Forest Cover Change in South Gondar, Ethiopia from 1985 to 2015: Landsat Remote Sensing Analysis and Conservation Implications

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ABSTRACT

Ethiopia has experienced drastic historical deforestation, concentrating the remaining indigenous forest cover in small patches that hold great ecological, economic, social, and religious significance. Ongoing forest loss in recent decades has been documented in various parts of Ethiopia, but overall vegetative cover may be increasing in certain regions due to the widespread use of the non-native plantation crop eucalyptus, even if native forest is still declining. No recent forest cover change has yet been investigated in the South Gondar, Amhara region, even though spatial assessment of forest cover change and trends in forest composition is critical for informing conservation efforts. I used the geospatial software ENVI to analyze two Landsat scenes of South Gondar from the dry seasons of 1985 and 2015. I carried out NDVI change detection between 1985 and 2015, conducted a supervised classification of the 2015 image to generate comparative forest cover maps, and analyzed land cover characteristics within three different elevation categories. Overall NDVI increased from 1985 to 2015, indicating promising vegetative growth or recovery, but nevertheless vegetation comprised less than 5% of the scene in the classified image of present day land cover, and native forest and eucalyptus stands each made up < 1% of the overall scene, but the abundance of eucalyptus is relatively high compared to persisting native forest. More areas at high elevations experienced a big increase in NDVI than at lower elevations. These trends suggest that overall vegetation has increased, but native forest ecosystems remain only a small fraction of the overall landscape, and the myriad ecological and cultural benefits that these biodiverse forests provide remain compromised.

KEYWORDS

Land cover change, ENVI, Amhara, church forest, eucalyptus

INTRODUCTION

People have altered the landscapes they inhabit throughout all of human history, but over the past few centuries, much of the planet's surface and natural cycles have been transformed at unprecedented levels (Vitousek et al. 1997). The expansion of agricultural land, urban settlement, and resource consumption has led to deforestation across the world with devastating consequences at both local and global scales (Foley et al. 2005). Deforestation signals the loss of the vital ecosystem services which forests provide – the direct and indirect benefits to humans – including the provision of food or material goods and environmental regulating services. Forest loss on a local level in rural communities jeopardizes the livelihoods of local people who depend on these services, depleting economic and cultural resources (Sunderlin et al. 2005, Vedeld 2007). The implications of deforestation also extend to the global public because deforestation increases carbon emissions, reduces climate change mitigation potential, and results in biodiversity loss (Defries et al. 2002). Developing nations in particular, such as Ethiopia, are grappling with extensive ongoing land cover changes as their populations and resource demands increase.

Ethiopia has suffered drastic historical deforestation, primarily due to agricultural expansion coupled with population growth (Bongers and Tennigkeit 2010, Hailu et al. 2015). The remaining indigenous forest cover is concentrated in inaccessible mountain regions and small forest patches of great conservation significance (Bongers and Tennigkeit 2010). In many cases, these small forest patches surround Ethiopian Orthodox Tewahido churches, whose clergy preserve the indigenous vegetation for spiritual reasons (Tilahun et al. 2015). The Ethiopian Orthodox Tewahido Church is one of the oldest Churches in the world with over 30 million followers in Ethiopia today, and its theology and biblical interpretation form the basis of its traditional forest conservation ethic (Wassie et al. 2005). Although religion serves as the original motivating factor in these forests' protection, their unique persistence in a degraded landscape now makes them de facto targets for environmental conservation to preserve their social, economic, religious, and ecological roles (Wassie et al. 2005, Wassie 2007, Reynolds et al. 2015). However, contemporary development pressures continue to erode these rare and valuable indigenous forest fragments, possibly at an accelerated rate compared to historical deforestation (Birhanu 2014).

Figure 1. The church forest of Debresena Mariam in South Gondar, Amhara, Ethiopia. Much of the land around it has been historically cleared for agriculture and other purposes, fragmenting native forest and leaving only this small forest remnant in the region as a refuge for biodiversity and provider of ecosystem services. Photo by author.

Contemporary human resource demands threaten the remaining forests of the Amhara region of northwest Ethiopia. Urbanization and an increasing population place pressure on forest resources in the highlands and lead to encroachment on the forest edges to expand available cropland (Grepperud 1996, Berhane et al. 2015). Introduced species – notably the plantation crop eucalyptus – could be causing an apparent increase in forest gain, even as they negatively affect ecosystem functioning through alterations to the hydrological cycle and soil properties (Michelsen et al. 1993, Michelsen et al. 1996, Bewket et al. 2002, Fritzsche et al. 2006). Despite the immense significance and urgent conservation needs of the forests of Amhara, critically needed analysis of spatial data for the state's South Gondar region is absent from existing scientific literature. A decline in forest cover over the past few decades has been documented in the country as a whole and in other parts of Ethiopia (Reusing 2000, Tekle and Hedlund 2000, Zeleke and Hurni 2001, Dessie and Kleman 2007, Getahun et al. 2013, Hansen et al. 2013, Kindu et al. 2013, Jacob et al. 2015). The same trend has largely been assumed in the South Gondar, Amhara region but not quantified. Without knowledge of the current status of forest cover and pattern of deforestation over time, conservation planning cannot optimally evaluate and prioritize measures to protect and possibly expand existing indigenous forest.

This study aims to quantify forest cover change in the South Gondar, Amhara region of Ethiopia from 1985 to 2015 by investigating the quantity and composition of forest cover. I will generate forest cover maps from two Landsat scenes from the dry season (March/April) of the years 1985 and 2015. Using the geospatial analysis software ENVI, I will determine spectral endmembers from training areas based on visual identification – cross-referencing with other satellite and aerial imagery – in order to conduct a supervised classification of land cover classes, including indigenous forest and non-native (eucalyptus) stands, for the 2015 image. This analysis will yield regional statistics on the amount of land occupied by each of these classes and an estimate of forest cover change between 1985 and 2015.

METHODS

Study system

The study area (Figures 2 and 3) comprises 33,217.35 km² and lies in the northwestern state of Amhara in Ethiopia. It is located just east of the city of Bahir Dar and Lake Tana in the Ethiopian highlands. Elevation of scene topography varies from 1150 to 4225 meters above sea level (masl). The study area is focused on the zone of South Gondar but includes portions of the neighboring zones North Gondar, Wag Himra, North Wollo, South Wollo, East Gojam, and West Gojam as well as the northeastern corner of Lake Tana. It is roughly centered on Mount Guna in South Gondar and approximately half of the area included in the scene delivers water to the Blue Nile Basin. The scene includes the municipality of Debre Tabor, which lies at 2410 meters above sea level and experiences a highly seasonal monthly average rainfall ranging from 6 mm in January to 501 mm in July, and mean monthly temperature ranging from 15.0°C – 18.7°C (Awulachew et al. 2009). As of 2007, the South Gondar region had a population of around 2 million, the vast majority of whom have occupations in agriculture and belong to the Ethiopian Orthodox Church (Central Statistical Agency 2007).

Figure 2. Map of study area within Ethiopia.

Figure 3. Study area in Amhara, Ethiopia. The study area (in purple) includes parts of the zones South Gondar, North Gondar, Wag Himra, North Wollo, South Wollo, East Gojam, and West Gojam.

Image acquisition

To assess landscape level changes in forest cover, I downloaded two 30 meter-resolution Landsat images from the EarthExplorer website of the United States Geological Survey (Figure 4, Table 1). Landsat satellite sensors capture spectral information about the electromagnetic radiation that is reflected off of the Earth's surface, including bands of visible light, near-infrared, and shortwave infrared radiation that I used in this study in addition to other data such as thermal radiation which I excluded from my analyses. Landsat images are publicly available at no cost and receive new image coverage from the satellite every 16 days, making them an easily accessible data source. I selected these particular images among other available ones because they had minimal cloud cover, which is critical for accurate analyses of ground cover. Both images date to the dry season (March/April) of their respective years as recommended by Professor Travis Reynolds of Colby College to emphasize permanent forest vegetation as opposed to seasonal fluctuations in agricultural or other vegetative productivity.

