Accounting for land cover changes and degradation in the Katse and Mohale Dam catchments of the Lesotho highlands

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Rangeland conditions in the Lesotho highland dam catchment areas is important for local livelihoods and regional water supply. We investigated changes in land cover and condition from 1991 (before construction) to 2013, using Landsat imagery. The Normalised Difference Vegetation Index (NDVI) decreased in the catchment areas, while increasing within two protected areas. NDVI decreases were greatest close to the dams and in the high altitude summer grazing areas. Land cover maps were generated for 1993, 2005 and 2013, using structural vegetation classes, as well as categories of grassland based on NDVI. High altitude areas were characterised by grasslands changing to lower NDVI categories, indicating overgrazing in climax sourveld grasslands. Mid-altitude areas were characterised by grasslands changing to higher NDVI categories and increases in woody vegetation, indicating overgrazing in Sweetveld. At lower altitudes, the increase in cultivated areas suggested disproportionately high population growth in the catchment areas. The results suggest that there has been widespread degradation that appears to be more as a result of overgrazing than climate change. The study demonstrates the importance of using a combination of land cover, NDVI and field data in assessing degradation. Natural capital accounting methods provide a useful framework for documenting, monitoring and understanding changes in ecosystem condition.

Keywords: bush encroachment, land degradation, natural capital accounting, NDVI, rangeland condition

Introduction

Land degradation has become one of the foremost concerns on the global agenda, to the extent that the United Nations (UN) has declared this as the decade of restoration. Goal 15 of the UN's Sustainable Development Goals (SDG) is to 'Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss', and the associated target 15.3 urges countries to strive to achieve a land degradation-neutral world by 2030. To this end, countries are required to report on the proportion of their total land area that is degraded (Indicator 15.3.1) on a regular basis. In addition, under the United Nations Convention to Combat Desertification (UNCCD), countries are required to define their Land Degradation Neutrality (LDN) Targets to achieve no net degradation relative to 2015, by 2030. This requires that countries assess degradation trajectories and devise strategies to halt and/or offset future degradation. At the same time, countries are also urged to start accounting for the extent and condition of their natural capital in a consistent and repeatable way using the recently developed System of Environmental Economics Accounting (United Nations et al. 2014; United Nations 2017).

However, little progress has been made on any of these fronts, especially in developing countries, such as the Kingdom of Lesotho, where land degradation poses a major threat to the Kingdom's natural capital assets. One of the main reasons for this is the difficulty in measuring and assessing land condition. Although monitoring rangeland condition has traditionally involved field surveys that take species composition, as well as vegetative cover into account (Svoray et al. 2013), this is challenging at large scales. The UN recommends using trends in satellite-derived data on land cover, Normalised Difference Vegetation Index (NDVI; a commonly used indicator of plant vigour, biomass and cover) and soil organic carbon to assess land degradation. Satellite remote sensing data allow for the assessment of long-term changes over large geographic regions, at sufficient spatial resolution to be useful for catchment-scale changes in land use and land cover (Weng 2002; Sohl and Sleeter 2012). Although such methods do require field data in order to train and calibrate the classification of land cover and interpret trends in indicators of vegetative productivity (Bai et al. 2008; Munyati et al. 2011; Venter et al. 2020), they are also reproducible and sustainable in terms of future data requirements, and are therefore increasingly being used to measure land degradation (Reinermann et al. 2020; Giuliani et al. 2020).

Nevertheless, interpreting these trends is particularly difficult when land degradation can involve either losses or gains in vegetation cover. Indeed, land degradation in southern Africa can take the form of desertification, bush encroachment and the proliferation of invasive alien plants that may be difficult to distinguish as degradation using simple land cover and productivity indices. In accounting for land condition and addressing LDN targets, it is important to understand spatial variation in the nature of degradation and its drivers, particularly *vis-à-vis* management *versus* external influences, such as climate change.

In this study, we assessed rangeland degradation in a large mountainous region of Lesotho, where the development of two major dams and associated road infrastructure could have facilitated increased pressures on rangelands that support a traditional pastoral lifestyle. The Katse and Mohale Dams (Figure 1) were constructed in the Lesotho Highlands as the first phase of the Lesotho Highlands Water Project (LHWP) that supplies water to South Africa. The reservoirs filled in 1996 and 2002, respectively. The ecological condition of their catchment areas is recognised as being crucial for controlling sedimentation and sustaining water delivery. We investigated changes in land cover and condition in the catchment areas of the Katse and Mohale Dams through a detailed spatio-temporal analysis of remote sensing data from 1991 to 2013. Our study shows that seemingly conflicting trends in land cover and NDVI data across a study area can be better interpreted when considered in relation to variation in ecological and socio-economic contexts. It also shows that natural capital accounting methods provide a useful framework for assessing and monitoring rates of degradation over time.

Materials and methods

Preparation and analysis of Landsat NDVI data

Time-series maximum NDVI data were generated from a combination of Landsat 5 TM, Landsat 7 TM and Landsat 8 OLI imagery for the period 1991–2014. Suitable images were defined as having minimal cloud cover, and taken during the growth season (November–April) when NDVI values were expected to be highest. All images were ortho-corrected to a precise UTM map projection format (UTM 35 South, datum WGS 84, spheroid WGS 84), using the US-EarthSAT precision rectified Stock 2000 Landsat images and the SRTM 90-m terrain model for spatial reference, with a root mean squared (RMS) error of less than 0.56. The suitable images were converted to a uniformly standardised 'top of atmospheric' radiance, and thereafter processed into NDVI scenes. NDVI per pixel is calculated using the formula: NDVI = (Near Infrared Band − RED Band) / (Near Infrared Band + RED Band). If there was more than one suitable scene in a single year then those scenes were merged. The merged scene portrayed the highest (*maximum)* NDVI value per pixel for the selected scenes for that year. The processed imagery was then stacked into a single image with 23 bands.

Overall rates of change in NDVI in the two catchment areas were compared with those of two protected areas on the border of the Katse catchment that acted as reference sites, the 19.72 km^2 Bokong Nature Reserve and 53.33 km^2 Ts'ehlanyane National Park, which were established between 2001 and 2003[1]. Changes in the protected areas were used as a reference level of change in NDVI over the period (i.e. effect of climate conditions only).

Rates of change in NDVI were examined in relation to distance from the reservoirs, altitude and aspect. To do this, the study area was stratified into seven altitude bands (Figure 2), as well as six distance bands (0–1 km; 1–2.5 km; 2.5–5 km; 5–7.5 km; 7.5–10 km and >10 km) from the inundation area, and the aspect of each 30 × 30 m grid cell was categorised as one of eight compass points. Since the dataset comprised over six million pixels, data were extracted from 100 pixels sampled randomly within each of the distance-altitude-aspect classes within the Katse and Mohale Dam catchments and the two protected areas. For each of the sampled pixels, the NDVI values were extracted for each year in the time series. Only the original NDVI data for the 'best years' in terms of data quality were used (1991, 1997–1999, 2001–2004, 2007–2009 and 2014). For each selected grid cell, the slope of a linear regression through the NDVI values was determined. These were summarised for the different altitude bands and compared with rainfall trends, using gridded (4.8 km resolution) daily rainfall data for 1991 to 2013 from the Climate Hazards Group (Funk et al. 2014).

Finally, general linear modelling (GLM) analyses were carried out using Stata 16.0 statistical software to explore the effects of altitude, distance from the dam inundation area and aspect (cos- and sin-transformed to northing and easting) on the rate of change in NDVI.

