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ABSTRACT

Agricultural expansion has resulted in both land use and land cover change (LULCC) across the tropics. However, the spatial and temporal patterns of such change and their resulting impacts are poorly understood, particularly for the pre-satellite era. Here we quantify the LULCC history across the 33.9 million ha watershed of Tanzania's Eastern Arc Mountains, using geo-referenced and digitised historical land cover maps (dated 1908, 1923, 1949 and 2000). Our time series from this biodiversity hotspot shows that forest and savanna area both declined, by 74% (2.8 million ha) and 10% (2.9 million ha), respectively, between 1908 and 2000. This vegetation was replaced by a five-fold increase in cropland, from 1.2 million ha to 6.7 million ha. This LULCC implies a committed release of 0.9 Pg C (95% CI: 0.4-1.5) across the watershed for the same period, equivalent to 0.3 Mg C ha^{-1} yr^{-1}. This is at least three-fold higher than previous estimates from global models for the same study area. We then used the LULCC data from before and after protected area creation, as well as from areas where no protection was established, to analyse the effectiveness of legal protection on land cover change despite the underlying spatial variation in protected areas. We found that, between 1949 and 2000, forest expanded within legally protected areas, resulting in carbon uptake of 4.8 (3.8-5.7) Mg C ha^{-1}, compared to a committed loss of 11.9 (7.2-16.6) Mg C ha^{-1} within areas lacking such protection. Furthermore, for nine protected areas where LULCC data is available prior to and following establishment, we show that protection reduces deforestation rates by 150% relative to unprotected portions of the watershed. Our results highlight that considerable LULCC occurred prior to the satellite era, thus other data sources are required to better understand long-term land cover trends in the tropics.

INTRODUCTION

Land cover is part of a constantly evolving dynamic anthropogenic-environment system with numerous complex drivers and impacts. Evidence of land use/land cover change (LULCC) is present in every biome on Earth (Hansen et al., 2013, Houghton, 1994), contributing to biodiversity loss and climate change (Houghton et al., 2012). The most extensive LULCC has been the increase in agricultural area, which now account for approximately one-third of the terrestrial land surface (Ellis et al., 2010, Krausmann et al., 2013). It is estimated that half of this long-term increase occurred in the last 100 years, although the majority of change within tropical regions has typically been estimated to have occurred within the last 50 years (Meiyappan & Jain, 2012).

Quantification of LULCC remains highly uncertain, particularly across large spatial and temporal scales (Grainger, 2008). Remote sensing provides LULCC data of the last few decades, with Landsat constituting the longest temporal record (1972 onwards (Hansen & Loveland, 2012, Hansen et al., 2013)). Relatively little is known about LULCC prior to the satellite era, particularly in tropical regions, however anthropogenic actions have resulted in landscape-scale changes for hundreds of years (Lewis & Maslin, 2015). Industrialisation led to dramatic shifts in rates of LULCC, with globalisation and mechanisation resulting in large-scale deforestation across many regions of the world (Gower, 2003). Models provide first-order estimates of historical LULCC, but are associated with a high level of uncertainty due to the paucity of suitable datasets for the calibration of sensitive model parameters (Alcamo et al., 2011). Historical records in the tropics are rare so where, when and why past LULCC occurs is very uncertain for low latitude regions of the world (Kay & Kaplan, 2015).

Understanding LULCC and its drivers is important for biodiversity conservation and climate change mitigation policies (Houghton et al., 2012). Although the precise combinations of drivers are debated, consensus is that anthropogenic LULCC results in a substantial carbon emission (Grace et al., 2014, Pan et al., 2011, van der Werf et al., 2009). National-scale initiatives (e.g. legally protected areas) were created to preserve forested areas as a valuable biodiversity and timber resource, acting as a protected carbon store. Furthermore, several global initiatives (such as the UNFCCC REDD+ mechanism and the Convention on Biological Diversity Aichi Targets) are aimed at reducing or even reversing LULCC to slow climate change and biodiversity loss. The evaluation of initiatives to slow LULCC, in part, rests on robust scientific information on the rates of LULCC and how they change over time (Grainger, 2008, Ramankutty et al., 2007, Verburg et al., 2011).

Although LULCC is known to occur within protected areas, the majority are thought to effectively reduce its rate (Geldmann et al., 2013). However, there are several difficulties when determining the effectiveness of protected areas. Ideally, the LULCC rates detected within a protected area should be compared to a counterfactual site, where the only difference between the two sites is the protected status; that is to say, the sites share the same ecological characteristics and experience the same social-ecological pressures. Such site-pairs rarely exist and so many studies compare LULCC rates within protected areas to nearby unprotected sites, despite known social-ecological differences (Andam et al., 2008, Jenkins & Joppa, 2009); particularly when the date the protected area was gazetted precedes the timespan of the investigation. At best, such imperfect site-pairs increase uncertainty in the estimate of protected area effectiveness; at worst, these methods result in pseudoreplication (Coetzee et al., 2014, Hurlbert, 1984). For example, Pfeifer et al. (2012) use MODIS data to evaluate the effectiveness of different protected area types in East Africa between 2001 and 2009 by comparing deforestation rates within the protected areas to controls in surrounding unprotected lands. However, the establishment and maintenance of protected areas may be biased towards areas at low risk of LULCC (Joppa & Pfaff, 2009). Furthermore, any displacement of resource demand driving LULCC caused by protection will likely fall on nearby, unprotected areas; artificially inflating the apparent effectiveness of the protected area (Green et al., 2013). The evaluation would be more robust given LULCC data from before and after protected area creation, as well as from surrounding areas where no protection was established over both time periods (Coetzee et al., 2014). Moreover, extending studies of LULCC to consider longer time periods also provides a greater number of conversion events, leading to improved projection accuracy (Sloan & Pelletier, 2012). Whilst the availability of remotely sensed data is normally limited to a maximum period of a few decades in many areas (Hansen & Loveland, 2012), other forms of historical data can be utilised. For example, Hall et al. (2002) combined estimates of land cover from census records with historical maps and modern remote sensing to estimate LULCC in Massachussetts, USA, over 300 years. Despite its advantages, extending LULCC studies to cover longer time periods may also introduce uncertainty; e.g. due to the discontinuity of land cover type definitions/classifications and differences in spatial resolution/accuracy (Hall et al., 2002, Putz & Redford, 2010).

