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Land cover change and carbon emissions over 100 years in an African biodiversity hotspot

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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 presatellite era. Here, we quantify the LULCC history across the 33.9 million ha watershed of Tanzania's Eastern Arc Mountains, using geo-referenced and digitized 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 fivefold 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 threefold 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 are 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.

Keywords: afforestation, carbon, deforestation, ecosystem service, emission, land use change, protected area, reforestation

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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 (Houghton, 1994; Hansen *et al.*, 2013), contributing to biodiversity loss and climate change (Houghton *et al.*, 2012). The most extensive LULCC has been the increase in agricultural area, which now

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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). Industrialization led to dramatic shifts in rates of LULCC, with globalization and mechanization 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 (van der Werf *et al.*, 2009; Pan *et al.*, 2011; Grace *et al.*, 2014). 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 (Ramankutty *et al.*, 2007; Grainger, 2008; 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 (Hurlbert, 1984; Coetzee *et al.*, 2014). 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 utilized. 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, digitized and geo-referenced all historical maps known for the study region. The maps obtained dated

1908, 1923, 1949 and 2000. To maximize 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 [Fig. 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 (Myers *et al.*, 2000; Burgess *et al.*, 2007; Platts *et al.*, 2013; Rovero *et al.*, 2014).

Map digitization and description

The four maps we used (1908, 1923, 1949, and 2000), are described below. In brief, we digitized and geo-referenced each map in ARCGIS DESKTOP version 9.2 (see Appendix S1 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; Fig. 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.

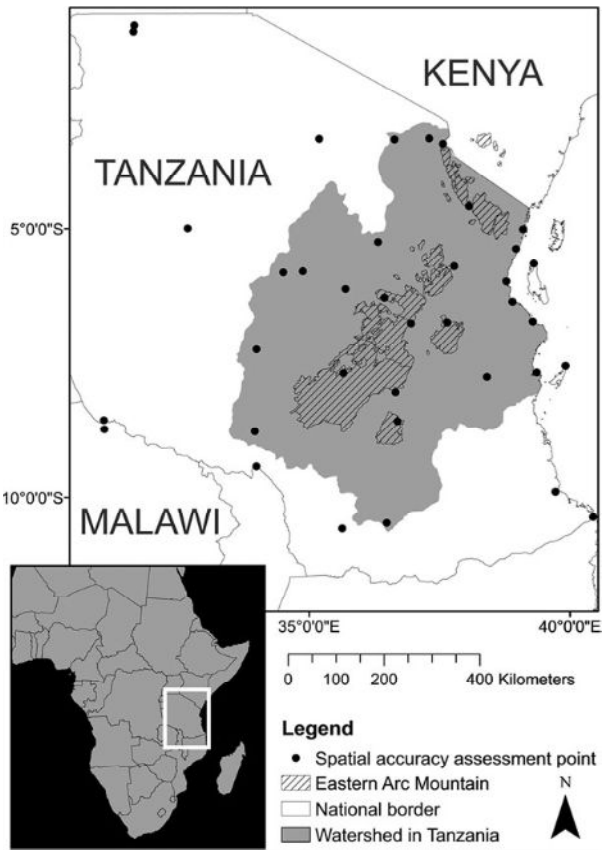


Fig. 1 Region for land cover change analysis is the Eastern Arc Mountain watershed in Tanzania (shaded) (Platts *et al.*, 2011; Swetnam *et al.*, 2011). Points locate towns and geographical features used to assess the spatial accuracy of historical maps.

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 digitized 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 = 6.4 km, median = 6.3 km, range = 0.9–13.5 km; Fig. 2).

Shantz & Marbut (1923) presented a generalized 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 digitized 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 = 13.7 km, median = 13.4 km, range = 2.1–22.9 km; Fig. 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 digitized study area boundary, with national borders and coastlines accurately illustrated. We

