IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 19 July 2022, accepted 5 August 2022, date of publication 16 August 2022, date of current version 24 August 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3198942

RESEARCH ARTICLE

Assessment of Urban Expansion's Impact on Changes in Vegetation Patterns in Dhofar, Oman, Using Remote Sensing and GIS Techniques

YASEEN AL-MULLA[1,2], (Member, IEEE), AMNA AL-RUHEILI[3], ALI AL-LAWATI[4], KRISHNA PARIMI[1], AHSAN ALI[1], (Member, IEEE), NADYA AL-SADI[5], AND FAISAL AL-HARRASI[6]

[1]Remote Sensing and GIS Research Center, Sultan Qaboos University, Al-Khod, Muscat 123, Oman
[2]Department of Soils, Water and Agricultural Engineering, Sultan Qaboos University, Al-Khod, Muscat 123, Oman
[3]Department of Plant Sciences, Sultan Qaboos University, Al-Khod, Muscat 123, Oman
[4]Natural and Medical Sciences Research Center, University of Nizwa, Birkat Al-Mauz, Nizwa 616, Oman
[5]Oman Animal and Plant Genetic Resources Center, The Research Council, Al-Athaiba, Muscat 123, Oman
[6]Earth Science Research Center, Sultan Qaboos University, Al-Khod, Muscat 123, Oman

Corresponding author: Yaseen Al-Mulla (yalmula@squ.edu.om)

This work was supported in part by the Oman Animal and Plant Genetic Resources Center under Grant CR/DVC/GISC/18/02, and in part by the Sultan Qaboos University under Grant SR/DVC/GISC/20/01.

ABSTRACT The impact of urbanization on vegetation is poorly studied in sparsely vegetated desert steppe-type vegetation. This study investigates the spatial and temporal impacts of urbanization over 40 years on plant species in Dhofar's mountains, plains, and bay areas. Satellite images covering 1978 to 2018 were used as Remote Sensing (RS) tools, along with Geographic Information System (GIS) techniques, to detect changes in vegetation patterns. The results showed an increase in urban development in Dhofar over the 40 years, reaching 173.3%, which contributed to the decline in vegetation cover of 36.4%. However, both percentages indicate that other factors, including climate change, have also impacted the vegetation. It was found that air temperature in the study area increased from 1978 to 2018 by 0.8 °C, whereas precipitation decreased by 104 mm. The results also indicate a 23.2% and 18.5% reduction in plant species in coastal areas and mountains, respectively, between 1978 and 2018 due to the increase in urbanization. This warns of the impact of urban expansion on rare plant species in the governorate, as 48 plant species only found in Dhofar are threatened with extinction due to construction and urbanization. We recommend making the biodiversity of Dhofar a priority in developing any urban projects, especially at sites that house rare species.

INDEX TERMS Image classification, image processing, remote sensing, geographic information systems, vegetation, geospatial and temporal mapping, urban areas.

I. INTRODUCTION

In earlier decades, people lived in balance with nature. This is because there were restrictions on the usage of natural resources such as wood for building and fires. Moreover, overgrazing and trampling were controlled by the seasonal movement of animals from area to area. As the population grew, the environment was degraded by the increase in urbanization, industrialization, the introduction of modern means of transport, and the overutilization of natural resources. For that reason, the quality of the grasslands had been decreasing ever since [1]. On a global scale, Seto [2] projected that, by 2030, urban area will triple all over the world, leading to a loss of habitat, biomass, and carbon storage of 5%. The loss of habitat and species is a risk for as long as urbanization and human influence coexist. In this context, various efforts have been proposed by researchers to mitigate impacts on the environment, such as increasing

The associate editor coordinating the review of this manuscript and approving it for publication was Andrea F. Abate.

people's awareness of the consequences of urbanization for plants and the environment as a whole [3].

As the urban population grew, an irreversible effect on ecosystems became inevitable. These changes in the population led to other changes in land use and land cover, economic activity, and culture that entailed a loss of habitat, decrease in biodiversity, and degradation of ecosystems. Urbanization has been associated with significant economic and social major changes [4]. The urban environment affects plant growth and the functionality of the ecosystem in both complementary and conflicting ways. For example, urban expansion has tripled near protected areas since 2000 and quadrupled in endemic species areas; expansion also threatens coastal habitats, especially in the Mediterranean [5]. The presence of particular plant species is impacted by various environmental factors such as climate, elevation, slope, rainfall, and topography [6]. Li *et al.* [7] conducted an empirical study of over 22 million plant phonologies from the USA and European countries, and found that the magnitude of urbanization's effects on plant phenology depended on the local temperature where the plants grew.

The Sultanate of Oman is the third-largest country in the Gulf States and is known for its biodiversity within the Arabian Peninsula. Oman is located in the southeastern quarter of the Peninsula and features varying topography, with mountains, valleys, and desert covering most of its landmass. That being said, the country is also known for its coastal plains, semi-arid cloud forest, woodland, and other environmental factors enhancing species diversity [8]. The climate of Oman is characterized as hot and arid, with a low annual rainfall of around 100 mm. A total of 1407 vascular plants and fern species have been found in Oman, which reflects its position in several biogeographical regions [9], [10], [11], [12].

The Dhofar Governorate lies in the extreme southwest of Oman and, for the most part, consists of sparsely vegetated desert steppe-type vegetation. Along the southern coast, however, there is a range of limestone monsoon-affected mountains covered by unique vegetation such as *Desmodio gangetico* and *Themedetum quadrivalvis* [13]. Although there is no official classification of habitat in Oman, Patzelt [8] mentioned that the habitats in Dhofar could be considered in six categories, namely 1) Coastal zone, dry hills, and wadis, 2) *Anogeissus dhofarica* forests (including *Acacia–Commiphora* woodland, 3) *Euphorbia balsamifera* cushion scrub, 4) *Dracaena* scrubland, 5) a *Boswellia sacra* zone, and 6) desert plateau.

Many vascular plants grow in the coastal areas of Dhofar—for example, grass and rush families from the Poaceae and Juncaceae families, sea-lavender from the Plumbaginaceae family, and pigweed from the Amaranthaceae family. All of these plants are known for their salt intolerance. However, these coastal areas are targeted for development and urbanization [8]. Every year, the Dhofar region experiences overspreading by moisture-laden clouds from June to mid-September [14]. These moisture-laden clouds give added benefit to Dhofar's environment as the precipitation enhances the growth of vegetation in Dhofar's plains and mountains. Moreover, the cool and moist winds bring rain and fog to the mountain range and create a dense vegetation cover and subtropical climatic monsoon conditions, known locally as the Khareef season. As a result, the temperature drops and the humidity ranges between 60% and 100% [15]. During the Khareef season, the coastal plain of Dhofar is affected by the monsoon circulation, which induces rainfall during the summer that results in an increase in precipitation to about 180–450 mm.