Mapping and accounting for land cover changes

Three land cover maps were produced using imagery for 1991–1993, 2004–2006 and 2012–2014. These are hereafter referred to as the 1993 (since most imagery was from 1993 in this case), 2005 and 2013 land cover maps. The same methods were used as for the 2004–2006 Maloti-Drakensberg Transfrontier Project (MDTP) land-cover mapping in the same area. The thematic 'land-cover' classes were (1) subsistence farming, (2) natural sandstone paving, (3) natural rocky ridgelines, (4) open water, (5) wetlands, (6) *Leucosidea* (tall shrub) communities, and (7) short shrubs (*Chrysocoma*). All remaining areas, representing 'open grass and low shrub dominated veld' were then defined in terms of qualitative NDVI data ranges. The land cover classification was validated by data from a detailed field study conducted over a similar period during field observations (NPB, unpubl. data), as well as by comparison with the MDTP land cover map.

Subsistence farming was mapped using a combination of geographically defined, unsupervised image classification techniques and NDVI difference modelling, using the available approximately September and approximately March images. The geographic mask was manually

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[1] Note that these parks are not perfect reference sites, but the best available for the study. Both had Management Efficiency Tracking Tool (METT) scores of approximately 67 in 2005, reduced to approximately 56 in 2009. (http://documents1.worldbank.org/curated/en/415891468053958262/text/ICR11770P052361C0disclosed081161101.txt)

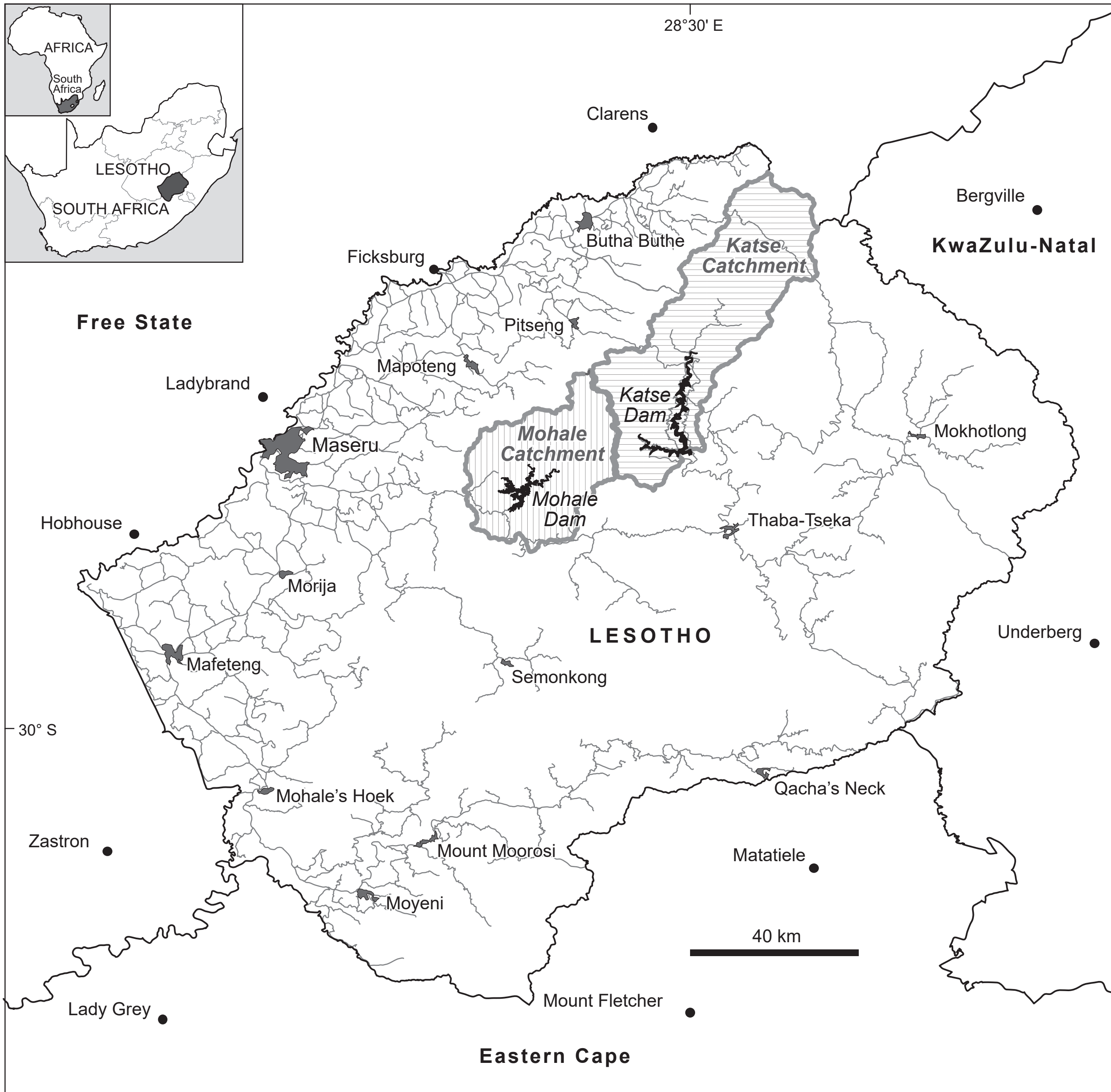

Figure 1: Inundation and catchment areas of the Katse and Mohale Dams in the Lesotho Highlands

delineated to define broadly all areas of subsistence cultivation within the study area. These image acquisition periods had minimal terrain shading and also maximum cover (and thus spectral) differences with the cultivated lands. In approximately September, most cultivated lands are being prepared for planting and will have little or no vegetative cover, whereas in approximately March there should be a good vegetative crop cover.

Ridgelines (i.e. naturally occurring low vegetation rocky areas) were first identified generically by topographical modelling, using the 90-m SRTM DEM. Ridges were defined as local areas (~1 ha), within which the aspect varied by 180° difference and there was a 20° difference in slope. Spectral image classification was used to further differentiate and delineate the actual rocky areas from vegetated areas.

Waterbodies were mapped using a combination of both geographically defined unsupervised image classification techniques and NDVI threshold modelling. A geographic mask was manually delineated to define broadly all areas of open water within the catchments. Both the unsupervised classification and NDVI modelling approaches were applied within the defined geographic mask, using the most suitable imagery, defined in terms of maximum seasonal water extent. The mapping results

