry	29.2	0.55
2017	Northern	Dry	29.2	0.6
2017	Northern Harbour	Dry	29.3	0.58
2017	South Eastern	Dry	30.1	0.6
2017	Southern Harbour	Dry	29.8	0.55
2017	Western	Dry	29.6	0.6

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2018

Year	District	Season	Mean LST	Mean TVSDI
2018	Gozo	Wet	16.8	0.55
2018	Northern	Wet	18.4	0.52
2018	Northern Harbour	Wet	18.9	0.52
2018	South Eastern	Wet	18.5	0.55
2018	Southern Harbour	Wet	19	0.52
2018	Western	Wet	18	0.52
2018	Gozo	Dry	27.9	0.58
2018	Northern	Dry	27.8	0.55
2018	Northern Harbour	Dry	27.6	0.55
2018	South Eastern	Dry	28.9	0.58
2018	Southern Harbour	Dry	28.5	0.55
2018	Western	Dry	28.3	0.58

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2019

Year	District	Season	Mean LST	Mean TVSDI
2019	Gozo	Wet	19.3	0.52
2019	Northern	Wet	19.6	0.55
2019	Northern Harbour	Wet	21.9	0.55
2019	South Eastern	Wet	20.1	0.52
2019	Southern Harbour	Wet	21.9	0.55
2019	Western	Wet	18.5	0.52
2019	Gozo	Dry	30.1	0.58
2019	Northern	Dry	30	0.55
2019	Northern Harbour	Dry	30.5	0.55
2019	South Eastern	Dry	30.6	0.58
2019	Southern Harbour	Dry	31	0.55
2019	Western	Dry	30.3	0.58

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2020

Year	District	Season	Mean LST	Mean TVSDI
2020	Gozo	Wet	26	0.58
2020	Northern	Wet	25.9	0.55
2020	Northern Harbour	Wet	25.5	0.55
2020	South Eastern	Wet	26.7	0.58
2020	Southern Harbour	Wet	26.2	0.55
2020	Western	Wet	25.6	0.58
2020	Gozo	Dry	30.6	0.6
2020	Northern	Dry	32.5	0.58
2020	Northern Harbour	Dry	31.3	0.58
2020	South Eastern	Dry	30.7	0.6
2020	Southern Harbour	Dry	31.2	0.6
2020	Western	Dry	30.7	0.6

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2021

Year	District	Season	Mean LST	Mean TVSDI
2021	Gozo	Wet	18.6	0.55
2021	Northern	Wet	18.9	0.55
2021	Northern Harbour	Wet	19.2	0.55
2021	South Eastern	Wet	19.4	0.55
2021	Southern Harbour	Wet	19.3	0.55
2021	Western	Wet	19.1	0.55
2021	Gozo	Dry	33	0.6
2021	Northern	Dry	32.6	0.58
2021	Northern Harbour	Dry	32.9	0.58
2021	South Eastern	Dry	33.1	0.6
2021	Southern Harbour	Dry	33.5	0.58
2021	Western	Dry	33.1	0.6

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2022

Year	District	Season	Mean LST	Mean TVSDI
2022	Gozo	Wet	21.7	0.55
2022	Northern	Wet	22.6	0.55
2022	Northern Harbour	Wet	23.1	0.55
2022	South Eastern	Wet	22.6	0.55
2022	Southern Harbour	Wet	22.9	0.55
2022	Western	Wet	22.3	0.55
2022	Gozo	Dry	28.9	0.58
2022	Northern	Dry	28.8	0.58
2022	Northern Harbour	Dry	28.6	0.55
2022	South Eastern	Dry	29.9	0.58
2022	Southern Harbour	Dry	29.4	0.55
2022	Western	Dry	29.3	0.58

