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ORIGINAL ARTICLE

Land changes and their drivers in the cloud forest and coastal zone of Dhofar, Oman, between 1988 and 2013

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Abstract The land-cover changes in the cloud forest and coastal plain of Dhofar, Oman, from 1988 to 2013 are reported, and their possible causes explored. Multiple endmember spectral mixture analysis, cluster analysis using local indicators of spatial association, and trend analysis of NDVI time series are used to measure environmental changes. The results demonstrate: systematic degradation and loss of vegetation types in the cloud forest; loss of native land covers to impervious surfaces on the coastal plain; decreases in woody plant vegetation in almost half of the cloud forest in distinctive hotspots of loss; and significant decreases in NDVI trends around the city of Salalah, along the coastal plain, and in parts of the cloud forest. The proximate drivers of these changes in the cloud forest appear to be changes in grazing activities, while the growth of Salalah, especially its peri-urban area, altered the coastal plain. These drivers, in turn, are linked to distal ones, foremost changes in Omani policies and investments in the Dhofar area, traced to government responses to the Dhofar War (1970–1975), which have resulted in increased livestock populations and urban growth.

Keywords Land cover · Land change science · Dhofar · Cloud forest · National policies · Remote sensing

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Introduction

Deforestation and land degradation are recognized problems in dryland environments, which cover about 41 % of the terrestrial surface of the Earth (Reynolds et al. 2007). Worldwide net primary production of grass and rangelands has declined due to intensified land uses (e.g., Bai et al. 2008; Li et al. 2012), and the loss of ecosystem services to dryland degradation affects some 250 million people (Reynolds et al. 2007). As a result, dryland deforestation and land degradation have drawn international attention through such programs as the UN's 1992 Convention to Combat Desertification (UNEP 1994) and the 2006 International Year of the Desert and Desertification.

The causes of this degradation have drawn substantial research attention under the auspices of land change science (Turner et al. 2007). Drivers of land change are generally arrayed along a continuum between proximate and distal causes, depending on the immediacy of human activities and processes to the actual land change and consequences in question (Serneels and Lambin 2001; Geist and Lambin 2002; Lambin et al. 2003; Turner et al. 2007). Proximate causes, such as agricultural expansion or land-use intensification, are readily observable, whereas distal causes (aka underlying or root causes, including teleconnections), such as international policies and market forces, are often difficult to demonstrate quantitatively (Brannstrom and Vadjunec 2014; Lambin et al. 2001; Liu

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et al. 2013; Vayda and Walters 1999). Distal and proximate causes can also interact to amplify or attenuate land change beyond their individual impacts (Defries et al. 2010; Seto and Reenberg 2014).

Dryland degradation is a critical topic of land change across the Arabian Peninsula. One region in particular, Dhofar, Oman, which is home to the country's second largest city, Salalah, and a large portion of an ecosystem known as the South Arabian Cloud Forest, has been the subject of concern due to increasing human encroachment. Dhofar's portion of the South Arabian Cloud Forest consists of forest, shrub, and grasslands that are thought to be decreasing in biomass, especially during the last few decades. The causes of this change are somewhat contested because a variable Indian Ocean Monsoon (IOM; Kumar et al. 2011) affects vegetation dynamics. The most immediate concerns, however, involve human activities, foremost increasing camel, goat, and bovine grazing that has led to grassland degradation and deforestation (Miller and Morris 1988; Ghazanfar 1998; Hildebrandt and Eltahir 2006; Patzelt 2011; El-Sheikh 2013). Local land managers and other observers identify two causes for this grazing intensification. The first focuses on increased herd sizes, developing over the last four or five decades, coinciding with increases in household income and improved access to water wells and animal support services. The second points to infrastructure development, primarily the construction of roads opening access to new areas of the cloud forest for grazing and the expansion of urban areas.

These proximate causes are linked to Oman's development strategies and national policies. As a response to internal revolts against the government in the 1970s, attention to livelihood improvements increased, particularly in the mountains of Dhofar where the cloud forest resides (Janzen 2000; Peterson 2004a, 2011). Investments were made specifically to increase water wells, subsidize cattle feed (Janzen 1986: 195–196), employ adult males (e.g., to fight against dissidents), and increase commercial investments in Salalah (Janzen 1986: 173–175). Complementing this policy change was one directed toward infrastructure modernization, especially emerging in the 1980s (O'Reilly 1998; Allen and Rigsbee 2000; Peterson 2004a, b), focusing on large infrastructure, such as roads, schools, and airports.

Cloud forest ecosystems occupy only a small portion of the world's forests, but are usually rich in ecosystem services and biodiversity (Higuera et al. 2013), and experience increasing stress from human activities within them. Dhofar's portion of the South Arabian Cloud Forest is no different, which makes this region an important study in dryland degradation and land change. Actual documentation of land-cover consequences and their causes in cloud forests, however, has been sparse. The research presented in this paper seeks to rectify this lacuna in two ways. First, satellite data are used to identify the systematic land-cover changes in the cloud forest and coastal plain of Dhofar from 1988 to 2013, determining the kind and amount of land-cover changes during this period. Second, the roles of two specific development paths—livelihood improvements and infrastructure development—are probed qualitatively to place them within the context of the land changes we observe. Data limitations impeded quantitative assessments of the causes.

Study area

The study area is the Dhofar portion of the South Arabian Cloud Forest and the coastal region within the Governate of Dhofar, Oman. The cloud forest is a drought-deciduous, seasonal cloud forest that lies along the southern coasts of Oman and Yemen (Hildebrandt 2005). Three dominant natural land covers (trees, grass, and shrubs) intermix to create three primary biomes: forests, shrublands, and grasslands. The forest biome consists of broadleaf and evergreen species of trees and shrubs (Miller and Morris 1988), usually found in southerly draining *wadis* (i.e., dry river valleys). Shrublands combine grass, tree, and shrub covers, but shrubs dominate. The grasslands maintain stands of trees and shrubs, but at much lower densities than the forest or shrublands and interspersed among the grass cover (Patzelt 2011). There is also a fourth subsidiary, hybrid biome, within the foothills of the mountains, consisting of mixes of grasses, shrubs, and trees in varying composition. The foothills run along the southern portion of the cloud forest and act as a partition between the coastal plain and the Dhofar Mountains. The coastal plain is affected by monsoon winds and has more vegetation than the barren deserts north of the cloud forest. Salalah is also situated on this coastal plain.

