Monitoring drought dynamics using Soil Moisture Content from Landsat 8 imagery in Southern Lam Dong province (former Binh Thuan province)

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Đánh giá hạn hán thông qua chỉ số độ ẩm đất từ ảnh Landsat 8 tại khu vực phía Nam tỉnh Lâm Đồng (trước đây là tỉnh Bình Thuận)

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ABSTRACT

In recent years, the Southern Lam Dong province (former Binh Thuan province) has experienced frequent and increasingly severe drought conditions during the dry season. This research utilizes the Soil Moisture Content (SMC), derived from Landsat 8 imagery processed via the Google Earth Engine (GEE) platform, and subsequent thematic mapping using QGIS software, to delineate and assess the area's most profoundly affected by drought. The results indicate that during the transition from the wet to the dry season, the most drought-affected areas are primarily concentrated in the southeastern parts of Bac Binh, Tuy Phong, and Ham Thuan Bac districts, as well as the coastal zones adjacent to Phan Thiet city (Former Binh Thuan Province). Temporally, the SMC maps correspond to periods of moderate to severe drought, typically occurring during the winter–spring cropping season from November to April, consequently impacting agricultural production. The area extent of regions exhibiting low SMC (SMC < 20%) primarily correlates with the total number of sunshine hours and total evaporation (R^2 > 0.55). The quantitative assessment of drought impact through the calculation and spatial distribution mapping of SMC serves as a foundational basis for policymakers to propose future drought-risk mitigation strategies, such as adjusting land-use models, optimizing water resource management, modifying cropping calendars, and selecting drought-resistant crop varieties.

Từ khóa:
Bình Thuận, độ ẩm đất, Google Earth Engine, hạn hán, Lansat 8.

TÓM TẮT

Trong những năm gần đây, hạn hán thường xuyên xuất hiện ở khu vực phía nam tỉnh Lâm Đồng (trước đây là tỉnh Bình Thuận) vào mùa khô với tần suất và mức độ khắc nghiệt ngày càng gia tăng. Nghiên cứu này sử dụng chỉ số độ ẩm đất tính toán từ ảnh Landsat 8 được xử lý bằng Google Earth Engine và thành lập bản đồ bằng phần mềm QGIS để khoanh vùng và đánh giá các khu vực chịu ảnh hưởng mạnh nhất bởi hạn hán. Kết quả cho thấy trong thời gian từ mùa mưa sang mùa khô các khu vực chịu ảnh hưởng của hạn hán tập trung chủ yếu nằm ở phía Đông Nam các huyện Bắc Bình, Tuy Phong, Hàm Thuận Bắc và các vùng ven biển tiếp giáp thành phố Phan Thiết (thuộc tỉnh Bình Thuận cũ). Về mặt thời gian, sơ đồ kết quả tính toán độ ẩm đất tương ứng với thời gian hạn vừa và hạn nặng chủ yếu vào vụ Đông Xuân từ tháng 11 đến tháng 4 năm sau gây ảnh hưởng đến nông nghiệp. Diện tích các khu vực có độ ẩm đất thấp (SMC < 20%) tương quan chủ yếu với tổng số giờ nắng và tổng lượng bốc hơi với R^2 > 0,55. Việc đánh giá định lượng ảnh hưởng tác động hạn hán thông qua tính toán và lập sơ đồ phân bố không gian độ ẩm đất là cơ sở để các nhà quản lý đề xuất chiến lược giảm thiểu rủi ro hạn hán trong tương lai như điều chỉnh mô hình sử dụng đất, quản lý nước, thay đổi mùa vụ, lựa chọn các loài cây trồng chịu hạn.

