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Mapping land use and dynamics of vegetation cover in Southeastern Arabia using remote sensing: the study case of Wilayat Nizwa (Oman) from 1987 to 2016

Fairouz Megdiche-Kharrat [1,2,3] • Rachid Ragala [2,3] • Mohamed Moussa [1]

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Abstract
The region of Wilayat Nizwa, in Northern Oman, is characterized by very high temperature and rare irregular rainfall. Local farmers relay on irrigation to maintain their lands productive. They get water by means of ancestral water acquisition systems called *aflaj* (plural of *falaj*). This study focalizes on the physical space of Wilayat Nizwa. Its main goal is to read and analyze the landscape of this area using a method based on multispectral electromagnetic spatial remote sensing. The processing of data from satellites Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI and TIRS relative to January 1987, October 2000, February 2009, and January 2016 allowed us to extract information on the landscape components of Nizwa and its surroundings, to generate a land use map, and to monitor the dynamics of the vegetation cover in Wilayat Niwza from 1987 to 2016. The study zone is mainly a mountainous region, rugged with many gullies and characterized by an important geological diversity and large sedimentary valleys and riverbeds. The non-supervised classification reveals six different classes of which the clay/sandy sedimentary soils and the very clayey rocky/gypsum blocs are the most important ones. The information extracted from the Perpendicular Vegetation Index 1 (PVI1) show that the area of irrigated vegetation remained relatively stable, with a minor increase, which equals to 805.91 ha, in 2009, compared with the spontaneous one in which the rise is 17,588.85 ha. Combined with socioeconomical and climatic parameters, these results would be good indicators to assess the functioning of *aflaj* and to anticipate the evolution of the local landscape.

Keywords Landscape · Land use · Vegetation cover · Irrigation · Remote sensing · Nizwa

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✉ Fairouz Megdiche-Kharrat
feirouzmekdish@gmail.com

Rachid Ragala
rachid.ragala@sorbonne-universite.fr

Mohamed Moussa
mohamed.moussa@ira.rnrt.tn

[1] Laboratory of Eremology and Combating Desertification, Institute of Arid Regions, 4100 Medenine, Tunisia

[2] Lettres Sorbonne Université, 1 Avenue Victor Cousin, 75005 Paris, France

[3] Laboratory Analysis and Social Mathematics Center CAMS-CNRS-EHESS, Paris, France

Introduction

Most of the Arabian Peninsula has arid climate. About one third of this area is covered by a large sandy desert Al-Rub Al-Khali (Besler, 1982, cited in Bray and Stokes 2004). Al-Rub Al-Khali is for most a large sedimentary basin that extends over an area of 600,000 km^2 (Anton, 1983, cited in Bray and Stokes 2004) and is bounded by Oman's mountains Al-Hajar in its east. Oman is situated in the southeast of the Arabian Peninsula. It has a total area of 309,500 km^2; it opens onto the Gulf of Oman and the Arabian Sea with a coastline of 1700 km (Hawley 2005). Oman shares borders with the United Arab Emirates, the Kingdom of Saudi Arabia, and the Republic of Yemen. Oman presents large landscape sets that can be classified into four families: plains of gravel or loess (silt clay and limestone), the deserts of sand, sebkha, and mountain ranges (El-Baz 2002). Oman can be divided into four distinct geologic areas: the chain of Al-Hajar Mountains in the north which forms a belt characterized by the wideness of its folds; the rocky plateaus in the center of the country which are covered with flat sedimentary layers; the Dhofar Mountains in the south which consist of calcareous layers and steep costal cliffs; and the sand plains of Al-Rub Al-Khali in the west side and the Wahiba ones in the central part of the country (El-Baz 2002).

Oman has an arid climate characterized by clear skies and light winds across the year; winters show moderate temperatures and summers are very hot and very dry (El-Baz 2002). The sun shines in Oman about 10 h/day as annual average, except on the mountains and the Dhofar region; the average humidity ranges from 40% in desert regions to 60% in the North of the country to reach 70% in the south (El-Baz 2002). The country is marked by irregular although, in general, very low rainfall, less than 50 mm in central Oman, except in the southwestern part and the northern mountains where it rains twice periods a year exceeding 300 mm yearly: in summer when the region is affected by the southeast winds from the Indian Ocean and in winter when it is impacted by the northeast winds from the Gulf (El-Baz 2002). Besides, Oman is subject to exceptional severe climatic conditions such as the cyclones Gonu and Phet that did hit the country, respectively, in 2007 and 2010, resulting in an unusual volume of runoff water (Fig. 1).

The area of study

At the foothill of the Al-Hajar chain, at around 600 m a.s.l. and despite the harsh climatic conditions, many oasis cities subsist due to groundwater availability such as the cities of Nizwa and Birkat Al-Mouz in Wilayat Nizwa. According to the national census 2010 (national censuses are conducted each 10 years), Wilayat Nizwa is the second most populated district in the country with 84,528 inhabitants and a relatively high density of 58.1 people per square kilometer (Census 2010 Final Results 2011). Willayat Nizwa is the regional capital of Ad-Dhakliyah region; it covers 13 small cities of which Nizwa is the largest. The city of Nizwa is situated near Al-Jabal Al-Akhadar, a 2000-m altitude mountain where rainfall can reach 325 mm yearly (El-Baz 2002). In general, this region is characterized by very high temperature and irregular rainfall. To maintain their lands productive, the local farmers relay on irrigation by means of *aflaj* (plural of *falaj*).

Aflaj, geology, soil types, and faults

Aflaj are ancestral water acquisition systems which present three different methods of water extraction: channeling surface flow, conveying springs' water, and draining groundwater from aquifers (Al-Marshudi, 2007 cited in Megdiche-Kharrat et al. 2017). Omani authorities has inventoried, between 1997 and 1999, 4112 systems of which 3017 are still active and consisting of a 2900-km-long network of tunnels and surface channels irrigating about 17,600 ha of cultivated areas (MRMWR, 2008 and Al-Ghafri, 2012 cited in Megdiche-Kharrat 2018). In Wilayat Nizwa, there are 134 *aflaj* of which 111 are still active and 23 dried up by the year 2000 (MRMWR, 2014 cited in Megdiche-Kharrat 2018).

Figure 2a, b shows, in Wilayat Nizwa, a very well correlation between the location of *aflaj* and the general direction of the tectonic discontinuities (fault zones) in the Al-Hajar Mountains' area in northeastern Nizwa oasis and into Al-Hajar super group geological formations (Megdiche-Kharrat et al. 2017). The secondary porosity of the fractured rocky system explains the hydrogeological recharge of the groundwater, thus, of the *aflaj* with underground channels; besides, in the valley aquifers, recharge is due to the high porosity of the sandy alluvial deposits in addition to the favorable environment characterized by sandy and loamy deep soil, slightly to moderately flooded and with slope less than 3% (Megdiche-Kharrat et al. 2017). This indicates that, in this arid environment, *aflaj* was sited and constructed by local people following a very good knowledge and pertinent macro-field observations (Megdiche-Kharrat et al. 2017).