Three mountains comprise the Dhofar range: Jabal Qara, Jabal Qamar, and Jabal Samhan. A contiguous area that includes Jabal Qara, Jabal Qamar, and the coastal plains constitutes the study area, capturing substantial portions of the cloud forest as well as the urban development of Salalah (Fig. 1). The total area examined covered 3069 km^2, of which about 28.6 % is forest. The topography is defined by sloping plateaus incised by wadis. Despite the usual desert conditions of southern Arabia, precipitation in the study area is reliable during the summer months (June to September) when the IOM forms. Cloud cover and fog moisture from the IOM are abundant enough to allow dense vegetation to grow despite interannual variability (Anderson et al. 2002; Goswami and Mohan 2001; Gupta et al. 2003; Kumar et al. 2006; Charabi and Abdul-Wahab 2009; Scholte and De Geest 2010). Monsoon moisture

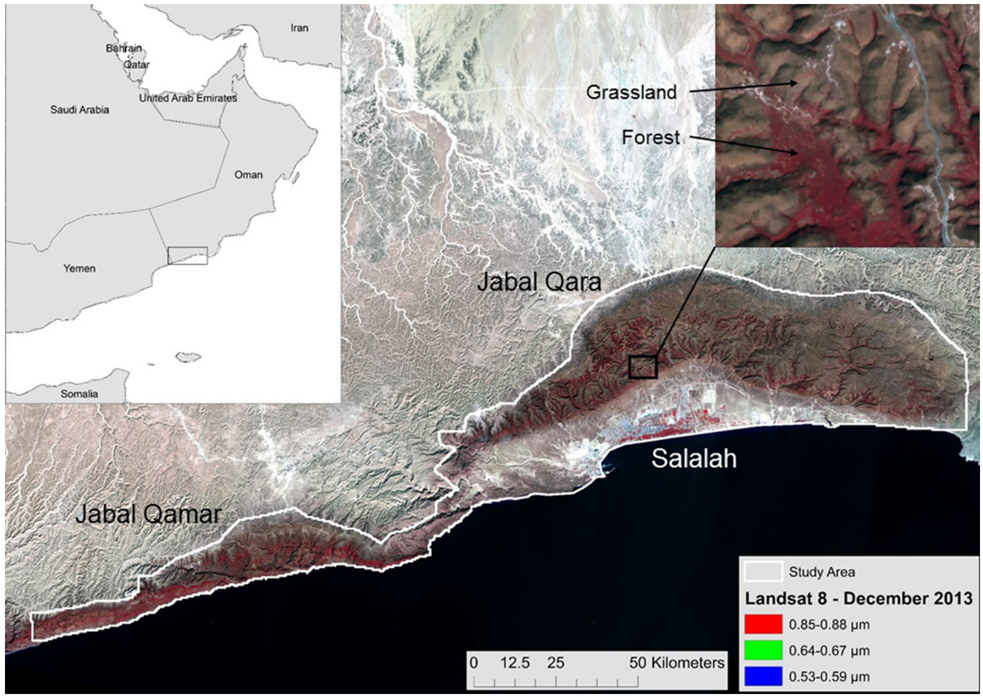


Fig. 1 The study area, showing the Dhofar portion of the South Arabian Cloud Forest along the Dhofar Mountain range (Jabal Qara and Jabal Qamar). The *insets* show the relative position of the cloud forest in relation to the Arabian Peninsula, and the contrast between forests, grasslands, and desert

usually arrives as fog, rather than heavy rainfall. Trees act as 'fog combs,' collecting moisture on their leaves and branches that then falls to the ground (Hildebrandt 2005; Hildebrandt and Eltahir 2006, 2007). Because of this, direct measurements of precipitation can be inaccurate, but estimates range up to 200 mm annually (Galletti forthcoming). Heavy bursts of rainfall are possible all year round, but most of the year is usually dry outside of monsoon season.

The cloud forest is home to hundreds of different floral species (Miller and Morris 1988; Patzelt 2011). Common tree species include *Anogeissus dhofarica* and *Commiphora* spp. While the grasslands are home to various grass species (Patzelt 2011), a variety of trees (including *Ficus* spp., and *Ziziphus spina-christi*) and shrubs (e.g., *Calotropis procera*, *Solanum incanum*) thrive there too. Along wadi courses and in foothills, large trees can be found, including *Sterculia africana*, *Adansonia digitata*, *Boscia arabica*, *Tamarindus indica*, and *Ficus* spp. Many endemic species are found throughout the cloud forest, including *A. dhofarica*, *Jatropha dhofarica*, *Maytenus dhofarensis*, *Aloe dhufarensis*, and *Zygocarpum dhofarense*. Many of these endemic species, as well as the other commonly found species, define the plant community in the South Arabian Cloud Forest and have affinities with other plant communities in southern Asia and Africa (Kürschner et al. 2004). In contrast to the dense flora of the cloud forest, the north facing portion of Jabal Qara and Jabal Qamar is generally more arid, sitting within the rain shadow of the watershed divide. This portion of the mountains is home to the Frankincense tree (*Boswellia sacra*) and a species of dragon blood tree (*Dracaena serrulata*).

The grasslands and forests are heavily grazed by goats, camels, and cattle belonging to several groups living in the Dhofar Mountains (Janzen 1986). Herds are kept in the mountains for most of the year and are brought down to the coastal plains at the start of the monsoon. While herding remains the primary occupation for many groups living in the mountains, the growing economy in Salalah has begun to attract a diverse range of activities. The income generated from oil revenues, shipping, livestock, frankincense trade, and agriculture has begun to shift livelihoods away from traditional lifestyles to urban professional ones, with an increasing portion of the population attending college and working in the city. This remains a process in transition; many individuals still practice traditional herding, part time in some cases, while working in Salalah.