Here we quantitatively analyse LULCC data spanning the twentieth century for the drainage basin of the Eastern Arc Mountains, Tanzania, to establish the main patterns of LULCC and resultant carbon impacts. Furthermore, we use the historical LULCC data to evaluate the effectiveness of protected areas in the region.

MATERIALS AND METHODS

First, we obtained, digitised and geo-referenced all historical maps known for the study region. The maps obtained dated 1908, 1923, 1949 and 2000. In order to maximise temporal resolution, we included all four maps in our analysis of LULCC. Second, by associating each land cover with carbon storage estimates for each land cover type, we estimated the change in carbon storage, and therefore committed carbon losses (ignoring any lags in carbon release to the atmosphere), associated with the observed LULCC. Finally, we investigate LULCC rates both within and outside protected areas.

We focus on the Tanzanian watershed of the Eastern Arc Mountains (hereafter, EAM), which cover 33.9 million ha (Figure 1; see Swetnam et al. (2011) for further details). The EAM watershed is a heterogeneous mix of cropland, savanna, miombo woodland and tropical forest, and includes the administrative and commercial capitals of Dodoma and Dar es Salaam. Ecosystems within the EAM are considered a global priority for biodiversity conservation, with high levels of plant and animal endemism (Burgess et al., 2007, Myers et al., 2000, Platts et al., 2013, Rovero et al., 2014).

Map Digitisation and Description

The four maps we used (1908, 1923, 1949, and 2000), are described below. In brief, we digitised and geo-referenced each map in ARCGIS Desktop version 9.2 (see SI1 for a full description of the procedure). The spatial errors were calculated by comparing the locations of towns and permanent geographical features (e.g. major water bodies) indicated on the maps to independently derived locations of the same features (30 unique locations were used for validation; 27 for the 1908 map, 23 for the 1923 map, 20 for the 1949 map and 28 for the 2000 map; Figure 1; Earth Tools (2010)). Spatial errors for each of these points were interpolated using inverse distance weighting (Lu & Wong, 2008), providing an indication of spatial error of the maps.

The 1908 map was produced by Engler (1908-10) to identify the spatial location of natural resources in Tanzania. The map illustrates land cover within the whole of Tanzania at a scale of 1:6,000,000, using a biome-type classification system consisting of 13 different land covers (Table S1). Prominent natural features of Tanzania (EAM, Kilimanjaro, Lake Nyasa, Lake Tanganyika and Lake Victoria) are identifiable on the map in the correct spatial location. Figure S1 shows that prior to geo-referencing the map image corresponded well to the digitised study area boundary, with national borders and coastlines accurately illustrated. We consider the 1908 map to be a reliable data source, having relatively low spatial errors (spatial error: mean = 6.4km, median = 6.3km, range = 0.9-13.5km; Figure 2).

Shantz and Marbut (1923) presented a generalised map of the vegetation in Africa at a 1:10,000,000 scale. The map uses a biome-type classification system consisting of 10 different land covers within our study area (Table S1). The 1923 map was the first such continental estimate (Whitlow, 1985). Prominent natural features of Tanzania (Kilimanjaro, Lake Nyasa, Lake Tanganyika and Lake Victoria) are identifiable on the map in the correct spatial location. Figure S2 shows that prior to geo-referencing the map image corresponded well to the digitised study area boundary, although the national border with Kenya shows minor discrepancies. We consider the 1923 map to be of medium reliability, having moderate spatial errors throughout the study area (spatial error: mean = 13.7km, median = 13.4km, range = 2.1-22.9km; Figure 2).

In 1943, Gillman was appointed to prepare a map of the vegetation of Tanganyika Territory (Gillman, 1949). Gillman had visited the territory regularly during the 30 year period leading up to this, accumulating a wealth of land cover data which he combined with detailed reconnaissance (Gillman, 1949). The 1:2,000,000 map illustrates land cover within the whole of Tanzania to a high resolution (identifying many small fragments of isolated land covers) and uses a biome-type classification system consisting of 16 different land covers (Table S1).

The 1949 map does not illustrate the names or locations of settlements, but does accurately represent the railway network present in Tanzania at the time. Prominent natural features of Tanzania (EAM, Kilimanjaro, Lake Nyasa, Lake Tanganyika, Lake Rukwa and Lake Victoria) are also identifiable on the map in the correct spatial location. Figure S3 shows that, prior to geo-referencing, the map image corresponded well to the digitised study area boundary, with national borders and coastlines accurately illustrated. We consider the 1949 to be a reliable data source, with relatively low spatial errors (spatial error: mean = 5.4km, median = 4.5km, range = 2.0-17.7km; Figure 2).

The 2000 map illustrates land cover within the whole of Tanzania to a high resolution, identifying many small fragments using a biome-type classification system consisting of 30 different land covers (Table S1, Figure S4). The 2000 map was derived from an estimate of land cover in 1995 (produced at a 1:250,000 scale by combining satellite based assessment with rigorous on-the-ground validation (HTSL, 1997)). The 1995 map was produced by Hunting Technical Services by analysing mosaics of Landsat Thematic Mapper and SPOT images acquired between May 1994 and July 1996 (Wang et al., 2003). This original map was updated by local experts and tropical biologists, taking into account any LULCC that had occurred between 1995 and 2000 (Swetnam et al., 2011). We categorise the reliability of the 2000 map as very high, having relatively low spatial errors (spatial error: mean = 2.0km, median = 1.5km, range = 0.0-8.1km; Figure 2).

Post-Processing

Following digitisation, the four land cover maps (1908, 1923 1949, and 2000) were processed to maximise the comparability across the entire time period. Post-processing involved three steps: 1) for the two earliest maps, simulating historical agricultural area; 2) interpolating maps to fill areas on the maps that lacked land cover data; and 3) harmonising the land cover categories across the four maps.