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2023

Year	District	Season	Mean LST	Mean TVSDI
2023	Gozo	Wet	19.5	0.52
2023	Northern	Wet	20.4	0.52
2023	Northern Harbour	Wet	21.3	0.55
2023	South Eastern	Wet	20.7	0.55
2023	Southern Harbour	Wet	21.3	0.55
2023	Western	Wet	20.2	0.52
2023	Gozo	Dry	31.5	0.6
2023	Northern	Dry	30	0.58
2023	Northern Harbour	Dry	28.5	0.58
2023	South Eastern	Dry	28.7	0.6
2023	Southern Harbour	Dry	29.3	0.55
2023	Western	Dry	30.4	0.6

Mean LST and TVSDI values for all the districts during the wet and dry seasons of 2024

Year	District	Season	Mean LST	Mean TVSDI
2024	Gozo	Wet	-	-
2024	Northern	Wet	20.6	0.58
2024	Northern Harbour	Wet	20.8	0.6
2024	South Eastern	Wet	20.9	0.6
2024	Southern Harbour	Wet	20.8	0.6
2024	Western	Wet	20.3	0.6
2024	Gozo	Dry	33.3	0.65
2024	Northern	Dry	31.9	0.65
2024	Northern Harbour	Dry	33	0.62
2024	South Eastern	Dry	34	0.65
2024	Southern Harbour	Dry	33	0.62
2024	Western	Dry	33	0.62

Appendix 4

Parameter Estimates

Dependent Variable: TVSDI

Parameter	B	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	.464	<.001	.426	.503
LST	**0.004**	<.001	.003	.006
[District=Gozo]	-.007	.471	-.026	.012
[District=Northern]	-.003	.736	-.022	.015
[District=Northern Harbour]	-.004	.704	-.022	.015
[District=South Eastern]	.000	.990	-.018	.019
[District=Southern Harbour]	-.004	.674	-.023	.015
[District=Western]	0[a]	.	.	.
[Season=dry]	.000	.979	-.026	.026
[Season=wet]	0[a]	.	.	.
[District=Gozo] * [Season=dry]	.003	.824	-.024	.030
[District=Gozo] * [Season=wet]	0[a]	.	.	.
[District=Northern] * [Season=dry]	-.010	.453	-.036	.016
[District=Northern] * [Season=wet]	0[a]	.	.	.
[District=Northern Harbour] * [Season=dry]	-.019	.157	-.045	.007
[District=Northern Harbour] * [Season=wet]	0[a]	.	.	.
[District=South Eastern] * [Season=dry]	.003	.838	-.023	.029
[District=South Eastern] * [Season=wet]	0[a]	.	.	.
[District=Southern Harbour] * [Season=dry]	-.024	.068	-.051	.002
[District=Southern Harbour] * [Season=wet]	0[a]	.	.	.
[District=Western] * [Season=dry]	0[a]	.	.	.
[District=Western] * [Season=wet]	0[a]	.	.	.

a. This parameter is set to zero because it is redundant.

Appendix 5

Parameter Estimates

Dependent Variable: LST

Parameter	B	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	-2.341	.627	-11.867	7.184
TVSDI	**41.162**	<.001	24.062	58.261
[District=Gozo]	-.045	.962	-1.912	1.821
[District=Northern]	.352	.701	-1.459	2.164
[District=Northern Harbour]	.830	.366	-.981	2.641
[District=South Eastern]	.547	.551	-1.265	2.358
[District=Southern Harbour]	.920	.316	-.891	2.731
[District=Western]	0[a]	.	.	.
[Season=dry]	**8.349**	<.001	6.388	10.310
[Season=wet]	0[a]	.	.	.
[District=Gozo] * [Season=dry]	.200	.879	-2.398	2.798
[District=Gozo] * [Season=wet]	0[a]	.	.	.
[District=Northern] * [Season=dry]	.014	.991	-2.556	2.584
[District=Northern] * [Season=wet]	0[a]	.	.	.
[District=Northern Harbour] * [Season=dry]	-.202	.878	-2.796	2.392
[District=Northern Harbour] * [Season=wet]	0[a]	.	.	.
[District=South Eastern] * [Season=dry]	-.630	.627	-3.191	1.931
[District=South Eastern] * [Season=wet]	0[a]	.	.	.
[District=Southern Harbour] * [Season=dry]	.303	.818	-2.303	2.908
[District=Southern Harbour] * [Season=wet]	0[a]	.	.	.
[District=Western] * [Season=dry]	0[a]	.	.	.
[District=Western] * [Season=wet]	0[a]	.	.	.

a. This parameter is set to zero because it is redundant.