However, over the centuries, Dhofar was found to be one of the most botanically understudied areas of southwest Asia. While a proper flora and fauna survey sponsored by the Oman Government was not carried out until 1977 [16], early travelers did remark on the luxuriance of the vegetation in the Governorate—although it was not until 1894 that Theodore and Mable Bent made the first scientific collections of plants [17]. The diversity of Dhofar's habitats is reflected in the richness of species that can be found in the region—over two-thirds of the plant diversity in the whole country of Oman, and at least 50 of these recorded species are endemic, with two main endemic genera, *Dhofaria* and *Cibirhiza* [14], [18], [19]. However, Dhofar has also witnessed a surge in urban development, especially between 1978 and 2018. Due to the large area of the Dhofar, 99,300 km^2, data collection is not easily accomplished without advanced technology tools including remote sensing and Geographic Information Systems. Satellite remote sensing is considered in the form of an earth observation satellite that is used for monitoring vegetation as it provides temporal observations at a range of geospatial scales. The advancement in remote sensing techniques has resulted in more accurate analyses in the fields of environmental monitoring and mapping and assessing vegetation changes [20]. Geographic Information Systems (GIS) is a computer-based mapping system that allows data to be displayed on maps and analyzed based on spatial factors. This platform is capable of producing maps with complete attributes and displaying factors. Vegetation mapping can benefit enormously from using GIS platforms to identify vegetation species and factors affecting vegetation using various mapping tools. Moreover, GIS platforms can perform statistical analyses and generate distinctive vegetation maps such as exploring the dynamic vegetation models used to study global biogeochemical cycles [21].

The impact of urbanization in the Dhofar region on plant habitats is poorly studied. Moreover, no research has been found to quantify how urbanization has impacted the green areas of this region. It is very important to have a study that shows the impact of urbanization on plant diversity in Oman. The results of this study will assist scientists, planners, and decision makers with current and future management and help conserve plant diversity in the Dhofar region. Hence, the main objective of this research was to investigate the impacts of urbanization on vegetation coverage in Dhofar's mountains, Salalah plain, and bay areas among Dhofar's five areas called "wilayat" (Mirbat, Taqah, Salalah, Rakhyut, and Dalkut), through the following tasks:

- Geospatial and temporal mapping of urbanization due to land-use change over the past 40 years (1978 to 2018).
- Geospatial and temporal mapping of the vegetation cover due to land-use change over the past 40 years (1978 to 2018).
- Creating a spatial database of plant families and species impacted by urbanization over the study period.

The rest of the paper is organized as follows: the methodology is in Section II, with the study area in A, the study approach in B, the data inquiry and processing in C, and the statistical analysis of plant species and families in D. Results from the study are reported in Section III. Results are discussed in Section IV followed by the Conclusions in Section V.

II. METHODOLOGY

A. STUDY AREA

Dhofar is the largest governorate in the Sultanate of Oman with a total area of 99,300 km^2, covering almost one-third of the total country area. It lies in the southern part of the country. The study area consists of five wilayats (areas): Mirbat, Taqah, Salalah, Rakhyut, and Dalkut. These areas are geographically located between 17°09'47" N latitude, 54°47'48" E longitude, and 16°39'47" N latitude, 53°06'07" E longitude, covering an area of 6857 km^2 (Fig. 1). They are the five main wilayat of the five regions of Dhofar.

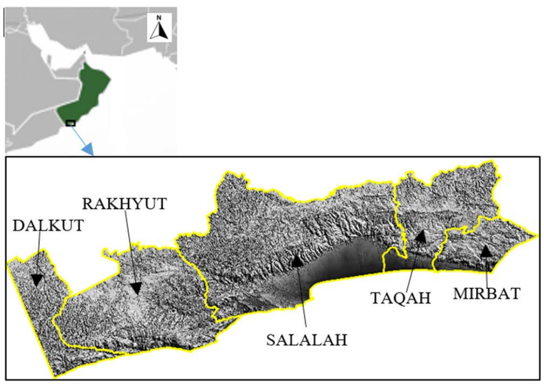

FIGURE 1. Study area.

B. STUDY APPROACH

The approach followed in this study can be illustrated as shown in Fig. 2 and is described in the following sections.

C. DATA INQUIRY AND PROCESSING

The historical meteorological data of the study areas were obtained from [22]. Twenty satellite images were acquired from Landsat 1 – 4 MSS, Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI. Image processing software was used to create and analyze geospatial datasets [23]. The software was used to process and analyze the 20 acquired images.

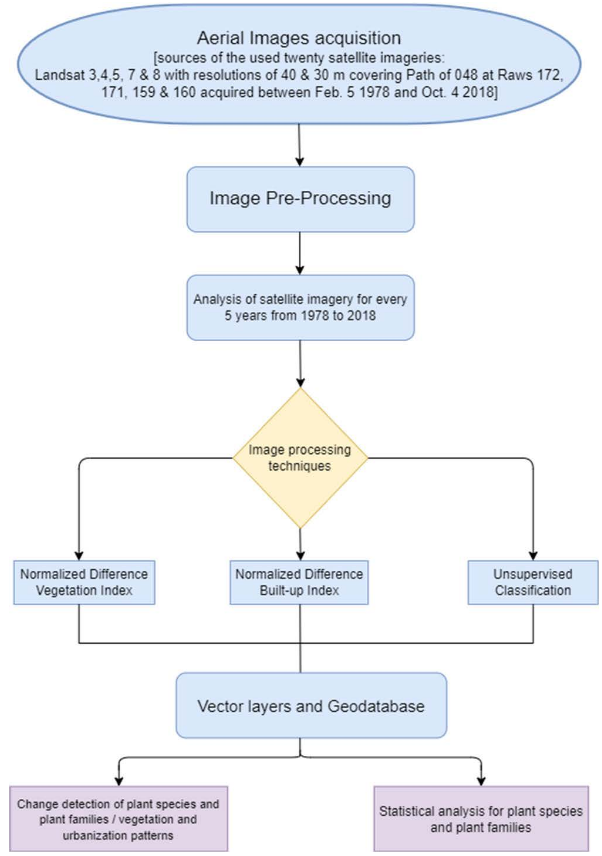

FIGURE 2. Illustration of the study approach.

Various preprocessing techniques were implemented such as atmospheric correction, geometric correction, resampling, and mosaicking, as detailed by [24], [25], [26]. Eight satellite images were produced by mosaicking two satellite images per year to cover the entire study area. The mosaicked images were further preprocessed through subsetting to concentrate on the study area. Three types of postprocessing techniques were applied to the raster datasets: Unsupervised Classification, Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI). The unsupervised classification was used, through ISO clustering, to classify different classes in each dataset such as woodland, vegetation, rugged surfaces, built-up areas, and water bodies. The ISO cluster tool uses a modified iterative optimization clustering procedure, also known as the migrating means technique. The algorithm separates all cells into a user-specified number of distinct unimodal groups in the multidimensional space of the input bands.

NDVI is used as an indicator to identify vegetation by measuring the ratio of the difference between the near-infrared and red portion of the spectrum and the summation of the two bands as follows:

$$NDVI = \frac{NIR - Red}{NIR + Red}. \tag{1}$$

The value of NDVI is between −1 and 1, in which the value of woodland ranges between 0.5 and 1, the values of shrub