Methods

Land change is addressed in three ways. First, a land change analysis identifies key transitions from one land cover to another between 1988 and 2013, focusing on the transitions among six land covers: coastal alluvium, grass, shrubs, trees, roads, and the built environment (urban). Second, a subpixel analysis measures changes in woody plant coverage, also between 1988 and 2013. Finally, a trend analysis identifies changes in a vegetation index (NDVI) signaling vegetation health from 2001 to 2013, a 14-year period that roughly coincides with the latest efforts to develop infrastructure across Oman and, especially, Dhofar.

Land change analysis

Two sets of Landsat images were classified each for 1988 and 2013, and each set comprised of four images (for 1988, LT41590481988340XXX02 and LT41600481988347AAA04; and for 2013, LC81600482013343LGN00 and LC81590482013336LGN00). The 1988 images were acquired by Landsat 5 and comprised of six bands of visual and near infrared multispectral reflectance data. The 2013 images were acquired by Landsat 8 and comprised of seven bands of visual and near infrared data. Both images were captured in the early part of December, when the distinction between grass, trees, and shrubs is fairly stark. Digital numbers were converted to reflectance values using metadata coefficients, a dark object subtraction (2013 image), and climate data records (Masek et al. 2006; USGS 2015). Principal component bands were calculated and added to the image stack to facilitate classification.

An object-based image analysis method (OBIA; Blaschke 2010) was employed for land-cover classification, a method shown to be superior to pixel-based methods for land use/cover classification (e.g., Galletti and Myint 2014). OBIA arranges pixels into polygon-like groupings, called objects, using a multiresolution segmentation algorithm (Baatz and Schape 2000). The segmentation algorithm uses shape and compactness parameters, as well as spectral information from each image band to form objects (Benz et al. 2004). These objects are classified using spectral and spatial information. For both the 1988 and 2013 images, nine land covers were classified (see Online Resource 1 for definitions): desert gravel plains (DGP), water (W), coastal alluvium (CA), agriculture (Ag), grass (Gr), trees (Tr), Shrubs (Shr), Roads (Rd), and built environment (BE). The land covers were selected based on field observations and environmental descriptions in Miller and Morris (1988). The overall accuracies of the classified images were 93.14 % for 1988 (kappa = 0.9227) and 94.01 % for 2013 (kappa = 0.9324).

Land-cover change transition matrices were used to identify which pixels changed classification between 1988 and 2013. This method provides *systematic* land-cover transformations, or a conversion from one land cover to another, while accounting for *expected* land-cover changes (Pontius et al. 2004). *Expected* land changes are due to possible random chance, small changes in large land-cover categories, errors in land-cover maps, and so on. Our transition matrix was developed using the methods outlined in Pontius et al. (2004) and Alo and Pontius (2008). *Observed* versus *expected* land-cover transitions are found by analyzing the trade-offs between land covers as shown in rows and columns of a transition matrix. Rows reflect the land covers as they stood in 1988, and columns represent the land covers in 2013. Diagonal values show persistence of land-cover types, while off-diagonal values show the transition from the land cover for that row (1988) to the land cover for that column (2013). At the end of each row, a sum shows the total land-cover *loss* plus persistence, as well as the total loss for that row's land-cover category. At the end of each column, a sum shows the total land-cover *gain* plus the persistence, as well as the total gain for that column's land-cover category. *Expected* transitions are calculated by analyzing the *observed* land-cover gains and losses and using the formulae in Alo and Pontius (2008: 288, equations 1 and 2). If the observed loss minus the expected loss is positive for a matrix cell, then that row's land cover is systematically losing to the land cover in the column; if it is negative, it is resisting systematic loss. If the observed gain minus the expected gain is positive for the matrix cell, then that column's land cover is systematically gaining from the land cover in the row; if it is negative, it rebuffs systematic gain from the land cover for that row (Alo and Pontius 2008).

Vegetation fraction and subpixel analysis

Ground covers occupying varying proportions of a pixel in a satellite image were extracted using subpixel analysis. The surface material proportions within a pixel are estimated by using a linear combination of reflectance values of known ground targets, or endmembers (Settle and Drake 1993), and are often used to model three primary land-cover components: vegetation, impervious surfaces, and soil (V–I–S). It is used here to extract vegetation fraction, a useful indicator of degradation and deforestation (e.g., Dawelbait and Morari 2012). Our subpixel approach uses multiple endmember spectral mixture analysis (MESMA; Roberts et al. 1998), which permits a subset of the total number of endmembers to be modeled for each pixel, rather than using a linear combination of all endmembers. Following Powell and Roberts (2010), a library of endmembers was constructed. For each endmember, the reflectance values from satellite images are recorded for each band. Finding representative endmembers was accomplished using reflectance values from a known spectral library or gathered from within the image by selecting 'pure' pixels (i.e., pixels that are made up almost entirely of a single endmember). Possible models of endmember combinations that best fit the known reflectance values at each pixel were constructed. To do this, the endmember proportions must equal 1, each endmember fraction must be constrained between 0 and 1, and the root-mean-square error (RMSE) cannot exceed a certain value (Powell and Roberts 2010).

A pixel purity index (PPI; Boardman et al. 1995) finds meaningful endmembers and was used to construct an endmember library. Over one hundred possible endmembers were reduced to three primary V–I–S categories, using methods developed by Dennison and Roberts (2003). A library of endmembers was selected for 1988 and 2013 separately. Vegetation endmembers were chosen mainly from areas of tree canopy (1988 $n = 5$, 2013 $n = 23$); impervious surface endmembers from roads, hard packed dirt tracks, buildings, and desert hard scrabble (1988, $n = 7$; 2013, $n = 16$); and soil, from exposed organic soils in the cloud forest and coastal alluvium (1988, $n = 4$; 2013, $n = 4$). A MESMA model was developed for each image year (1988 and 2013). A four endmember model (V–I–S + shade) with the RMSE set to 0.25 was used to derive the final models. Any pixels that could not meet the RMSE criteria were masked from our analysis, along with water pixels and shaded areas.