1. INTRODUCTION

Drought is one of the most widespread and prolonged natural hazards associated with climate change, causing substantial economic, social, and environmental losses, particularly in developing countries whose economies depend heavily on agriculture, such as Vietnam. According to the World Meteorological Organization (WMO) and Wilhite & Glantz [1], drought can be classified into four categories: meteorological drought, agricultural drought, hydrological drought, and

socioeconomic drought. Agricultural drought refers to the imbalance between the actual water content in the soil and the water requirements of crops. Agricultural drought is essentially a physiological drought, defined by water conditions that are either suitable or unsuitable for crops, agricultural production systems, or natural vegetation. Consequently, agricultural drought reduces crop productivity [2], diminishes cultivable capacity, and leads to an increased risk of desertification [3]. In recent years, the frequency and severity of agricultural drought have increasingly intensified. Therefore, forecasting and delineating areas affected by agricultural drought are essential for implementing appropriate response and mitigation measures.

Drought conditions typically occur over large areas, yet traditional observation methods remain limited, especially in developing countries where investments in monitoring systems and environmental data collection are insufficient. As a result, drought prediction often lacks accuracy, leading to significant agricultural risks such as saline intrusion, irrigation water shortages, and an increased likelihood of forest fires [4]. In contrast, satellite-derived information provides rapid and consistent detection of drought occurrence, including its duration and intensity across broad regions. Landsat 8, originally known as the Landsat Data Continuity Mission (LDCM), was successfully launched by the United States on February 11, 2013. Equipped with the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), the satellite features improved design aimed at minimizing atmospheric noise (SNR) [5]. Landsat 8 imagery offers sharper quality compared to previous versions, making it highly suitable for drought assessment.

Soil moisture information plays a crucial role in monitoring agricultural drought, as it provides direct evidence of rainfall deficiency across different areas [6]. The use of optical remote sensing to monitor soil moisture has been successfully demonstrated in numerous studies [7, 8]. Calculations and validations of Soil Moisture Content (SMC) using Landsat 8 imagery in the Central Highlands of Vietnam have shown a strong relationship between SMC and regional drought conditions [9]. Therefore, this method is considered one of the potential approaches for assessing drought in areas with similar natural conditions.

Former Binh Thuan Province, located in the South-Central Coast region of Vietnam, is one of the most drought-prone areas in the country. Drought and desertification frequently occur in former Binh Thuan at varying levels of severity, affecting the region's socio-economic activities in different scales and intensities. These hazards pose significant risks to human populations, ecosystems, and agricultural production, especially during years influenced by the El Niño phenomenon. On May 7, 2020, the provincial government issued Decision No. 1039/QĐ-UBND, declaring a Level-2 drought emergency across Binh Thuan Province [10]. Drought typically occurs during the dry season, coinciding with the winter–spring cropping calendar. However, in recent years, agricultural production has not been entirely favorable even during the rainy season; in areas lacking water-regulating infrastructure, drought may still occur despite rainfall [11]. Identifying the causes, progression, and severity of drought is therefore essential for disaster prevention and mitigation, and for developing appropriate agricultural planning policies, crop structure adjustments, and long-term strategies to reduce drought-related impacts in former Binh Thuan.

This study aims to (i) estimate soil moisture content using Landsat 8 imagery, (ii) analyze its spatio-temporal variation during the 2019–2020 dry season in former Binh Thuan province, and (iii) examine its relationship with key meteorological factors associated with drought. SMC estimation equation that was developed and validated using the variation in soil reflectance spectra corresponding to the image spectral bands in relation to SMC from field samples collected in the Northern Central Highlands and Nghe An region [9]. The monitoring results are compared with previous studies on the drought status of the province to evaluate the potential of this method. Spatial patterns of SMC derived from Landsat 8 images are analyzed to identify regions frequently

affected by drought within the province. The relationship between the calculated SMC and weather parameters related to drought in the province is also examined to better understand the controlling factors of SMC and to assess the practicality of the estimation results.