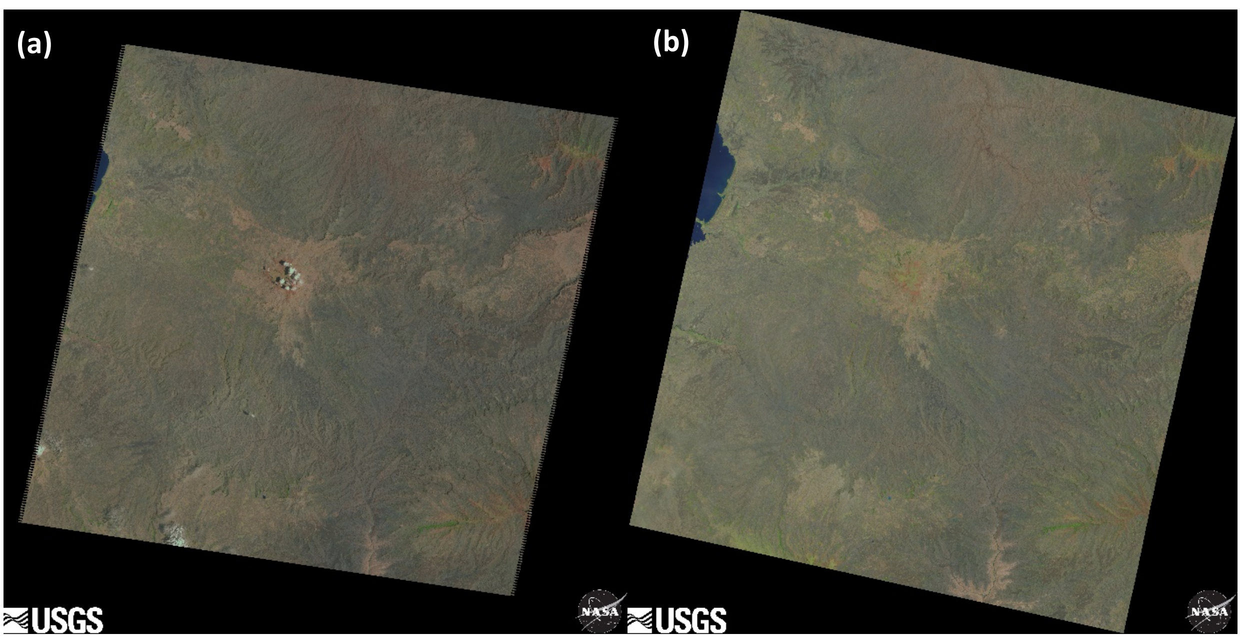

Figure 4. Landsat scenes of the study area, dating to (a) March 14, 1985 and (b) April 18, 2015.

Table 1. Landsat Image Attributes

Characteristic	1985 Image	2015 Image
Landsat Scene Identifier	LT51690521985073AAA03	LC81690522015108LGN00
Date Acquired	March 14, 1985	April 18, 2015
Landsat Spacecraft	Landsat 5	Landsat 8
WRS Path, Row	169, 52	
Projection	WGS 1984 UTM zone 37N	

To correct for atmospheric influence, I performed a radiometric calibration to top of atmosphere reflectance on both images in ENVI (Figure 5). Because satellite sensors pick up all incoming electromagnetic radiation, standardization to reflectance – the relative brightness, which is a property of the surface itself as opposed to a measure dependent on external conditions - is particularly important for images taken from different time periods (Campbell and Wynne 2011). To carry out the calibration, I ensured that both images had the six bands corresponding to blue, green, red, near infrared, shortwave infrared 1, and shortwave infrared 2. This eliminated thermal bands as well as the coastal aerosol band from the Landsat 8 image, which was added to the new satellite sensor but is not present in images captured by Landsat 5.

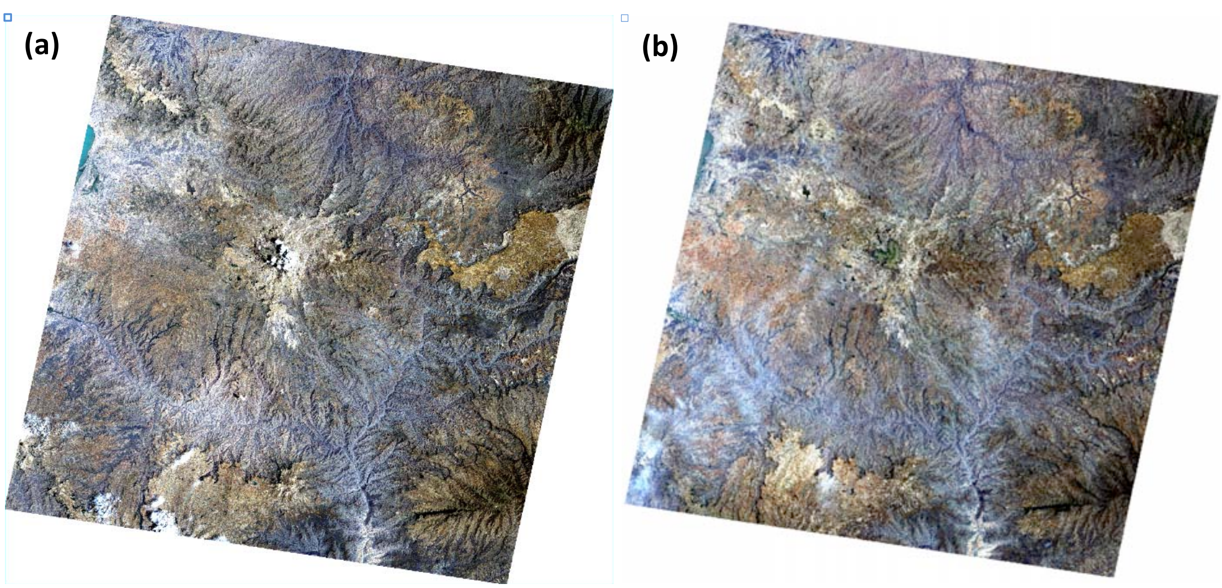

Figure 5. Landsat images radiometrically calibrated to reflectance. Images taken from the years (a) 1985 and (b) 2015.

Due to the slight offset in image coverage, I clipped both images to their overlap. The resulting images, which I used in all of my analyses, were then defined by the new coordinates found in Table 2.

Table 2. Coordinates of original images and overlap polygon used in analyses.

	1985 Image		2015 Image		Overlap Polygon	
Corner	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
Northwest	12°28'40.73"N	37°40'01.06"E	12°36'51.84"N	37°38'01.82"E	12°29'23.054"N	37°40'31.419"E
Northeast	12°13'59.88"N	39°20'58.74"E	12°15'14.58"N	39°20'35.59"E	12°14'54.643"N	39°20'17.066"E
Southeast	10°38'36.71"N	38°59'49.74"E	10°30'42.62"N	38°57'29.81"E	10°38'15.292"N	38°58'56.775"E
Southwest	10°53'12.73"N	37°19'25.18"E	10°52'28.96"N	37°15'34.99"E	10°52'45.359"N	37°19'47.179"E

Normalized difference vegetation index (NDVI)

To obtain an overall measure of vegetation cover, I calculated the normalized difference vegetation index (NDVI) across the entire area of each image. NDVI data functions as a vegetation index to provide estimates of canopy cover, forest density, and net primary productivity. ENVI calculates NDVI according to the following standard formula that involves the red light reflected in the image (band 3) and the near-infrared image (band 4):

$$NDVI = (NIR - Red) / (NIR + Red)$$

I used ENVI’s image change detection tools to obtain the difference in NDVI between the two images.

In the image change workflow, I allowed for automatic image registration and exported the difference image. I used the default thresholding method Otsu’s, which automatically calculates an optimum threshold and separates image pixels into binary classes to minimize spread. Thresholding resulted in the three classes of “Big Increase” (greater than +0.074 change in NDVI value), “Big Decrease” (greater than -0.040 change in NDVI value) and “Other,” the latter meaning no large change in NDVI between the 1985 and 2015 images.