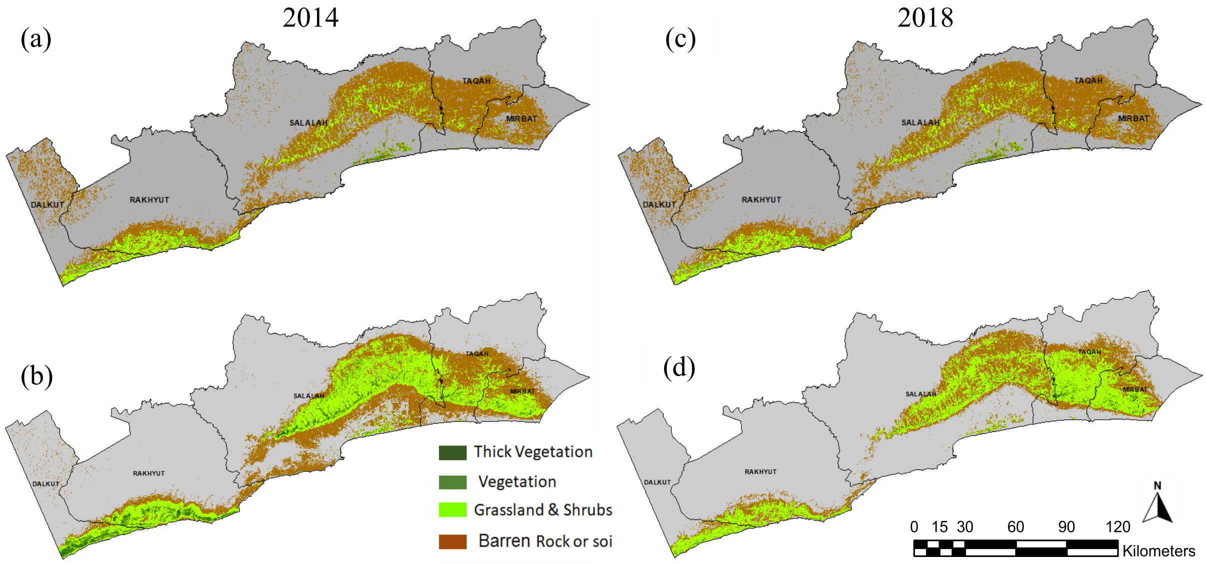

FIGURE 3. Vegetation cover before (a,c) and after (b,d) the monsoon season for the years 2014 and 2018.

and grassland lie in the range between 0.2 and 0.4, the value of soil and rock lies in the range of -0.1 to 0.1, and the NDVI value for clear water lies in the lowest range close to -1 [27].

NDBI is used to identify the spatial distribution and growth of urban built-up areas by measuring the ratio of the difference between the shortwave infrared and near-infrared portion of the spectrum and the summation of the two bands as follows:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}. \quad (2)$$

The value of NDBI is between -1 and 1, in which negative values of NDBI represent less built-up areas whereas higher values represent more built-up areas [28].

The plant species list, consisting of 5738 data points, was provided by the Oman Animal and Plant Genetic Resources Center (OAPGRC) [29] as an Excel spreadsheet. The dataset was built on herbarium plant vouchers from the Natural History Museum of Oman and other international data [30]. The format of every point was corrected and converted into geospatial data using the GIS platform. A geodatabase was created to store, query, and manipulate individual plant species and urban built-up features' data over the years. It incorporated raster classification results with existing plant species. This was used to observe changes in plants and identify urban expansion so that the effect of urbanization on vegetation patterns over time (years) could be detected.

D. STATISTICAL ANALYSIS OF PLANT SPECIES AND FAMILIES

Descriptive statistical analysis, including correlation and regression analyses between the NDVI and NDBI, was applied to analyze vegetation changes at the family and plant species levels from 1978 to 2018. The maximum and minimum numbers of plant families and species were identified using the plant species list provided by OAPGRC.

E. ACCURACY ASSESSMENT

Accuracy of the unsupervised classifications was assessed by error matrix. The overall accuracy of unsupervised classifications ranged from 76% to 84% with Kappa statistics coefficient ranging from 0.74 to 0.82.

III. RESULTS

A. GEOSPATIAL–TEMPORAL ANALYSIS OF VEGETATION COVERAGE

From 1978 to 2018, there was a decrease in natural vegetation in the study areas of Dhofar. The geospatial and temporal changes in vegetation during these years can be inferred to be the impact of urbanization, agricultural practices, and environmental factors including climate change, such as increasing air temperature and increasing frequency of rainstorms [31]. Just after the monsoon season, from September–October, the vegetation in 2014 (Fig. 3a) and 2018 (Fig. 3c) covered areas of 100,255 hectares and 97,817 hectares, respectively, twice the area covered by vegetation during the off-monsoon season, from March to April, for both years (Fig. 3b, d).

It was found that vegetation coverage, including woodland, vegetation, grassland, and shrub, in 1978 was more condensed in the southwest regions (Dalkut and Rakhyut) of Dhofar, while the vegetation coverage was more dispersed in the northeast regions (Mirbat and Taqah). The estimated area of vegetation coverage for this year was 61,046 hectares. Based on the NDVI analysis of the 1984 satellite images, the vegetation coverage pattern in the southwest and northeast of Dhofar was similar to the pattern observed for 1978. In addition, the study area showed a slight increase in vegetation coverage in comparison to 1978. The estimated area of vegetation coverage for this year was 48,882 hectares. There was a similar vegetation coverage pattern in 1988. However, the vegetation coverage in the study area did not show a perceptible change from what was observed in 1984. The estimated area of vegetation coverage for this year was 45,048 hectares. Although there was a similar vegetation coverage pattern in the year 1993 to that in 1988, the vegetation coverage in the northeast region of Dhofar was slightly reduced in comparison to 1988. Furthermore, there was a noticeable increase in vegetation coverage in the study area as compared to 1988. The estimated area of vegetation coverage for this year was 45,529 hectares. The vegetation coverage pattern of 1998 remained similar to the vegetation coverage pattern of 1988. However, the northeast region of Dhofar (Mirabt and Taqah) showed a clear reduction in vegetation coverage compared to previous years. At the same time, vegetation coverage in the study area remained similar to 1993. The estimated area of vegetation coverage for this year was 44,827 hectares. The northeast region of Dhofar (Mirabt and Taqah) showed increased vegetation coverage in 2003 compared to previous years. Vegetation coverage in the study area remained similar to that in 1998. The estimated area of vegetation coverage for this year was 41,934 hectares. The vegetation coverage pattern of 2014 remained similar to the vegetation coverage pattern of the previous year in the northeast region of Dhofar (Mirabt and Taqah). At the same time, vegetation coverage in the study area increased in comparison to previous years. The estimated area of vegetation coverage for this year was 45,884 hectares. The vegetation coverage in the northeast region of Dhofar (Mirabt and Taqah) in 2018 reduced in comparison to 2014. However, a slight increase was seen in the southwest region of Dhofar. The estimated area of vegetation coverage for this year was 40,768 hectares. Fig. 4 shows examples of vegetation coverage maps of one of the study regions (Salalah) for the years 1978, 1984, 1998, and 2018.

In summary, Table 1 shows that there was a 36.4% reduction in vegetation between 1978 and 2018, and a significant change (reduction) between 1978 and 1984, as shown in Fig. 5.

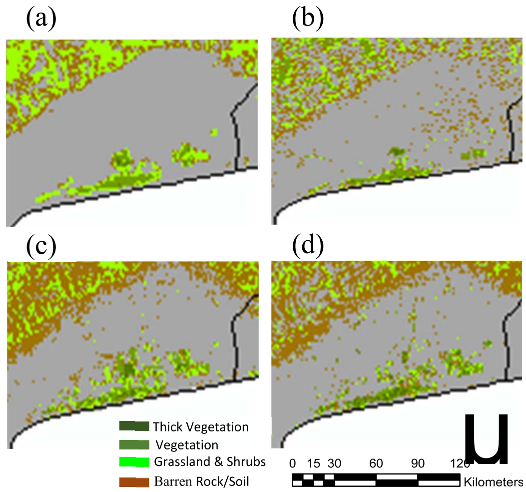

FIGURE 4. Examples of vegetation coverage maps of one of the study regions (Salalah) for the years (a) 1978, (b) 1984, (c) 1998, and (d) 2018.