2. RESEARCH METHODS

2.1. Study area

The study area encompasses the entire mainland territory of Southern Lam Đong Province (Former Binh Thuan Province) (excluding Phu Quy district). The geographic coordinates of Binh Thuan range from 10°33'42" to 11°33'18" N latitude and from 107°23'41" to 108°52'18" E longitude. The province features complex topography with short and steep rivers. Drought in former Binh Thuan does not occur throughout all months of the year; it is limited to the dry season and varies considerably over time and space [12]. The total land area of Binh Thuan province in 2020 was 794,246 hectares [13].

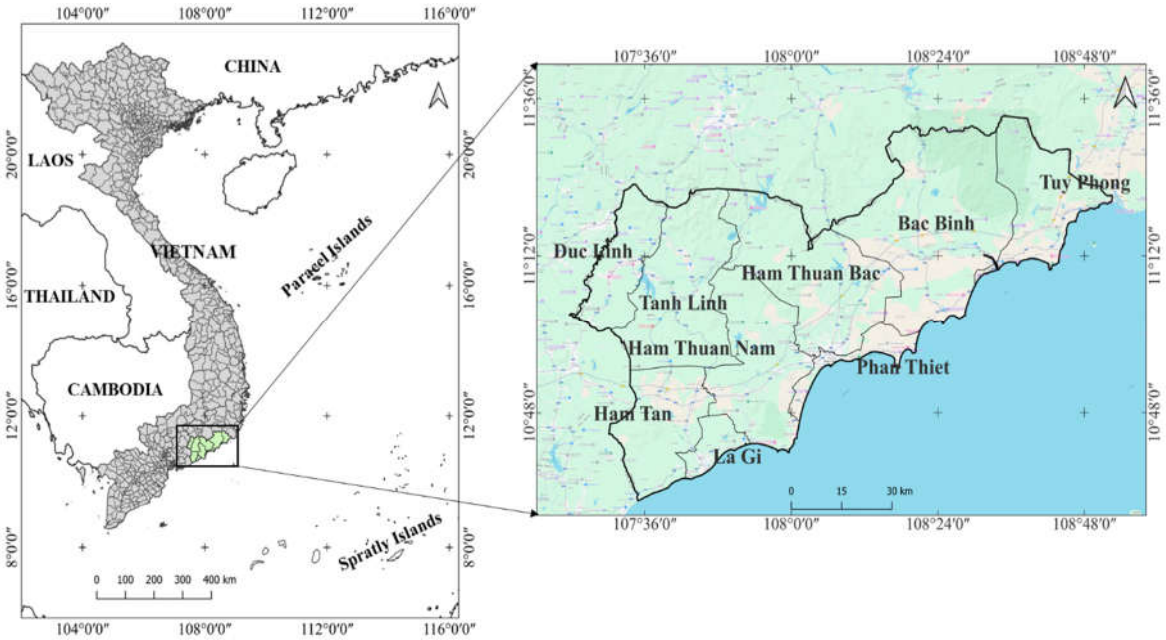


Figure 1. The study area comprising the mainland districts of Southern Lam Đong Province (Former Binh Thuan Province)

(all districts except Phu Quy district)

Meteorological Data Analysis Meteorological factors related to drought, such as temperature, humidity, precipitation, total evaporation, and sunshine duration, recorded at the Phan Thiet station, Lam Dong province, during the period from November 2019 to March 2020, were compiled in Table 1. The meteorological data reveal a distinct variation consistent with the dry season pattern. November 2019 marked the end of the rainy season, thus exhibiting a still substantial amount of precipitation (130.6 mm). However, from December 2019 onwards, rainfall completely dropped to zero and persisted for four consecutive months, indicating that the area had entered a prolonged arid phase. The average air temperature during this period remained relatively high (25–28°C), with March 2020 recording the highest temperature. Concurrently, the total number of sunshine hours gradually increased across the months, peaking in March, signifying strong and extended solar radiation intensity. Additionally, the evaporation rate tended to increase, peaking in February 2020 at 135.7%, indicating a rapid process of surface water loss. Although average humidity fluctuated between months (72.9-78.8%), it was generally insufficient to compensate for the rainfall deficit and high evaporation. In summary, the confluence of climatic factors indicates that this period was characterized by hot and dry weather conditions, abundant sunshine, no precipitation, and intense evaporation, creating the typical arid climate backdrop of the dry season in the study area.