Appendix 6

Results of the Moran’s I test assessing spatial autocorrelation for the LST and TVSDI wet and dry seasons from 2015 to 2024

Year	Parameter	Season	Moran's I
2015	LST	wet	0.96
2015	LST	dry	0.93
2015	TVSDI	wet	0.84
2015	TVSDI	dry	0.77
2016	LST	wet	0.96
2016	LST	dry	0.93
2016	TVSDI	wet	0.77
2016	TVSDI	dry	0.79
2017	LST	wet	0.97
2017	LST	dry	0.92
2017	TVSDI	wet	0.9
2017	TVSDI	dry	0.89
2018	LST	wet	0.98
2018	LST	dry	0.94
2018	TVSDI	wet	0.82
2018	TVSDI	dry	0.76
2019	LST	wet	0.98
2019	LST	dry	0.91
2019	TVSDI	wet	0.77
2019	TVSDI	dry	0.73
2020	LST	wet	0.91
2020	LST	dry	0.95
2020	TVSDI	wet	0.82
2020	TVSDI	dry	0.78
2021	LST	wet	0.96
2021	LST	dry	0.94
2021	TVSDI	wet	0.8
2021	TVSDI	dry	0.79
2022	LST	wet	0.93
2022	LST	dry	0.94
2022	TVSDI	wet	0.74
2022	TVSDI	dry	0.78
2023	LST	wet	0.94
2023	LST	dry	0.96
2023	TVSDI	wet	0.74
2023	TVSDI	dry	0.84
2024	LST	wet	0.7
2024	LST	dry	0.7
2024	TVSDI	wet	0.98
2024	TVSDI	dry	0.98

Appendix 7

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.537[a]	.288	.199	.053828070808145

a. Predictors: (Constant), Soil moisture

b. Dependent Variable: TVSDI

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.009	1	.009	3.238	.110[b]
	Residual	.023	8	.003		
	Total	.033	9			

a. Dependent Variable: TVSDI

b. Predictors: (Constant), Soil moisture

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.931	.032		29.279	<.001
	Soil moisture	-.008	.005	-.537	-1.800	.110

a. Dependent Variable: TVSDI

Appendix 8

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.895[a]	.801	.776	.028492512164058

a. Predictors: (Constant), Soil temperature

b. Dependent Variable: TVSDI

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.026	1	.026	32.110	<.001[b]
	Residual	.006	8	.001		
	Total	.033	9			

a. Dependent Variable: TVSDI

b. Predictors: (Constant), Soil temperature

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.613	.048		12.658	<.001
	Soil temperature	.009	.002	.895	5.667	<.001

a. Dependent Variable: TVSDI

Appendix 9

Model Summary[b]

Model	R Square	Adjusted R Square	R Square Change	Sig. F Change
1	.801	.745	.801	.003

a. Predictors: (Constant), Soil moisture, Soil temperature

b. Dependent Variable: TVSDI

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.026	2	.013	14.113	.003[b]
	Residual	.006	7	.001		
	Total	.033	9			

a. Dependent Variable: TVSDI

b. Predictors: (Constant), Soil moisture, Soil temperature

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	.622	.075		8.299	<.001		
	Soil temperature	.008	.002	.876	4.252	.004	.669	1.494
	Soil moisture	-.001	.003	-.033	-.161	.877	.669	1.494

a. Dependent Variable: TVSDI