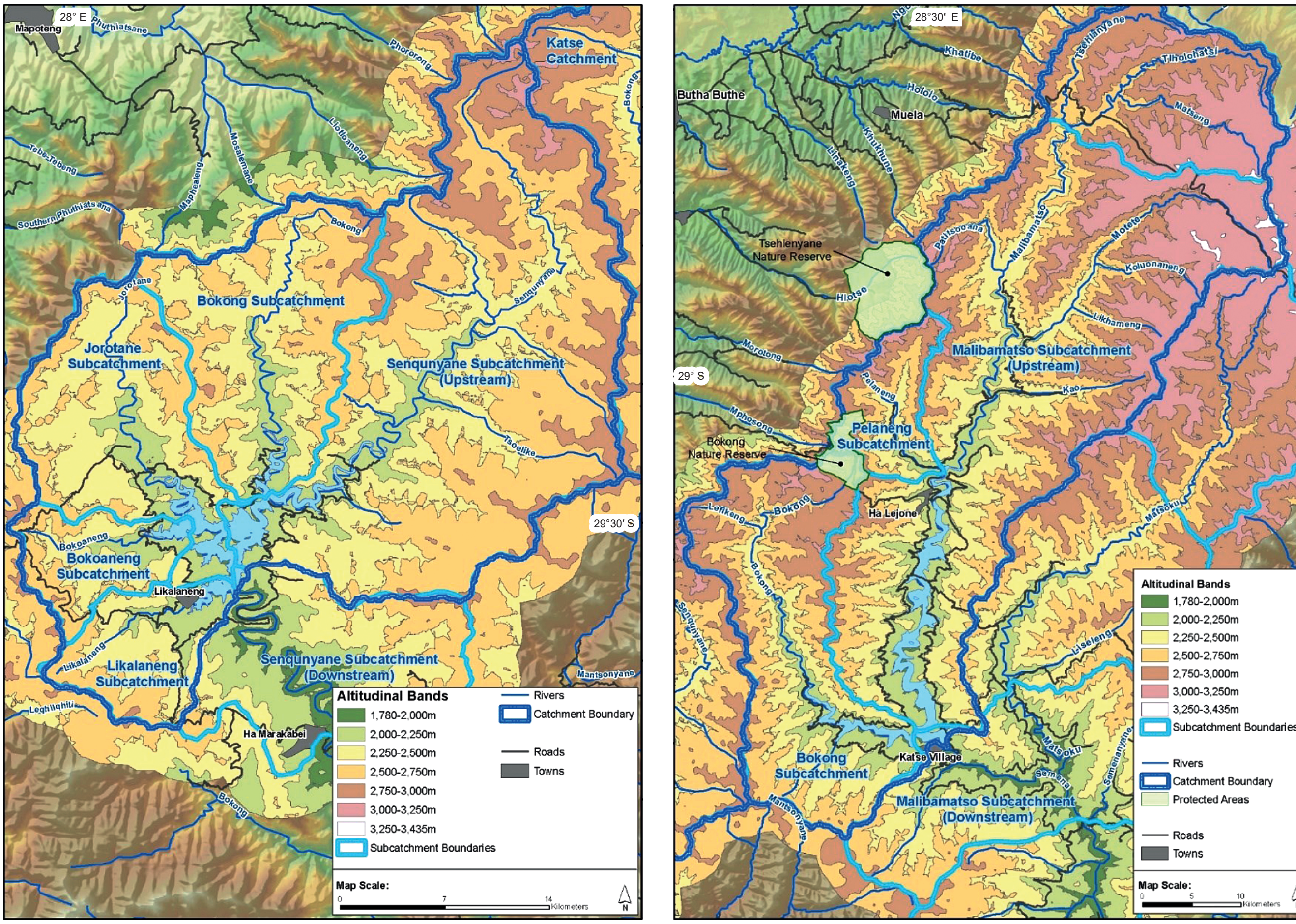

Figure 2: Map of (a) Mohale and (b) Katse Dam inundation areas, catchment and downstream area showing the altitudinal bands used in the study

of both the unsupervised image classification and NDVI threshold modelling techniques were spatially combined to generate the final water class extent. A detailed inventory of all wetlands had been mapped from high-resolution SPOT imagery as part of the MDTP. This was embedded into the maps, although the extent was modified in the 2013 dataset where more recent cultivation activities had encroached into previous wetland areas.

Bush and low shrub communities were initially broadly delineated using an analysis of multiseason NDVI values, and comprised areas that had relatively high NDVI values all year round, because of their more evergreen characteristics. The taller woody bush class (i.e. *Leucosidea* spp.) was then defined from within the combined bush and low shrub extent using a more precise NDVI thresholding. The remaining areas of 'open grass and low shrub dominated veld' were then assigned to one of five subclasses, based on the NDVI values for approximately March.

After completion of each the land-cover for each assessment period, a final 'logic test' was performed across the three time periods to eliminate any mapping inconsistencies, representative of highly unlikely changes that may have been generated in error. This was an important final stage in order to ensure viable time-series land-cover datasets for comparison and change detection between the assessment periods. The only classes modified during the logic tests were the *Leucosidea* communities, Low Shrub (*Chrysocoma*), Wetlands, and Subsistence farming. For example, if an area was classified as subsistence farming in both 1993 and 2013, but not in 2005, it is highly likely that the same area should in fact be classified as subsistence farming in 2005 as well.

Finally, the extent of different land cover classes and the changes between the three time periods were summarised and analysed using accounting tables and matrices. These were used to quantify changes in absolute and relative terms, to examine what types of changes took place over the time period, and whether the rates of change were different in the two time periods (roughly before and after dam construction).

Results

Trends in NDVI

NDVI had a decreasing trend on average in both catchment areas, but an increasing trend in both the protected areas over the same period (Figure 3). The rate of decrease was greater overall in the Katse Dam catchment, which has both a higher average altitude and a higher population than the Mohale Dam catchment. The rate of decline in NDVI was highest at the lowest and highest altitudes in both catchments (Figure 4), apart from the lowest altitude band in Mohale catchment. This pattern was not related to rainfall.

The rate of change of NDVI was significantly related to altitude, distance from the dam and aspect ($F_{(7,35292)}$ = 585.52, p < 0.001) (Table 1). There was an overall hyperbolic relationship to both altitude and distance, but the sign of the distance relationship changed in the absence of altitude. The standardised regression coefficients, as well as the comparison of fit across the three models clearly showed that altitude was the most important determinant of the rate of change in NDVI, with middle altitudes having a slower decline than lowest and highest altitudes. Aspect was the next most important variable, with north-facing slopes having a slower rate of decline. The regression results also reiterated that rates of degradation were higher in Katse catchment than Mohale. Distance to the dam had the weakest effect, and in the absence of altitude (Model 3) its effect was inverted and insignificant (Table 1).

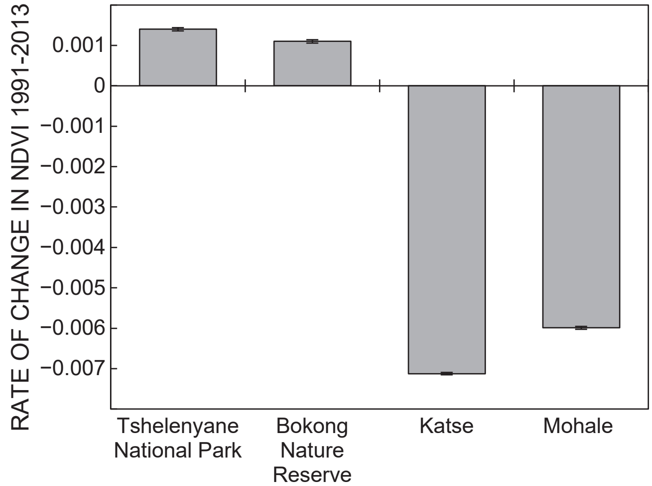

Figure 3: Average annual rate of change in NDVI (± standard deviation) within two protected areas and in the Katse and Mohale catchment areas, over the period 1991 to 2013

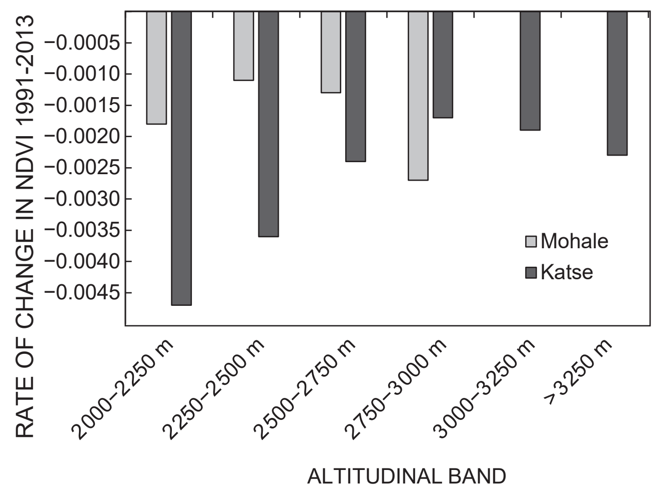

Figure 4: Average annual rate of change in NDVI over the period 1991 to 2013 within different altitude bands in the Katse and Mohale Dam catchment areas

Catchment-wide changes in land cover

The changes in land cover over 1993 to 2013 are presented in accounting format in Tables 2 and 3. Over the 23-year period, the area of subsistence farming increased from 1 373 ha (1%) to 5 702 ha (6%) in the Mohale catchment and from 5 623 ha (3%) to 12 423 ha (7%) in the Katse catchment. The annual rate of growth of subsistence farming was 60% and 37% higher in the second period than the first, respectively. The area under *Chrysocoma* shrubland increased by approximately 5 000 ha and 8 700 ha in the Mohale and Katse catchments, with rates of change being approximately 4.7 and 2.9 times higher in the second period. This suggests that bush encroachment is a rapidly increasing problem in the study area. The highest two NDVI categories of grassland were both lost much more rapidly in the second period than the first, at an average rate of 610 ha and 1 541 ha y^{-1} in the two catchments, respectively.