Table 1. Meteorological data for the period from November 2019 to March 2020 at Phan Thiet station, Lam Dong province

Meteorological parameters	11/2019	12/2019	01/2020	02/2020	03/2020
Total rainfall (mm)	130.6	0	0	0	0
Average air temperature (^{o}C)	26.9	25.5	25.9	26.0	27.6
Total number of sunshine (hours)	225.8	289.1	298.0	283.2	331.5
Total evaporation (mm)	94.8	115.5	118.7	135.7	121.8
Average humidity (%)	77.7	76.3	76.1	72.9	78.8

2.2. Method and materials

a) Methods for processing satellite images and data collection

Google Earth Engine (GEE) is a cloud computing platform that provides access to a massive database of satellite imagery and the necessary algorithms for satellite imagery processing. GEE is widely applied in drought monitoring research through the use of various drought indices or related variables such as precipitation, temperature, moisture, and vegetation indices, owing to its capability for multi-temporal analysis [14]. On the GEE platform, the imagery was first filtered to exclude clouds (cloud cover less than 30%). Subsequently, a monthly image collection was synthesized using the Median function (Table 2). Supporting data about natural conditions (including geographical location, topography, and climate) were gathered to assess their influence on drought occurrence.

Table 2. Landsat satellite imagery data used in the study (LANDSAT/LC08/C02/T1_L2)

No.	ID imagery	Acquisition date	No.	ID imagery	Acquisition date
1	LC08_124052	12/11/2019	17	LC08_123052	24/01/2020
2	LC08_124053	12/11/2019	18	LC08_123053	24/01/2020
3	LC08_123052	21/11/2019	19	LC08_124052	31/01/2020
4	LC08_123053	21/11/2019	20	LC08_124052	16/02/2020
5	LC08_124052	28/11/2019	21	LC08_124053	16/02/2020
6	LC08_124053	28/11/2019	22	LC08_123052	25/02/2020
7	LC08_124052	14/12/2019	23	LC08_123053	25/02/2020
8	LC08_124053	14/12/2019	24	LC08_124052	03/03/2020
9	LC08_123052	23/12/2019	25	LC08_124053	03/03/2020
10	LC08_123053	23/12/2019	26	LC08_123052	12/03/2020
11	LC08_124052	30/12/2019	27	LC08_123053	12/03/2020
12	LC08_124053	30/12/2019	28	LC08_124052	19/03/2020
13	LC08_123052	08/01/2020	29	LC08_124053	19/03/2020
14	LC08_123053	08/01/2020	30	LC08_123052	28/03/2020
15	LC08_124052	15/01/2020	31	LC08_123053	28/03/2020
16	LC08_124053	15/01/2020			

This study employed a SMC calculation equation previously developed for the Central Highlands region. This equation is fundamentally built upon the physical relationship between the spectral reflectance and theoretical SMC across various soil types, including bazan, ferralsol, gley soil, alluvial soil [9]. Consequently, it is tentatively applicable to former Binh Thuan province, where the dominant soil types are ferralsol (46.77%) and degraded grey soil (17.54%) [15]. However, the coastal area of former Binh Thuan is notably characterized by a significant area (15.01%) of sand and coastal dunes [15], which possess poor water retention capacity [16] and may therefore not be entirely suitable for the direct application of this equation. Hence, it is necessary to test and validate this SMC calculation equation as a basis for further development in future research, specifically addressing this particular soil type. The SMC was calculated from L8 images by the following Equation 1:

$$SMC = 8{,}14 + 40{,}29 \times \log(\frac{B5}{B7}) \quad (1)$$

where, SMC units in % and B5/B7 is the ratio of reflectances corresponding to L8 B5 and B7.