Yet, *aflaj* survival depends on several factors, mainly social and economic ones, such as the good management of the systems and their maintenance with transmitting the knowledge over generations, limiting the urban expansion over

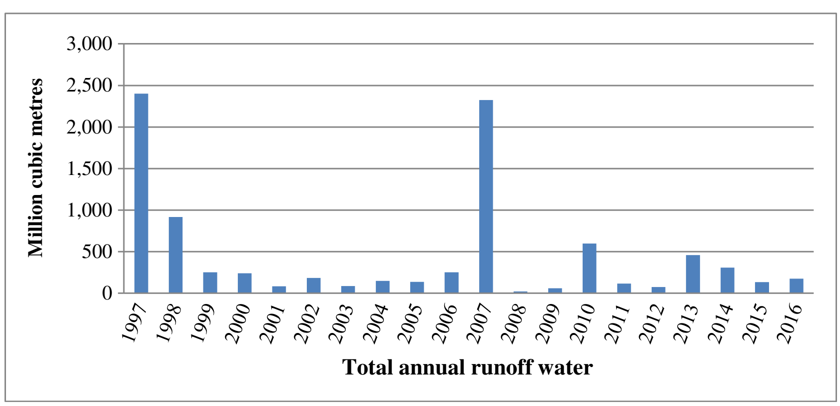


Fig. 1 Total annual runoff water in the Sultanate of Oman from 1997 to 2016. Source: elaborated according to the data published by the Ministry of Regional Municipalities and Water Resources (MRMWR) of Oman (Megdiche-Kharrat 2018)

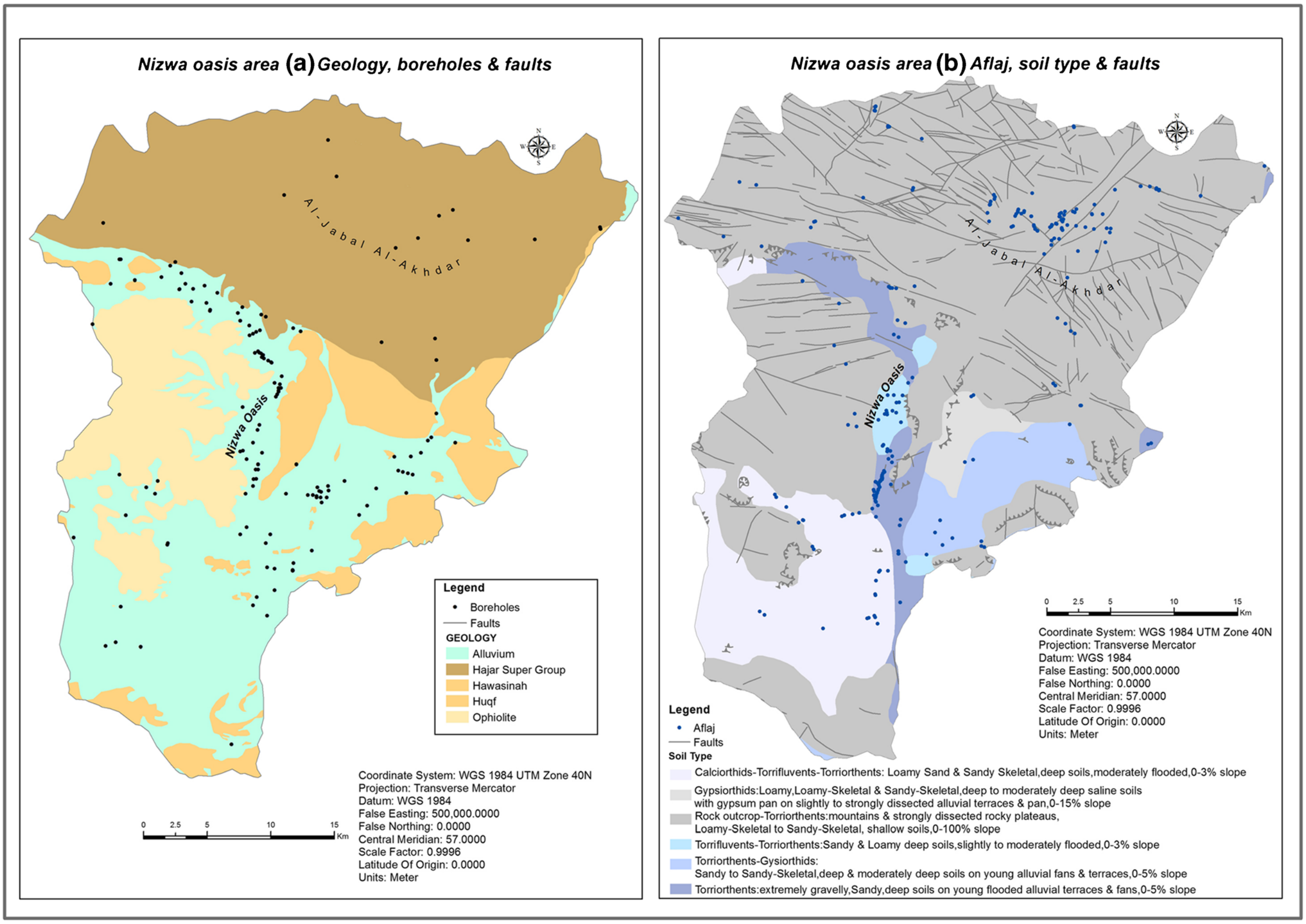


Fig. 2 Wilayat Nizwa: (**a**) Geology, boreholes, and faults and (**b**) *aflaj*, soil types, and faults (Megdiche-Kharrat et al. 2017)

cultivated lands and rural population displacement for job opportunities in other sectors like the fossil energy industry, and avoiding harmful behaviors that may waste and pollute the water (Megdiche-Kharrat et al. 2017).

Scope and aims of the study

This study is a part of a research about *aflaj* and qanats as ancestral and sustainable groundwater acquisition system and their associated social structures and generated landscapes. Its general scope includes Middle Eastern societies practicing irrigation, with a focus on Omani ones. This paper focalizes on the physical space that gives Wilayat Nizwa in Northern Oman its typical landscape characteristics. Its goal is to read and analyze the landscape of this area by focusing on land use and its spatio-temporal dynamics using a method based on multispectral electromagnetic spatial remote sensing. Since this region is known by its landscape diversity and agricultural practice with community-based water management for irrigation, the scope of this study includes generating a land use map and monitoring the dynamics of the vegetation cover with separating the irrigated one from the non-irrigated one in Wilayat Niwza from 1987 to 2016. In an area rarely investigated within this thematic, such as the region of Nizwa, the time-basis approach can be adopted by using remote sensing which also consists of an innovative method to be applied to the area of study. Besides, no previous research projects were conducted targeting the dynamics of the local landscape. A comparable study, targeting one landscape component and using remote sensing, was conducted soon later on mangrove forest in the Persian Gulf and the Gulf of Oman (specifically, Al Qurm region) from 1977 to 2017 (Milani 2018).