TABLE 1. change in vegetation between 1978 and 2018.

Year	Area (ha)	Change (%)	Cumulative Change (%)
1978	61,046[a]		
1984	48,882[b]	–19.9	–19.9
1988	45,048[b]	–7.8	–27.8
1993	45,529[b]	1.1	–26.7
1998	44,827[b]	–1.5	–28.2
2003	41,934[b]	–6.5	–34.7
2014	45,884[b]	9.4	–25.3
2018	40,768[b]	–11.1	–36.4
Minimum	40,768		
Maximum	61,046		
1st Quartile	44,103.750		
Median	45,288.500		
3rd Quartile	46,633.500		
Mean	46,739.750		
Std. dev.	5881.474		

a: denotes a statistical difference for 1978 compared to the other years.

B. GEOSPATIAL–TEMPORAL ANALYSIS OF URBANIZATION

There was an increase in urbanization in the study areas of Dhofar, especially from 1978 to 2018. Little urbanization was detected in 1978, especially in the study area and along the coastline. The estimated built-up area for this year was 1027 hectares. A significant increase in urbanization was detected in 1984, by 132.7%. The estimated built-up area for that year was 2390 hectares. The urbanization in 1988 compared to 1984 had increased by 13.3%. The estimated built-up area for this year was 2709 hectares. The urbanization in 1993 showed almost no change from 1988. However, in 1998, urbanization increased by 8.6% in comparison to 1993. The built-up area for that year was 2932 hectares. Urbanization in the period between 1998 and 2003 showed a decrease, but not significant, of 4.8%. During this period, Dhofar was struck by a rare cyclone with 300% of normal rainfall, causing $25 million worth of damage [32]. The built-up area of the study area in 2003 was 2790 hectares. Urbanization in 2014 increased by 9.4% in comparison to 2003. The built-up area for this year was 3053 hectares. Another significant increase (14.4%) in urbanization in this area was detected in 2018 compared to the previous five years. The built-up area for that year was 3492 hectares. Fig. 6 shows examples of urbanization maps of one of the study regions (Salalah) for the years 1978, 1984, 1998, and 2018. In summary, Table 2 shows that there was a 173.3% increase in urbanization between 1978 and 2018 and

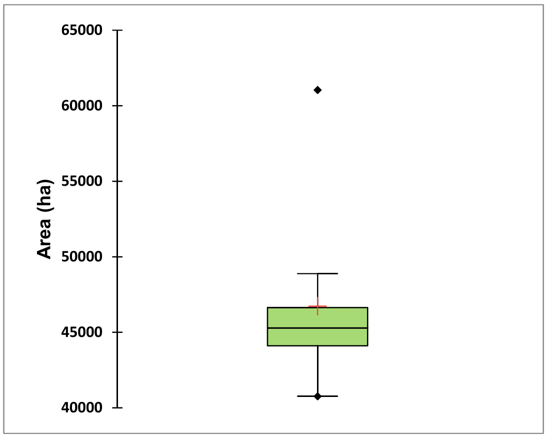

FIGURE 5. Box and Whisker Plots of vegetation areas in the study area for 1978–2018. The minimum, 1st quartile, median, mean, and 3rd quartile are displayed together with both limits (the ends of the "whiskers") beyond which values are considered anomalous. The mean is displayed with a red +, and a black line corresponds to the median.

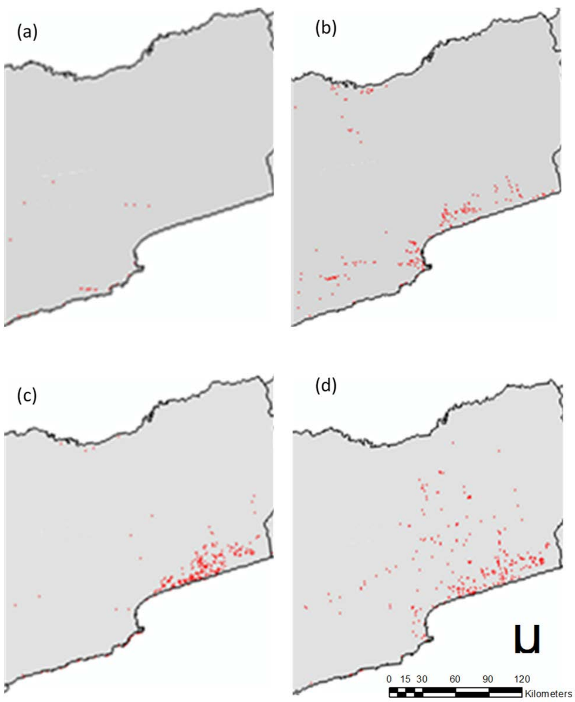

FIGURE 6. Examples of urbanization (red) in one of the study regions (Salalah) for the years (a) 1978, (b) 1984, (c) 1998, and (d) 2018.

a significant change (increase) between 1978 and1984 and between 2014 and 2018, as shown in Fig. 7.

C. VEGETATION COVERAGE VERSUS URBANIZATION ANALYSIS

To examine the impact of urbanization on plant species diversity in the study area, a pixel-by-pixel comparison between the urbanization cover of 2018 and vegetation cover of 1978 was conducted. The results of this analysis showed that 14% of plant species were affected over the 40 years, reducing the total number of plant species from 691 species

TABLE 2. Change in urbanization between 1978 and 2018.

Year	Area (ha)	Change (%)	Cumulative Change (%)
1978	1027[a]		
1984	2390[b]	132.7	132.7
1988	2709[b]	13.3	146.1
1993	2701[b]	–0.3	145.8
1998	2932[b]	8.6	154.3
2003	2790[b]	–4.8	149.5
2014	3053[b]	9.4	158.9
2018	3492[a]	14.4	173.3
Minimum	1027.000		
Maximum	3492.000		
1st Quartile	2623.250		
Median	2749.500		
3rd Quartile	2962.250		
Mean	2636.750		
Std. dev.	677.948		

a: denotes a statistical difference for the years 1978 and 2018 compared to the other years.

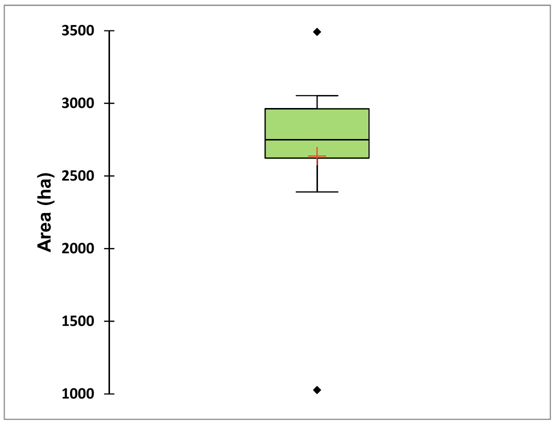

FIGURE 7. Box and whisker Plots of urbanization areas in the stud area for 1978–2018.

in 1978 to 593 in 2018. Seventy-nine rare plant species were directly impacted by construction (urba-nization) in the study area, Dhofar, during the 40 years. By cross-checking the distribution of these species in other governorates of Oman using records provided by OAPGRC and the four volumes of Ghazanfar [33], [34], [35], [36], we found that 48 of the 79 plant species were present only in Dhofar (Table 3). The remaining 32 species were found in Dhofar and at least one other place in Oman (Table 4). Of these, 11 species were present in one governorate in addition to Dhofar. Six plant species were present in two governorates in addition to Dhofar, while 14 were found to be widespread throughout the country.