Since there is no test to determine the statistical significance for the vegetation fraction, we identified systematic areas of increase and decrease in this fraction by searching for statistically significant spatial clusters. We determined significant spatial clusters by using local indicators of spatial association (LISA; Anselin 1995), which organizes pixels of high vegetation fraction (vegetation fraction gains) and pixels of low vegetation fraction (vegetation fraction losses) into clusters. LISA statistics help breakdown the global Moran's I test for spatial autocorrelation into local components. These local components can be interpreted as spatial clusters or hot spots. The clusters are tested for significance by using a conditional permutation framework.

Time series analysis

NDVI observations from MODIS were used in a time series analysis. Trend analysis was used to determine whether NDVI time series were increasing or decreasing with time, providing a proxy of ecosystem health (Bai et al. 2008; Hilker et al. 2014). An increase in the trend (positive slope) indicates an NDVI value is growing stronger with time and implies that net primary production may be increasing. A decreasing trend (negative slope) indicates and implies the opposite. To calculate these trends, NDVI observations were obtained from the MODIS 16-day NDVI product at 250 m resolution for the years 2001 to 2013 (MODIS tile: 23 horizontal, 7 vertical).

Yearly observations were modeled to extract key parameters. The seasonal trend analysis methods outlined in Eastman and others (2009; 2013) were used to model the mean annual NDVI (referred to as Amplitude 0) and the NDVI annual cycle (referred to as Amplitude 1). The Amplitude 1 signal is the difference between the minimum and maximum NDVI observations (Eastman et al. 2013), whereas Amplitude 0 is an average of the annual NDVI signal. These two observations were extracted by using a harmonic regression to model the yearly NDVI cycle. A Theil–Sen median slope was calculated on the Amplitude 0 and 1 values for each year. This median slope calculation is robust and can reliably estimate the trend slope even in the presence of noise and outliers (Theil 1950; Sen 1968). Up to 29 % of the observations can be outliers. Once the slope was calculated, a Mann–Kendal test for trend significance was conducted and z values generated, of which we used the z values to help determine statistical significance.

Results

Transition matrix

Considerable change in the environment of the cloud forest is revealed (see the land-cover change figure in Online Resource 1). Trees had a net loss of about 23,165 ha, and coastal alluvium about 13,469 ha. In contrast, roads gained about 12,535 ha, the built environment increased by about 9157 ha, and grass and shrub covers had a net gain of 15,147 and 59 ha, respectively. The net gains in shrubs and grasses, however, masks a more complex exchange between land covers.

Table 1 shows the transition matrix (see Online Resource 1 for a table showing systematic gains and losses). According to these matrices, trees are systematically losing coverage to only one other land-cover category, shrubs. About 4 % of the landscape transitioned this way (Table 1), barely above what was expected from random chance (Online Resource 1). Tree cover resisted transition to roads or the built environment. Only about 0.45 % of the landscape transitioned from trees to roads, and even less to the built environment (0.06 %), both well within the expected ranges. Coastal alluvium lost cover to roads and the built environment (about 4.5 % of the total landscape), a result well beyond expectations (Online Resource 1). Grass cover also transitioned to road cover above expectations, occurring mainly in the cloud forest.

The structure of environmental change is registered in the transitions from trees to shrubs, shrubs to grass, and grass to roads (Tables 1). At Jabal Qamar, trees transitioned to shrubs in one particularly large area close to the eastern end of the mountain. Jabal Qamar also saw several clusters of change from shrubs to grass between 1988 and 2013, mainly around small settlements just south of the