Methodology

The general approach consists of locating and characterizing the components of the Earth's surface based on multispectral electromagnetic space remote sensing combined with a good knowledge of the terrain. To implement our method, based on spectral analysis, we used the data recorded by sensors from the Landsat 5, Landsat 7, and Landsat 8 satellites (Earthdata (https://earthdata.nasa.gov/) accessed in 2016) in the following spectral domains: visible, near-infrared (NIR), and medium-infrared (MIR). The data are made available free of charge for the resolution 30×30 m^2/pixel which is adequate considering the particular characteristics of the study zone, specifically the low density in land use. We picked the good quality available images taken during the winter rainy season at a time interval of more or less 10 years (Table 1).

Pretreatment and image-processing

To process and exploit the collected data, we started by verifying the spatial overlapping of downloaded satellite images. Then, we improved the quality of spectral responses by calibrating the satellite images by applying the necessary radiometric corrections relating to the disturbances due to sensor technology (sensor compensation correction) and those due to sun's azimuth and elevation and the value of the average exo-atmospheric solar illumination (transition from true spectral radiance $L\lambda$ to true Top-of-Atmosphere (ToA) Reflectance $\rho\lambda$) (Bildgen 1989). This process is performed by applying specific correction formulas on each channel, in our case, the visible, the near-infrared and the medium-infrared channels. Finally, we extracted the studied area (Wilayat Nizwa); this process corresponds to a spatial cutting that highlights our study area, carried out on all the images and on each channel.

Extraction of information

After processing the data, we started extracting the information by making RGB (red, green, blue)-colored compositions for the selected area and on each date, with targeting two main objectives which are the elaboration of a descriptive land use map for the most recent date (January 2, 2016) and the exploration of vegetation cover dynamics in all the selected dates (from 1987 to 2016).

The colored composition RGB

We used the channels of green, red, and near-infrared (NIR). These compositions allow us to explore visually the components of the landscape of the extracted area for each date.

Dynamics of vegetation cover (from 1987 to 2016)

The concept consists of getting reliable information about vegetation based on the remotely sensed values by applying a vegetation index. "The usual form of a vegetation index is a ratio of reflectance measured in two bands, or their algebraic combination" (Mroz and Sobieraj 2004). The most popular index NDVI (Normalized Difference Vegetation Index), introduced by Rouse et al. (1974 cited in Mroz & Sobieraj 2004) and based on near-infrared (NIR) and red (R) bands, has been widely used in satellite assessment and monitoring of global vegetation cover in the last decades; however, several studies show that this greenness classic indicator is low representative of vegetation biomass in arid and semi-arid areas (Leprieur et al. 2000; Fadaei et al. 2012; Zucca et al. 2015). Instead, distance-based vegetation indices are based on the soil line concept in which pixels near the soil line are considered to represent the soil and those far from it to represent vegetation (Mroz and Sobieraj 2004). They consider the slope (b) and the intercept (a) of the line as inputs in calculations (Fig. 1). First, Richardson and Wiegand (1977 cited in Jackson 1983) developed a Perpendicular Vegetation Index based on two *Landsat* bands: the infrared and the red; later, in 1982, they introduced to it a soil line index (cited in Jackson 1983). Its derivation mainly consists of finding the orthogonal distance from a line, representing soils, to a point, representing vegetation which is very useful for the discrimination of vegetation from soil background (Jackson 1983). The PVI1 (Perpendicular Vegetation Index 1) is a distance-based vegetation indices developed by Perry and Lautenschlager (1984 cited in Mroz & Sobieraj 2004); we applied the PVI1 because it attenuates soil influence in vegetation reflectance and highlights the presence of low-density vegetation with low chlorophyll activity (Mroz and Sobieraj 2004).

$$\mathrm{PVI1} = \frac{(b \times \mathrm{NIR} - R + a)}{\sqrt{b^2 + 1}}$$

where NIR is the wavelength of the near-infrared, R is the wavelength of the red, and a and b are the coefficients of the regression line between channels R and NIR (Fig. 3).

On PVI1 and for each date, we proceeded by thresholding regarding the spectral responses of the overall pixels in the green, the red, and the near-infrared wavelengths through the identification, visually, of the similarities indicating the presence of a vegetation cover and the quality of its chlorophyll activity. Our objective is to extract three classes: a non-

Table 1 Description of the used satellite images

	Acquisition date	Type	Space sensor	Types of detectors	Resolution (m^2/pixel)
Image 2016	January 2, 2016	Multispectral imagery	Landsat 8	OLI and TIRS, Pushbroom	30 × 30
Image 2009	February 7, 2009	Multispectral imagery	Landsat 7	ETM+, WhiskBroom	30 × 30
Image 2000	October 28, 2000	Multispectral imagery	Landsat 7	ETM+, WhiskBroom	30 × 30
Image 1987	January 18, 1987	Multispectral imagery	Landsat 5	TM	28.5 × 28.5

Source: Earthdata (https://earthdata.nasa.gov/) accessed in 2016

OLI Operational Land Imager, TIRS Thermal Infrared Sensor, ETM+ Enhanced Thematic Mapper Plus, TM Thematic Mapper