1) Although a proportion of the study area was farmed in the early twentieth century (SI2; (Börjeson, 2004, Iliffe, 1971)), the 1908 and 1923 maps do not include a cropland category. To avoid biasing our analysis towards detecting deforestation (by ignoring existing cropland at that time), we simulated agricultural area for both maps using population census data and cropland/population census ratios from 1949 and 2000 (Figure S5, Table 1). We estimated population in 1908 and 1923 from population growth over time using data on the total population of Tanzania (World Bank, 2010) and older census results of the mainland (Boesen et al., 1986) (Figure S5; p-value < 0.001, R-sq = 99.97%). To spatially map our historic cropland estimate, we assume that agricultural land is created adjacent to existing agricultural land; similar to the assumptions applied by Swetnam et al. (2011) when building scenarios for the same area. We progressively removed agricultural land at random from the margins of land cover marked as agriculture on the 1949 land cover map, until the estimated agricultural areas for 1923 and 1908 were obtained.

2) Following this, areas on the maps that lacked land cover data were filled with the land cover type from the subsequent map. This was required for 3.7% [1.25 million ha] of the 1908 map; 4.2% [1.42 million ha] of the 1923 map; and 0.2% [0.07 million ha] of the 1949 map; and none of the 2000 map.

3) Each group of cartographers used differing classification of land use and land cover. We therefore harmonised amongst the classifications across the maps. For example, compared to the other maps, an extremely large amount of the 1949 map is classified as woodland. It is unlikely that woodland showed a rapid expansion in land area throughout the study area between 1923 and 1949 only to sharply decline again between 1949 and 2000. A more

feasible explanation is that the 1949 cartographers classified some woodier areas of savanna as woodland whilst the other maps used a different classification, for example calling them savanna. Less ambiguous classifications negated such problems. Thus, all pixels of all maps were allocated to one of four categories common to all maps: forest (high carbon density tree-dominated systems, including montane forest, coastal lowland forest, mangroves and tree plantations), savanna spectrum (medium carbon density mixed tree and grass systems, including miombo woodland, Acacia-Commiphora savanna, bushland/thicket and grassland), crop (anthropogenic arable systems) and 'other' (largely dominated by low carbon systems, such as semi-desert and snow, occupying <0.6% of the study area). These harmonised land cover categories were necessary to ensure closer to like-for-like comparison across all maps as each used slightly different land cover categories originally (Figure 3, Table S1, SI1).

Carbon Flux Estimation

LULCC inferred from the historical maps described above was then associated with a carbon flux. Regionally derived carbon storage values for five carbon pools (total aboveground live, coarse woody debris, litter, belowground and soil) were estimated for each of the original and harmonised land use categories using a look-up table method detailed in Willcock et al. (2012), whereby each land cover category was assigned the resampled median carbon value from studies whose site description closely matched the land cover category (Table S2-4).

Evaluation of Protected Area Effectiveness

Tanzania has a long history of using protected areas to conserve its natural resources, creating formal ordinances allowing legally protected areas to be established and enforced in 1904 (SI2). We used the World Database of Protected Areas (WDPA) to identify legally protected areas within our study area (IUCN & UNEP-WCMC, 2015). WDPA identifies 340 protected areas of which 111 (33%) are associated with data indicating the year of establishment. The remaining 229 protected areas were checked against protected area establishment data from National Parks Worldwide (NPW, 2015), adding another 90 establishment dates. Overall, this procedure resulted in 201 (59%) of the protected areas having an estimated date of establishment. From these 201 protected areas, we calculated the mean creation date, weighted by the size of each protected area. In addition, we identified a sub-sample of nine protected areas that were established between 1923 and 1949 for which there were therefore LULCC data available for complete periods before (1908-1923) and after (1949-2000) protected area establishment: Chenene East Forest Reserve (established 1924), Hanang Forest Reserve (established 1936), Kihuhwi Sigi Forest Reserve (established 1934), Msumbugwe Forest Reserve (established 1947), Mtanza Forest Reserve (established 1947), Mtibwa Forest Reserve (established 1944), Udzungwa Scarp Forest Reserve (established 1929), Uluguru South Forest Reserve (established 1930), and Vigoregore Forest Reserve (established 1929). We evaluated the long-term effectiveness of protected areas using two complementary methods. First, we used the spatial data within the WDPA to extract the LULCC information over time from our land cover maps for both legally protected areas and those lacking legal protection. We then compared the LULCC rates before and after the area-weighted mean of the creation dates of protected areas (1951). Second, we compared the LULCC rates before (1908-1923) and after (1949-2000) legal protection was established for our sub-sample of nine protected areas with the rate of LULCC for areas of the watershed that never received any form of legal protection.

RESULTS

Temporal and Spatial Trends in Land Use/Land Cover Change

Considering the harmonised land cover categories across the 33.9 million ha watershed, forest area declined an estimated 74% between 1908 and 2000, from 3.75 to 0.96 million ha (Figure 3). There was a net loss of forest cover (2.9 million ha) over the first half of the twentieth century followed by an increase of forest cover (0.1 million ha) by the year 2000. Savanna area declined by 10% between 1908 and 2000, from 28.9 to 26.0 million ha. There was a net increase in savannah between 1908 and 1923 (2.1 million ha), followed by a loss of 5.0 million ha by the year 2000. Peak forest loss occurred earlier in the century than peak savanna loss. Forest and savanna were replaced by cropland which increased across every time interval from an estimated 1.2 million ha in 1908 to 6.7 million ha in the 2000 map.

On a per hectare basis, within currently legally protected areas (weighted mean creation date of 1951), the area classified as forest (harmonised category) increased by 0.027 ha between 1949 and 2000, compared with a decrease of 0.007 ha for every hectare within unprotected regions. Savanna decreased by 0.042 ha for every hectare within currently protected areas and by 0.146 ha for every hectare in unprotected regions over the same period. By contrast, between 1949 and 2000 cropland area increased in both protected and unprotected areas, although the increase in protected areas was an order of magnitude lower (0.009 ha for every protected hectare and 0.155 ha for every unprotected hectare respectively). Thus, between 1949 and 2000, legal protection reversed forest losses, slowed savanna losses, and decreased agricultural encroachment, compared to unprotected zones (Figure 4).