The equation was developed for bare or sparsely vegetated soils. Consequently, there is no monitoring in the region where the NDVI > 0.4.

b) Methods for statistical analysis

IBM SPSS Statistics 20 software was utilized to perform the research's statistical procedures, including regression analysis, fundamental descriptive statistics, multivariate statistics, and error calculation. All analyses were conducted based on the 95% distribution of the numerical series.

3. RESULTS AND DISCUSSION

3.1. Soil moisture content values derived from satellite imagery and their spatial variation for drought assessment

The SMC for Southern Lam Đong province (former Binh Thuan province), calculated using Equation (1) from Landsat 8 satellite imagery from November 2019 to March 2020, was modeled and illustrated in Figure 2. Accordingly, the SMC in the study area exhibited dynamic temporal variations, which were clearly evidenced by the shifting area and the redistribution of moisture zones across the map. Specifically, districts within the former Binh Thuan province such as Tuy Phong and Bac Binh, along with coastal zones adjacent to Phan Thiet city, were identified as the areas with the lowest SMC during the 2019–2020 dry season (SMC < 20%). In contrast, regions with higher SMC (>30%) are predominantly situated in the Western and Southwestern areas, encompassing Duc Linh and Tanh Linh districts, as well as portions of Ham Thuan Bac and Ham Thuan Nam.