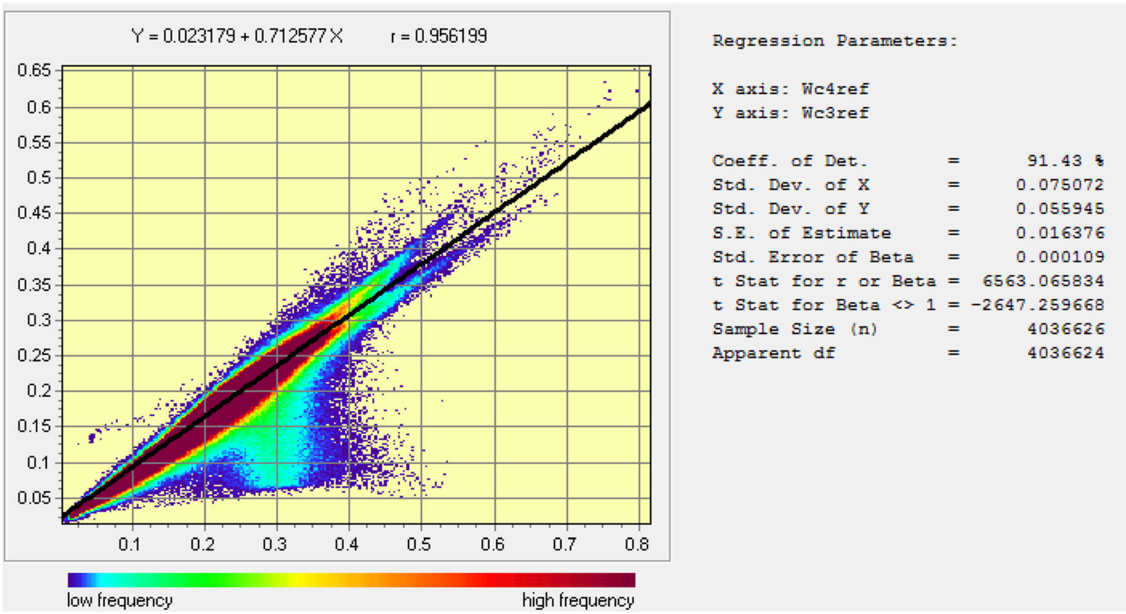


Fig. 3 Chart and regression parameters for the calculation of the Perpendicular Vegetation Index 1

vegetation class (class 0), a sparsely dense rain-fed vegetation class (class 1), and an irrigated dense vegetation class (class 2). To verify and, consequently, to adjust our threshold choices, we compared the spectral signatures of the classes in the green, the red, and the near-infrared wavelengths. In the first trial, the class 1 corresponds to a threshold of "1 to 6" and the class 2 to "6 to 100" (Fig. 4a). In the second trial, the class 1 corresponds to a threshold of "2 to 6" and the class 2 to "6 to 100" (Fig. 4b). This adjustment is based on the fact that the spectral behavior of vegetation is characterized by a reflectance in the wavelength of green which varies according to the color of the vegetation (the greener it is, the higher the reflectance), an absorption of radiation in the wavelength of red which indicates the presence of chlorophyll activity (the higher the absorption, the higher the chlorophyll activity), and a strong reflectance in the near infrared which is due to the cellular structure of the plant. Thus, the graphic form of the spectral signature is similar to the letter "V." On the other hand, we sampled pixels belonging to identifiable zones that we explored in the fieldwork (Fig. 5) and which appear as vegetation on the PVI1, while on the colored composition, the red appears little. We compared the spectral signatures of four samples (1 up to 8 pixels by sample), picked in the study area, in the green, red, and near-infrared wavelengths to verify again our threshold choices that we validated regarding the obtained results (Fig. 6).

Land use map of Wilayat Nizwa (January 2, 2016)

To generate a land use map of Wilayat Nizwa, we applied an unsupervised classification by discriminant analysis on the image of January 2, 2016. This unsupervised technique of information reduction "is categorizing the data according to the similarities in pixel values" (Collet 1992). We used the channels of green, red, near-infrared (NIR), and medium infrared (MIR). The wavelength of the MIR allows a good discrimination of the different types of soil. We started by masking the vegetation classes on the different canals, then we classified the pixels by the *K*-means data partitioning method (random partition) with fixing a number *K* of classes, in total five classes to which will be added the two classes of vegetation elaborated previously on the neo-channels PVI1.

Results and discussion

Description of the landscape components

The colored compositions RGB (Fig. 7), overlaying data from the channels of green, red, and near-infrared (NIR), combined with a good knowledge of the terrain, allow to describe the landscape of the region of Wilayat Nizwa in each of the considered dates, thus to observe the changes regarding the main specific components of this zone.

The studied area appears mainly as a mountainous region, rugged with many gullies. It is characterized by an important geological diversity and large sedimentary valleys and river beds that reveal recent river sedimentary deposits. These dry river beds have a spectral signature almost horizontal due to the presence of organic matter and humidity which is revealed by a slight decrease in the near-infrared (NIR). We also observed rock formations with different shades of color: in dark gray in the east and west, probably rich in iron, and in light greenish gray

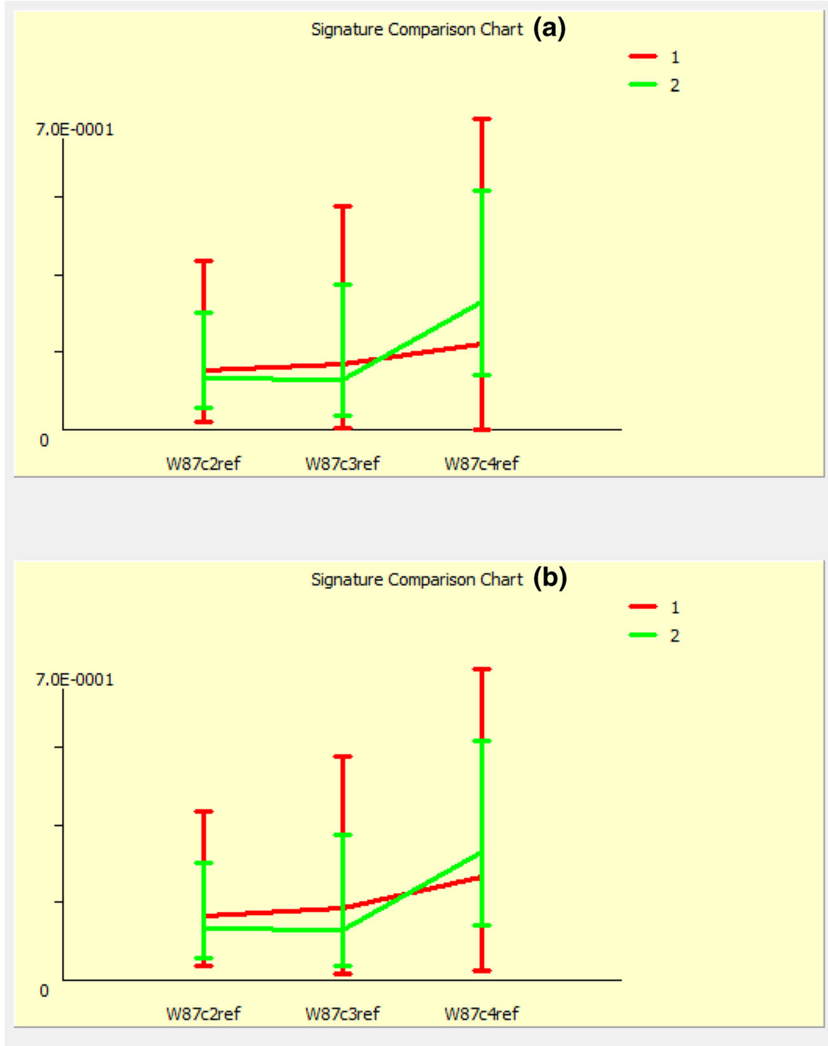


Fig. 4 Comparison chart of spectral signatures of class 1 (rain-fed vegetation) and class 2 (irrigated vegetation): **a** First thresholding, respectively, "1 to 6" and "6 to 100" and **b** second thresholding, respectively, "2 to 6" and "6 to 100" (wavelengths of green, red, and near infrared, Landsat 5, January 18, 1987)