Using these categories of Big Increase, Big Decrease, and Other, I created layers by which I could subset the classification image obtained through the methods in the following section to enable analysis of which land cover types may be becoming more prevalent in line with NDVI shifts.

Supervised classification

To create a present-day land cover map of the study area, I carried out a supervised classification of the 2015 image after calibration to reflectance. Supervised classification uses samples of known identity to classify unknown pixels by comparing their spectral signatures (Campbell and Wynne 2011).

To generate land cover classes, I established regions of interest (ROIs) for different land cover types. To distinguish cover type, I compared specific regions of the Landsat images to high resolution Google Earth imagery, which was provided by CNES / Astrium and DigitalGlobe. Thus, the resolution varied but was 1.5 m or better in all areas. Using this comparison between the aligned Landsat and Google Earth imagery, I manually marked polygons encompassing examples of each cover type using the ROI tool in ENVI, which created spectral databases for each class (Figure 6). I then ran a maximum likelihood classification on the 2015 image, a process which compared each pixel to the database of ROIs, determined the likelihood of that pixel belonging to each class based on the similarity of its spectral signature to the ROIs, and classified the pixel as the cover type which it most resembled.

Upon carrying out the maximum likelihood classification for the entire image, I visually examined various areas of the map to assess whether the classification correctly identified cover types. I adjusted the ROIs accordingly by adding new polygons and new ROI classes encompassing the incorrectly classified areas based on a comparison with the corresponding Google Earth image. I repeated this classification and refinement process until it accurately identified the vast majority of pixels. In the final version of the ROIs, my continual reprocessing yielded 19 classes within the categories of native forest, eucalyptus stands, shrub land, bare ground, uncultivated grassland (plain), built/urban areas, canyon land, agricultural land, and lake (the last of which I removed for analysis). Due to the spectral variety of agricultural land and canyon lands and a semitransparent haze from smoke that covered a small portion of the land in the southwestern corner of the image, I had a total of nine cover classes for agriculture and three for canyon lands.

(a)

(b)

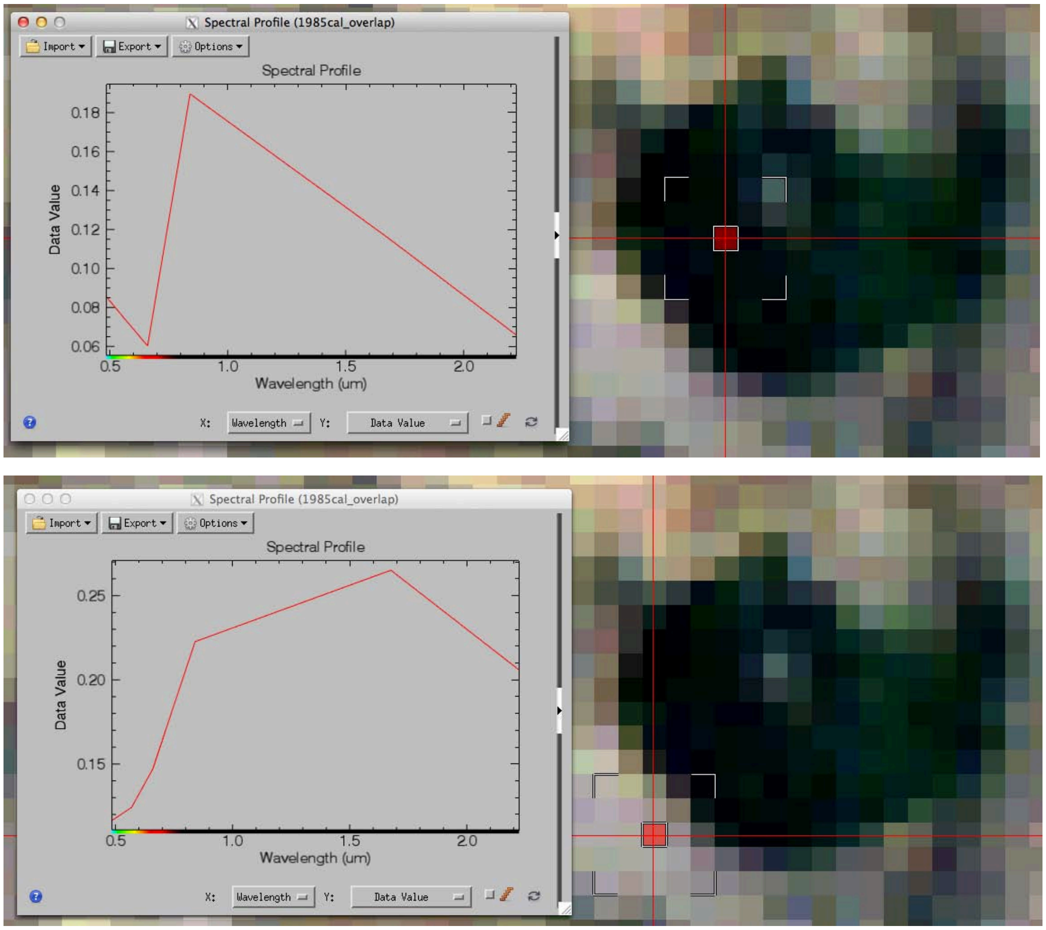

Figure 6. Example of variation in spectral signature between pixels. The spectral signature of electromagnetic radiation reflected off of the surface and captured by the Landsat sensor of (a) a native forest pixel differs greatly from the spectral signature of (b) a pixel in adjacent agricultural land.

I did not carry out supervised classification on the 1985 image because I did not have access to high resolution imagery from that time period, which is commercially available but costly. Applying the ROIs from the 2015 image to the 1985 image, even with the removal of the ROIs that accounted for the haze anomaly and the addition of ROIs for clouds and cloud shadows, did not yield usable results, so I excluded the 1985 image from my supervised classification analyses.

Elevation categories

To analyze the scene by elevation, I divided my classification and NDVI images into sub regions. In accordance with the World Wildlife Fund's Global 200 Ecoregions, which prioritized areas of exceptional and representative biodiversity for conservation, I created three elevation categories: land below 1800 masl, which was not included as a WWF ecoregion; the Ethiopian montane grasslands and woodlands, between 1800 – 3000 masl; and the Ethiopian montane moorlands, above 3000 meters above sea level (masl) (Olson and Dinerstein 2002). Out of the 33,217 km² in the study area, 5873 km² fell under 1800 masl (17.68%), the majority of the area (24,949 km², or 75.11%) was between 1800 – 3000 masl, and 2,396 km² rose above 3000 masl (7.21%).

I downloaded an SRTM 90m DEM (version 4) elevation raster from the CGIAR Consortium for Spatial Information (CGIAR-CSI) that encompassed all of Ethiopia. Within ArcMap, I then clipped the raster to the study area and created new selections that contained all of the pixels corresponding to the elevation categories. For each category, I next carried out a raster to polygon conversion that transformed the rectangular grid of pixels to cohesive vector units. To combine all of the features in each category, I dissolved the thousands of polygons into a single polygon shapefile that I then imported into ENVI and converted to an ROI. I subset the NDVI change and maximum likelihood classification files into each of the three elevation categories using these ROIs.

RESULTS

Normalized Difference Vegetation Index (NDVI)

Across the entire scene, more area saw a large increase (12.75%) than a large decrease (3.16%) in NDVI, but overall most of the study area (84.10%) did not experience a large change in NDVI between 1985 and 2015 (Figure 7). However, disparities existed between elevation categories (Figure 8). NDVI trends at the midrange elevations were in line with the overall area. In contrast, at the lower elevations, over 91% of the area remained stable with respect to NDVI, with only 5.54% experiencing a large increase in NDVI. The difference was greatest for the area above 3000 masl: only 66.42% of the area stayed relatively constant, with a full 32.82% of the area undergoing a big increase in NDVI and a mere 0.75% showing a big decrease.