Table 1 Land-cover transition matrix

		2013										
		DGP	W	CA	Ag	Gr	Tr	Shr	Rd	BE	Total	Gross Losses
1988	DGP	**0.33**	**0.00**	**0.00**	**0.00**	**0.09**	**0.01**	**0.01**	**0.06**	**0.00**	**0.50**	**0.17**
			0.00	*0.02*	*0.00*	*0.05*	*0.05*	*0.02*	*0.02*	*0.01*	*0.50*	*0.17*
			0.00	0.01	0.00	0.05	0.00	0.03	0.03	0.02	0.47	0.14
	W	**0.00**	**0.53**	**0.06**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**	**0.61**	**0.08**
		0.00		*0.01*	*0.00*	*0.02*	*0.02*	*0.01*	*0.01*	*0.00*	*0.61*	*0.08*
		0.00		0.01	0.00	0.06	0.00	0.03	0.04	0.02	0.70	0.17
	CA	**0.02**	**0.11**	**12.77**	**0.07**	**0.01**	**0.04**	**0.84**	**2.53**	**1.93**	**18.32**	**5.56**
		0.03	*0.05*		*0.06*	*2.11*	*1.95*	*0.73*	*0.62*	*0.31*	*18.32*	*5.56*
		0.01	0.02		0.04	1.87	0.12	0.92	1.13	0.69	17.57	4.80
	Ag	**0.00**	**0.00**	**0.02**	**0.66**	**0.01**	**0.00**	**0.00**	**0.13**	**0.10**	**0.92**	**0.26**
		0.00	*0.00*	*0.04*		*0.08*	*0.07*	*0.03*	*0.02*	*0.01*	*0.92*	*0.26*
		0.00	0.00	0.01		0.09	0.01	0.05	0.06	0.03	0.91	0.25
	Gr	**0.01**	**0.00**	**0.00**	**0.00**	**23.90**	**0.13**	**0.08**	**1.57**	**0.33**	**26.01**	**2.12**
		0.01	*0.02*	*0.40*	*0.03*		*0.82*	*0.31*	*0.26*	*0.13*	*26.01*	*2.12*
		0.02	0.03	0.35	0.06		0.16	1.30	1.61	0.98	28.41	4.51
	Tr	**0.02**	**0.01**	**0.05**	**0.00**	**3.93**	**28.18**	**3.47**	**0.45**	**0.06**	**36.17**	**8.00**
		0.05	*0.08*	*1.75*	*0.11*	*3.88*		*1.35*	*1.15*	*0.57*	*36.17*	*8.00*
		0.02	0.05	0.49	0.08	3.69		1.81	2.24	1.36	37.92	9.74
	Shr	**0.01**	**0.00**	**0.77**	**0.01**	**2.78**	**0.24**	**6.34**	**0.52**	**0.11**	**10.77**	**4.44**
		0.02	*0.03*	*0.69*	*0.04*	*1.54*	*1.42*		*0.46*	*0.23*	*10.77*	*4.44*
		0.01	0.01	0.15	0.02	1.10	0.07		0.67	0.40	8.77	2.43
	Rd	**0.00**	**0.00**	**0.20**	**0.05**	**0.16**	**0.03**	**0.04**	**3.55**	**1.05**	**5.08**	**1.54**
		0.01	*0.01*	*0.01*	*0.01*	*0.50*	*0.46*	*0.18*		*0.07*	*5.08*	*1.54*
		0.00	0.01	0.07	0.01	0.52	0.03	0.25		0.19	4.63	1.09
	BE	**0.00**	**0.01**	**0.07**	**0.08**	**0.06**	**0.00**	**0.02**	**0.36**	**1.00**	**1.60**	**0.60**
		0.00	*0.00*	*0.08*	*0.01*	*0.19*	*0.17*	*0.07*	*0.06*		*1.60*	*0.60*
		0.00	0.00	0.02	0.00	0.16	0.16	0.08	0.10		1.38	0.38
	Total	**0.40**	**0.67**	**13.94**	**0.88**	**30.95**	**28.63**	**10.79**	**9.17**	**4.58**	**100.0**	**22.75**
		0.45	*0.73*	*15.99*	*0.92*	*32.27*	*33.15*	*9.03*	*6.14*	*2.34*		
		0.40	0.67	13.88	0.88	30.95	28.63	10.79	9.17	4.58		
	Gross gains	**0.07**	**0.13**	**1.17**	**0.22**	**7.05**	**0.45**	**4.46**	**5.62**	**3.58**	**22.75**	
		0.12	*0.20*	*3.22*	*0.26*	*8.37*	*4.97*	*2.69*	*2.59*	*1.34*		
		0.07	0.13	1.17	0.22	7.55	0.40	4.46	5.62	3.70		

Rows represent land covers from 1988, and columns are 2013. Diagonal values show persistence. Off-diagonal cells show observed and expected transitions from row to column. The observed transitions are in bold, expected losses in italics, and expected gains are in normal font. Values are in terms of percent of landscape

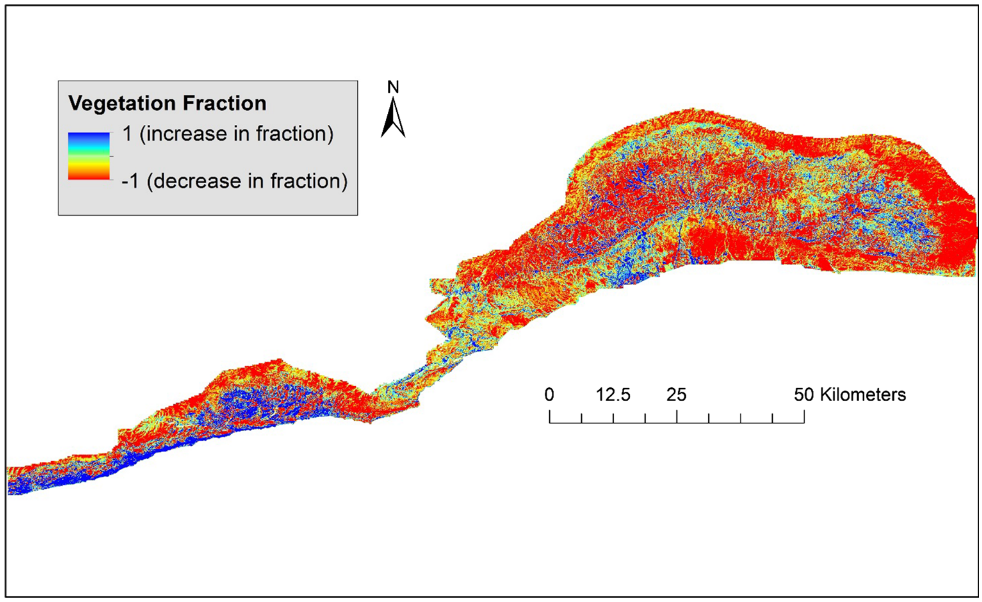
DGP desert gravel plains, *W* water, *CA* coastal alluvium, *Ag* agriculture, *Gr* grass, *Tr* trees, *Shr* shrubs, *Rd* roads, *BE* built environment

main east–west highway. At the far eastern part of Jabal Qara, a similar transition was noted. A large cluster of shrubs were converted to grass between 1988 and 2013 and several clusters of tree-to-shrub conversion are noted in this region too. Across the whole study area, tree and shrub covers that converted to road covers between 1988 and 2013 comprised only about 1 % of the landscape (0.45 and 0.52 %, respectively), which was below the expectations for trees and close to the expected transition for shrubs.