The correlation analysis between the Normalized Difference Vegetation Index and Normalized Difference Built-up

TABLE 3. Distribution of rare plant species impacted directly by construction in the governorate of dhofar in 1978–2018 and found in Dhofar governorate only.

No.	Plant Species	Plant Family	No.	Plant Species	Plant Family
1	*Barleria hochstetteri*	Acanthaceae	25	*Jasminum grandiflorum f.*	Oleaceae
2	*Arisaema flavum*	Araceae	26	*Arthraxon prionodes*	Poaceae
3	*Caralluma quadrangula*	Asclepiadaceae	27	*Chrysopogon macleishii*	Poaceae
4	*Launaea castanosperma*	Asteraceae	28	*Coelachyrum poiflorum*	Poaceae
5	*Tagetes erecta*	Asteraceae	29	*Coelachyrum yemenicum*	Poaceae
6	*Commiphora foliacea*	Burseraceae	30	*Dichanthium aristatum*	Poaceae
7	*Delonix elata*	Caesalpiniaceae	31	*Digitaria pennata*	Poaceae
8	*Cleome omanensis*	Capparaceae	32	*Digitaria velutina*	Poaceae
9	*Hildebrandtia africana*	Convolvulaceae	33	*Microchloa kunthii*	Poaceae
10	*Ipomoea aitonii*	Convolvulaceae	34	*Paspalum districhium v.*	Poaceae
11	*Corallocarpus glom.*	Cucurbitaceae	35	*Stipagrostis raddiana*	Poaceae
12	*Mukia maderaspatana*	Cucurbitaceae	36	*Stipagrostis xylosa*	Poaceae
13	*Euphorbia cuneata*	Euphorbiaceae	37	*Tripogon subtilissimus*	Poaceae
14	*Euphorbia dhofarensis*	Euphorbiaceae	38	*Reseda sphenocleoides*	Resedaceae
15	*Flueggea virosa*	Euphorbiaceae	39	*Ziziphus spinachristi*	Rhamnaceae
16	*Crotalaria leptocarpa*	Fabaceae	40	*Azima tetracantha*	Salvadoraceae
17	*Crotalaria medicaginea*	Fabaceae	41	*Campylanthus antonii*	Scrophulariaceae
18	*Sesbania bispinosa*	Fabaceae	42	*Kickxia dhofarense sp. N.*	Scrophulariaceae
19	*Exacum affine*	Gentianaceae	43	*Solanum cordatum*	Solanaceae
20	*Erodium malacoides*	Geraniaceae	44	*Solanum villosum*	Solanaceae
21	*Plectranthus marrub.*	Lamiacae	45	*Hermannia testacea*	Sterculiaceae
22	*Plectranthus barbatus*	Lamiacae	46	*Lantana camara*	Verbenaceae
23	*Gossypium stocksii*	Malvaceae	47	*Lantana n.d. L. v.*	Verbenaceae
24	*Acacia nilotica kraussiana*	Mimosaceae	48	*Fagonia mahrana*	Zygophyllaceae

TABLE 4. Distribution of rare plant species impacted directly by construction in Dhofar in 1978–2018.

			Oman Governorates										
No.	Plant Species	Plant Family	Df	Wt	SS	SN	AD	Mc	BS	BN	Dh	Br	Mn
1	*Justicia heterocarpa*	Acanthaceae	■										■
2	*Glossonema boveanum*	Asclepiadaceae	■	■				■					
3	*Iphiona scabra*	Asteraceae	■		■	■	■	■	■		■		
4	*Launaea bornmuelleri*	Asteraceae	■	■		■	■						■
5	*Osteospermum vaillantii*	Asteraceae	■				■						■
6	*Pluchea dioscorides*	Asteraceae	■					■		■			
7	*Pulicaria undulata*	Asteraceae	■	■	■		■						
8	*Cordia nevillii*	Boraginaceae	■	■									
9	*Heliotropium kotschyi*	Boraginaceae	■	■	■	■	■	■	■	■	■	■	■
10	*Trichodesma africanum*	Boraginaceae	■		■		■						
11	*Cleome austroarabica*	Capparaceae	■	■									
12	*Convolvulus hystrix dhofarica*	Convolvulaceae	■	■			■						
13	*Cucumis prophetarum*	Cucurbitaceae	■	■	■	■	■		■	■			
14	*Euphorbia granulata*	Euphorbiaceae	■	■	■	■		■	■	■			■
15	*Indigofera hochstetteri*	Fabaceae	■			■	■						
16	*Indigofera rubromarginata*	Fabaceae	■	■									
17	*Tephrosia purpurea*	Fabaceae	■	■	■	■	■	■	■	■			■
18	*Loranthus n.d. - L. acacia or L. schimperi*	Loranthaceae	■	■									
19	*Acacia tortilis*	Mimosaceae	■	■	■	■	■	■	■	■	■	■	■
20	*Commicarpus boissieri*	Nyctaginaceae	■					■					
21	*Olea europaea*	Oleaceae	■				■						
22	*Epipactis veratrifolia*	Orchidaceae	■		■	■	■				■	■	■
23	*Oxalis corniculata*	Oxalidaceae	■				■						
24	*Plantago ovata*	Plantaginaceae	■				■	■		■			■
25	*Hyparrhenia hirta*	Poaceae	■		■	■	■						■
26	*Panicum maximum*	Poaceae	■		■		■	■	■				
27	*Panicum turgidum*	Poaceae	■	■	■	■		■					
28	*Setaria viridis*	Poaceae	■						■				
29	*Sporobolus airiformis*	Poaceae	■				■						
30	*Tetrapogon villosus*	Poaceae	■			■	■						■
31	*Cometes abyssinica*	Caryophyllaceae	■	■									

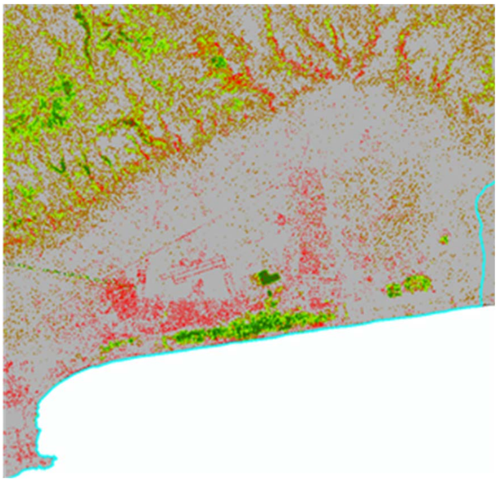

FIGURE 8. Urbanization cover (red) in 2018 in comparison to vegetation cover (green) in 1978 in one of the study regions (Salalah).

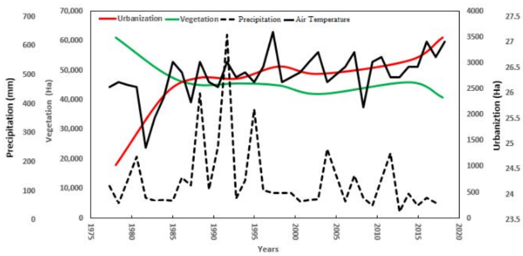

FIGURE 9. Vegetation coverage versus urbanization, air temperature, and precipitation in the study areas in Dhofar, 1978 to 2018.