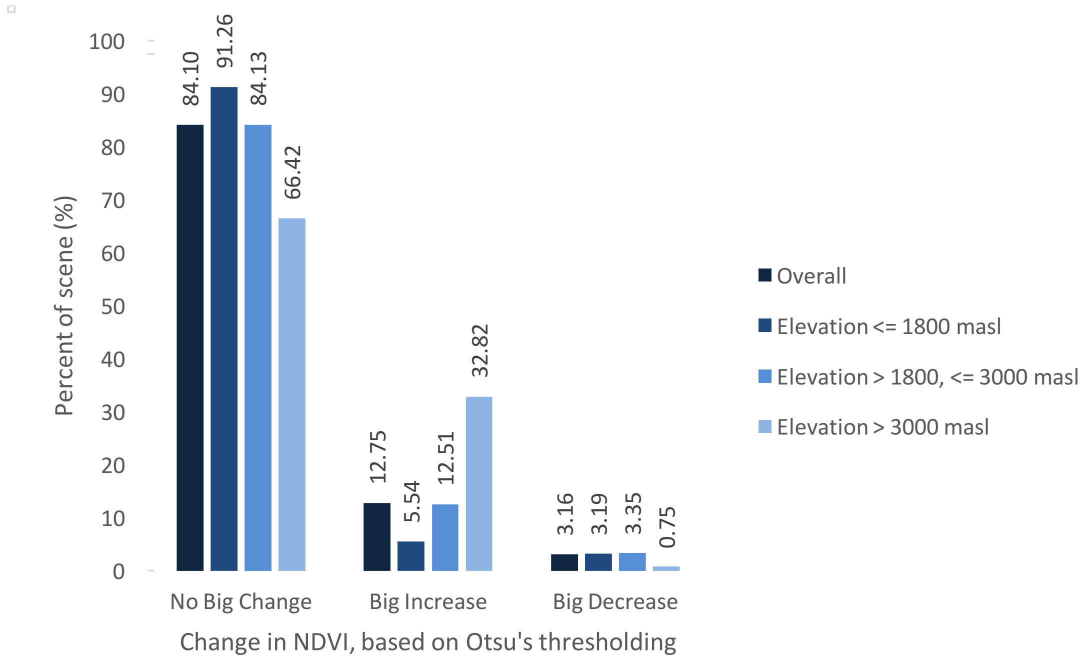

Figure 7. Percent of area experiencing change in NDVI between 1985 and 2015. Column chart comparisons displaying the percentage of area in each elevation category (overall, equal to or less than 1800 meters above sea level (masl), greater than 1800 masl but equal to or less than 3000 masl, and greater than 3000 masl).

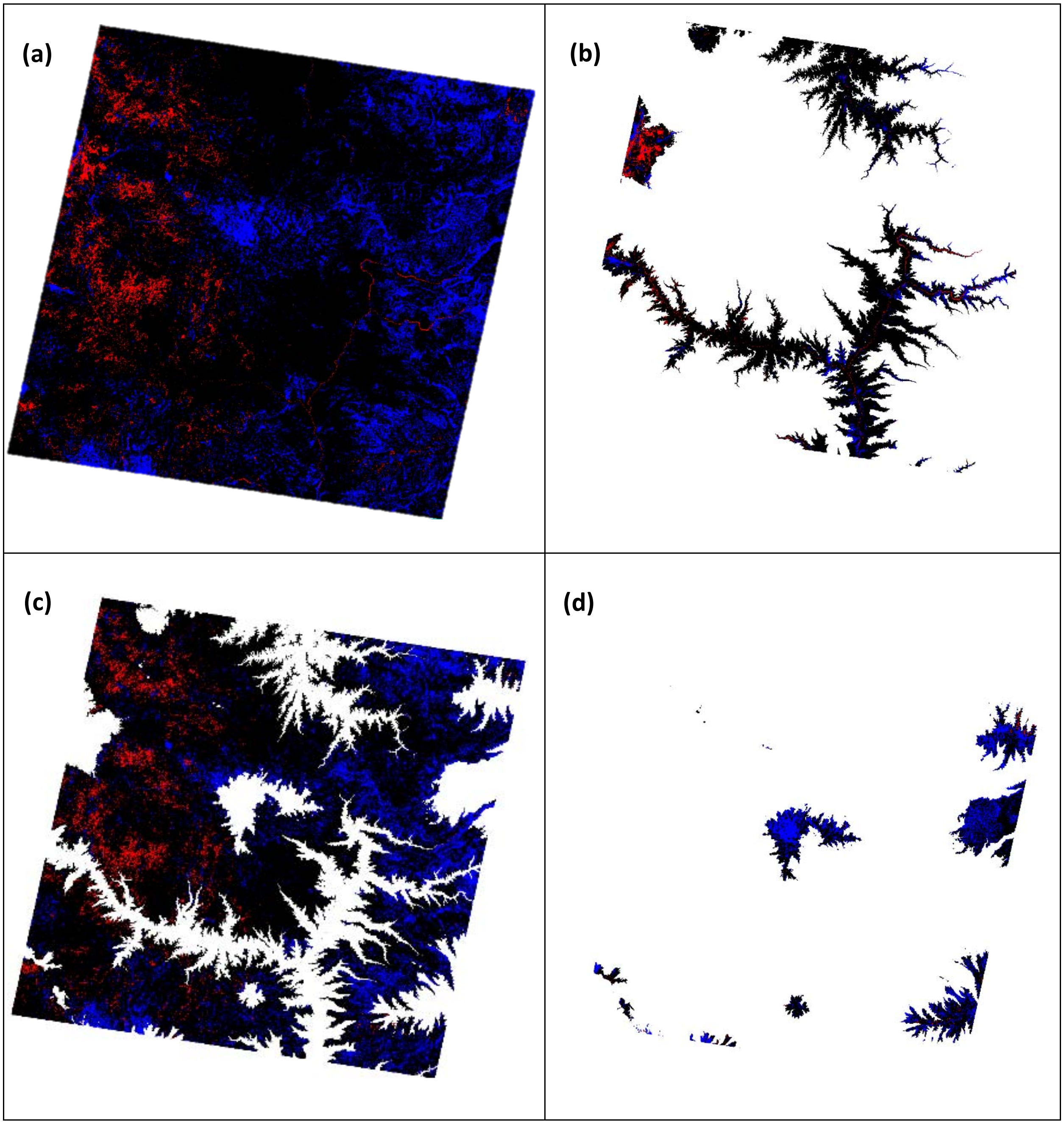

Figure 8. NDVI change from 1985 – 2015 mapped per elevation category. Images of NDVI change for: (a) the overall study area, (b) 1800 masl or lower, (c) 1800 – 3000 masl, and (d) above 3000 masl. Using Otsu's automatic thresholding, the change classes are big increase (blue), big decrease (red), and other/no big change (black).

Supervised classification

The study area is dominated by agricultural and canyon land, which respectively make up 42% and 47% of the overall scene (Figures 9 and 10). Only 4.23% of the land is covered with vegetation, and at every elevation, shrub land comprises the vast majority of vegetative cover followed by native forest and then eucalyptus. However, there is far more vegetation at higher elevations than lower ones: at elevations lower than 1800 masl, a mere 0.63% of the land is covered by any sort of vegetation, while vegetative cover makes up 4.37% of land at midrange elevations and 11.34% of land above 3000 masl.