The land cover change matrices (Tables 4 and 5) showed that in addition to losses due to reservoir inundation, grassland areas, particularly of the highest NDVI category, were mainly lost to subsistence farming in the first interval, with changes to shrubbier vegetation (bush encroachment) also accounting for significant losses of all grassland classes. In the second period, bush encroachment became the dominant change. From 2005 to 2013, similar areas of grassland changed to higher or lower NDVI categories in Mohale (18 274 vs 18 448 ha), but in the Katse, more grassland area changed to a lower NDVI category (30 080 ha) than to a higher category (22 730 ha).

Land cover change in relation to altitude

In 1993, prior to the dams being built, there was already subsistence farming in the lowest altitude bands (Figure 5). Following inundation, most of the land in the 1 780–2 000 m band was flooded, and what remained became highly degraded grassland in both catchment areas. The greatest increases in extent of subsistence farming from 1993 to 2005 and from 2005 to 2013 occurred in the 2 000–2 250 m altitude band, but there were also increases in extent at higher altitudes. The *Chrysocoma*-dominated vegetation and *Leucosidea* communities both increased mainly within the 2 250–2 750 m altitudinal band. This may account for the lower rates of loss in NDVI in these middle altitudes (Figure 4).

The high-altitude areas were already dominated by lower NDVI grassland classes in both catchments during 1993, prior to dam construction. In Mohale catchment, the higher altitude grassland areas showed a change in cover towards higher-NDVI classes from 1993 to 2005, and then a slightly reversed trend from 2005 to 2013. However, there was very little change in the higher altitude grasslands in Katse catchment.

Table 1: Results of the generalised linear modelling analysis of the rate of change in NDVI from 1991 to 2013. Beta is the standardised regression coefficient. Significance: *** $p < 0.001$, ** $p < 0.1$

	Model 1		Model 2		Model 3	
	Coeff, SE	Beta	Coeff, SE	Beta	Coeff, SE	Beta
Altitude	−0.000014***	−1.161	−0.000014***	−1.154		
	(0.000001)		(8.19 E^{-7})			
Altsq	0.000000***	1.293	3.20 E ***	1.283		
	(0.000000)		(1.69 E^{-10})			
Distance	−0.000104**	−0.076			5.02 E^{-6}	0.004
	(0.000033)				(0.0000329)	
Distsq	0.000008**	0.071			5.13 E^{-6}	0.044
	(0.000003)				(2.79 E^{-6})	
Northing	0.001303***	0.240	0.001302***	0.240	0.0013001***	0.240
	(0.000027)		(0.0000273)		(0.0000277)	
Easting	0.000389***	0.071	0.000391***	0.072	0.0003911***	0.072
	(0.000028)		(0.0000275)		(0.0000279)	
Mohale	0.001394***	0.161	0.001396***	0.161	0.0011578***	0.133
	(0.000045)		(0.0000446)		(0.0000444)	
Constant	0.007850***		0.007537***		−0.0074063***	
	(0.000992)		(0.0009741)		(0.0000841)	
Adj R^2	0.1039		0.1037		0.0819	

Discussion

This study showed that there have been significant reductions in NDVI in both the Katse and Mohale dam catchments from 1991 to 2013, with the rate of reduction having escalated after the dams were constructed. Given that the opposite trend was observed in nearby protected areas (Bokong and Ts'ehlanyane), this suggests that the observed trend was more likely attributable to human activities within the dam catchments than to exogenous influences, such as climate change. This concurs with the findings of De Jong et al. (2013), who provide evidence of widespread degradation in parts of southern Africa, including Lesotho, that is not climate-induced. Indeed, estimates of stocking rates suggest that the rangelands in Lesotho could be overstocked by 40–80% (MFLR 2014), or even as much as 300% in some areas (Marake et al. 1998).

The rate of reduction in NDVI was higher in the Katse than the Mohale catchment area, suggesting that this catchment may have degraded more rapidly in terms of loss of vegetative cover. Indeed, the vegetation surveys undertaken in 2014 found lower basal cover of vegetation in the Katse catchment than in the Mohale catchment (NPB, unpubl. data). This can be attributed to the fact that the Katse dam was completed first, and that the area now has a higher population than in the Mohale catchment. This supports the hypothesis that degradation in these catchment areas has largely been the result of the increase in populations in these catchments that has resulted from their increased accessibility, as a result of dam construction.

The rate of decrease in NDVI was found to be strongly linked to altitude, with rates being highest at the lowest and highest altitudes. This was the case even though the highest altitudes in Mohale catchment are lower than those in the Katse catchment. This suggests that the degradation is linked to relative position in the catchment rather than altitude *per se.* Livestock is grazed in the higher altitude areas in summer. These summer grazing areas are accessible to herders coming from beyond, as well as within the catchment areas, whereas the village and winter grazing areas at lower altitudes are mainly used by locals. It is likely that human settlement and the associated livestock have contributed to a loss of vegetative cover at lower altitudes, while increased grazing pressure from local and non-local livestock has contributed to the same at higher altitudes. Most of Lesotho's livestock are based in the lowlands and foothills, but many are moved into the mountain areas for summer grazing (BoS 2012), with transhumance from lowlands to the highlands having been practiced for the past 100 years in Lesotho (Quinlan 1995). Approximately half of the livestock that are based within mountainous areas across the Kingdom are within the mountainous areas of Butha-Butha, Leribe, Maseru and Thaba-Tseka, which encompass the study area. Altitude was correlated with distance from the dams, but changes in NDVI were better correlated with altitude than distance.

This study also found that the warmer north-facing slopes tended to be more resilient than other aspects, suggesting that the sourveld of the cooler south facing slopes could be more sensitive to grazing pressure. Aspect has a significant effect on the 50% floristic crossover point from C_4 to C_3 grasses in Lesotho, with C_4 grasses occurring farther up the slopes with northerly aspects (Morris 2017). Although they cannot sustain the same grazing capacity year round, the C_3 grasses that characterise sourveld tend to be more nutritious and palatable for pastoral livestock (Lodge and Whalley 1983, Archer and Robinson 1988). Hence the high altitude areas of Lesotho are sought after for summer grazing. Being less efficient at photosynthesis in low CO_2 environments, C_3 grasses are also more likely to benefit from the carbon fertilisation effect (Köhler et al. 2018). However, given that the colder slopes have fared poorer than the north-facing slopes, it seems that over

Table 2: Change in land cover of the Mohale Dam catchment from 1993 to 2013, also showing the change in the average rate of change between two accounting intervals. Turnover = additions + reductions. Total accounting area = 92 743 ha