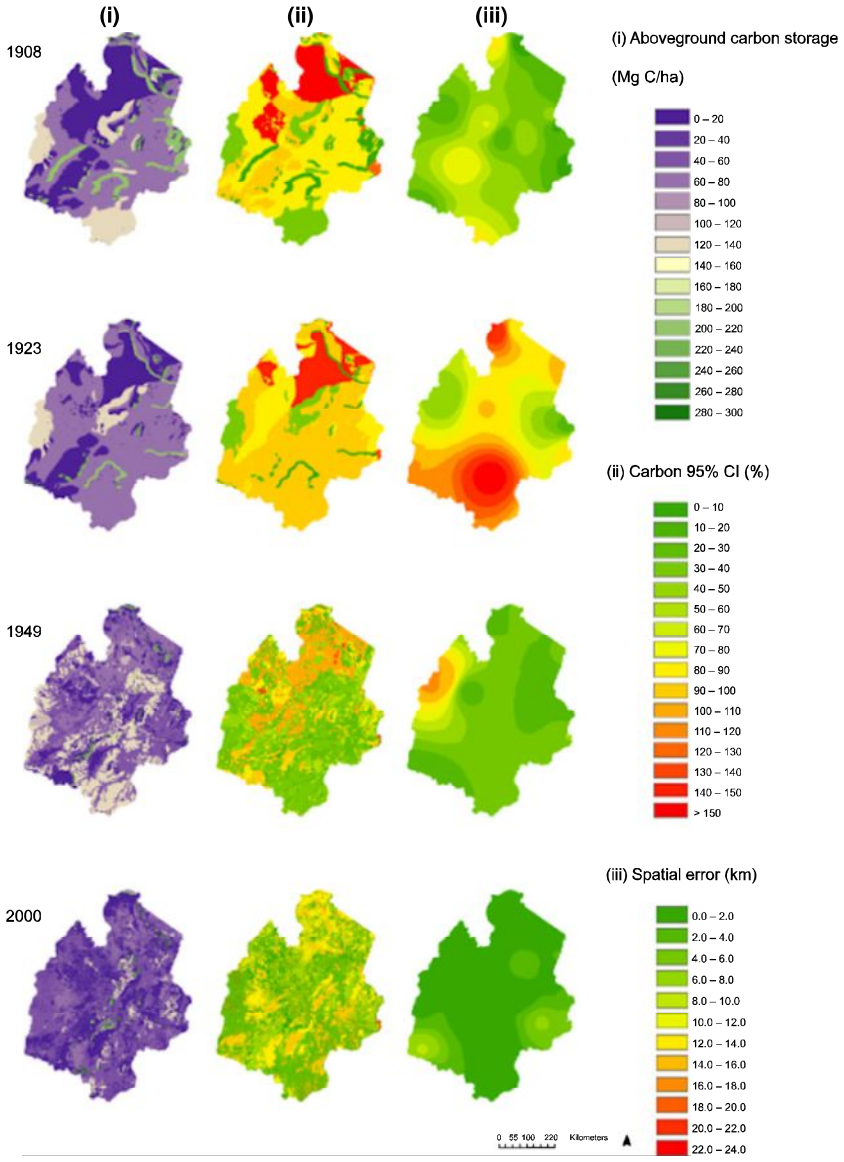


Fig. 2 The spatial distribution of (i) aboveground carbon storage, (ii) the 95% confidence intervals, both based on regionally appropriate values derived from Willcock *et al.* (2012), and (iii) spatial errors within the watershed, calculated by interpolating the distance between identifiable features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

consider the 1949 to be a reliable data source, with relatively low spatial errors (spatial error: mean = 5.4 km, median = 4.5 km, range = 2.0–17.7 km; Fig. 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; Fig. 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 categorize the reliability of the 2000 map as very high, having relatively low spatial errors (spatial error: mean = 2.0 km, median = 1.5 km, range = 0.0–8.1 km; Fig. 2).

Postprocessing

Following digitization, the four land cover maps (1908, 1923 1949 and 2000) were processed to maximize the comparability across the entire time period. Postprocessing 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) harmonizing the land cover categories across the four maps.

1. Although a proportion of the study area was farmed in the early twentieth century [Appendix S2; (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 (Fig. 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) (Fig. 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 harmonized 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 semidesert and snow, occupying <0.6% of the study area). These harmonized 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 (Fig. 3; Table S1; Appendix S1).

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 harmonized 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 (Tables S2–S4).

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 (Appendix S2). 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

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 harmonized land use categories (the latter in bold)

Year	Aboveground carbon storage, Pg (95% CI)	Litter carbon storage, Pg (95% CI)	Coarse woody debris carbon storage, Pg (95% CI)	Belowground carbon storage, Pg (95% CI)	Soil carbon storage, Pg (95% CI)	Total carbon storage, Pg (95% CI)
1908	2.33 (2.06–2.60)	0.24 (0.21–0.27)	0.36 (0.32–0.40)	0.78 (0.69–0.87)	3.56 (3.50–3.62)	7.27 (7.12–7.42)
	2.40 (2.12–2.68)	**0.21 (0.19–0.23)**	**0.34 (0.30–0.38)**	**0.71 (0.63–0.80)**	**3.74 (3.71–3.77)**	**7.39 (7.29–7.49)**
1923	2.05 (2.04–2.06)	0.20 (0.19–0.20)	0.34 (0.33–0.34)	0.71 (0.70–0.71)	3.59 (3.58–3.59)	6.89 (6.88–6.90)
	1.99 (1.98–2.00)	**0.20 (0.19–0.20)**	**0.33 (0.32–0.33)**	**0.61 (0.60–0.62)**	**3.73 (3.72–3.73)**	**6.86 (6.85–6.86)**
1949	2.38 (1.92–2.84)*	0.24 (0.19–0.29)*	0.41 (0.33–0.49)*	0.81 (0.65–0.97)*	3.78 (3.48–4.06)*	7.62 (6.40–8.86)*
	1.80 (1.70–1.90)	**0.18 (0.17–0.19)**	**0.31 (0.29–0.32)**	**0.56 (0.53–0.59)**	**3.74 (3.65–3.83)**	**6.60 (6.28–6.92)**
2000	1.58 (1.56–1.60)	0.15 (0.14–0.15)	0.25 (0.24–0.25)	0.60 (0.59–0.61)	3.74 (3.43–4.05)	6.33 (5.92–6.74)
	1.64 (1.52–1.76)	**0.16 (0.15–0.17)**	**0.28 (0.26–0.30)**	**0.51 (0.47–0.55)**	**3.80 (3.78–3.82)**	**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.