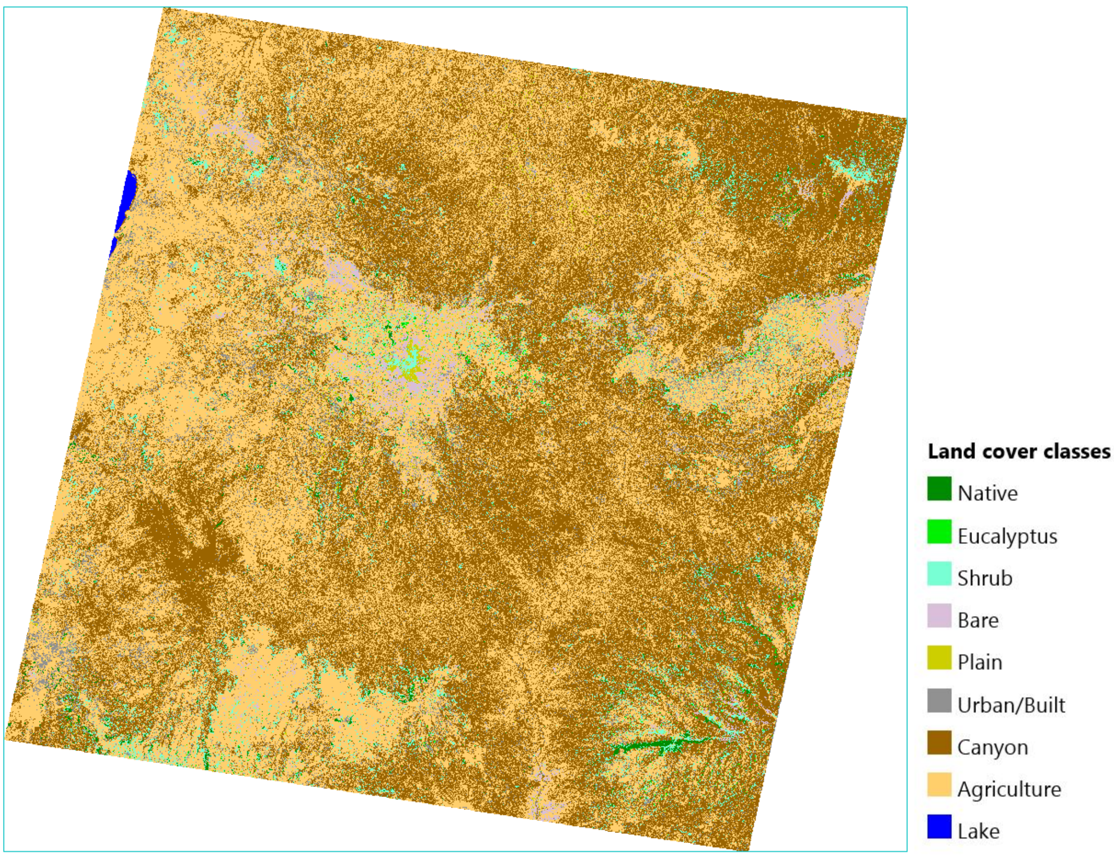

Figure 9. Classified land cover image of study area. Cover classes includes native forest, eucalyptus stands, shrub land, bare ground, plains/uncultivated grasslands, urban/built areas, canyon lands (uncultivated and sparsely vegetated with steep slopes), agricultural land, and Lake Tana (which was removed for analysis).

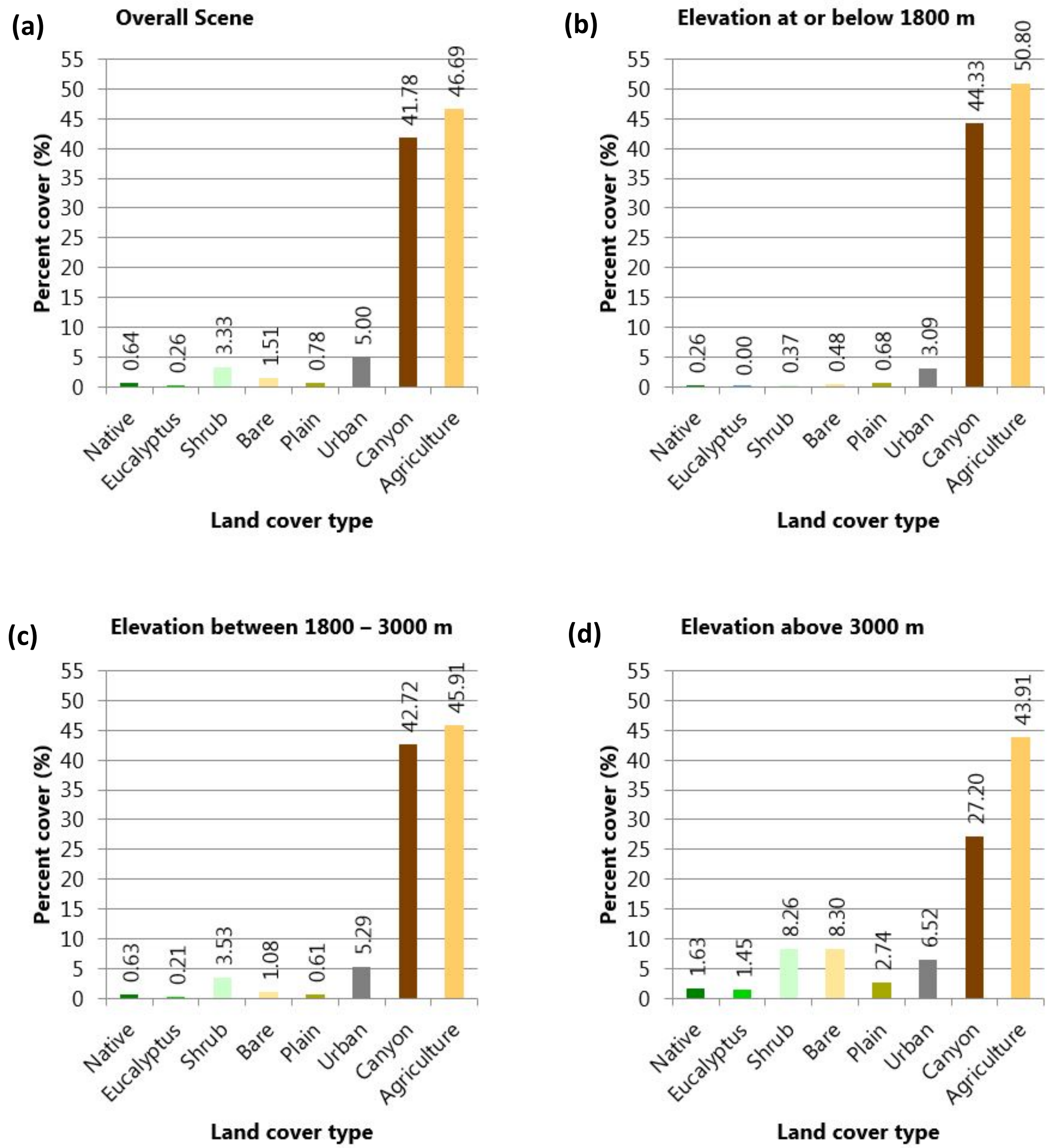

Figure 10. Percentages of land cover types within each elevation category.

Representation of present-day land cover types across the image showed stark differences in areas with big increases in NDVI versus big decreases (Table 3). Land that is currently used for agriculture or urban/built environments saw more of a trend toward NDVI decreases, while every other category, including vegetative classes and canyon lands, saw more areas with a big increase in NDVI rather than a large decrease.

Table 3. Present day land cover types represented in areas that experienced a large change in NDVI from 1985 to 2015.

	Big Increase in NDVI	Big Decrease in NDVI
Native	3.34%	0.29%
Eucalyptus	1.73%	0.02%
Shrub	16.11%	1.43%
Bare	1.28%	0.41%
Plain	2.22%	0.27%
Urban	5.43%	7.92%
Canyon	41.33%	36.38%
Agriculture	28.56%	53.29%

DISCUSSION

Spatial change detection analysis is critical for understanding forest cover change, documentation of which is necessary to spur conservation actions to prevent further decline. My findings indicate that non-native eucalyptus expansion coupled with dwindling native forest cover in the South Gondar, Amhara region of Ethiopia has serious implications for the future of the region's forests. With native forest contraction, communities risk losing a variety of ecological, economic, and cultural ecosystem services. At the same time, expansion of non-native eucalyptus can have detrimental impacts on the local ecosystem. Trends in forest cover change are linked to a myriad environmental, sociopolitical, and economic factors which must be addressed in order to plan effective conservation of native forest lands.