	Land cover classes	No data	Subsistence farming	Ridgelines	Water	Wetlands	*Leucosidea* communities	Short shrub (*Chrysocoma*)	Grassland 1 (highest NDVI)	Grassland 2	Grassland 3	Grassland 4	Grassland 5 (lowest NDVI)
	Opening stock 1993	147	1 373	14 594	330	2 280	2 079	3 619	19 117	14 927	12 798	12 286	9 194
	Additions	0	2 265	0	1 057	0	452	874	8 410	11 139	8 259	6 765	5 282
	Reductions	1	599	0	214	170	1 585	0	8 941	10 092	9 670	9 025	4 207
	Net change	−1	1 666	0	843	−170	−1 133	874	−531	1 048	−1 411	−2 260	1 075
1993 to 2005	As % of opening	−0.6%	121.3%	0.0%	255.6%	−7.5%	−54.5%	24.2%	−2.8%	7.0%	−11.0%	−18.4%	11.7%
	Average annual net change	0	139	0	70	−14	−94	73	−44	87	−118	−188	90
	Unchanged	146	774	14 594	116	2 110	494	3 619	10 176	4 835	3 128	3 261	4 987
	As % of opening	99.3%	56.4%	100.0%	35.3%	92.5%	23.8%	100.0%	53.2%	32.4%	24.4%	26.5%	54.2%
	Turnover	1	2 864	0	1 270	170	2 037	874	17 351	21 231	17 929	15 790	9 489
	Closing stock 2005	146	3 040	14 594	1 173	2 110	946	4 493	18 585	15 974	11 387	10 026	10 269
	Additions	0	2 662	0	259	0	770	4 158	5 953	9 074	10 502	7 715	3 632
	Reductions	0	0	0	112	54	138	55	10 993	11 352	7 971	7 339	6 712
2005 to 2013	Net change	0	2 662	0	147	−54	632	4 103	−5 039	−2 278	2 531	376	−3 081
	As % of opening	0.0%	87.6%	0.0%	12.5%	−2.5%	66.8%	91.3%	−27.1%	−14.3%	22.2%	3.8%	−30.0%
	Average annual net change	0	222	0	12	−4	53	342	−420	−190	211	31	−257
	Unchanged	146	3 040	14 594	1 061	2 057	808	4 438	7 593	4 622	3 416	2 688	3 557
	As % of opening	100.0%	100.0%	100.0%	90.4%	97.5%	85.4%	98.8%	40.9%	28.9%	30.0%	26.8%	34.6%
	Turnover	0	2 662	0	371	54	908	4 213	16 946	20 425	18 473	15 054	10 344
	Closing stock 2013	146	5 702	14 594	1 320	2 057	1 578	8 596	13 546	13 696	13 918	10 403	7 188
	Overall net change in stock (1993–2013)	−1	4 328	0	990	−224	−501	4 978	−5 570	−1 230	1 120	−1 883	−2 005
	As % of opening	−0.6%	315.1%	0.0%	300.1%	−9.8%	−24.1%	137.5%	−29.1%	−8.2%	8.7%	−15.3%	−21.8%

Table 3: Change in land cover of the Katse Dam catchment from 1993 to 2013, also showing the change in the average rate of change between two accounting intervals. Turnover = additions + reductions. Total accounting area = 186 581 ha

	Land cover classes	No data	Subsistence farming	Ridgelines	Water	Wetlands	*Leucosidea* communities	Short shrub (*Chrysocoma*)	Grassland 1 (highest NDVI)	Grassland 2	Grassland 3	Grassland 4	Grassland 5 (lowest NDVI)
1993 to 2005	Opening stock 1993	7	5 623	32 338	873	3 788	2 118	7 105	36 121	28 378	27 140	25 986	17 104
	Additions	0	4 859	0	2 897	0	1 827	3 001	15 791	16 252	15 787	11 518	6 394
	Reductions	0	0	1 296	499	95	1 205	0	12 945	19 258	18 009	16 866	8 153
	Net change	0	3 563	0	2 398	−95	622	3 001	2 847	−3 007	−2 222	−5 347	−1 759
	As % of opening	4.9%	63.4%	0.0%	274.6%	−2.5%	29.3%	42.2%	7.9%	−10.6%	−8.2%	−20.6%	−10.3%
	Average annual net change	0	297	0	200	−8	52	250	237	−251	−185	−446	−147
	Unchanged	7	5 623	31 042	374	3 693	913	7 105	23 176	9 120	9 131	9 120	8 952
	As % of opening	100.0%	100.0%	96.0%	42.8%	97.5%	43.1%	100.0%	64.2%	32.1%	33.6%	35.1%	52.3%
	Turnover	0	4 859	1 296	3 396	95	3 032	3 001	28 736	35 510	33 796	28 384	14 546
2005 to 2013	Closing stock 2005	8	9 186	32 338	3 271	3 693	2 740	10 106	38 967	25 372	24 917	20 638	15 345
	Additions	0	3 237	0	530	0	1 606	5 785	8 109	15 077	13 581	10 058	6 422
	Reductions	0	0	0	401	55	291	44	20 000	15 515	13 200	9 547	5 353
	Net change	0	3 237	0	129	−55	1 315	5 741	−11 891	−438	381	511	1 069
	As % of opening	0.0%	35.2%	0.0%	4.0%	−1.5%	48.0%	56.8%	−30.5%	−1.7%	1.5%	2.5%	7.0%
	Average annual net change	0	405	0	16	−7	164	718	−1 486	−55	48	64	134
	Unchanged	8	9 186	32 338	2 870	3 638	2 449	10 062	18 967	9 857	11 717	11 092	9 992
	As % of opening	100.0%	100.0%	100.0%	87.7%	98.5%	89.4%	99.6%	48.7%	38.9%	47.0%	53.7%	65.1%
	Turnover	0	3 237	0	932	55	1 896	5 829	28 110	30 591	26 781	19 605	11 775
	Closing stock 2013	8	12 423	32 338	3 400	3 638	4 055	15 847	27 077	24 934	25 298	21 150	16 414
	Overall net change in stock (1993–2013)	0	6 800	0	2 527	−150	1 937	8 742	−9 044	−3 445	−1 842	−4 836	−690
	As % of opening	4.9%	120.9%	0.0%	289.5%	−4.0%	91.4%	123.0%	−25.0%	−12.1%	−6.8%	−18.6%	−4.0%

Table 4: Land cover change matrix over two intervals for Mohale Catchment. Changes are read from left to right, for example, 154 ha of subsistence farming in 1993 became area under water by 2005. Areas in grey were unchanged. All areas in ha

Mohale 1993–2005	No data	Subsistence farming	Ridgelines	Water	Wetlands	*Leucosidea* communities	Short shrub (*Chrysocoma*)	Grassland 1 (highest NDVI)	Grassland 2	Grassland 3	Grassland 4	Grassland 5 (lowest NDVI)
No data	*146*											
Subsistence farming		*774*		154		2	2	249	111	46	22	13
Sandstone paving												
Ridgelines			*14 594*									
Water		43		*116*		0	0	69	34	19	18	31
Wetlands		141		26	*2 110*							3
Leucosidea communities		23		0		*494*	267	527	331	211	144	82
Short shrub (*Chrysocoma*)							*3 619*					
Grassland 1 (highest NDVI)	0	1 477		359		260	220	*10 176*	4 017	1 503	721	384
Grassland 2		384		198		90	174	4 625	*4 835*	2 542	1 442	638
Grassland 3		123		128		49	109	1 901	3 841	*3 128*	2 288	1 231
Grassland 4		53		104		35	74	762	2 230	2 865	*3 261*	2 902
Grassland 5 (lowest NDVI)		21		87		16	27	276	576	1 073	2 130	*4 987*
Mohale 2005–2013												
No data	*146*											
Subsistence farming		*3 040*										
Sandstone paving												
Ridgelines			*14 594*									
Water		0		*1 061*					0	0	1	111
Wetlands		51		3	*2 057*							
Leucosidea communities		2				*808*	97	35	3	1	0	0
Short shrub (*Chrysocoma*)		52					*4 438*					3
Grassland 1 (highest NDVI)		1 669		81		112	1 433	*7 593*	4 117	2 258	905	416
Grassland 2		505		59		95	1 090	3 449	*4 622*	3 662	1 726	766
Grassland 3		182		37		98	666	1 455	2 558	*3 416*	2 088	886
Grassland 4		112		35		155	520	718	1 617	2 733	*2 688*	1 449
Grassland 5 (lowest NDVI)		88		43		311	352	296	779	1 848	2 995	*3 557*

Table 5: Land cover change matrix over two intervals for Katse Catchment. Changes are read from left to right, for example, 94 ha of wetlands in 1993 became area under subsistence farming by 2005. Areas in grey were unchanged. All areas in ha