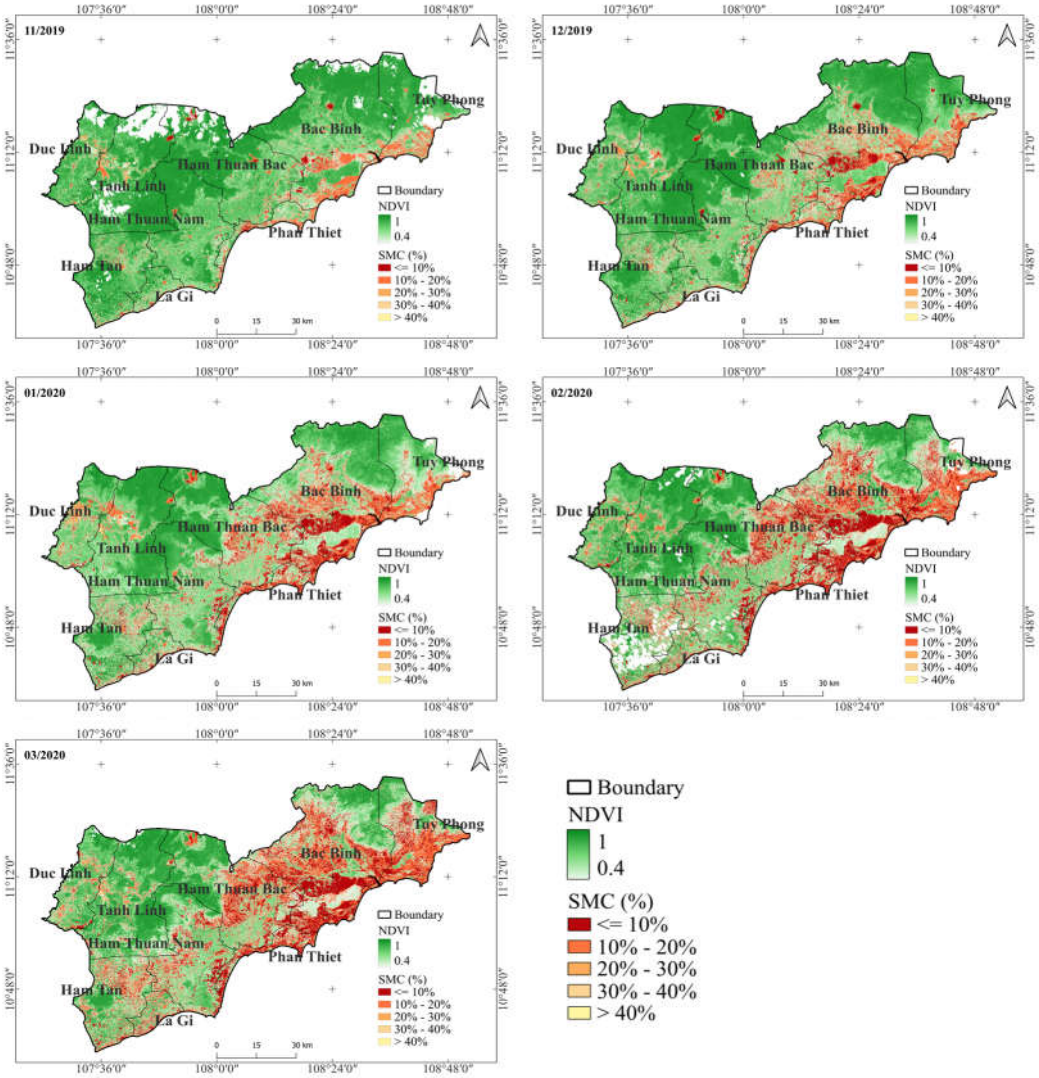


Figure 2. The SMC distribution in former Binh Thuan province was calculated using Landsat 8 images collected from November 2019 to March 2020

3.2. The relationship between calculated soil moisture content values and meteorological parameters

Table 3 presents the area of SMC across the distribution levels shown in Figure 2, excluding the vegetated area (corresponding to NDVI > 0.4: areas with medium or higher vegetation density [17], where SMC calculation was not applied. Accordingly, the area of land with vegetation cover experienced a gradual decline, decreasing from 84.69% to 68.21% during the November 2019 – March 2020 period. Concurrently, the area of land falling into the SMC<20% category continuously and sharply increased throughout the entire period. The results show that in November 2019, the extremely dry land area (SMC< 10%) accounted for only about 8.7 thousand hectares (ha), but by March 2020, this figure had surged to over 100 thousand ha—an increase of more than ten times within five months. Similarly, the area with SMC ranging from 10–20% rose from over 82 thousand ha to more than 261 thousand ha by March 2020. This substantial increase indicates that the desiccation process was rapid and continuous, which is consistent with the characteristic transition from the late rainy season to the peak of the dry season. Conversely, areas with higher SMC showed a tendency to shrink significantly. The land area with SMC in the 30–40% range decreased by nearly 50%, dropping from over 421 thousand ha to approximately 215 thousand ha by March 2020. This reduction reflects the natural moisture loss under the influence of reduced precipitation, rising temperatures, and intensified evaporation during the dry season. The area with moderate SMC (20%<SMC<30%) showed a slight increase until January 2020, followed by a decrease in February and March. This suggests that the moderate moisture level was sustained for only a short duration before being replaced by regions of lower moisture content. This observation confirms that residual moisture remaining after the rainy season is rapidly depleted upon entering the prolonged arid period.

Table 3. The area of SMC in former Binh Thuan over the period from November 2019 to March 2020

Unit: ha

Categories	11/2019	12/2019	01/2020	02/2020	03/2020
SMC (<10%)	8,679.02	28,662.93	53,969.31	90,192.23	100,647.52
10%<SMC<20%	82,867.00	141,746.30	205,501.45	227,746.24	261,426.05
20%<SMC<30%	182,913.18	239,967.51	268,277.03	193,552.23	191,411.15
30%<SMC<40%	421,621.51	351,919.30	240,918.74	209,631.96	214,922.40
NDVI>0.4	672,676.09	682,648.87	631,093.93	550,622.96	541,756.30