For the sub-sample of nine protected areas where data on pre- and post-protection LULCC can be estimated, prior to legal established three showed deforestation and one showed increasing forest area between 1908 and 1923 (-996 ha yr^{-1}, -8 ha yr^{-1}, -3 ha yr^{-1}, +345 ha yr^{-1} respectively), whilst five show no change over the same time period (Table 2). This result is not sensitive to our crop area estimation method as no cropland was simulated in these nine areas in either 1908 or 1923. Between 1949 and 2000, after legal protection had been established, only one reserve continued to show a decline in forest area (although at a reduced rate to the previous time period, -1 ha yr^{-1}) and six showed increasing forest area (+3 ha yr^{-1}, +12 ha yr^{-1} , +13 ha yr^{-1}, +110 ha yr^{-1} , +150 ha yr^{-1}, +866 ha yr^{-1} respectively; Table 2); whilst two show no change. Overall, before legal protection was established (1908-1923) the nine protected areas show, on average, a decrease in forest area of 0.24% yr^{-1} (661 ha yr^{-1}), which shifts to an increase of 0.42% yr^{-1} (1151 ha yr^{-1}) between 1949 and 2000, after legal protection was instigated; contrasting to declines in forest area of 0.42% yr^{-1} and 0.01% yr^{-1} in unprotected lands over the same time periods (96,416 ha yr^{-1} and 3,061 ha yr^{-1} respectively; Table 2).

Carbon flux

Total carbon storage across the 33.9 million ha watershed declined from an estimated 7.3 (7.1-7.4) Pg C in 1908 (7.4 [7.3-7.5] using harmonised categories) to 6.3 (5.9-6.7) Pg C in 2000 (6.4 [6.3-6.4]), a decline of 0.9 (0.4-1.5) Pg C (13%; Figure 2; Figure 3; Figure 5; Table 1), or 1.0 (0.9-1.2) Pg C (14%) using harmonised categories. The committed carbon emission was over four-fold greater in the first half of the twentieth century (19.3 [9.0 to 29.5] Tg C yr^{-1} between 1908 and 1949 using harmonised values) than the second half (4.3 [-2.9 to 11.6] Tg C yr^{-1} between 1949 and 2000 using harmonised values). Committed carbon emissions were consistently dominated by the aboveground live carbon pool which was a net source of 0.8 (0.5-1.0) Pg C (based on original land use categories; Figure 5; Table 1) or 0.8 [0.4-1.2] Pg C (using harmonised categories) between 1908 and 2000; similarly dominated by committed emission from the first half of the twentieth century (14.6 [5.4 to 23.9] Tg C yr^{-1}) as opposed to the latter half (3.1 [-1.2 to 7.5] Tg C yr^{-1}).

The impact of legal protection of land is reflected in estimated carbon fluxes. Protected areas are estimated to have had a net carbon uptake of 4.77 (3.84-5.70) Mg C ha^{-1} yr^{-1} between 1949 and 2000 as forest expanded, while there was an estimated net carbon release of 11.89 (7.21-16.57) Mg C ha^{-1} yr^{-1} from unprotected areas as forest and savanna were converted to croplands. Similarly, overall the sub-sample of nine protected areas show a committed carbon emission between 1908 and 1923 (before legal protection was established) of 0.15 (-0.13 to 0.30) Mg C ha^{-1} yr^{-1} which switched to uptake of 0.97 (0.88 to 0.99) Mg C ha^{-1} yr^{-1} between 1949 and 2000 (after legal protection was established).

DISCUSSION

Twentieth Century Land Use/Land Cover Change

Between 1908 and 2000, we estimate that 4.7 million hectares of forest and savanna vegetation within the Eastern Arc watershed (14% of total area) was converted to other land cover types, overwhelmingly to croplands, predominantly maize, the main staple, but also cash crops like tobacco (lowlands) and coffee and tea (mountains) (Börjeson, 2004). This LULCC exhibits a clustered distribution, principally, (1) near the Indian Ocean, where the proximity of export markets makes timber exploitation favourable; (2) near to the most populous city within Tanzania, Dar es Salaam, from which waves of degradation have previously been identified (Ahrends et al., 2010), and (3) the mountainous regions which harbour valuable timbers and climates favourable for both large and small-scale agriculture. Our estimate of the 92-year decrease in forest area of 74% (85% of which occurred between 1908 and 1923) is consistent with previous studies of Eastern Tanzania which estimate between 70% and 96% of the original forest cover to have been lost (Hall et al., 2009, Newmark, 2002). Historiographical studies also support our results and suggest additional LULCC occurred prior to 1908 (see SI2). During the early twentieth century, the arrival of German colonialists and the preparation and fighting of the first world war coincided with agricultural expansion, converting forested lands to agriculture in predominantly in lowland areas (Börjeson, 2004). Much remaining lowland forest was converted to savanna via increased grazing and/or the increased incidences of fire associated with the expanding human population century (Börjeson, 2004, Iliffe, 1971). As remaining forests became restricted to relatively inaccessible, often steep areas which were less suitable for agriculture, savanna became the focus of conversion to agriculture (Börjeson, 2004).