Implications of minimal extent of native forest cover for ecosystem services

The low proportion of indigenous forest cover in the present day, at only 0.64% of the overall study area, is roughly in line with but more shocking than expectations based off of historical deforestation and ongoing pressures. Previous studies from other regions throughout Ethiopia have documented declines in and small extent of natural forest cover over the past few decades, and my spatial analyses have shown that the latter is true for South Gondar, even though overall vegetative greenness appears to have increased based on the NDVI maps (Figures 7 and 8) (Dessie and Kleman 2007, Getahun et al. 2013, Jacob et al. 2015, Kindu et al. 2013, Reusing 2000, Tekle and Hedlund 2000, Zeleke and Hurni 2001). The lack of a supervised classification of the 1985 image limits land cover mapping to the 2015 image, so whether land originally occupied by native forest was converted to a different cover class is indeterminable at present. Regardless, with such low coverage of the landscape, which falls far below the 2001 national estimate of 4.2% forest cover and pales in comparison to the 40% forest cover at the beginning of the 1900s, Ethiopia's ecological and human communities have lost or stand to lose the benefits that forests provide (Wassie 2007).

The historical decline of native forest cover has diminished the provision of ecosystem services that are critical to both the local ecosystem and nearby communities. Forests help to regulate the availability of water on which people, crops, and native plants and creatures depend (Gebrehiwot 2015). With less native forest modulating surface and groundwater, farmers could see negative impacts on agricultural productivity and therefore food security. Forests also assist in preventing soil erosion, which is a large cause of land degradation and is linked to the resulting decrease in agricultural productivity (Taddese 2001, Holden and Shiferaw 2004). Native forests contain many endemic species and maintain biodiversity, which is important for continued ecosystem functioning (Wassie et al. 2005, Wassie et al. 2010). Ethiopian montane woodlands are included in the Global 200 Ecoregions as a priority ecosystem type to conserve biodiversity (Olson and Dinerstein 2002). Furthermore, forests in Ethiopia are highly relevant to vegetative carbon sequestration efforts worldwide, with deforestation as a recorded source of greenhouse gas emissions (e.g. DeFries et al. 2002). However, climate change itself may be damaging their mitigation potential by causing native tree diebacks (Mokria et al. 2015).

Native forests also offer many more direct benefits to local human communities. Because many of the remaining indigenous forest patches surround Ethiopian Orthodox Tewahido Churches, they hold deep spiritual and religious value that could be lost with further forest deterioration (Tilahun et al. 2015, Wassie et al. 2005). In addition, they provide provisioning services in the form of wood for construction, edible plants, and religious objects made from forest resources (Wassie et al. 2005). Many native plants also offer medicinal value that is of the utmost importance to cultural preservation and local health (e.g. Giday et al. 2007, Ragunathan and Abay 2009). Despite the obvious importance of preserving these forests for the health of the ecosystem and for the benefit to human communities, indigenous forest could continue to decline in the face of non-native eucalyptus expansion, exacerbating the loss of these ecosystem services.

Figure 11. Fungi in Debresena Mariam church forest. Church forests harbor high levels of Afromontane biodiversity, from insects to primates to plants and beyond, and many persist in landscapes included in the World Wildlife Fund's designated Global 200 Ecoregions, which are priority conservation areas. The species in and ecosystem services provided by these forests could be imperiled with continuing deforestation. Photo by author.

Eucalyptus expansion

The overall gain in vegetative cover may be linked to afforestation and reforestation with exotic eucalyptus plantations. Of the total area that saw a big increase in NDVI, 1.73% was classified as eucalyptus cover which is more than six times the 0.26% of overall land cover occupied by eucalyptus stands, suggesting that eucalyptus expansion is indeed contributing to increases in overall forest cover at a rate outpacing that of native forest cover. The amount of eucalyptus cover is nearly 40% that of native forest, which is incredibly high considering its exotic origin, and could continue to rise.

An increase in forested area – even non-native forest cover – could potentially be viewed as positive for climate change mitigation efforts, particularly since eucalyptus forests in Australia have a very high biomass carbon density, but primary indigenous forests are a far cry from the monoculture eucalyptus plantations prevalent in Ethiopia (Keith 2009). The potential benefits of increasing eucalyptus cover are probably outweighed by its detrimental impacts on the local ecosystem. Exotic eucalyptus plantations have been linked to environmental changes that could impair ecosystem functioning. Eucalyptus has been found to deplete groundwater (Fritzsche et al. 2006). Depletion of the groundwater table could impact native forest health as well as agricultural productivity and thus food security in a region that already experiences highly seasonal rainfall that alternates with incredibly arid seasons. Eucalyptus has been shown to alter soil structure, nutrient content, and soil fertility in Ethiopia, which could impact the surrounding vegetation and retard nearby reforestation efforts (Michelsen et al. 1993, Michelsen et al. 1996).

Figure 12. Eucalyptus plantation near Debre Tabor. Eucalyptus is a common plantation crop valued as a building material and can greatly boost household incomes. However, it can also have detrimental effects on the local ecosystem such as groundwater depletion and alteration of soil nutrient concentrations.

Since eucalyptus is often planted as a cash crop, farmers must ensure its continued economic sustainability to avoid further environmental degradation. Above-ground biomass for Eucalyptus plantations declined after the initial 7-10 cutting cycles, indicating that productivity will decline in the long-term and that the economic sustainability of such plantations is dependent upon changes in forestry practices (Zewdie et al. 2009). If the continued productivity of exotic plantations cannot be maintained, foresters and farmers may resort to clearing more land in order to remain economically viable, resulting in a negative downward spiral of land degradation.

Factors contributing to forest cover change trends

The observed state of forest cover could be attributed to a constellation of environmental, sociopolitical, and economic factors. Climate change is the likely culprit of escalating tree mortality in native dry Afromontane forests, primarily for the foundation species *Junipera procera* and *Olea europaea* that dominate many forest patches (Aynekulu et al. 2011, Mokria et al. 2015). Hiltner et al. found that moisture availability during the dry season limits tree growth in dry tropical montane forests in Ethiopia, with their model predicting that both biomass production and biodiversity would decrease with increasing drought stress (2016). Beyond the symptoms of climate change such as drought, forest patches may also suffer from edge effects, small patch size, and extinction/extirpation debts from generations of habitat destruction and fragmentation (e.g. Bender et al. 1998, Tilman et al. 1994). However, environmental changes alone cannot explain the extent of land degradation – anthropogenic impacts in the form of land use and land cover change are largely to blame for land degradation (Nyssen et al. 2004).

Figure 13. Transition from native forest to agricultural land at Debresena Mariam church forest. The forest edge often marks a sharp transition that could exacerbate ecosystem declines due to edge effects. Photo by author.

Environmental policy over the past few decades had a formative hand in shaping forest cover change trends in Ethiopia. The *Derg* regime, which ruled from 1974-1991, abolished the existing legal framework for land rights from the mid-1970s onward, giving way to a legal pluralism of nationalized forest lands (Stellmacher 2007). While the reforms were meant to promote equity and productivity, the lack of enforcement led to a vacuum of both usage rights and incentives for sustainable management of forests, aggravating their depletion. *Derg* regime conservation policies included afforestation and reforestation, which led to forest gain in some areas but not necessarily of indigenous species; Bewket et al. ascribed their study's documented positive trend in forest cover to afforestation under the *Derg* (2002). Under the Derg, fuelwood plantations of eucalyptus became widespread in the 1980s (Pohjonen and Pukkala 1990). In addition to government policies, social changes also have the potential to alter attitudes towards forests. Though the church's traditional role in the community offers opportunities for conservation, cultural modernization and shifting societal priorities may undermine the historical status and ability of the Ethiopian Orthodox Church to protect church forests (Bongers et al. 2006, Haustein and Ostebo 2011).