Katse 1993–2005	No data	Subsistence farming	Ridgelines	Water	Wetlands	*Leucosidea* communities	Short shrub (*Chrysocoma*)	Grassland 1 (highest NDVI)	Grassland 2	Grassland 3	Grassland 4	Grassland 5 (lowest NDVI)
No data	*7*											
Subsistence farming		*4 327*										
Sandstone paving												
Ridgelines					44		39	17	753	249	119	55
Water		31			*374*		14		107	57	51	54
Wetlands		94			1	*3 693*						
Leucosidea communities		8			3		*913*	570	266	145	124	68
Short shrub (*Chrysocoma*)								*7 105*				
Grassland 1 (highest NDVI)		3 325			764		1 198	1 318	*23 176*	4 674	1 201	346
Grassland 2		985			634		343	636	10 111	*9 120*	4 788	1 439
Grassland 3		309			479		137	281	3 311	7 293	*9 131*	5 098
Grassland 4		83			416		66	130	919	3 088	7 543	*9 120*
Grassland 5 (Lowest NDVI)	0	25			557		30	48	325	745	1 962	4 459
Katse 2005–2013												
No data	*8*											
Subsistence farming		*9 186*										
Sandstone paving												
Ridgelines				*32 338*								
Water		0			*2 870*			0	1	1	2	9
Wetlands		26			30	*3 638*						
Leucosidea communities		2			0		*2 449*	252	24	7	2	2
Short shrub (*Chrysocoma*)		44						*10 062*				
Grassland 1 (highest NDVI)		2 341			112		395	1 761	*18 967*	8 018	4 148	2 024
Grassland 2		482			60		294	1 450	4 982	*9 857*	4 463	2 405
Grassland 3		227			56		463	1 321	2 236	4 348	*11 717*	2 990
Grassland 4		84			60		328	759	740	2 180	3 503	*11 092*
Grassland 5 (lowest NDVI)		32			213		125	242	126	523	1 464	2 628

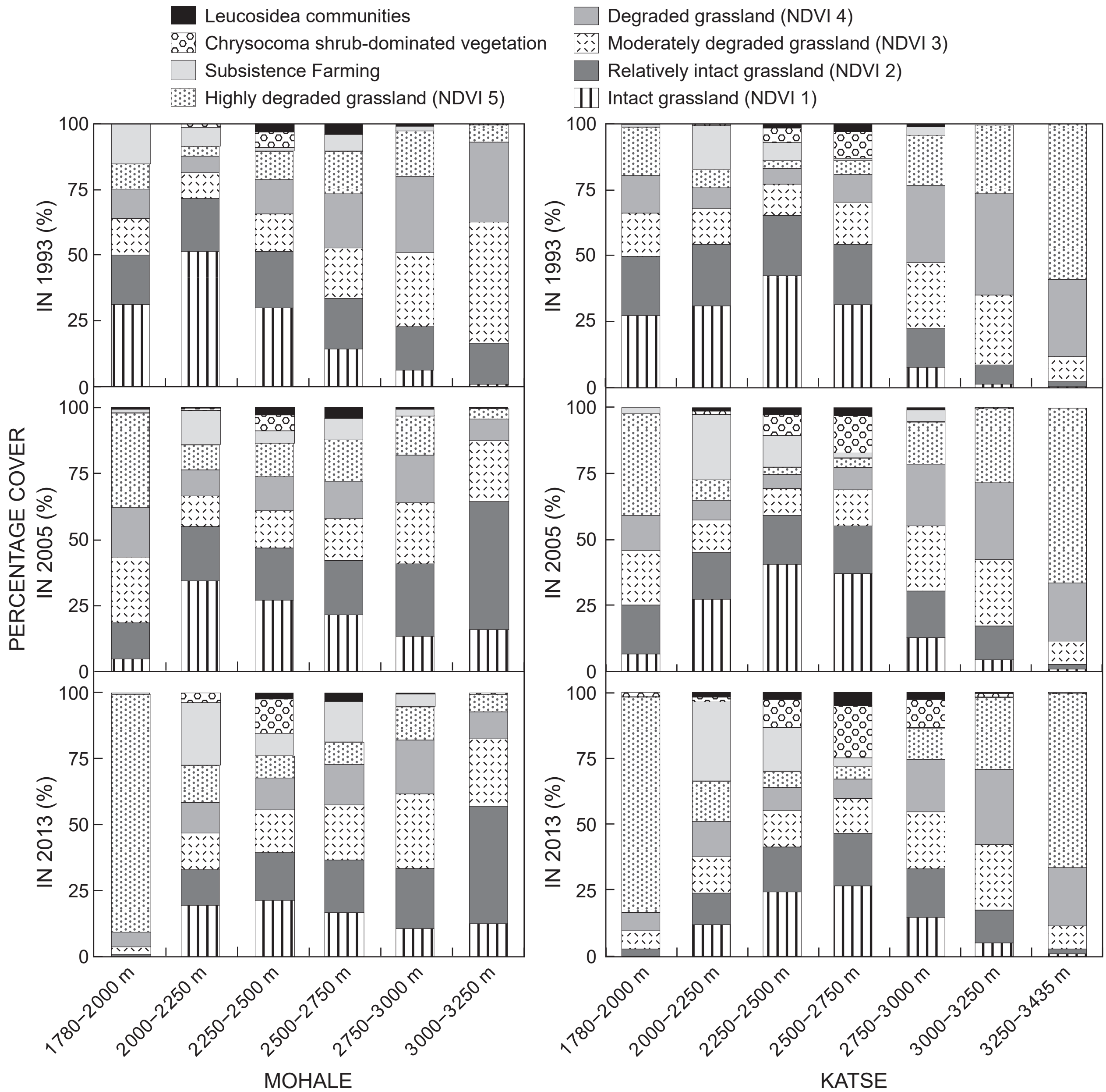

Figure 5: Percentage cover for each land cover class within Mohale and Katse Dam catchments (above the inundation area) within different altitudinal bands for the three time periods (1992, 2005 and 2013). Note that the lowest altitudinal band was small

grazing could have been the stronger determinant of higher altitude grassland condition during the study period.

The land cover analysis added further insight on the extent of degradation by identifying areas of bush encroachment, particularly in the mid-altitudes of the catchment areas. Indigenous woody vegetation had increased considerably in both catchments. The evergreen tree *Leucosidea sericea*, known as 'ouhout', is an important source of fuel and indigenous medicine. Normally associated with river courses, *Leucosidea* forms dense thickets on overgrazed and disturbed areas, and can become an aggressive invader (Daemane et al. 2010; Pond et al. 2002; Mafole et al. 2017). Similarly, *Chrysocoma* occurs naturally in grassland and shrubland ecosystems (Quinlan and Morris 1994), but can become problematic where grass cover has become reduced by overgrazing (Nüsser 2002; Rutherford et al. 2012), leading to a reduction in rangeland grazing capacity. By 1998, approximately 16% of Lesotho's rangelands were already estimated to have been invaded by *Chrysocoma* (Marake et al. 1998). The presence of *Chrysocoma* in the study area and its eventual dominance under overgrazing is supported by anecdotal evidence from one of us (NPB) who undertook the vegetation surveys. It was observed that *Chrysocoma* was frequent in the plots as small, single-stemmed plants where the grass sward was healthy. However, where this competition had been removed by overgrazing, they were more commonly prevalent as dominant shrubs.

These findings suggest that overgrazing is leading to a denudation of the high-altitude grasslands and bush encroachment in the mid-altitude grasslands. High-altitude C_3 grasslands are sourveld, which is 'true grassland', i.e. grassland is the climax community. Mid-altitude C_4 grasslands are Sweetveld, which is 'false grassland', i.e. a form of savanna (Lehmann et al. 2011). Here, grassland is maintained by factors, such as grazing and fire or seasonal waterlogging, and changing conditions may permit succession into shrubland, woodland or forest (Booysen and Tainton 1984). The C_4 grasses are flammable and form the main fuel for fires in savannas, rather than woody biomass (Baudena et al. 2015). These grasses also recover quickly from fire (Higgins et al. 2007), whereas tree seedlings and some adult trees will be damaged or killed by fire (Sankaran et al. 2008; Higgins et al. 2000). Fire fuelled by healthy dry season grass cover thus acts to keep savannas open.