The Long-term Effectiveness of Protected Areas

Tanzania has a long history of establishing protected areas (see SI2), enabling their long-term effectiveness to be assessed. The oldest protected area in the study area dates back to 1907, however the weighted mean protected area creation date is 1951 (IUCN & UNEP-WCMC, 2015, NPW, 2015). This study highlights the long-term effectiveness of protected areas in reducing LULCC rates. In the first half of the twentieth century (i.e. before most protected areas were created), land within the current protected area network shows similar rates of LULCC as those outside it, indicating that the establishment of protected areas was not biased towards areas of low LULCC (Figure 4). Forest area declined by 10.3% and 7.8%

(30,000 and 47,000 ha yr^{-1}) and savanna area increased by 7.3% and 0.1% (26,000 and 18,000 ha yr^{-1}) in currently protected and unprotected areas respectively. In the second half of the century, forest area increased by 2.7% (7,000 ha yr^{-1}) within currently protected areas, whilst decreasing 0.7% (3 ha yr^{-1}) in unprotected areas; meanwhile, savanna area decreased by 4% and 14% (20,000 and 154,000 ha yr^{-1}) respectively (Figure 4). Thus indicating that: 1) the establishment of protected areas within our study area did not show a large bias towards areas of low LULUCC; and 2) protection slowed/reversed LULCC relative to unprotected lands.

Similarly, using a sub-sample of nine protected areas created between 1923 and 1949, we demonstrate that deforestation rates of 661 ha yr^{-1} shifted to net increases in forest cover at rates of 1151 ha yr^{-1}, once legal protection had been established; contrasting this to regions where no protection was instigated which show a decline in the rate of deforestation over time 64% smaller than that within protected areas and so no shift to afforestation (Table 2). Thus, whilst the sub-sample do show lower rates of LULCC than unprotected areas of the watershed between 1908 and 1923 (before protection was established), the establishment of protection further reduced deforestation rates, having an effect 1.5 fold greater than unprotected areas of the watershed.

Other studies, often covering much shorter time frames and smaller extents, have found similar patterns (Defries et al., 2005, Green et al., 2013, Laurance et al., 2012, Pfeifer et al., 2012). For example, Pfeifer et al. (2012) demonstrate that National Parks within Tanzania are very effective, increasing in forest area against a back-drop of deforestation in unprotected lands between 2001 and 2009. However, the authors report mixed results, with other forms of protected areas in East Africa (e.g. Forest Reserves) shown to be ineffective at slowing/reversing deforestation over this time period (Pfeifer et al., 2012). Studies that assess the effectiveness of protected areas via comparison with surrounding lands may over- or under-estimate the impact of protection due to spatial variation in LULCC drivers. Green et al. (2013) improve on these estimates by accounting for underlying spatial variation using modelled estimates, showing LULCC rates were 40% lower than expected within protected areas in the EAM between 1975 and 2000. Our before and after protection comparison provides a more robust evaluation; removing the pervasive problem that protected areas are not random subsamples of a given landscape and may be biased towards locations with lower LULCC rates (Andam et al., 2008, Joppa & Pfaff, 2009), whilst also accounting for any changes in pressures over time and thus background shifts in LULCC rates (Coetzee et al., 2014, Meyfroidt et al., 2013).

Carbon Flux

Applying the carbon values to the modern day (2000) land cover map results in landscape-scale carbon estimates similar to comparable regional estimates presented elsewhere in the literature (Willcock et al., 2014, Willcock et al., 2012), but larger than most globally derived estimates (Baccini et al. (2012), Baccini et al. (2008), Saatchi et al. (2011); see Willcock et al. (2014) for further details). Uniquely, by comparing the carbon storage estimates across the four land cover maps (1908, 1923, 1949 and 2000), we are able to estimate the committed carbon flux associated with the LULCC. Over the 92-year period the general trend was for high carbon-density vegetation to be replaced by vegetation of lower carbon-density. This trend led to an estimated committed landscape-scale release of 0.9 (0.4-1.5) Pg C, likely to have been driven by the rapidly growing human population and associated demand for agricultural land (Lambin et al., 2003, Meyfroidt et al., 2013).

Our estimated fluxes are higher than previous comparable estimates over the same area and time-span (Hurtt et al., 2006). Hurtt et al. (2006) present two carbon model outputs (HYDE and HYDE-SAGE, the latter using more resolute data to estimate cropland area). The HYDE-SAGE model suggests that the watershed of the EAM was a substantial carbon source over the twentieth century, though much less than we estimate here (Figure 5). The HYDE model suggests that the study area has been a net carbon sink, which is highly unlikely (Ahrends et al., 2010, Green et al., 2013, Pfeifer et al., 2013, Willcock et al., 2014). Such global databases are less accurate in the tropics due to a lack of data and low resolution when compared to regional studies (Klein Goldewijk & Verburg, 2013). Caution must be exercised when databases like HYDE are used to provide LULCC feedbacks in earth system models.

Uncertainty

Although historical maps contain interesting information to derive knowledge of historical landscapes and changes in those landscapes over time, cartographical studies contain inherent uncertainty; typically divided into production-orientated uncertainty (associated with map production), transformation-orientated uncertainty (associated with data- and post-processing) and application-orientated uncertainty (uncertainty dependent on the application) (Leyk et al., 2005). Historical maps generally carry a higher degree of uncertainty than contemporary geographic databases, however it is often impossible to measure the uncertainty of historical data (Tucci & Giordano, 2011). For example, without independently produced maps from the same years it is impossible to validate the land cover categories assigned to each pixel.

Despite this, it is possible to estimate specific parts of uncertainty of historical maps. For example, spatial errors associated with our land cover maps, which could result in spurious LULCC via map misalignment rather than actual modification in land cover. Whilst it is difficult to reliably measure the positional accuracy of historical data, this can be estimated using fixed points, shared between maps (Tucci & Giordano, 2011). By interpolating the distances between identifiable features on each map, and the independently derived spatial locations of the same features (Figure 1 and Figure 2), we have demonstrated that the spatial error associated with the historical maps used in this study are relatively low (with mean spatial error ranging from 2-14km), assuming that the spatial error associated with these fixed points is representative of the uncertainty associated with the positional accuracy of land cover patches. Small spatial errors may have a substantial impact in highly fragmented landscapes. However, using the broader, harmonised land cover categories reduces fragmentation and thus reduces the impact of misalignment errors.