Economic drivers have further aggravated environmental degradation. The increasing rural population's demand for resources leads to land scarcity followed by encroachment on forests in the Ethiopian highlands (e.g. Grepperud 1996, Birhanu 2014, Berhane et al. 2015, Wubie et al. 2016). Liu et al. determined a high level of current and projected food insecurity in the region, which – coupled with expected population growth – will likely exacerbate the continued clearing of native forest (2008). In addition, many Ethiopian households establish and tend eucalyptus plantations adjacent to farmland and forest patches as an additional source of income (e.g. e.g. Yitaferu et al. 2013), which contributes to the observed increase in eucalyptus cover – potentially at the expense of native forest, whether directly by clearing or indirectly via impacts on nutrient cycling or other disruptions of normal ecosystem functioning.

Future forest conservation

Efforts to conserve forests in the Ethiopian highlands should focus on maintaining existing forest through community participation and investigate means of forest restoration. Nyssen et al. documented natural forest regrowth in steep mountainous regions in other parts of Ethiopia, but in more disturbed environments surrounded by actively cultivated land reforestation likely needs to be actively reinforced (2009). This trend was reinforced by the disproportionate increase in NDVI and percentage of forest cover in the highest elevation category, suggesting that lower regions may need extra conservation intervention to restore native forest cover. Regeneration will likely be relatively easy for herbaceous species which accumulate more seeds in the soil, but difficult for tree species given the low abundance of their seeds in soil seed banks; therefore, maintaining existing stands of trees is important for encouraging vegetative growth, while regeneration after the destruction of forest is less likely to be successful (Wassie and Teketay 2006). Foundation tree species grow slowly with the potential to hamper restoration efforts (Mokria et al. 2015). Regeneration (through seed germination, survival, and growth) is impacted by microsites – location relative to the edge of the forest – and seedling care, as well as seed predation and grazing pressures (Wassie et al. 2009a, 2009b, 2009c). Excluding grazing through walled exclosures around church forests could lift the pressure on seedling regeneration, while any planting efforts must take location within the forest (at microsites) and seedling care into account. Efforts to conserve existing forest indirectly may include other forms of conservation, such as reducing land degradation through soil and water conservation (Nyssen et al. 2009). Establishment of community exclosures to promote regeneration on degraded land requires a focus on enforcement and engendering a sense of responsibility for the land (Yami 2013). Bolstering the Ethiopian Orthodox Tewahido Church's role in forest management could improve knowledge transfer and strengthen this sense of community responsibility (Tilahun et al. 2015).

Limitations

My study was necessarily restricted in geographical and temporal scope. The high cost of commercial high resolution imagery from the study period did not allow me to conduct finer-scale analysis; as such, I focused instead on regional change detection. I selected two Landsat scenes to limit my geographical range for the study to constrain the scope and ensure attention to details in coregistration and analysis. Because of the narrow geographical focus of this study, my results are only immediately relevant to the topography and environmental and cultural context of South Gondar in the Amhara state of Ethiopia, but the regional focus enables me to cover an area not previously subjected to such spatial analysis in past studies throughout Ethiopia, and contributes to the overall knowledge of forest cover change in the northwestern highlands. Furthermore, my methods can be repeated in other regions to achieve comparable results.

Without freely and publicly available high resolution imagery for 1985, I could not carry out a supervised classification of the 1985 image and had to rely on subsetting by NDVI change classes and elevation categories to make inferences about trends in land cover change over the past 30 years.

Early in my study I began an exploration of herbarium specimens, hoping to compare documented occurrences with specific areas experiencing forest declines to paint a picture of potential biodiversity loss, but could not progress due to the lack of digitized archives and associated geospatial data. Proper collection and digitization of herbarium specimens would aid in documenting species/community composition changes within the forests and on a landscape scale.

Future Directions of Study

Further studies could investigate forest cover changes at a finer spatiotemporal resolution and include field validation on land cover types and the status of degraded forests. Ground-truthing of what degraded forests look like – corresponding to spatial records thereof – could help discern edge effects or changes to ecosystem functioning, structure, and biodiversity. The purchase of commercial high resolution imagery from the years corresponding to the Landsat data would allow for finer-scale change detection and possibly improved classification techniques in conjunction with field data collection, potentially building on Hishe et al.'s work on the classification of individual tree species from satellite imagery (2015). The acquisition of high resolution imagery would allow for supervised classification of the 1985 image and could be followed by change detection tools that would track shifts between specific land cover classes, such as native forest to agricultural land or agricultural land to eucalyptus. The price of commercial high resolution imagery continues to decline, so such analyses may soon become financially feasible.

Conclusions

The confirmation of low indigenous forest cover in the present day adds to the urgency of conservation planning for the Amhara region of Ethiopia. The small amount of indigenous forest cover and relatively large extent of non-native eucalyptus cover compared to native forest is problematic for the local communities and ecosystems alike that depend on the few remaining wooded patches in a heavily deforested region. Ethiopian forests also hold relevance for global environmental issues, namely the mitigation of climate change. Conservation planning must acknowledge the dire state of native forest extent and exotic plantation cover, the constellation of factors driving these changes, and the evidence regarding effective preservation and regeneration to prevent further deterioration and the associated environmental, cultural, and economic cost thereof.

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REFERENCES

Awulachew, S.B., M. McCartney, T.S. Steenhuis, and A.A. Ahmed. 2009. A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin. International Water Management Institute, Colombo, Sri Lanka.

Aynekulu, E., M. Denich, D. Tsegaye, R. Aerts, B. Neuwirth, and H.J. Boehmer. 2011. Dieback affects forest structure in a dry Afromontane forest in northern Ethiopia. Journal of Arid Environments 75:499-503.

Bender, D.J., T.A. Contreras, and L. Fahrig. 1998. Habitat loss and population decline: A metaanalysis of the patch size effect. Ecology 79(2):517-533.

Berhane, A., O. Totland, M. Haile, and S.R. Moe. 2015. Intense use of woody plants in a semiarid environment of Northern Ethiopia: Effects on species composition, richness and diversity. Journal of Arid Environments 114:14-21.

Bewket, W. 2002. Land cover dynamics since the 1950s in Chemoga Watershed, Blue Nile Basin, Ethiopia. Mountain Research and Development 22(3): 263-269.

Birhanu, A. 2014. Environmental degradation and management in Ethiopian highlands: Review of lessons learned. International Journal of Environmental Protection and Policy 2(1):2434.

Bongers, F., A. Wassie, F.J. Sterck, T. Bekele, and D. Teketay. 2006. Ecological restoration and church forests in northern Ethiopia. Journal of the Drylands 1(1):35-44.

Bongers, G. and T. Tennigkeit. 2010. Degraded Forests in Eastern Africa: Management and Restoration.

Campbell, J.B. and R.H. Wynne. 2011. Introduction to Remote Sensing, Fifth Edition. The Guilford Press, New York, NY, United States of America.

Central Statistical Agency - Ethiopia. Census Tabular Report. 2007.

Dawelbait, M. and F. Morari. 2012. Monitoring desertification in a Savannah region in Sudan using Landsat and spectral mixture analysis. Journal of Arid Environments 80:45-55.

DeFries, R.S., R.A. Houghton, M.C. Hansen, C.B. Field, D. Skole, and J. Townshend. 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. PNAS 99:22.

Dessie, G. and J. Kleman. 2007. Pattern and magnitude of deforestation in the South Central Rift Valley region of Ethiopia. Mountain Research and Development 27(2):162-168.

Esri. 2014. ArcMap 10.2.2. Esri, Redlands, California, United States of America.

Exelis Visual Information Solutions, Inc. 2015. ENVI 5.3.1. Harris Corporation, Melbourne, Florida, United States of America.

Exelis Visual Information Solutions, Inc. 2015. Introduction to ENVI Analytics. Harris Corporation, Melbourne, Florida, United States of America.

Foley, J.A., R. DeFries, G.P. Asner, et al. 2005. Global consequences of land use. Science 309:570-574.

Fritzsche, F., A. Abate, M. Fetene, E. Beck, S. Weise, and G. Guggenberger. 2006. Soil-plant hydrology of indigenous and exotic trees in an Ethiopian montane forest. Tree Physiology 26:1043-1054.

Gebrehiwot, S.G. 2015. Forests, water and food security in the northwestern highlands of Ethiopia: Knowledge synthesis. Environmental Science and Policy 48:128-136.