in the south, less rich in iron and organic matter and less moist, thus, an increase in the reflectance. Chlorophyll vegetation appears with a bright red hue, especially in the oases corresponding to broadleaf type vegetation, and with a dark red hue indicating the presence of conifer vegetation located mainly in the mountains in the northern part of the study area. The white spots, observed mainly in the central part of the area, indicate the presence of sandy soils in the valley and around the oases. These are bare soils or areas of building expansion. The pixels with whitish or yellowish hue indicate a high reflectance that increase from the visible wavelengths to the near-infrared (NIR); this signifies the presence of dry sandstone or limestone rocks. Besides, when comparing the four colored compositions, we can clearly see the evolution of residential areas around the oases and the appearance of new urban areas. This is evident on the 2000 and 2016 year maps. We notice that most of the new constructions are in the dry wadi beds, which means in potentially floodable areas. The drainage lines, very visible on the 2000 year map, are clear indicators of this risk. This shows that the adopted urban planning and development strategy is either not taking in consideration both the physical and landscape characteristics of this zone or not respected by residents. The road infrastructure appears to be much more advanced on the 2016 map with the construction of several main roads and secondary roads, still within wadi beds, linking oases, new neighborhoods, and isolated settlements. We also note the spread of general chlorophyll vegetation over time.

The major landscape sets of Wilayat Nizwa (in 2016)

On the obtained land use map of Wilayat Nizwa (Fig. 8), we can distinguish six major different classes, five of which are associated to the main landscape sets that

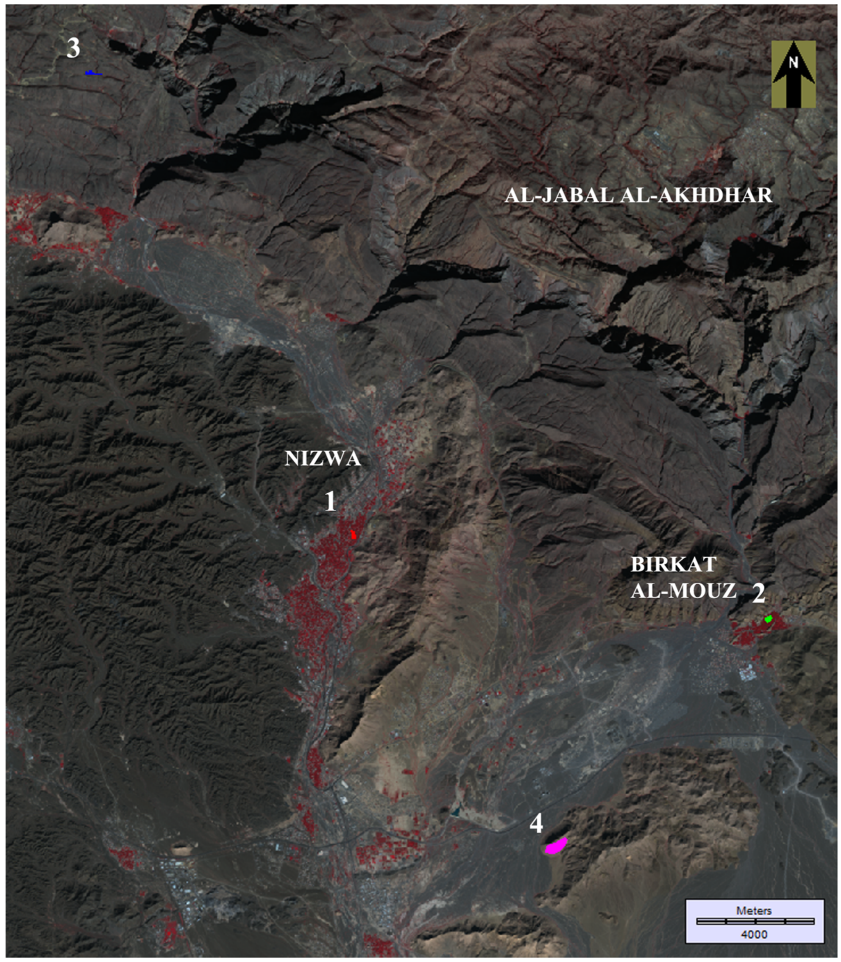


Fig. 5 Geospatial referencing of the four picked samples in the study area, colored composition RGB of Wilayat Nizwa. Landsat 8 OLI, January 2, 2016. Geographic coordinate system: GCS_WGS_1984. Projection: UTM_Zone_40N

characterize this zone. In fact, the number of classes was fixed to five (plus a sixth one for the drop shadow masking the information) based on the official data collected from the ministry of regional municipalities and water resources (MRMWR) of Oman regarding the geology and the soil types of the study area. These classes indicating the various landscape sets, their characteristics, and the identified soil types fit to a high extent the maps generated from the official data (Fig. 2). Besides, during the fieldwork, we visually identified the main landscape