Subpixel (MESMA)

Figure 2 shows the vegetation fraction difference between 1988 and 2013. Visual interpretation reveals areas of decreasing vegetation fractions around the northern and eastern portions of the cloud forest, as well as areas to the east of Salalah. Some areas show an increase in the vegetation fraction, mainly in the forested areas of Jabal Qamar in the west and parts of Jabal Qara, mainly in the

Fig. 2 Vegetation fraction differences derived from MESMA analysis. *Negative* (*positive*) values indicate a decrease (increase) in vegetation fraction between 1988 and 2013



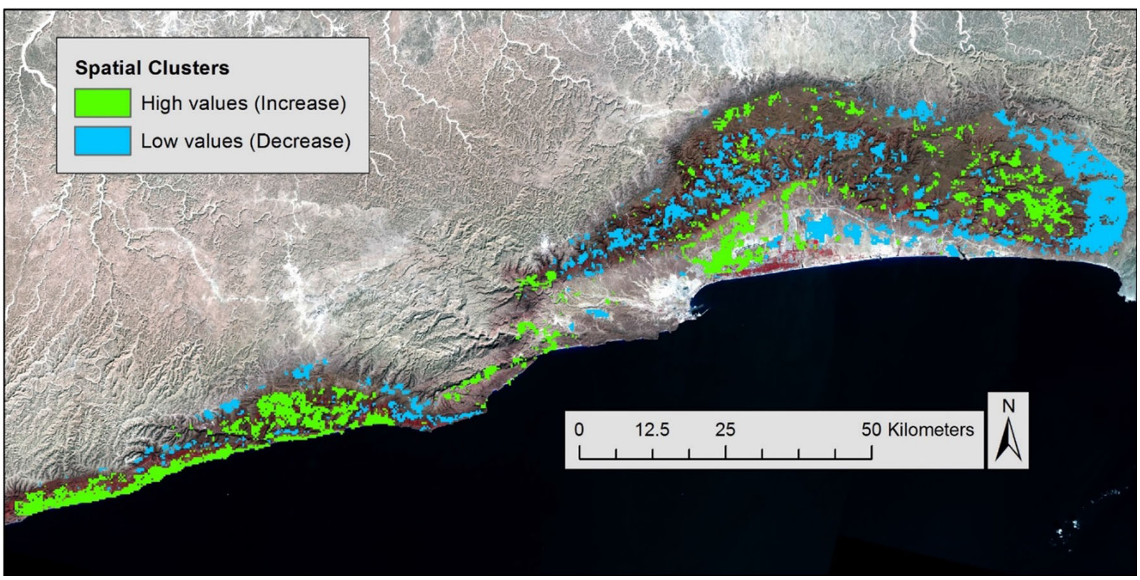


Fig. 3 Spatial clusters of the vegetation fraction—only significant spatial clusters of high–high values and low–low values are presented. High–high clusters are pixels of increasing vegetation fraction located near other pixels of increasing in vegetation fraction, while low–low clusters are decreasing in vegetation fraction

eastern sections. The number of pixels that are decreasing in vegetation fraction (<−10 %) far exceeded those that were increasing in fraction (>10 %), and somewhat more than the number of pixels that showed little evidence of change (i.e., those between −10 and 10 % difference; see Online Resource 1).

Figure 3 illustrates the results of the LISA analysis. Two types of spatial clusters are highlighted: high–high and low–low. The high–high clusters are areas where pixels of increasing woody plant vegetation (i.e., vegetation fraction) are surrounded by other pixels of increasing woody plant vegetation. Low–low clusters are the opposite. The LISA analysis has the benefit of showing only statistically significant clusters, which helps to isolate areas where increasing or decreasing fractions are prevalent. Jabal Qamar, in the western part of the study area, has witnessed spatially consistent increases in fractions, while areas in the eastern portions of Jabal Qara show a number of pixels of decreasing vegetation fractions. Just west of this area, in the interior of Jabal Qara's eastern half, the vegetation fractions appear to have increased. The western part of Salalah shows increased vegetation fractions, while the

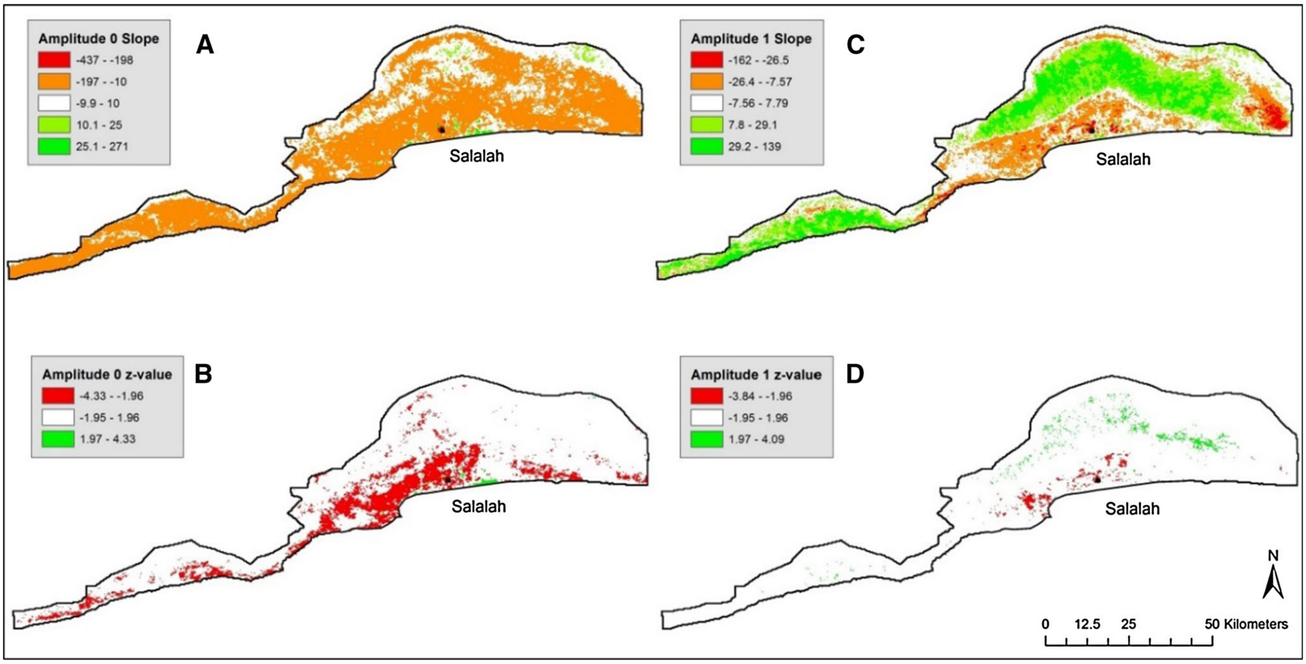


Fig. 4 Results of the NDVI trend analysis. **a** Amplitude 0 (annual mean NDVI) trend analysis results, which shows the slope of the trend as changes in average NDVI per year (MODIS NDVI = NDVI × 10,000). **b** The *z* values used to measure significance (greater than 1.96 or less than −1.96) for the Amplitude 0 trend. **c** Amplitude 1 (difference between peak and minimum yearly NDVI) trend analysis results, which shows the slope of the trend as changes in peak NDVI per year (MODIS NDVI = NDVI × 10,000). **d** The *z* values used to measure significance (same range as B) for the Amplitude 1 trend

eastern portion of the city has consistently decreased in this fraction.