Further uncertainty may arise due to misclassification error, whereby spurious LULCC is identified due to misclassification of land cover categories by cartographers. This is compounded by the fact that several land cover categories, for example forest (Putz & Redford, 2010), have been shown to change in definition over time. Forests were classified as areas of nearing 100% canopy closure in the early half of the century (Engler, 1908-10, Gillman, 1949, Shantz & Marbut, 1923) but lower canopy covers (>20%) were included within the forest category of the latest map (HTSL, 1997, Swetnam et al., 2011). Whilst this is likely to mask some LULCC in our study, it is unlikely to drive our result as: a) such shifts in classification are largely avoided when using our broader harmonised land cover categories; and b) these classification changes impact the entire watershed and, despite this, forests showed higher rates of ‘loss’ than in unprotected areas than protected areas.

Whilst it is impossible to retrospectively validate the land cover categories assigned to each pixel of the historical maps, the literature provides indications of how reliable the maps were considered at the time of production; triangulation with these data can increase confidence in our conclusions. The 1908 map was widely considered at the time as accurate (Cowles, 1910). By contrast, the 1923 map was criticised in the literature for the broad land cover categories used during the mapping process. Michelmore (1934) felt that land covers grouped together by Shantz and Marbut (1923) were in fact different and distinct due to wide geographical separation and thus should not grouped. The author of the 1949 map provided spatially explicit indications of map reliability which were, on the whole, favourable (with 55% of the map classed as of 'high reliability', 25% as 'medium reliability and 20% as low reliability (Gillman, 1949)). These publications provide us with some estimate of map uncertainty, but are qualitative in nature and do not indicate if our results are robust to such uncertainties. However, our estimated forest area decline of 74% is consistent with previous estimates for the region derived from independent sources, which range from 70% to 96% (Hall et al., 2009, Newmark, 2002). Thus, our LULCC trend is likely robust to the production-orientated uncertainty associated with the historical maps.

Transformation-orientated uncertainty arises as a result of post-processing. In this study, we simulated agricultural area in both 1908 and 1923 using estimated population during those periods. This approach assumes that there has been no change in the amount of agricultural land per person over time. However, data suggest that the amount of agricultural land per person has declined over time within Tanzania (a reduction of 0.04 ha yr^{-1} between 1961 and 2012 (World Bank, 2010), although we found no data for our study area prior to this), in line with other regions (Kaplan et al., 2011); thus, our historic estimates of agricultural area are likely to be conservative. Although our method will not exactly replicate the precise size and distribution of past agricultural land, there are few alternatives; e.g. extrapolation of the World Bank (2010) trend may be erroneous as this trend may not continue prior to 1961, nor may it be representative of our specific study area. Our simulation of agricultural area indicated that most agricultural land was situated in unprotected areas, with 6.4% and 7.7% of agricultural land within currently protected areas in 1908 and 1923 respectively. Thus, our LULCC estimates for unprotected areas may slightly overestimate deforestation rates relative to protected areas; however, we consider this a less serious error than the likely larger overestimation of LULCC by failing to estimate the extent and location of agricultural land to older maps.

Since the historical maps were created as estimates of land cover, there is unlikely to be substantial application-orientated uncertainty associated with the LULCC trends. However, the association of carbon storage values with the land cover categories and the subsequent estimation of carbon emissions may induce application-orientated uncertainty. Comparing the carbon flux associated with original land cover categories (which had uniquely assigned carbon values according to the category description) to that resulting from the harmonised land cover categories (in which all maps had a singular carbon value assigned to each of the shared land cover categories) shows that our conclusion are robust to this uncertainty. However, in our study, we did not account for degradation within land use categories, despite it being known to occur (Ahrends et al., 2010). If degradation is highly correlated (in both space and time) with deforestation, then our emission estimates will be approximately correct. However, as previously discussed, several land cover categories included in our maps show changes in definitions over time (Putz & Redford, 2010). In general, the changing definitions indicate that the level of degradation has increased over time (Engler, 1908-10, Gillman, 1949, HTSL, 1997, Shantz & Marbut, 1923, Swetnam et al., 2011), suggesting that our carbon stock estimates for the early twentieth century may be underestimates, but that those from the year 2000 may be approximately correct as all stock estimates are based on tree inventory data from the late twentieth century. This probably leads to an underestimation of carbon flux to the atmosphere (Lambin et al., 2003). Forest degradation and the concomitant carbon release are more difficult to map than deforestation and thus less well documented; although degradation is accounted for in both the HYDE and HYDE-SAGE models (Hurtt et al., 2006), highlighting the underestimation of the carbon flux resulting from

LULCC using these models. Initial estimates of emissions due to degradation, which are yet to be confirmed, include losses of 0.25 Mg C ha^{-1} yr^{-1} in the Congo (Brown et al., 2005) and of 0.01-0.08Pg C yr^{-1} for Africa as a whole (Bombelli et al., 2009, Grace et al., 2014); although some forests recover from degradation over time and so the impacts are likely to be complex. By contrast we did not account for the CO2 fertilisation effect on vegetation which causes vegetation within a land cover category to store more carbon over time, e.g. savannah thickening and increasing carbon stocks in mature forest (Lewis et al., 2009, Mitchard & Flintrop, 2013, Pan et al., 2011). For example, intact African forest has shown an increase in carbon storage at a rate of 0.6 Mg C ha^{-1} yr^{-1}, totalling 0.3 Pg C yr^{-1} for the continent as a whole (Lewis et al., 2009). Thus, the net carbon flux is not simply the changes in land cover vegetation types but additionally must include changes within land cover categories. Future studies will be required to disentangle the loss of carbon from degradation and the addition of carbon via CO2 fertilization effects on carbon storage within a given land cover type.

In conclusion, we show dramatic changes in land cover over a century across a 33.9 million ha area of Tanzania. Forest area declined rapidly in the first half of the twentieth century, while savanna area decreased rapidly in the second half of the century; meanwhile cropland area expanded five-fold. Concomitant with this LULCC was a major committed flux of carbon to the atmosphere of 0.94 (0.37-1.50) Pg (aboveground live, coarse woody debris, litter, belowground and soil carbon combined). Legal protection reversed the trends in LULCC, reducing deforestation and increasing forest establishment, converting these areas from net carbon emitters to areas of net carbon sequestration. This study highlights that future policy and management decisions can have significant impacts on retaining and restoring various land cover types with significant climate mitigation and other ecosystem service benefits.