Index was very high, with $R^2 = 0.92$, indicating that urbanization had a major effect on vegetation cover over the last 40 years. Fig. 8 informs us that the urbanization area increased during the 40 years from 1027 ha to 3492 ha, while vegetation decreased from 61,046 ha to about 40,768 ha, i.e., urbanization increased by 173.3% while the vegetation coverage decreased by 36.4%, indicating that other factors have also impacted the vegetation. These factors can include climate change. Therefore, an investigation was conducted, concentrating on air temperature as well as the amount of precipitation in the study area from 1978 to 2018. It was found that these weather parameters might have contributed to the reduction in vegetation cover, as illustrated in Fig. 9. The air temperature increased from 1978 to 2018 by an average of 0.8 °C, whereas the total precipitation decreased during the same period by 104 mm.

D. PLANT FAMILIES AND SPECIES ANALYSIS

Overall, vegetation coverage in the study area has decreased by 60% over the last 40 years, with some fluctuations between 1978 and 2018. Spatial mapping for plant families and species analysis were used to determine the geographic distribution of the dominant plant families and their species over the 40 years between 1978 and 2018, as summarized in Table 5 and shown in Fig. 10. The analysis showed that five plant families were

TABLE 5. List of dominant plant families and species over 40 years.

Years	Dominant Plant Families	Dominant Plant Species
1978	1. Poaceae	A-*Apluda mutica* B-*Oplismenus burmannii* C-*Heteropogon contortus*
1984	1. Poaceae 2. Commelinaceae	D- *Themeda quadrivalis* E- *Aneilema forskaolei* F- *Capillipedium parviflorum*
1988	1. Poaceae 3. Combretaceae	B-*Oplismenus burmannii* G- *Eustachys paspaloides* H- *Anogeissus dhofarica*
1993	1. Poaceae 4. Fabaceae 3. Combretaceae	B-*Oplismenus burmannii* I-*Crotalaria retusa* H-*Anogeissus dhofarica*
1998	1. Poaceae 5. Cucurbitaceae	B- *Oplismenus burmannii* G- *Eustachys paspaloides* J- *Corallocarpus epigaeus*
2003	1. Poaceae	K- *Sporobolus ioclados* A-*Apluda mutica* L- *Chrysopogon plumulosus*
2014	1. Poaceae 3. Combretaceae 2. Commelinaceae	B-*Oplismenus burmannii* H-*Anogeissus dhofarica* E-*Aneilema forskaolei*
2018	1. Poaceae 4. Fabaceae 3. Combretaceae	D-*Themeda quadrivalis* I-*Crotalaria retusa* H-*Anogeissus dhofarica*

dominant during the study period. Among them, Poaceae was the only plant family that remained dominant over the 40 years, whereas the dominance of the other four plant families fluctuated from year to year. Combretaceae dominated from 1988 to 1993 and from 2014 to 2018. Commelinaceae dominated in 1984 and 2014. Fabaceae dominated in 1993 and 2018, while Commelinaceae dominated only in 1998.

On the other hand, 12 plant species were shown as dominant during the study period. The most dominant plant species was *Oplismenus burmannii*, which dominated in 1978, from 1988 to 1998, and in 2014. This was followed by *Anogeissus dhofarica*, which dominated from 1988 to 1993 and from 2014 to 2018. Five plant species appeared twice over the 40 years, including *Apluda mutica*, which dominated in 1978 and 2003; *Themeda quadrivalis*, which dominated in 1984 and 2018; *Aneilema forskaolei*, which dominated in 1984 and 2014; *Eustachys paspaloides*, which dominated in 1988 and 1998; and *Crotalaria retusa*, which dominated in 1993 and 2018. The remaining five plant species appeared only once as dominant species during the study period: *Heteropogon contortus*, which dominated in 1978; *Capillipedium parviflorum*, which dominated in 1984; *Corallocarpus epigaeus*, which dominated in 1998; and *Sporobolus ioclados* and *Chrysopogon plumulosus*, which both dominated only in 2003.

E. ACCURACY ASSESSMENT

For accuracy assessment purposes, a ground-truthing process was conducted through a field survey during the first

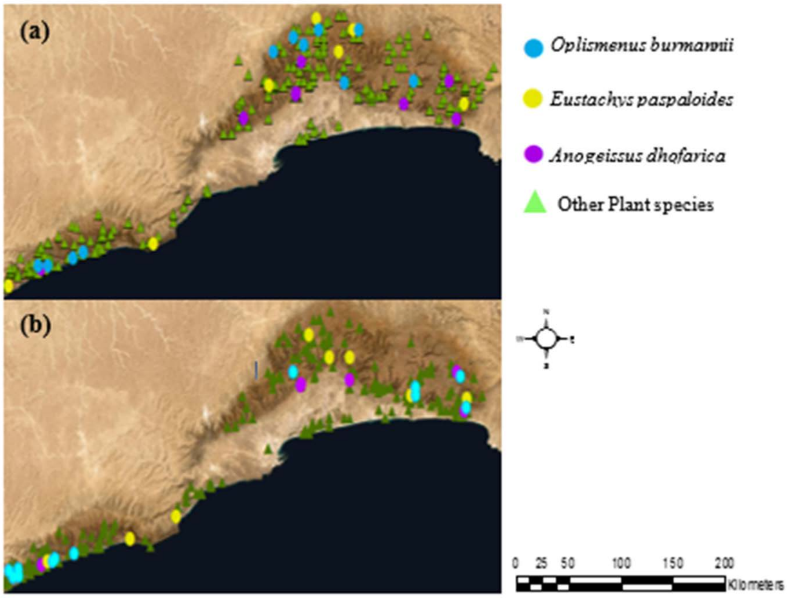

FIGURE 10. Examples of the geographic distribution of the dominant plant species between (a) 1988 and (b) 2014.

week of December 2019. A density map was created as a base for random sampling, following Richardson [37]. This process resulted in collecting 5–13 plant samples from each of the following areas: Dalkut, Rakhyut, Salalah, Salalah plain, Taqah, and Mirbat. The geographical location and a photograph of each collected plant sample were obtained using a global positioning system (OREGON-750, Garmin GPS, Olathe, Kansas, USA) and a camera (Nikon D3500 18–55 mm, Tokyo, Japan). The collected plant samples were brought to Sultan Qaboos University and identified by an expert at the Department of Biology, College of Science. The location error between the random samples created within the density map and the ground-truthing collected samples from the field ranged between 1 and 5 m. Then the collected samples were cross-checked against the data provided by OAPGRC. The accuracy assessment analysis showed that 87.5% of the field observations of the plant samples matched the data provided by the OAPGRC.

IV. DISCUSSION

The urbanization area doubled in 1984 as compared to 1978. During the same period, vegetation coverage decreased by 20%. In 1988, the change pattern was similar to 1984, by which the urbanization increased by 12% whereas the vegetation cover decreased by 8%. This change pattern was repeated in the following years, which indicated that urbanization negatively impacted on the vegetation coverage in the study area, although it was not the only factor. Nevertheless, it was noted that between 2003 and 2014 the urbanization and vegetation coverage increased in parallel, implying the introduction of agricultural practices mostly for commercial purposes. Measurements taken by concerned authorities during the period of study mitigated the impact of urbanization. Nevertheless, the study showed that urbanization through construction affected 59 plant species that were restricted to a very limited habitat in the Dhofar region. There was a 23.2% reduction in plant species distributed in coastal areas between 1978 and 2018. This reduction was attributed to the increase in urbanization in these areas. On the other hand, there was an 18.5% reduction in plant species in the mountains over the 40 years. This reduction was attributed to urbanization, as shown by the analysis, but also might have been related to environmental factors. Plant species including *Apluda mutica*, *Capillipedium parviflorum*, *Chrysopogon plumulosus*, *Eustachys paspaloides*, *Heteropogon contortus*, *Oplismenus burmannii*, *Sporobolus ioclados*, and *Themeda quadrivalis* that belong to the Poaceae family were present mostly in mountainous areas over the study period. Based on this, Poaceae can be considered a plant family resilient to the Dhofar region's climate. Poaceae was the dominant family throughout the 40 years, while the plant species under this family changed except for *Oplismenus burmannii*. Moreover, the Combretaceae family was the next most dominant family across the last 40 years, and *Anogeissus dhofarica* was the dominant plant species in this family.