Time series analysis

The results of the time series analysis are shown in Fig. 4. Areas around Salalah and to the west of the city maintain large pockets of statistically significant decreasing trends in the mean annual NDVI (Amplitude 0, Fig. 4), as well as some areas to the east of the city. There are only a few small pockets of pixels that show statistically significant increasing trends in Amplitude 0.

For Amplitude 1, that is, the difference between the minimum and maximum NDVI values (Fig. 4), pockets of significantly increasing or decreasing trends were generally fewer than those found for Amplitude 0. The areas that showed decreasing Amplitude 1 trends seem to have occurred mainly around Salalah, while increasing trends appear to be occurring at several small areas in the cloud forest.

Discussion

Land changes

The analysis of vegetation fractions suggests there are complex changes occurring across the study area. Most of the cloud forest witnessed a decrease in vegetation fraction or had minimal change (Figs. 2, 3, and Online Resource 1). Some areas of the cloud forest, however, actually increased in vegetation fractions, contradicting the prevalent local notion of ubiquitous degradation or deforestation. Several explanations for this increase are plausible. Increased atmospheric CO_2 has been shown to lead to greening in warmer, arid environments (Donohue et al. 2013)—a phenomenon referred to as the CO_2 fertilization effect. Dhofar is one region thought to be experiencing this effect (Fig. 2 in Donohue et al. 2013). Another possible reason is shrub encroachment, usually on grasslands (Asner et al. 2004) and associated with a disturbance to the ecosystem, such as fires or grazing (Anadón et al. 2014). In the case of Dhofar, shrub encroachment is generally associated with grazing, because the dominant and most abundant types of shrubs are those that are unpalatable to livestock (Miller and Morris 1988; Pickering and Patzelt 2008). Shrub encroachment can have different effects on an ecosystem. It may possibly lead to both increases and decreases in primary production (Eldridge et al. 2011). Since the transition matrix does not show any systematic transitions between grass and shrub covers, the shrub encroachment is likely occurring at a level where grasses are still the dominant land cover, and where shrub encroachment could lead to an increase in the woody plant fraction.

Perhaps the most complex changes are those happening along the coast of Jabal Qamar. Here, there appears to be places that are increasing in vegetation fraction but decreasing in the mean annual NDVI trend analysis (Amplitude 0). This odd result may indicate a long-term increase in woody plant vegetation, but with decreasing health more recently, which may be the result of a greening-browning process (de Jong et al. 2012, 2013). Additional research and more time series observations will be needed to understand this process.

A gross reduction in forest land covers comprising about 8 % of the study area between 1988 and 2013 suggests that human activities, perhaps with minor climate changes (see below), have led to modest deforestation. The widespread reductions in the vegetation fraction show that many parts of the cloud forest have undergone a greater than 10 % reduction in woody plant fractions (Figs. 2, 3, and Online Resource 1). The primary cause of deforestation and decrease in vegetation fraction is likely grazing, given the noted increase in herd sizes and grazing intensity since the 1970s (Janzen 1986, 2000), and the noted consequences of such pressures on shrub prevalence (Miller and Morris 1988; Pickering and Patzelt 2008).

The effects of overgrazing may amplify desertification or lead to a higher prevalence of xeric vegetation. One of the effects noted in our study shows decreased woody plant vegetation along the margins of the cloud forest. Recent climate analyses of Dhofar have shown that temperatures are significantly increasing (Kwarteng et al. 2009; AlSarmi and Washington 2011). The IOM also appears to have changed, though the effects of this change are variable and only well understood over the Indian subcontinent (Kumar et al. 2011; Krishnan et al. 2013; Krishnaswamy et al. 2014). In Dhofar, the IOM manifests primarily as fog that blankets the southern facing watershed divide and coastal plain, a mist not registered adequately in the local records (Hildebrandt and Eltahir 2007). We can surmise, however, that the margins of the cloud forest adjacent to the desert may be vulnerable to any variability in the monsoon cloud cover. Based on the LISA analysis (Fig. 3), distinct clusters of decreased vegetation fractions occurred along these margins and are potential areas of vulnerability to climate change. If continued warming of the atmosphere leads to increased variability or decreased stability of the monsoon, then increased pressure from grazing could lead to further degradation in the future. The clusters of low–low vegetation fractions (Fig. 3) are, perhaps, hotspots of potential desertification and will thus need to be monitored over the long term.

The time series analysis demonstrates that the most consistent decreases in the mean annual NDVI trend (Amplitude 0) occurred near Salalah, especially in the adjacent foothills of the Dhofar Mountains. The foothills benefit from the monsoon clouds and have a diverse collection of woody plants—a vital part of the cloud forest ecosystem. They are also home to a diverse array of trees and shrubs. One species in particular, *B. arabica*, is acknowledged to be threatened (Pickering and Patzelt 2008). The significant decreases in the mean annual NDVI trend (Amplitude 0) and the peak NDVI trend (Amplitude 1) around Salalah, apparently in its areas of expansion, suggest that development pressure placed on foothills has resulted in significant decreases in vegetation health.