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FIGURE LEGENDS

Figure 1 Region for land cover change analysis is the Eastern Arc Mountain watershed in Tanzania (shaded) (Platts et al., 2011, Swetnam et al., 2011). Points locate towns and geographical features used to assess the spatial accuracy of historical maps

Figure 2 The spatial distribution of (i) aboveground carbon storage, (ii) the 95% confidence intervals, both based on regionally appropriate values derived from Willcock et al. (2012), and (iii) spatial errors within the watershed, calculated by interpolating the distance between identifiable features on each map and the independently derived spatial location of the same features, for the years 1908, 1923, 1949 and 2000.

Figure 3 Four harmonised land use categories (forest, green; savanna spectrum, brown; crop, red; other, blue) showing LULCC for the Eastern Arc Mountain watershed between 1908 and 2000. Also indicated are the original land use categories (white) and how they were harmonised (for key to numbers, see Table S5).

Figure 4 The trend in LULCC between 1908 and 2000 for the EAM watershed: land covers are separated into a) forest; b) savanna; c) forest and savanna combined; and d) crop. Land covers currently within legally protected areas are indicated by blue lines and unprotected areas in red. The weighted mean creation date of Tanzania's current protected areas is shown as a dashed line

Figure 5 The change in aboveground live carbon storage (±95% CI) within the Eastern Arc Mountain watershed during the 20thcentury; comparing our results to modelled outputs from HYDE and HYDE-SAGE (Hurtt et al., 2006).

TABLES

Table 1 Carbon storage in the Eastern Arc Mountain watershed over time for all five IPPC carbon pools, shown for original land use categories and harmonised land use categories (the latter in bold).

1908	2.33 (2.06-2.60) **2.40 (2.12-2.68)**	0.24 (0.21-0.27) **0.21 (0.19-0.23)**	0.36 (0.32-0.40) **0.34 (0.30-0.38)**	0.78 (0.69-0.87) **0.71 (0.63-0.80)**	3.56 (3.50-3.62) **3.74 (3.71-3.77)**	7.27 (7.12-7.42) **7.39 (7.29-7.49)**
1923	2.05 (2.04-2.06) **1.99 (1.98-2.00)**	0.20 (0.19-0.20) **0.20 (0.19-0.20)**	0.34 (0.33-0.34) **0.33 (0.32-0.33)**	0.71 (0.70-0.71) **0.61 (0.60-0.62)**	3.59 (3.58-3.59) **3.73 (3.72-3.73)**	6.89 (6.88-6.90) **6.86 (6.85-6.86)**
1949	2.38 (1.92-2.84)* **1.80 (1.70-1.90)**	0.24 (0.19-0.29)* **0.18 (0.17-0.19)**	0.41 (0.33-0.49)* **0.31 (0.29-0.32)**	0.81 (0.65-0.97)* **0.56 (0.53-0.59)**	3.78 (3.48-4.06)* **3.74 (3.65-3.83)**	7.62 (6.40-8.86)* **6.60 (6.28-6.92)**
2000	1.58 (1.56-1.60) **1.64 (1.52-1.76)**	0.15 (0.14-0.15) **0.16 (0.15-0.17)**	0.25 (0.24-0.25) **0.28 (0.26-0.30)**	0.60 (0.59-0.61) **0.51 (0.47-0.55)**	3.74 (3.43-4.05) **3.80 (3.78-3.82)**	6.33 (5.92-6.74) **6.38 (6.33-6.43)**

*Carbon storage estimated from the 1949 original map legend is anomalously high due to the misclassification of the woodland category.

Table 2 The pre- and post-protection rates of change in forest area and carbon storage over time for nine legally protected areas in our study area.

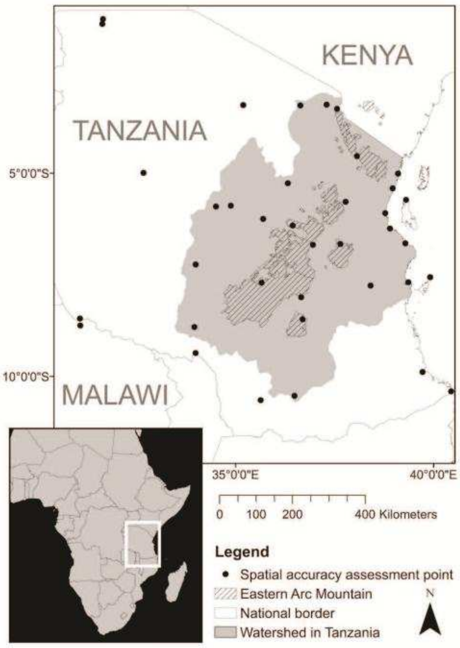
[redacted]						
Chenene East Forest Reserve	22,737	1924	0.0000	4.57 (3.06 to 7.25)	0.0000	0.09 (0.06 to 0.48)
Hanang Forest Reserve	5,913	1936	0.0000	0.00 (-0.08 to 0.09)	0.0186	4.03 (3.99 to 11.96)
Kihuhwi Sigi Forest Reserve	909	1934	-0.0028	-0.61 (-0.64 to -0.54)	-0.0009	-0.36 (-1.50 to -0.31)
Msumbugwe Forest Reserve	4,562	1947	0.0000	0.00 (-0.08 to 0.09)	0.0025	0.56 (0.55 to 1.67)
Mtanza Forest Reserve	10,835	1947	-0.0007	-0.16 (-0.17 to -0.14)	0.0002	0.04 (0.03 to 0.08)
Mtibwa Forest Reserve	818	1944	0.0000	0.00 (-0.08 to 0.09)	0.0159	3.38 (3.30 to 9.85)
Udzungwa Scarp Forest Reserve	208,368	1929	-0.0048	-1.05 (-1.10 to -0.93)	0.0041	0.93 (0.89 to 2.85)
Uluguru South	17,481	1930	0.0197	4.35 (3.84 to 4.52)	0.0086	2.15 (2.14 to 7.06)