Mansour [38] found that urban planning in their study region in the interior of Oman required a susceptibility study and evaluation of the urban impact on the existing vegetation of the area. MacLaren [39] found that the decrease in the Zeravshan juniper population was mainly due to climate change in Jabal Akhdar of the Nizwa region of Oman. Moreover, no major impact of anthropogenic activities, including grazing, clearing, and burning, was found by Ramadan [40] in terms of the vegetation reduction in the Dhofar Mountains. The latter two studies support our findings that urbanization impacted vegetation less than climate change in the study area of Dhofar.

Although Galletti *et al.* [31] mentioned that there was an impact of nationwide development of infrastructure on forests, grassland, and the coastal environment, they did not quantify the matter. Our study provides this information in the results section above. Our analysis showed that cloud cover creates a favorable seasonality in this ecosystem, which is crucial for maintaining trees. This is achieved by prolonging the growing season from three months to six months and allowing deeper infiltration, which ensures the competitiveness of trees in an otherwise too dry environment [41].

V. CONCLUSION

The impact of urbanization on vegetation is poorly studied in sparsely vegetated desert steppe-type vegetation. Moreover, no research has been found to quantify how urbanization impacted vegetation areas in the Governorate of Dhofar. It was very important to have a study that shows the impact of urbanization on plant diversity in Oman. The diversity of the Governorate of Dhofar's habitats constitutes over two-thirds of the plant diversity in the whole country of the Sultanate of Oman, where at least 50 of these recorded species are endemic. This Governorate has witnessed a surge in urban development, especially between 1978 and 2018.

Different remote sensing and GIS techniques were used to quantify the interaction of urbanization and vegetation from 1978 to 2018 over the five wilayat of Dhofar, representing the five regions of the Governorate. The approaches used in this work, including remote sensing and GIS tools, provided a cost-effective spatiotemporal analysis of the impact of urbanization on vegetation coverage in the study area. The results showed that, over the 40 years, urban development increased by 173.3%, whereas vegetation cover decreased by 36.4%. It was found that the correlation between the vegetation index and building index was very high and indirectly indicated the impact of urbanization on vegetation between 1978 and 2018. It was found that 48 rare plant species impacted by urbanization were only present in the study sites of Dhofar. Hence, these sites must be preserved to save the natural habitats of these plant species and not expose them to extinction risk due to urbanization. There are 17 other rare plant species in Dhofar, located in one or two sites in the Sultanate, that must also be preserved from the impact of urban development. However, we believe that other factors have also affected vegetation, including climate change, and especially air temperature, which increased by 0.8°C during the same period in the study area, and precipitation, which decreased by 104 mm. As this study is limited to the application of satellite imagery in the study area, there is room for more research to investigate in detail the effects of climate change on vegetation patterns in the Governorate of Dhofar. We recommend taking the biological and plant diversity of Dhofar into consideration and making it a priority when developing any urban projects, especially at sites that contain rare species. The results of this study can help scientists, planners, and decision makers with the current and future management of urbanization to conserve plant diversity in the Dhofar region.

REFERENCES

[1] J. K. Jacka, "The impact of mining development on settlement patterns, firewood availability and forest structure in Porgera," in *Tropical Forests of Oceania: Anthropological Perspectives*, J. A. Bell, P. West, and C. Filer, Eds. Canberra, ACT, Australia: ANU Press, 2015, pp. 95–127.

[2] K. C. Seto, B. Güneralp, and L. R. Hutyra, "Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools," *Proc. Nat. Acad. Sci. USA*, vol. 109, no. 40, pp. 16083–16088, Oct. 2012.

[3] M. L. McKinney, "Urbanization, biodiversity, and conservation: The impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems," *Bioscience*, vol. 52, pp. 883–890, Oct. 2002.

[4] M. Dociu and A. Dunarintu, "The socio-economic impact of urbanization," *Int. J. Academic Res. Accounting, Finance Manag. Sci.*, vol. 2, no. 1, pp. 47–52, 2012.

[5] B. Güneralp, R. I. M. McDonald Fragkias, J. Goodness, P. J. Marcotullio, and K. C. Seto, "Urbanization forecasts, effects on land use, biodiversity, and ecosystem services," in *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Dordrecht, The Netherlands: Springer, 2013, pp. 437–452.

[6] D. D. Ackerly, W. K. Cornwell, S. B. Weiss, L. E. Flint, and A. L. Flint, "A geographic mosaic of climate change impacts on terrestrial vegetation: Which areas are most at risk?" *PLoS ONE*, vol. 10, no. 6, Jun. 2015, Art. no. e0130629.

[7] D. Li, B. J. Stucky, J. Deck, B. Baiser, and R. P. Guralnick, "The effect of urbanization on plant phenology depends on regional temperature," *Nature Ecol. Evol.*, vol. 3, no. 12, pp. 1661–1667, Dec. 2019.

[8] A. Patzelt, "Synopsis of the flora and vegetation of oman, with special emphasis on patterns of plant endemism," in *Proc. Jahrbuch Braunschweigischen Wissenschaftlichen Gesellschaft*, 2015, pp. 282–317.

[9] S. A. Ghazanfar, "Quantitative and biogeographic analysis of the flora of the Sultanate of Oman," *Global Ecol. Biogeogr. Lett.*, vol. 2, no. 6, pp. 189–195, 1992.

[10] S. A. Ghazanfar and M. Fisher, Eds., *Vegetation of the Arabian Peninsula*, vol. 25. The Netherlands: Springer, 2013.

[11] A. Patzelt, *Oman Plant Red Data Book*. Muscat, Oman: Diwan of Royal Court, 2014.

[12] A. Patzelt, T. Harrison, S. G. Knees, and L. Al Harthy, "Studies in the flora of Arabia XXXI: New records from the Sultanate of Oman," *Edinburgh J. Botany*, vol. 70, no. 2, pp. 1–20, 2014.

[13] A. Patzelt, "The *Themeda quadrivalvis* tall-grass savannah of Oman at the crossroad between Africa and Asia," *Edinburgh J. Botany*, vol. 68, no. 2, pp. 301–319, 2011.

[14] A. G. Miller, M. Morris, and S.-S. Smith, *Plants of Dhofar, the Southern Region of Oman, Traditional, Economic and Medicinal Uses*. Muscat, Oman: Diwan of Royal Court, 1988.

[15] S. Carranza *et al.*, "Diversity, distribution and conservation of the terrestrial reptiles of Oman (Sauropsida, Squamata)," *PLoS ONE*, vol. 13, no. 2, Feb. 2018, Art. no. e0190389.