The distribution of SMC percentages, illustrated in Figure 3, clearly indicates a complete shift in the moisture profile towards a progressively drier state. Specifically, in November 2019, the 30%<SMC<40% constituted the largest proportion of the total area. By January 2020, the average moisture level began to decrease, signaling a transition into a drier phase. In February 2020, desiccation intensified rapidly, leading to a swift expansion of the dry land area. By March 2020, the proportions of land within the 10%<SMC<20% and the 30%<SMC<40% were nearly equivalent, and the proportion of the extremely dry category SMC<10% had increased significantly. Consequently, the SMC within the study area exhibited a distinct downward trend over time, particularly during the transition period from late 2019 to early 2020. This trend is demonstrated by the sharp increase in the area of regions classified with low (SMC<20%) and the corresponding decline in regions with high (SMC>30%).

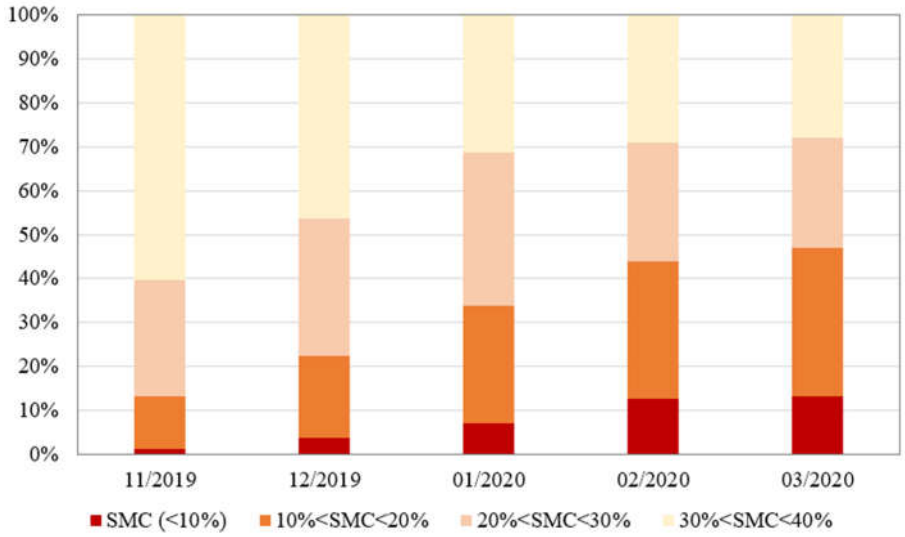


Figure 3. Binh Thuan's SMC rate between November 2019 and March 2020

This observation is entirely consistent with the climatic regulations of the dry season and accurately explains the evolution of the SMC maps previously analyzed. Univariate regression analysis revealed varying degrees of meteorological influence on the fluctuation of low moisture land area (Table 4). For extremely dry areas (SMC<10%), the variables of total evaporation and total number of sunshine durations showed the highest correlation, with R^2 = 0.55. Conversely, precipitation exhibited only a low correlation (R^2 = 0.25). For low moisture areas (10%<SMC<20%), the number of sunshine hours was the most influential factor R^2 = 0.70, followed closely by evaporation (R^2 = 0.69). Average air temperature and average humidity also explained a significant portion of the SMC variation (R^2 = 0.64), while total rainfall had negligible influence (R^2 = 0.21). These findings accurately reflect the arid climatic conditions characteristic of the dry season, where total number of sunshine hours and total evaporation are the two primary factors driving the reduction of SMC.

Table 4. The coefficient of determination (R^2) between meteorological factors and low-SMC areas

Categories	Total rainfall	Average air temperature	Total number of sunshine hours	Total evaporation	Average humidity
SMC<10%	0.25	0.47	0.55	0.55	0.47
10%<SMC<20%	0.21	0.64	0.70	0.69	0.64

3.3. Discussion

The expansion of areas with low SMC is a direct consequence of extreme climatic conditions during the 2019-2020 dry season. A complete absence of rainfall (0 mm) for four consecutive months resulted in the depletion of the water supply for the topsoil. Simultaneously, intense solar radiation and peak evaporation levels (135.7 mm in February 2020) accelerated surface water loss, leading to rapid soil dehydration. Regression analysis in this study confirms that sunshine hours and evaporation are the two primary variables driving surface dryness in former Binh Thuan, rather than rainfall during the peak drought months.