Getahun, K., A. Van Rompaey, P. Van Turnhout, and J. Poesen. 2013. Factors controlling patterns of deforestation in moist evergreen Afromontane forests of Southwest Ethiopia. Forest Ecology and Management 304:171-181.

Giday, M., T. Teklehaymanot, A. Animut, and Y. Mekonnen. 2007. Medicinal plants of the Shinasha, Agew-awi and Amhara peoples in northwest Ethiopia. Journal of Ethnopharmacology 110:516-525.

Google Inc. 2015. Google Earth 7.1.5.1557. Google Inc., Mountain View, California, United States of America.

Grepperud, S. 1996. Population pressure and land degradation: the case of Ethiopia. Journal of Environmental Economics and Management 30:18-33.

Hailu, B.T., E.E. Maeda, J. Heiskanen, and P. Pellikka. 2015. Reconstructing pre-agricultural expansion vegetation cover of Ethiopia. Applied Geography 62:357-365.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.S. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, S.J. Goetz, T.R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.O. Justice, and J.RG. Townshend. 2013. High-resolution global maps of 21st-century forest cover change. Science 342:850-853.

Haustein, J. and T. Ostebo. 2011. EPRDF's revolutionary democracy and religious plurality: Islam and Christianity in post-Derg Ethiopia. Journal of Eastern African Studies 5(4):755-772.

Hiltner, U., A. Bräuning, A. Gebrekirstos, A. Huth, and R. Fischer. 2016. Impacts of precipitation variability on the dynamics of a dry tropical montane forest. Ecological Modelling 320:92-101.

Holden, S. and B. Shiferaw. 2004. Land degradation, drought and food security in a lessfavoured area in the Ethiopian highlands: a bio-economic model with market imperfections. Agricultural economics 30:31-49.

Jacob, M., A. Frankl, H. Beeckman, G. Mesfin, M. Hendrickx, E. Guyassa, and J. Nyssen. 2015. North Ethiopian afro-alpine tree line dynamics and forest-cover change since the early 20th century. Land Degradation and Development 26:654-664.

Keith, H., B.G. Mackey, and D.B. Lindenmayer. 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proceedings of the National Academy of Science 106(28):11635-11640.

Kindu, M., T. Schneider, D. Teketay, and T. Knoke. 2013. Land use/land cover change analysis using object-based classification approach in Munessa-Shashemene landscape of the Ethiopian highlands. Remote Sensing 5:2411-2435.

Liu, J., S. Fritz, C.F.A. van Wesenbeeck, M. Fuchs, L. You, M. Obersteiner, and H. Yang. 2008. A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. Global and Planetary Change 64:222-235.

Michelsen, A., N. Lisanework, and I. Friis. 1993. Impacts of tree plantations in the Ethiopian highland on soil fertility, shoot and root growth, nutriet utilization and mycorrhizal colonization. Forest Ecology and Management 61:299-324.

Michelsen, A., N. Lisanework, I. Friis and N. Holst. 1996. Comparisons of understorey vegetation and soil fertility in plantations and adjacent natural forests in the Ethiopian highlands. Journal of Applied Ecology 33(3):627-642.

Mokria, M., A. Gebrekirstos, E. Aynekulu, and A. Bräuning. 2015. Tree dieback affects climate change mitigation potential of a dry afromontane forest in northern Ethiopia. Forest Ecology and Management 344:73-83.

Nyssen, J., J. Poesen, J. Moeyersons, J. Deckers, M. Haile, and A. Lang. 2004. Human impact on the environment in the Ethiopian and Eritrean highlands – a state of the art. Earth-Science Reviews 64:273-320.

Nyssen, J., J. Poesen, and J. Deckers. 2009. Land degradation and soil and water conservation in tropical highlands. Soil and Tillage Research 103:197-202.

Olson, D. M. and E. Dinerstein. 2002. The Global 200: Priority ecoregions for global conservation. Annals of the Missouri Botanical Garden 89(2):199-224.

Pohjonen, V. and T. Pukkala. 1990. *Eucalyptus globulus* in Ethiopian forestry. Forest Ecology and Management 36:19-31.

Ragunathan, M. and S.M. Abay. 2009. Ethnomedicinal survey of folk drugs used in Bahirdar Zuria district, Northwestern Ethiopia. Indian Journal of Traditional Knowledge 8(2):281284.

Reusing, M. 2000. Change detection of natural high forests in Ethiopia using remote sensing and GIS techniques. International Archives of Photogrammetry and Remote Sensing XXXIII:B7.

Reynolds, T., T.S. Sisay, A. Wassie, and M. Lowman. 2015. Sacred natural sites provide ecological libraries for landscape restoration and institutional models for biodiversity conservation. Global Sustainable Development Report, Brief.

Taddese, G. 2001. Land degradation: A challenge to Ethiopia. Environmental Management 27(6):815-824.

Tekle, K. and L. Hedlund. 2000. Land cover changes between 1958-1986 in Kalu District, Southern Wello, Ethiopia. Mountain Research and Development 20(1):42-51.

Tilahun, A., H. Terefe, and T. Soromessa. 2015. The contribution of Ethiopian Orthodox Tewahido Church in forest management and its best practices to be scaled up in North

Shewa Zone of Amhara Region, Ethiopia. Agriculture, Forestry and Fisheries 4(3):123137.

Tilman, D., R.M. May, C.L. Lehman, and M.A. Novak. 1994. Habitat destruction and the extinction debt. Nature 371:65-66.

Stellmacher, T. 2007. The historical development of local forest governance in Ethiopia: from imperial times to the military regime of the Derg. Africa Spectrum 42(3):519-530.

Sunderlin, W.D., A. Angelsen, B. Belcher, P. Burgers, R. Nasi, L. Santoso, and S. Wunder. 2005. Livelihoods, forests, and conservation in developing countries: an overview. World Development 33(9):1383-1402.

Vedeld, P., A. Angelsen, J. Bojo, E. Sjaastad, and G.K. Berg. 2007. Forest environmental incomes and the rural poor. Forest Policy and Economics 9:869-879.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth's ecosystems. Science 277(5325):494-499.

Wassie, A., D. Teketay, and N. Powell. 2005. Church forests in North Gonder Administrative Zone, Northern Ethiopia. Forests, Trees and Livelihoods 15(4):349-373.

Wassie, A. and D. Teketay. 2006. Soil seed banks in church forests of northern Ethiopia: Implications for the conservation of woody plants. Flora: Morphology, Distribution, Functional Ecology of Plants 201(1):32-43.

Wassie, A. 2007. Ethiopian church forests: Opportunities and challenges for restoration. Thesis, Wageningen University, Wageningen, The Netherlands.

Wassie, A., T. Bekele, F. Sterck, D. Teketay, and F. Bongers. 2009a. Postdispersal seed predation and seed viability in forest soils: implications for the regeneration of tree species in Ethiopian church forests. African Journal of Ecology 48:461-471.

Wassie, A., F.J. Sterck, D. Teketay, and F. Bongers. 2009b. Effects of livestock exclusion on tree regeneration in church forests of Ethiopia. Forest Ecology and Management 257:765-772.

Wassie, A., F.J. Sterck, D. Teketay, and F. Bongers. 2009c. Tree regeneration in church forests of Ethiopia: Effects of microsites and management. Biotropica 41(1):110-119.

Wassie, A., F.J. Sterck, and F. Bongers. 2010. Species and structural diversity of church forests in a fragmented Ethiopian Highland landscape. Journal of Vegetation Science 21:938948.

Yami, M., W. Mekuria, and M. Hauser. 2013. The effectiveness of village bylaws in sustainable management of community-managed exclosures in Northern Ethiopia. Sustainability Science 8:73-86.

Zeleke, G. and H. Hurni. 2001. Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. Mountain Research and Development 21(2):184-191.

Zewdie, M., M. Olsson, T. Verwijst. 2009. Above-ground biomass production and allometric relations of Eucalyptus globulus Labill. coppice plantations along a chronosequence in the central highlands of Ethiopia. Biomass and Bioenergy 33:421-428.