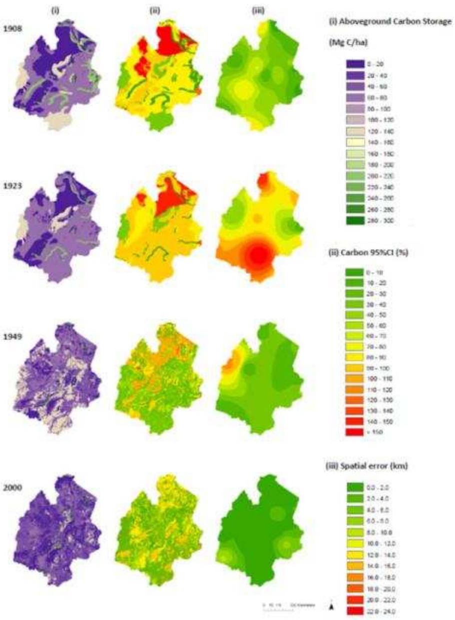
Forest Reserve						
Vigoregore Forest Reserve	540	1929	0.0000	0.00 (-0.08 to 0.09)	0.0000	0.00 (-0.08 to 0.09)
TOTAL	272,163	n/a	-0.0024	-0.15 (-0.30 to 0.13)	0.0042	0.98 (0.88 to 0.99)
Land without legal protection	22,586,047	n/a	-0.0043	-0.98 (-1.00 to -0.89)	-0.0001	-0.23 (-0.35 to -0.17)

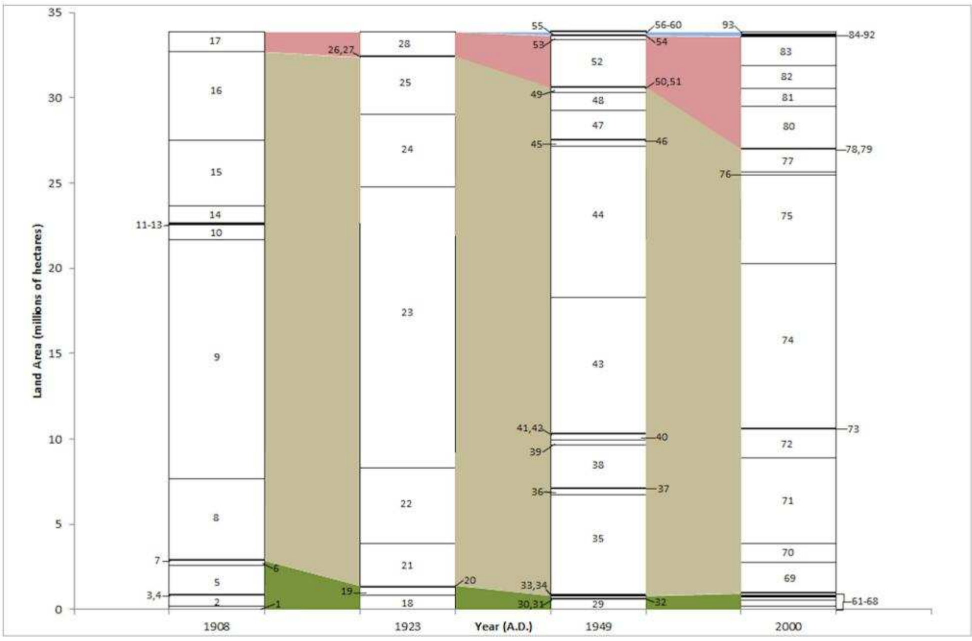
SUPPORTING INFORMATION LEGENDS

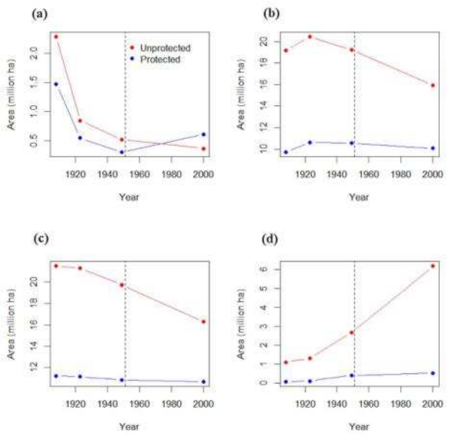
SI1 – Geo-Referencing and Digitisation Procedure

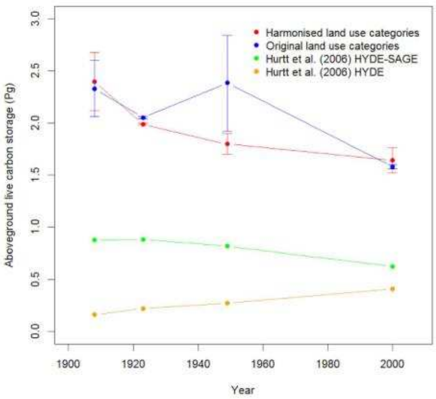
SI2 - History of Forest Protection for Timber Production and Conservation in Tanzania


KENYA
TANZANIA
MALAWI
5°0'0"S
10°0'0"S
35°0'0"E
40°0'0"E
0 100 200 400 Kilometers
Legend
Spatial accuracy assessment point
Eastern Arc Mountain
National border
Watershed in Tanzania
N


(i)
(ii)
(iii)
1908
1923
1949
2000
(i) Aboveground Carbon Storage
(Mg C/ha)
(ii) Carbon 95%CI (%)
(iii) Spatial error (km)


Land Area (millions of hectares)
Year (A.D.)
1908
1923
1949
2000


(a)
Unprotected
Protected
Area (million ha)
Year
1920 1940 1960 1980 2000
(b)
Area (million ha)
Year
(c)
Area (million ha)
Year
(d)
Area (million ha)
Year


Harmonised land use categories
Original land use categories
Hurtt et al. (2006) HYDE-SAGE
Hurtt et al. (2006) HYDE
Aboveground live carbon storage (Pg)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1900
1920
1940
1960
1980
2000
Year