[16] E. N. Arnold, "The scientific results of the Oman flora and fauna survey 1977 (Dhofar). The reptiles and amphibians of Dhofar, southern Arabia," *J. Oman Stud. Special Rep.*, no. 2, pp. 273–332, 1980.

[17] A. Al Jabri, "Indigenous-flora: Oman flora history," e-Flora Sultanate Oman, 2015. [Online]. Available: https://omanflora.myspecies.info

[18] *The Anglo-Omani Society Brochure*, AOSOC, Dhofar, Oman, 2009, p. 18.

[19] M. A. El-Sheikh, "Weed vegetation ecology of arable land in Salalah, southern Oman," *Saudi J. Biol. Sci.*, vol. 20, no. 3, pp. 291–304, Jul. 2013.

[20] C. P. Giri, *Remote Sensing of Land Use and Land Cover: Principles and Applications*. Boca Raton, FL, USA: CRC Press, 2016.

[21] J. Miller and J. Rogan, "Using GIS and remote sensing for ecological mapping and monitoring," in *Integration of GIS and Remote Sensing*. U.K.: Wiley, 2007, pp. 233–268.

[22] Visual Crossing. (2021). *Visual Crossing Weather Data and Weather API*. [Online]. Available: https://www.visualcrossing.com

[23] M. Necsoiu, "Software validation test plan and report ERDAS IMAGINE," U.S. Center Nucl. Waste Regulatory Analyses, San Antonio, TX, USA, Tech. Rep. ML063050162, 2004.

[24] A. Runge and G. Grosse, "Mosaicking Landsat and Sentinel-2 data to enhance LandTrendr time series analysis in northern high latitude permafrost regions," *Remote Sens.*, vol. 12, no. 15, p. 2471, Aug. 2020.
[25] J. Useya and S. Chen, "Comparative performance evaluation of pixel-level and decision-level data fusion of Landsat 8 OLI, Landsat 7 ETM+ and Sentinel-2 MSI for crop ensemble classification," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 11, no. 11, pp. 4441–4451, Nov. 2018.
[26] R. Richter and D. Schläpfer, "Atmospheric/topographic correction for airborne imagery," ATCOR-4 User Guide, ReSe Appl. Schlapfer, Switzerland, Tech. Rep. 565-02, 2011.
[27] M. S. Mkhabela, M. S. Mkhabela, and N. N. Mashinini, "Early maize yield forecasting in the four agro-ecological regions of Swaziland using NDVI data derived from NOAA's-AVHRR," *Agricult. Forest Meteorol.*, vol. 129, nos. 1–2, pp. 1–9, Mar. 2005.
[28] L. Chen, M. Li, F. Huang, and S. Xu, "Relationships of LST to NDBI and NDVI in Wuhan City based on Landsat ETM+ image," in *Proc. 6th Int. Congr. Image Signal Process. (CISP)*, vol. 2, 2013, pp. 840–845.
[29] *Personal Communication*, Oman Animal Plant Genet. Resour. Center, Res. Council, Seeb, Oman, 2019.
[30] A. H. A. Lawati, N. A. Saady, H. C. A. Khafaji, A. Patzelt, J. Phillips, N. Maxted, A. H. Al Balushi, D. Al-Maqbali, A. S. A. Naabi, K. A. A. Busaidi, M. A. Kharusi, M. S. A. Shukaili, A. A. A. Jabri, and H. M. A. Nabhani, "Socioeconomic plants conservation strategy for the Sultanate of Oman," Oman Animal Plant Genet. Resour. Center, Res. Council Sultanate of Oman, Muscat, Oman, 2017.
[31] C. S. Galletti, B. L. Turner, and S. W. Myint, "Land changes and their drivers in the cloud forest and coastal zone of Dhofar, Oman, between 1988 and 2013," *Regional Environ. Change*, vol. 16, no. 7, pp. 2141–2153, Mar. 2016.
[32] *WWMO/ESCAP Panel on Tropical Cyclones Annual Review 2002*, World Meteorol. Org., United Nations Econ. Social Commission Asia Pacific, Geneva, Switzerland, 2004.
[33] S. A. Ghazanfar, *Flora of the Sultanate of Oman: Piperaceae-Primulaceae* (Scripta Botanica Belgica Series), vol. 1. Meise, Belgium: National Botanic Garden of Belgium, 2003, p. 262.
[34] S. A. Ghazanfar, *Flora of the Sultanate of Oman: Crassulaceae-Apiaceae* (Scripta Botanica Belgica), vol. 2. Meise, Belgium: National Botanic Garden of Belgium, 2007, p. 220.
[35] S. A. Ghazanfar, *Flora of the Sultanate of Oman: Loganiaceae-Asteraceae* (Scripta Botanica Belgica Series), vol. 3. Meise, Belgium: National Botanic Garden of Belgium, 2015, p. 386.
[36] S. A. Ghazanfar, *Flora of the Sultanate of Oman: Hydrocharitaceae-Orchidaceae* (Scripta Botanica Belgica Series), vol. 4. Meise, Belgium: National Botanic Garden of Belgium, 2018.
[37] E. Richardson, M. Good, G. McGrath, and S. J. More, "The use of geographic information system (GIS) and non-GIS methods to assess the external validity of samples postcollection," *J. Veterinary Diagnostic Invest.*, vol. 21, no. 5, pp. 633–640, Sep. 2009.
[38] S. Mansour, M. Al-Belushi, and T. Al-Awadhi, "Monitoring land use and land cover changes in the mountainous cities of Oman using GIS and CA-Markov modelling techniques," *Land Use Policy*, vol. 91, Feb. 2020, Art. no. 104414.
[39] C. A. MacLaren, "Climate change drives decline of *Juniperus seravschanica* in Oman," *J. Arid Environ.*, vol. 128, pp. 91–100, May 2016.
[40] E. Ramadan, T. Al-Awadhi, and Y. Charabi, "Land cover/land use change and climate change in Dhofar Governorate, Oman," *Int. J. Geoinform.*, vol. 17, no. 4, pp. 41–47, 2021.
[41] A. Hildebrandt and E. A. B. Eltahir, "Ecohydrology of a seasonal cloud forest in Dhofar: 2. Role of clouds, soil type, and rooting depth in tree-grass competition," *Water Resour. Res.*, vol. 43, no. 11, Nov. 2007, Art. no. W11411.

YASEEN AL-MULLA (Member, IEEE) is an Associate Professor and the Director of the Remote Sensing and GIS Research Center, Sultan Qaboos University, Al-Khod, Sultanate of Oman.

AMNA AL-RUHEILI is an Assistant Professor with the Department of Plant Sciences, Sultan Qaboos University, Al-Khod, Sultanate of Oman.

ALI AL-LAWATI is an Assistant Professor with the Natural and Medical Sciences Research Center, University of Nizwa, Birkat Al-Mauz, Nizwa, Sultanate of Oman.

KRISHNA PARIMI is a Research Assistant with the Remote Sensing and GIS Research Center, Sultan Qaboos University, Al-Khod, Sultanate of Oman.

AHSAN ALI (Member, IEEE) is a Postdoctoral Researcher with the Remote Sensing and GIS Research Center, Sultan Qaboos University, Al-Khod, Sultanate of Oman.

NADYA AL-SADI is the Executive Director of the Oman Animal and Plant Genetic Resources Center, Ministry of Higher Education, Research and Innovation, Muscat, Sultanate of Oman.

FAISAL AL-HARRASI is a Technician with the Earth Science Research Center, Sultan Qaboos University, Al-Khod, Sultanate of Oman.