Several phenomena might help explain why the expansion of Salalah and the vegetation health of the foothills and surrounding areas are intertwined. Demand for relief during the hot Arabian summer has led to tourists flooding into foothills during the monsoon season. These tourists come from all parts of the Arabian Peninsula, and speculation suggests that Oman will continue to grow its tourism sector with even more tourists expected in the future (Lefebvre 2010). Another possible factor is the relocation of summer herding camps due to the development of Salalah. During the summer monsoon season, camel herds are brought from the mountains to live on the coastal plains around Salalah until the heavy fog and mud brought on by the monsoon clears (Janzen 1986). As Salalah expands, including fragmented residential development at its margins, these temporary encampments are pushed farther from the city's core and closer to the foothills, which increases both grazing pressures and vehicle traffic there (Janzen 2000).

National policies and land change in Dhofar

The proximate causes of land-cover changes in the Dhofar cloud forest and adjacent coastal plains appear to be changes in herding practices and economic development. Why have these changes taken place, and are they linked to distal causes? The evidence points to policies generated by the Omani government as a response to the Dhofar War of 1970 to 1975—an uprising by Yemini backed rebels against the Sultan of Oman's armed forces and British Special Forces. These policies aimed to improve the livelihoods of the rural poor in the area but in some cases had, as an unforeseen consequence, increased herd size and grazing intensity in Dhofar. Table 2 shows the various policy decisions made by the government and their possible environmental outcomes.

A policy designed to provide easier access to water for herds was, perhaps, the most proximate cause to changes in herding practices. The government constructed 160 wells in the region, not only improving access to water but eliminating the need for lengthy excursions elsewhere to obtain it, thus concentrating herds for intensive grazing. Another important policy created a paid militia system, or

Table 2 Policy decisions and their likely environmental outcomes

National developmental policies	Policy outcome	Environmental outcome		
		Deforestation	Grassland degradation	Coastal degradation
Land tenure changes	Increased camel grazing and changes to grazing pattern	X	X	
Infrastructure development	Urban expansion (Salalah)			X
	Road construction	X	X	X
	Building development (towns and villages)	X	X	X
Water well development	Increased herd size	X	X	
Income supplements (e.g., Firqat)	Increased herd size	X	X	
Expansion of veterinary services	Increased herd size	X	X	

Deforestation and grassland degradation refer to changes in the cloud forest, whereas coastal degradation applies to land changes in the coastal plains and foothills

firqat, providing an important supplementary income used by herders to help maintain and grow their herds, especially regarding the purchase of fodder required during the winter vegetation senescence. Fodder has been at various times subsidized, but families usually pay a nontrivial amount of money each year for it. As herd sizes increase, more fodder must be purchased, which can put considerable pressure on monthly family budgets (Janzen 2000). The *firqat* system is maintained today in part to help the local economy (Peterson 2004a), and it has also become an important part of herd maintenance. In addition, veterinary services, heretofore absent in the area, were introduced during the Dhofar War and have subsequently been expanded. Begun by the British Special Forces (Hughes 2009; also see Higgins 2011) during the war and continued by the Omani government since, herders across the cloud forest today vaccinate their herds and have them medically treated. Livestock health and lifespan has increased as a result. By the 1980s, the population of cattle, camel, and goats had tripled since the end of the war and are thought to have increased even more since then (Janzen 2000).

Changes to land tenure may also have played a role in land-cover changes. Traditionally, pasture lands across Dhofar were grazed only in areas that were considered a part of a tribal boundary (Janzen 1986). New nationally imposed rules emerging in the 1980s decreed all land were under the ownership of the Omani national government (Janzen 2000, citing Omani Royal Decree 5/80, 3/83, and 81/84), generating at least two important outcomes (Janzen 2000). Camel breeders, who formerly stayed on the fringes of the cloud forest, began to graze their herds on lands that traditionally belonged to cattle herders; they cited the nationalized land tenure policy as a rationale for this action. In addition, the government also constructed buildings, schools, and mosques throughout the cloud forest, encouraging the formerly nomadic population to settle in one place in order to take advantage of the new benefits. As a result, grazing became more sedentary and intensive, and the traditional transhumance practice is undertaken by fewer herders and mainly by camel herders.

Finally, infrastructure development was a key factor of land change in Dhofar, particularly around the City of Salalah. Dhofar received about 40 % of government expenditures, much of it for infrastructure development and related projects, despite only having about 10–25 % of the population (Peterson 2004b). More than 4 % of the total study area was converted to urban use around Salalah and other parts of the coastal plain, and a deep water port was built just outside of Salalah, as well as a paved road from Salalah to Jabal Qamar (Allen and Rigsbee 2000). Road development in the cloud forest led to transitions from grass, shrub, and forest covers to road covers. Both of these changes were possible because of development investments.

Land change mitigation factors

While there have been notable changes to the environment of the cloud forest, common wisdom suggests there should be much more. Part of this conundrum may reside in Oman's import of key food staples and the subsequent impact on local cultivation. In the past, cultivation was more widespread in the cloud forest, possibly as late as the 1970s (Janzen 1986). At some point after the 1970s, cultivation was reduced to small frankincense plots, walled areas for hay production, plantations in Salalah, or reforestation plots. Our results suggest little change in cropped land between 1988 and 2013. With Oman's oil boom in the late 1960s, there has been little need to expand the cultivation of staple crops, despite significant economic development and demand for food, given import options (OEC 2015).

Conclusion

The Dhofar cloud forest and coastal plains have witnessed land changes over the 25-year period of this study. These changes have been more complex than local, commonly expressed views of them. Systematic transitions have occurred between several types of land cover in the cloud forest, primarily tree cover to shrub cover, shrub cover to grass cover, and grass cover to road cover, while the coastal plains systematically transitioned to road cover and the built environment. Vegetation fractions showed significant clusters of decreasing woody plant cover along the cloud forest margins and various parts of the coastal plain, and NDVI trend analysis indicates decreasing NDVI around the city of Salalah since 2001. These changes would appear to be linked primarily to changes in herding practices and road and peri-urban development, most of which appear to be a response to changes in government policies directed to developing the southern part of Oman. Whether these policies have led to a path dependent outcome—land-cover trends that are difficult to reverse or alter—remains an open question.

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