The factors that maintain or disturb the balance of grasses and trees in savanna ecosystems has been the subject of much research and modelling (Walker and Noy-Meir 1982; Scholes and Walker 1993; Scholes and Archer 1997; Higgins et al. 2000; House et al. 2003; Scheffer and Carpenter 2003; Sankaran et al. 2005; Scholes 2009; Bond and Midgley 2012; Buitenwerf et al. 2012). Depending on soil characteristics, increased rainfall and increased rainfall period increases woody cover, whereas lower rainfall, longer dry seasons and increased fire moves them towards grassland systems. Bush encroachment typically occurs in areas of seasonal rainfall where grass biomass that normally fuels fires in the dry season has not been able to accumulate, e.g. due to overgrazing, or where burning is suppressed for whatever reason (Uys et al. 2004; O'Connor et al. 2014; Devine et al. 2017).

Bush encroachment may also be facilitated by increases in atmospheric CO_2 (Bond and Midgley 2000; Kgope et al. 2010; Buitenwerf et al. 2012), and this has been cited as a probable causal factor for *Chrysocoma* spread in Lesotho (Marake et al. 1998). However, given the evidence of overgrazing in the higher altitude areas, as well as the findings of the vegetation surveys (NPB, unpubl. data), it is likely that overgrazing has been a significant cause of the observed changes. One caveat, however, is that some of the increase in woody vegetation is attributable to invasive alien plants (IAPs), notably *Rosa*, whose spread is not related to overgrazing (it is spread by human utilisation), but does affect grazing capacity. It should also be noted that although the land cover classification was characterised in terms of two key woody species, indigenous bush encroachment can involve many species, and there is also evidence of encroachment by other species, such as *Rhus* (now *Seersia*) and *Artemesia afra* in the study area (NPB, pers. obs.).

While the changes in grassland to lower NDVI categories was strongly indicative of degradation, it is quite likely that most of the changes to a higher NDVI category were also the result of degradation through earlier stages of bush encroachment or IAP invasion. This is strongly suggested by the fact that transitions to lower NDVI categories tended to occur in higher altitudes, whereas transitions to higher NDVI categories tended to occur in the mid-altitude bands (Figure 5). This requires further investigation, however.

The land cover analysis also showed that grasslands have become cultivated at an increasing rate, especially in the lower altitude areas of both catchment areas. There are no records of population changes in the study area. However, the increase in the cultivated area in Mohale (315% of the 1993 extent) and Katse (121%) over the study period exceeded the changes in national population over the same period (116%; https://www.worldometers.info/world-population/lesotho-population/ accessed 20/10/2020), suggesting that the area did experience a disproportionally high population growth rate after construction of the dams, particularly the Mohale catchment. Given the strong tradition of livestock keeping among people in the area, this further validates the suggestion that grazing pressure has increased in these catchments.

The results of this study paint a clear picture that the vegetation of the Katse and Mohale Dam catchments has undergone significant transformation and degradation. Increasing populations have led to increasing rates of cultivation of lower altitude areas around the inundation areas and along their influent rivers, while sustained and/or increasing grazing pressure has led to bush encroachment in the middle altitudes and denudation of vegetation cover in the higher altitudes. Unless this trend is reversed there could be significant consequences not only for the capacity of the dams to supply water to the region, but also for the capacity of the area to support the pastoral livelihoods that form the backbone of Basotho culture and tradition.

This study also showed the importance of combining information on land cover and NDVI in assessing land degradation. Although bush encroachment was prevalent in the middle reaches, these areas still experienced an overall decrease in NDVI. This suggests that bush encroachment may not be detectible by NDVI trends where it is offset by a concomitant loss in basal vegetation cover. This supports the UN guidelines that degradation is measured based on land cover, NDVI and soil organic carbon, using the one-out all-out principle. However, this may only be reliable if land cover has been mapped at a sufficiently high level of resolution, as was attempted in this study.

Finally, we also showed that natural capital accounting methods provide a useful framework for documenting, monitoring and understanding changes in ecosystem extent and condition over time. This format will allow for the continued tracking of the observed trends in future in relation to any policy responses to improve catchment management in the dam catchment areas.

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References

Archer KA, Robinson GG. 1988. Agronomic potential of native grass species on the Northern Tablelands of New South Wales. II. Nutritive value. *Australian Journal of Agricultural Research* 39: 425–436. https://doi.org/10.1071/AR9880425.

Bai ZG, Dent DL, Olsson L, Schaepman ME. 2008. Proxy global assessment of land degradation. *Soil Use and Management* 24: 223–234. https://doi.org/10.1111/j.1475-2743.2008.00169.x.

Baudena M, Dekker SC, Van Bodegom PM, Cuesta B, Higgins SI, Lehsten V, Reick CH, Rietkerk M, Scheiter S, Yin Z, et al. 2015. Forests, savannas, and grasslands: Bridging the knowledge gap between ecology and Dynamic Global Vegetation Models. *Biogeosciences* 12: 1833–1848. https://doi.org/10.5194/bg-12-1833-2015.

Bureau of Statistics (BoS) Lesotho. 2012. *Agricultural census results 2009/2010*. Lesotho: Maseru.

Bond WJ, Midgley GF. 2000. A proposed CO_2-controlled mechanism of woody plant invasion of grasslands and savannas. *Global Change Biology* 6: 865–869. https://doi.org/10.1046/j.1365-2486.2000.00365.x.

Bond WJ, Midgley GF. 2012. Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 367: 601–612. https://doi.org/10.1098/rstb.2011.0182.

Booysen P de V, Tainton NM. 1984. *Ecological Effects of Fire in South African Ecosystems.* Berlin, Heidelberg: Springer-Verlag. https://doi.org/10.1007/978-3-642-69805-7.

Buitenwerf R, Bond WJ, Stevens N, Trollope WSW. 2012. Increased tree densities in South African savannas: >50 years of data suggests CO_2 as a driver. *Global Change Biology* 18: 675–684. https://doi.org/10.1111/j.1365-2486.2011.02561.x.

Daemane ME, van Wyk B-E, Moteetee A. 2010. Checklist of ferns and seed plants of the Golden Gate Highlands National Park, South Africa. *Bothalia* 40: 205. https://doi.org/10.4102/abc.v40i2.222.

De Jong R, Schaepman ME, Furrer R, de Bruin S, Verburg PH. 2013. Spatial relationship between climatologies and changes in global vegetation activity. *Global Change Biology* 19: 1953–1964. https://doi.org/10.1111/gcb.12193.

Devine AP, McDonald RA, Quaife T, Maclean IM. 2017. Determinants of woody encroachment and cover in African savannas. *Oecologia* 183: 939–951. https://doi.org/10.1007/s00442-017-3807-6.

Funk CC, Peterson PJ, Landsfeld MF, Pedreros DH, Verdin JP, Rowland JD, Romero BE, Husak GJ, Michaelsen JC, Verdin AP. 2014. A quasi-global precipitation time series for drought monitoring. *US Geological Survey Data Series* 832. https://doi.org/10.3133/ds832.

Giuliani G, Chatenoux B, Benvenuti A, Lacroix P, Santoro M, Mazzetti P. 2020. Monitoring land degradation at national level using satellite Earth Observation time-series data to support SDG15 – exploring the potential of data cube. *Big Earth Data* 4: 3–22. https://doi.org/10.1080/20964471.2020.1711633.