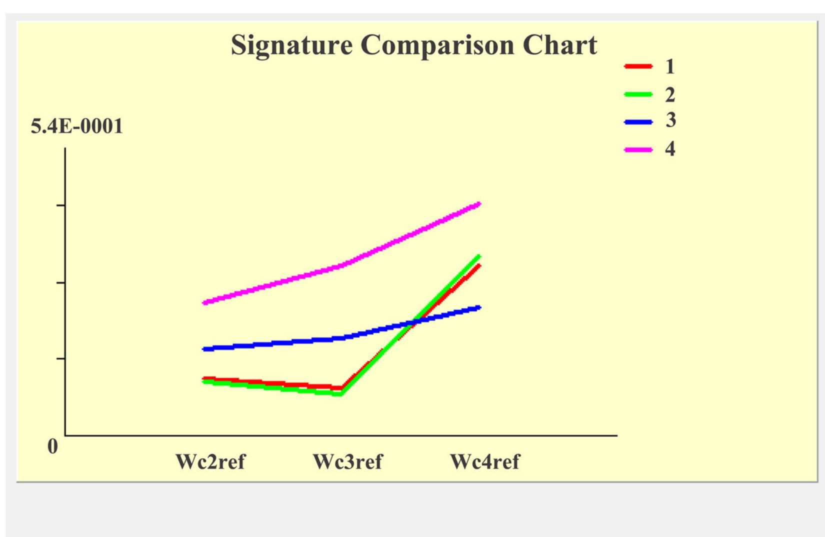
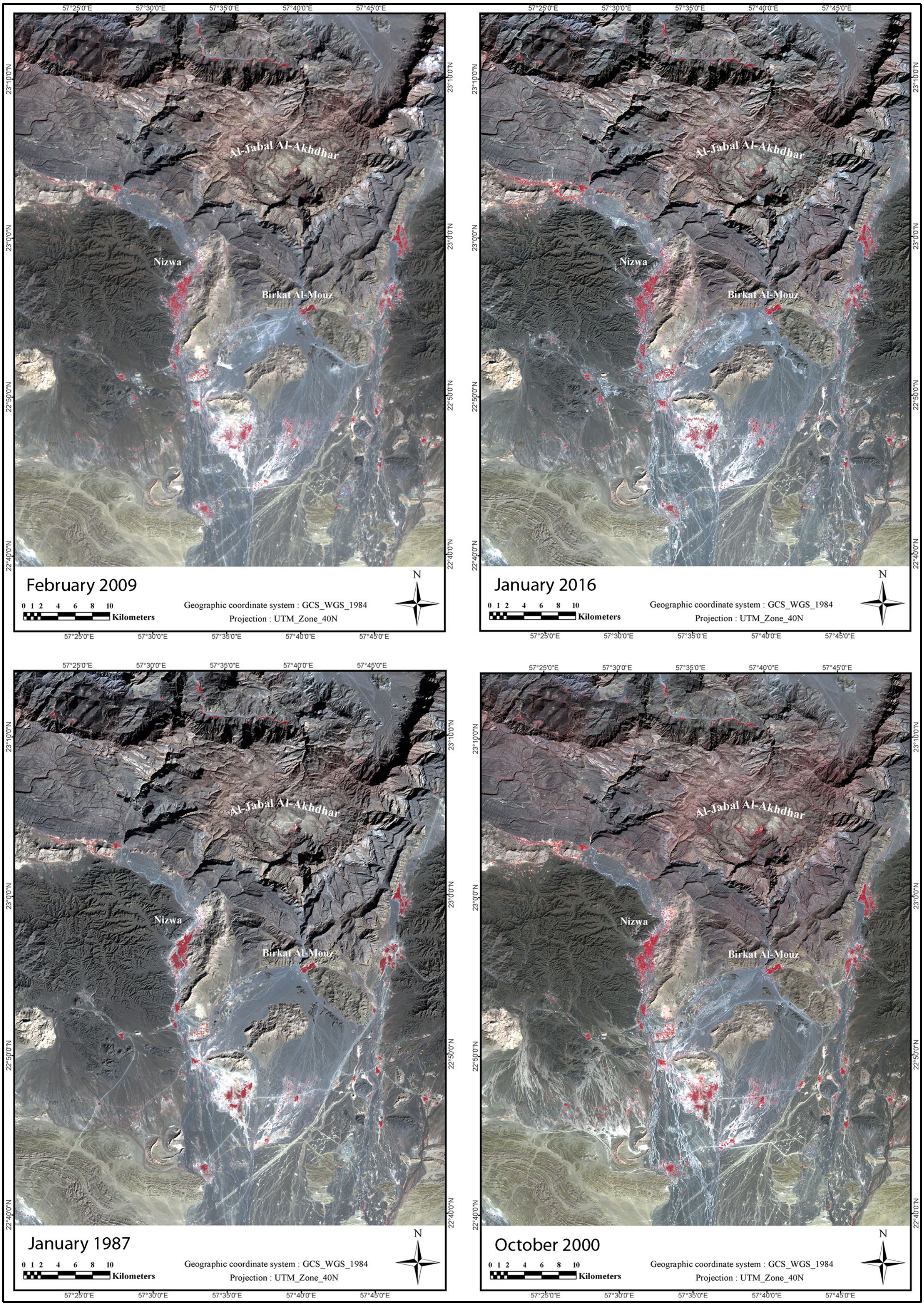


Fig. 6 Comparison chart of spectral signatures of samples 1, 2, 3, and 4 picked in the study area (Wilayat Nizwa, Oman, Landsat 8, January 2, 2016)


57°25'0"E
57°30'0"E
57°35'0"E
57°40'0"E
57°45'0"E
23°10'0"N
23°0'0"N
22°50'0"N
22°40'0"N
Al-Jabal Al-Akhdhar
Nizwa
Birkat Al-Mouz
February 2009
0 1 2 4 6 8 10
Kilometers
Geographic coordinate system : GCS_WGS_1984
Projection : UTM_Zone_40N
N
Al-Jabal Al-Akhdhar
Nizwa
Birkat Al-Mouz
January 2016
0 1 2 4 6 8 10
Kilometers
Geographic coordinate system : GCS_WGS_1984
Projection : UTM_Zone_40N
N
Al-Jabal Al-Akhdhar
Nizwa
Birkat Al-Mouz
January 1987
0 1 2 4 6 8 10
Kilometers
Geographic coordinate system : GCS_WGS_1984
Projection : UTM_Zone_40N
N
Al-Jabal Al-Akhdhar
Nizwa
Birkat Al-Mouz
October 2000
0 1 2 4 6 8 10
Kilometers
Geographic coordinate system : GCS_WGS_1984
Projection : UTM_Zone_40N
N

◀ **Fig. 7** Nizwa and its surroundings (Oman), in 1987, 2000, 2009, and 2016. Colored compositions RGB: Landsat 8 OLI, January 2, 2016; Landsat 7 ETM+, February 7, 2009; Landsat 7 ETM+, October 28, 2000; and Landsat 5 TM, January 18, 1987. Geographic coordinate system: GCS_WGS_1984. Projection: UTM_Zone_40N

sets that we documented by on-map commented sketches and photographic screening. The classification resulted in the following, listed from the highest to the lowest in terms of surface areas:

- The clayey/sandy sedimentary soils that cover mainly valleys and gullies
- The rocky, clayey/gypsum-like, highly ravenous mountain (the Al-Hajar range)
- The stony/sandy soils in riverbeds (along with urban areas and infrastructure)
- The sparsely dense, predominantly conifer vegetation that covers Al-Jabal Al-Akhdhar and grows everywhere in riverbeds and on the edges of oases
- The irrigated dense vegetation concentrated in the valleys as oases in various sizes

Dynamics of the vegetation cover in Wilayat Nizwa (from 1987 to 2016)

On these maps (Fig. 9), we separated two classes: (1) non-irrigated, rain-fed, and sparsely dense vegetation and (2)