In practice, low-moisture regions correspond directly to areas affected by drought. The Southeastern and coastal areas adjacent to former Phan Thiet city, characterized by sandy soils and dunes with poor water retention, are highly susceptible to severe drought due to dry winds and high temperatures. Most of these regions consist of

built-up areas, residential zones, and agricultural areas, which tend to experience increased dryness as the dry season progresses. Consequently, implementing irrigation systems and reservoirs is essential for proactively responding to drought and improving land-use efficiency. Conversely, the West and Southwest regions maintain better moisture levels due to higher elevations, lower temperatures, and natural forest cover. These areas primarily feature red-yellow soils on schist bedrock or light grey soil on sandstone, benefiting from lower temperatures, higher rainfall, and relatively fertile land, natural vegetation with cool humid evergreen forest cover, and abundant agricultural cropping systems [18]. Forest cover acts as a 'biological buffer,' reducing surface temperatures and limiting direct evaporation. This underscores that maintaining vegetation is a core strategy for mitigating drought risks. Temporally, the map of calculated SMC results in this study corresponded to periods of moderate and severe drought, primarily during the Winter-Spring cropping season (from November to April of the following year), which significantly impacted agriculture [19]. Therefore, it is essential to implement irrigation systems and water reservoirs for the dry season to proactively cope with drought, increase cultivation capacity, and improve land-use efficiency. Spatially, the SMC map for March 2020 aligned with the distribution trend of drought severity determined by the drought index K [19] and also with applications of the agricultural drought index (Prescot) over the 1978–2020 period [20]. The year 2020 recorded a relatively high area of low SMC due to the strong influence of the El Niño phenomenon [21], which corresponded to the severe drought event in former Binh Thuan, where the districts above were all declared drought-affected at Level 2 (Natural Disaster Risk Level due to Drought) [22].

The results demonstrate that while Equation (1) was developed using soil samples from the Northern Central Highlands, it remains suitable for calculating moisture in regions such as former Binh Thuan. The SMC dynamics from November 2019 to March 2020, derived from Landsat 8 imagery, accurately reflect real-world drought conditions and align with previous studies. Thus, the soil moisture index provides a rapid and quantitative measure of drought impact, facilitating proactive response. However, the absence of local, *in situ* SMC data for validation is one of the study's limitations. Future research should integrate automated monitoring stations to optimize the accuracy of remote sensing algorithms. These findings provide a crucial scientific basis for assessing drought risk and proposing sustainable water resource management strategies in the region.

4. CONCLUSION

The research underscores the effectiveness of utilizing Landsat 8 imagery and the Google Earth Engine platform for the rapid monitoring of agricultural drought through SMC in Southern Lam Đong Province (Former Binh Thuan Province). Findings reveal that the drying process reached its peak in March 2020, with drought predominantly concentrated in the southeastern parts of former Tuy Phong and Bac Binh districts, as well as coastal regions adjacent to former Phan Thiet city. A significant reduction in areas with medium to high moisture levels suggests that water reserves from the rainy season were insufficient and depleted rapidly during the dry phase. Furthermore, the spatial variation of SMC reflects local topography and land-use characteristics; specifically, urban and agricultural lands exhibit faster drying trends, whereas riverside areas and lowlands with dense vegetation maintain more stable moisture. It was also determined that SMC is strongly driven by two weather factors: sunshine duration and total evaporation. These results provide policymakers with a crucial scientific foundation for modifying land-use models, managing water resources, and selecting drought-resistant crops to mitigate risks associated with climate change. While currently constrained by the absence of *in-situ* SMC data for validation, future research will

prioritize field data collection to refine the precision of SMC monitoring in Southern Lam Đong Province .

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