Higgins SI, Bond WJ, February EC, Bronn A, Euston-Brown DIW, Enslin B Govender N, Rademan L, O'Regan S, Potgieter AL, Scheiter S, et al. 2007. Effects of four decades of fire manipulation on woody vegetation structure in savanna. *Ecology* 88: 1119–1125. https://doi.org/10.1890/06-1664.

Higgins SI, Bond WJ, Trollope WSW. 2000. Fire, resprouting and variability: A recipe for grass-tree coexistence in savanna. *Journal of Ecology* 88: 213–229. https://doi.org/10.1046/j.1365-2745.2000.00435.x.

House JI, Archer S, Breshears DD, Scholes RJ. 2003. Conundrums in mixed woody-herbaceous plant systems. *Journal of Biogeography* 30: 1763–1777. https://doi.org/10.1046/j.1365-2699.2003.00873.x.

Köhler P, Frankenberg C, Magney TS, Guanter L, Joiner J, Landgraf J. 2018. Global retrievals of solar-induced chlorophyll fluorescence with TROPOMI: first results and intersensor comparison to OCO-2. *Geophysical Research Letters* 45: 10456–10463. https://doi.org/10.1029/2018GL079031.

Lehmann CER, Archibald SA, Hoffmann WA, Bond WJ. 2011. Deciphering the distribution of the savanna biome. *The New Phytologist* 191: 197–209. https://doi.org/10.1111/j.1469-8137.2011.03689.x.

Lodge G, Whalley R. 1983. Seasonal variations in the herbage mass, crude protein and in-vitro digestibility of native perennial grasses on the north-west slopes of New South Wales. *The Rangeland Journal* 5: 20–27.

Mafole TC, Aremu AO, Mthethwa T, Moyo M. 2017. An overview of *Leucosidea sericea* Eckl. & Zeyh.: A multi-purpose tree with potential as a phytomedicine. *Journal of Ethnopharmacology* 203: 288–303. https://doi.org/10.1016/j.jep.2017.03.044.

Marake M, Mokuku C, Majoro M, Mokitimi N. 1998. *Global change and subsistence rangelands in southern Africa: Resource variability, access and use in relation to rural livelihoods and welfare. A preliminary report and literature review for Lesotho*. INCO-DC Project No. ERBIC18CT970162. Lesotho: National University of Lesotho.

Ministry of Forestry and Land Reclamation (MFLR) 2014. *National range resources management policy*. Maseru, Lesotho: Ministry of Forestry and Land Reclamation.

Morris C. 2017. Historical vegetation–environment patterns for assessing the impact of climatic change in the mountains of Lesotho. *African Journal of Range & Forage Science* 34: 45–51. https://doi.org/10.2989/10220119.2017.1333150.

Munyati C, Shaker P, Phasha MG. 2011. Using remotely sensed imagery to monitor savanna rangeland deterioration through woody plant proliferation: a case study from communal and biodiversity conservation rangeland sites in Mokopane, South Africa. *Environmental Monitoring and Assessment* 176: 293–311. https://doi.org/10.1007/s10661-010-1583-4.

Nüsser M. 2002. Pastoral utilization and land cover change: a case study from the Sanqebethu Valley, eastern Lesotho. *Erdkunde* 56: 207–221https://doi.org/10.3112/erdkunde.2002.02.07.

O'Connor TG, Puttick JR, Hoffman MT. 2014. Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science* 31: 67–88. https://doi.org/10.2989/10220119.2014.939996.

Pond U, Beesley BB, Brown LR, Bezuidenhout H. 2002. Floristic analysis of the Mountain Zebra National Park, Eastern Cape. *Koedoe* 45: 35–38. https://doi.org/10.4102/koedoe.v45i1.18.

Quinlan T. 1995. Grassland Degradation and Livestock Rearing in Lesotho. *Journal of Southern African Studies* 21: 491–507. https://doi.org/10.1080/03057079508708459.

Quinlan T, Morris CD. 1994. Implications of changes to the transhumance system for conservation of the mountain catchments in eastern Lesotho. *African Journal of Range & Forage Science* 11: 76–81. https://doi.org/10.1080/10220119.1994.9647851.

Reinermann S, Asam S, Kuenzer C. 2020. Remote sensing of grassland production and management—a review. *Remote Sensing* 12: 1949. https://doi.org/10.3390/rs12121949.

Rutherford MC, Powrie LW, Husted LB. 2012. Plant diversity consequences of a herbivore-driven biome switch from Grassland to Name-Karoo shrub steppe in South Africa. *Applied Vegetation Science* 15: 14–25. https://doi.org/10.1111/j.1654-109X.2011.01160.x.

Sankaran M, Hanan NP, Scholes RJ, Ratnam J, Augustine DJ, Cade BS, Gignoux J, Higgins SI, Le Roux X, Ludwig F, et al. 2005. Determinants of woody cover in African savannas. *Nature Letters* 438: 846–849. https://doi.org/10.1038/nature04070.

Sankaran M, Ratnam J, Hanan N. 2008. Woody cover in

African savannas: the role of resources, fire and herbivory. *Global Ecology and Biogeography* 17: 236–245. https://doi.org/10.1111/j.1466-8238.2007.00360.x.
Scheffer M, Carpenter SR. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology & Evolution* 18: 648–656. https://doi.org/10.1016/j.tree.2003.09.002.
Scholes RJ, Walker BH. 1993. *An African savanna: synthesis of the Nylsvley study*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511565472.
Scholes RJ, Archer S. 1997. Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics* 28: 517–544. https://doi.org/10.1146/annurev.ecolsys.28.1.517.
Scholes RJ. 2009. Syndromes of dryland degradation in southern Africa. *African Journal of Range & Forage Science* 26: 113–125. https://doi.org/10.2989/AJRF.2009.26.3.2.947.
Sohl TL, Sleeter BM. 2012. Role of remote sensing for land-use and land-cover change modeling. In: *Remote sensing and land cover: principles and applications*. Giri C (Ed.). Boca Raton, Florida: Taylor and Francis, CRC Press. pp 225–240. https://doi.org/10.1201/b11964-18.
Svoray T, Perevolotsky A, Atkinson PM. 2013. Ecological sustainability in rangelands: the contribution of remote sensing. *International Journal of Remote Sensing* 34: 6216–6242. https://doi.org/10.1080/01431161.2013.793867.
United Nations, European Commission, Food and Agricultural Organization of the United Nations, Organisation for Economic Co-operation and Development, The World Bank. 2014. *System of Environmental-Economic Accounting 2012 – Experimental Ecosystem Accounting*. New York: United Nations. New York: United Nations Statistical Division.
United Nations. 2017. *System of Environmental Economic Accounting - Experimental Ecosystem Accounting: Technical Recommendations*. Prepared as part of the joint UNEP / UNSD / CBD project on Advancing Natural Capital Accounting funded by NORAD. New York: United Nations Statistical Division. Available at: https://seea.un.org/sites/seea.un.org/files/Presentations/Training_China_2017/seea_eea_tech_rec_final_v3.2_16oct2017.pdf.
Uys RG, Bond WJ, Everson TM. 2004. The effect of different fire regimes on plant diversity in southern African grasslands. *Biological Conservation* 118: 489–499. https://doi.org/10.1016/j.biocon.2003.09.024.
Venter ZS, Scott SL, Desmet PG, Hoffman MT. 2020. Application of Landsat-derived vegetation trends over South Africa: Potential for monitoring land degradation and restoration. *Ecological Indicators* 113: 106206. https://doi.org/10.1016/j.ecolind.2020.106206.
Walker BH, Noy-Meir I. 1982. Aspects of the stability and resilience of savanna ecosystems. In: Huntley BJ, Walker BH (Eds). *Ecology of Tropical Savannas*. Berlin, Heidelberg: Springer Berlin and Heidelberg. pp 556–590. https://doi.org/10.1007/978-3-642-68786-0_26.
Weng Q. 2002. Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. *Journal of Environmental Management* 64: 273–284. https://doi.org/10.1006/jema.2001.0509.