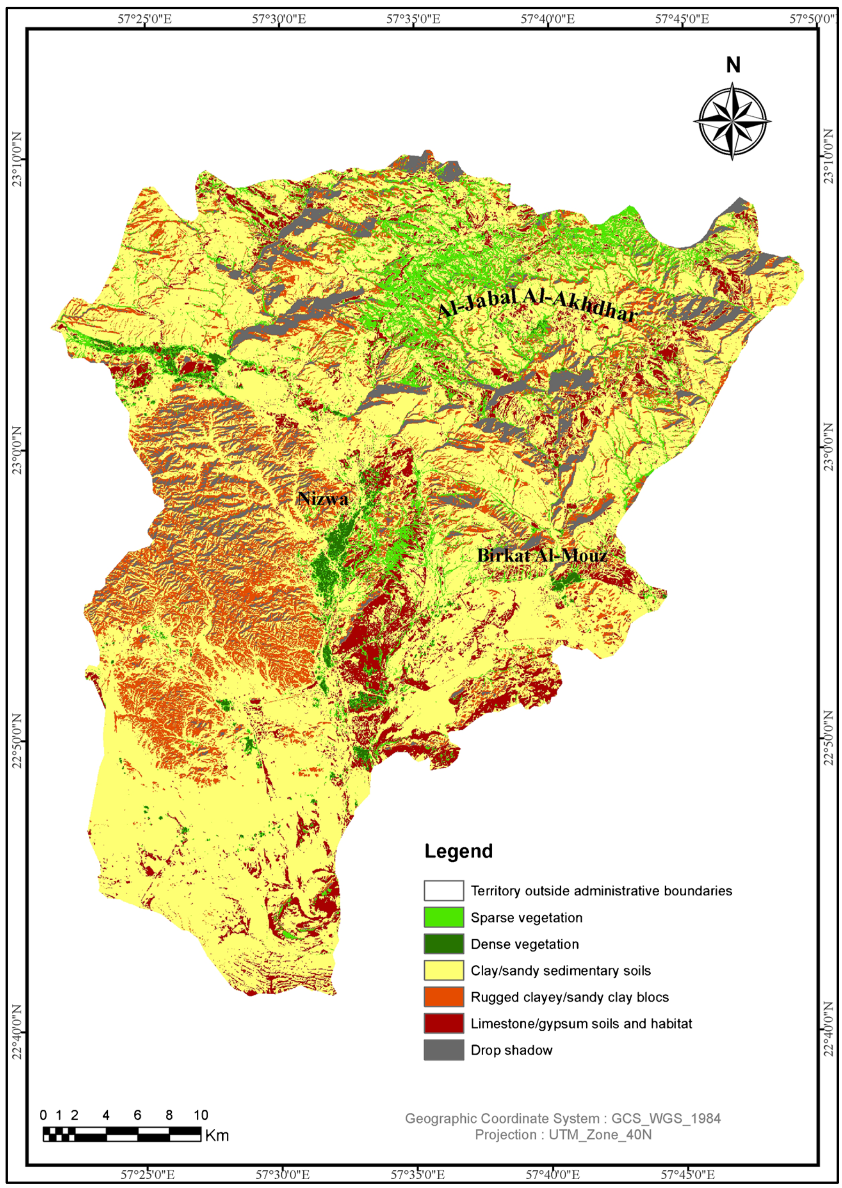
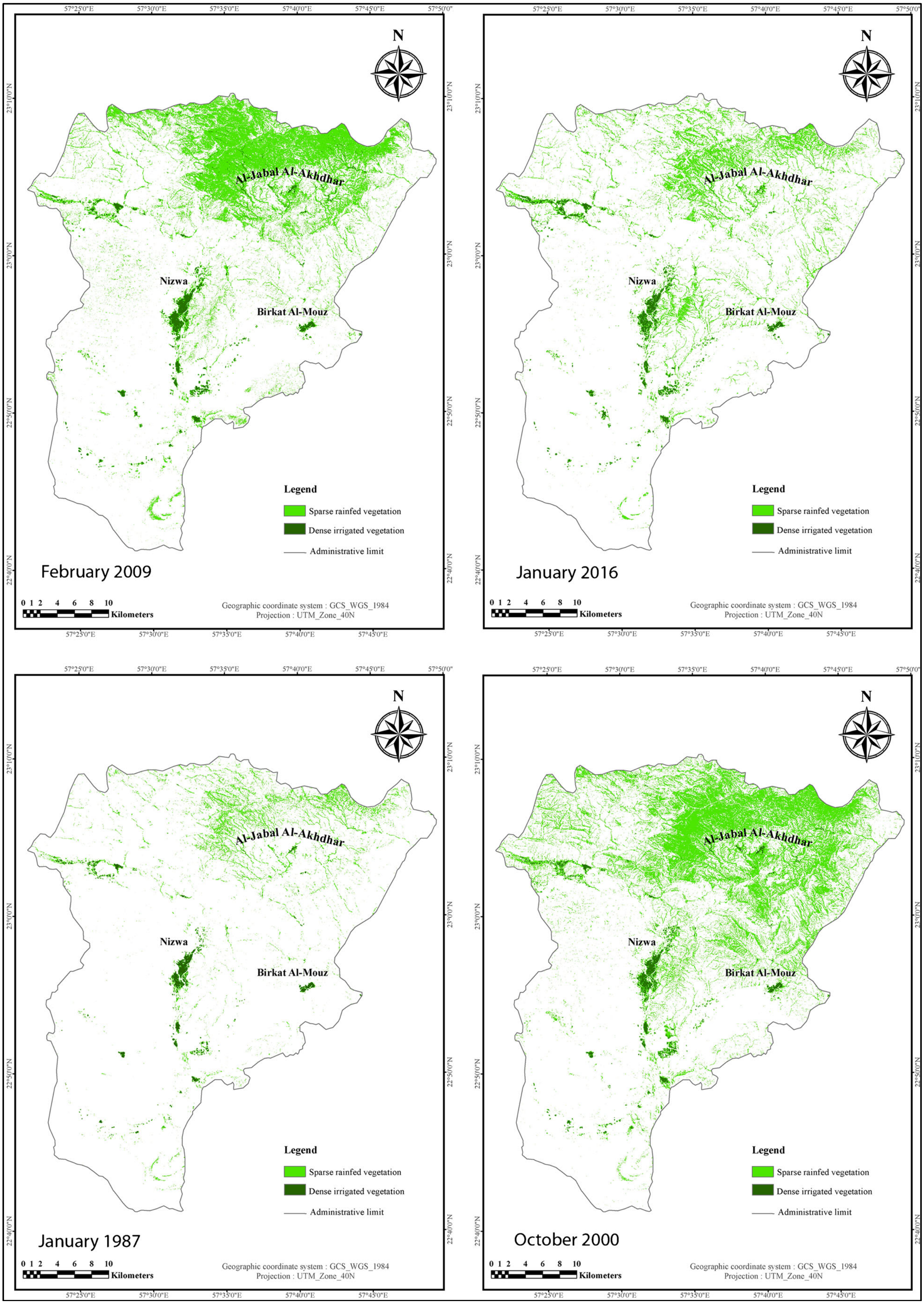


Fig. 8 Land use map of Wilayat Nizwa (Oman) in 2016. Landsat 8 OLI, January 2, 2016. Geographic coordinate system: GCS_WGS_1984. Projection: UTM_Zone_40N


N
Al-Jabal Al-Akhdhar
Nizwa
Birkat Al-Mouz
Legend
Sparse rainfed vegetation
Dense irrigated vegetation
Administrative limit
February 2009
0 1 2 4 6 8 10
Kilometers
Geographic coordinate system : GCS_WGS_1984
Projection : UTM_Zone_40N
January 2016
January 1987
October 2000
57°25'0"E
57°30'0"E
57°35'0"E
57°40'0"E
57°45'0"E
57°50'0"E
23°10'0"N
23°0'0"N
22°50'0"N
22°40'0"N

◀ **Fig. 9** Classification and spatial location of vegetation cover types in Wilayat Nizwa (Oman). Landsat 8 OLI, January 2, 2016; Landsat 7 ETM+, February 7, 2009; Landsat 7 ETM+, October 28, 2000; and Landsat 5 TM, January 18, 1987

irrigated dense vegetation. The irrigated dense vegetation (in dark green) refers to the cereal and market gardening crops and to the tree-growing and palm groves that form the oases; the non-irrigated (in light green) sparsely dense vegetation appears especially in the ravines of rock outcrops and on the mountain AL-Jabal Al-Akhdhar.

In order to make the information on vegetation in Wilayat Nizwa comparable, the data we used were all collected over the same season with those for 1987 and 2016 having been acquired during the same month, on January 18 and 2, respectively. The different classes on the PVI1 images are quantified in number of pixels. Knowing the specific resolutions of each satellite, we were able to calculate the areas of vegetation classes in hectares. Table 2 presents the results obtained on the different dates. The area of vegetation cover, all classes combined, increased significantly during the first studied decade from 6641.44 ha in 1987 to 10,980.84 ha in 2000, and more than doubled during the second decade to 25,036.20 ha in 2009. During the third decade, there was a marked decline and the total area fell by almost half, to 13,918.23 ha. The peak observed in 2009 can only be explained by exceptional rainfall during this period, including the couple of years before (such as in 2007) (Fig. 1). Despite the variability observed from one class to the other, the area occupied by vegetation from all classes more than doubled in the space of 30 years (*2.1). With regard to vegetation types, the area of light vegetation increased more rapidly (*2.2) than the area of irrigated dense vegetation (*1.7).

In terms of land use, between 1987 and 2016, the share of vegetation in Wilayat Nizwa more than doubled, from overall 4.6 to 9.6% (Table 3). The same is valid for the proportion of vegetation that is not very dense. The variations observed are largely due to irregular and variable seasonal rainfall from 1 year to the next, alternating with major periods of drought (Fig. 1). On the other hand, irrigated dense vegetation has not experienced the same variability and its share has remained more or less constant, at around 1%, despite a slight peak in 2009. This is very characteristic of the oasis spaces whose exploited surface remains generally stable, even in the presence of heavy rainfall. It can also be noted that it is eight times less important than the spontaneous, sparse vegetation. Although rainfall over the region Ad-Dakhliyah has been more or less stable during the recent period, from 2010 to 2016 (Fig. 10), we note a slight decrease in the area of irrigated vegetation that might be due to socioeconomic parameters such us those affecting the good functioning and survival of *aflaj* systems.

Conclusions

The studied area is suitable for the establishment of oases that disperse at the foothills of the mountains and are irrigated by *aflaj*. Wilayat Nizwa, covering 13 oasis cities, has typical landscape features that we have classified on a land cover map into five large landscape ensembles: valleys and ravines, mountainous scrublands, dry river beds (along with habitat

Table 2 Quantification in hectares of vegetation types' areas in Wilayat Nizwa by date of data acquisition

		Date of data acquisition			
		January 18, 1987	October 28, 2000	February 7, 2009	January 2, 2016
Classes (in ha)	Sparsely dense vegetation	5729.60	9582.15	23,318.46	12,360.96
	Irrigated dense vegetation	911.83	1398.69	1717.74	1557.27
	Total vegetation	6641.44	10,980.84	25,036.20	13,918.23

Table 3 Shares of vegetation types in Wilayat Nizwa, by date of data acquisition (%)

		Date of data acquisition			
		January 18, 1987	October 28, 2000	February 7, 2009	January 2, 2016
Classes (%)	Sparsely dense vegetation	3.9	6.6	16.0	8.5
	Irrigated dense vegetation	0.7	1.0	1.2	1.1
	Total vegetation	4.6	7.6	17.2	9.6

Shares of vegetation types are in proportion to the total area of Wilayat Nizwa according to its current administrative territorial limits

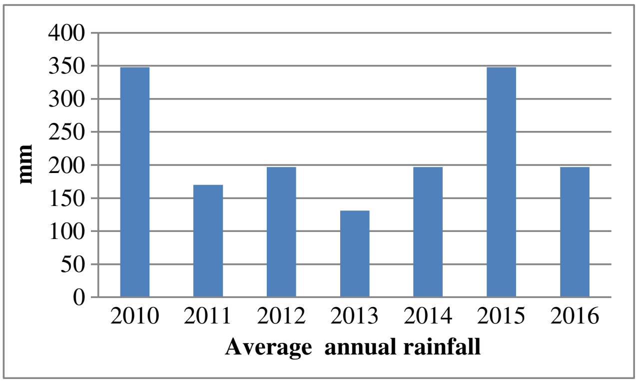


Fig. 10 Average annual rainfall in the region Ad-Dakhliyah from 2010 to 2016. Source: elaborated according to the data published by the Ministry of Regional Municipalities and Water Resources (MRMWR) of Oman (Megdiche-Kharrat 2018)

and urban infrastructure), spontaneous disparate vegetation (from resinous dominant type), and oases with dense vegetation cover. The areas of the vegetation cover varied considerably over the studied period, this is largely due to irregular seasonal rainfall variable from 1 year to the next with large periods of drought. We also noticed that the spontaneous vegetation class area increased significantly in 2000, doubled in 2009, and declined slightly in 2016, while the irrigated dense class area did not experience the same variability with only a slight peak in 2009. This is characteristic of the oasis spaces, whose surface area is generally stable even in the presence of heavy rainfall. This is often due to landscape and labor force constrains. With considering that the oases in Wilayat Nizwa are mainly irrigated by *aflaj*, the obtained results, combined with socioeconomic and climatic factors, are good indicators to anticipate the evolution of the local landscape and to rate the functioning of *aflaj* which constitute a national heritage and involve a cultural frame and a social lifestyle very compatible with local environments.

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