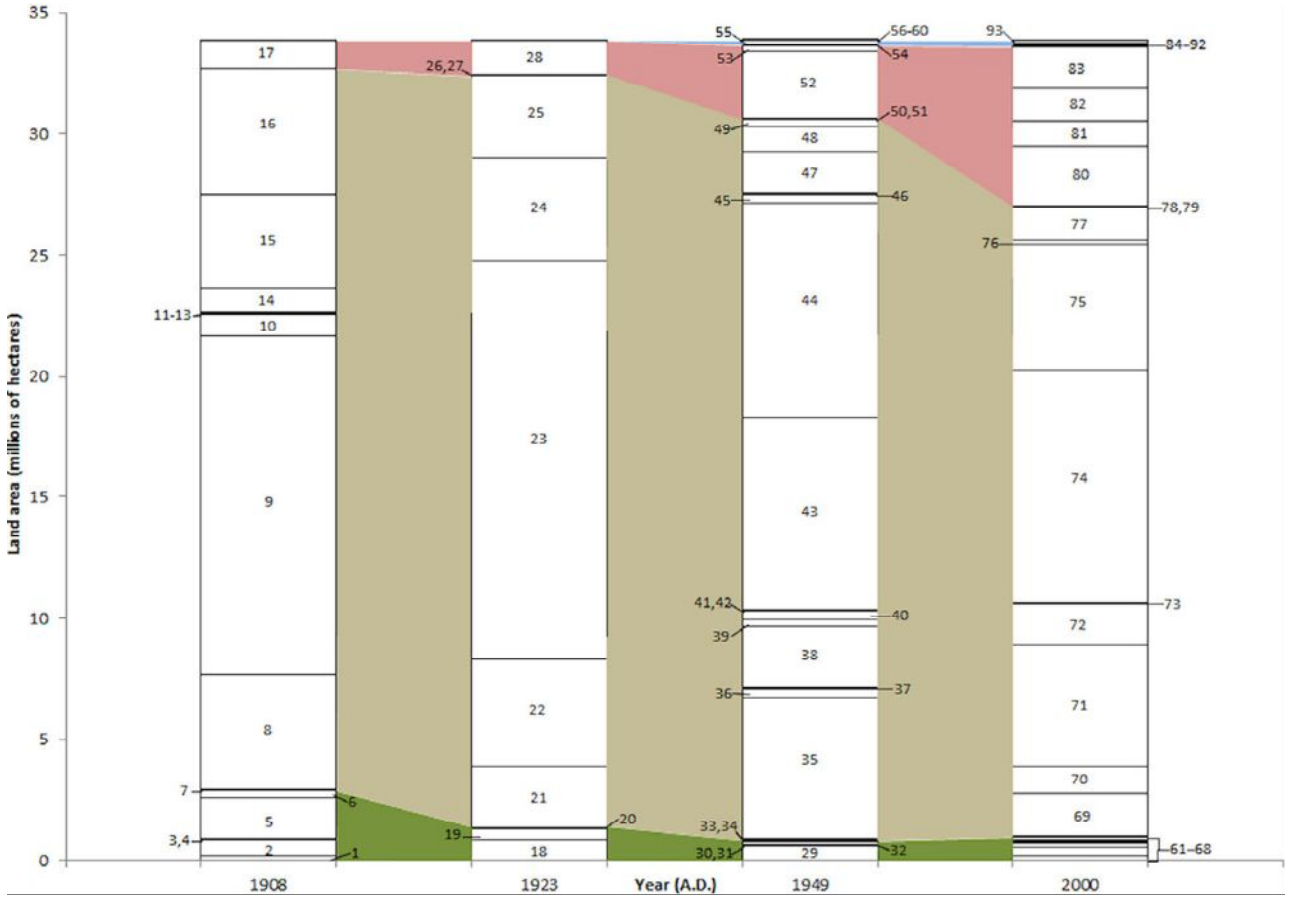


Fig. 3 Four harmonized land use categories (forest, green; savanna spectrum, brown; crop, red; other, blue) showing LULCC for the Eastern Arc Mountain watershed between 1908 and 2000. Also indicated are the original land use categories (white) and how they were harmonized (for key to numbers, see Table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

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 subsample 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 subsample 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 harmonized 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 (Fig. 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 (harmonized 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 (Fig. 4).

For the subsample of nine protected areas where data on pre- and postprotection 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 3061 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 harmonized categories) to 6.3 (5.9–6.7) Pg C in 2000 (6.4 [6.3–6.4]), a decline of 0.9

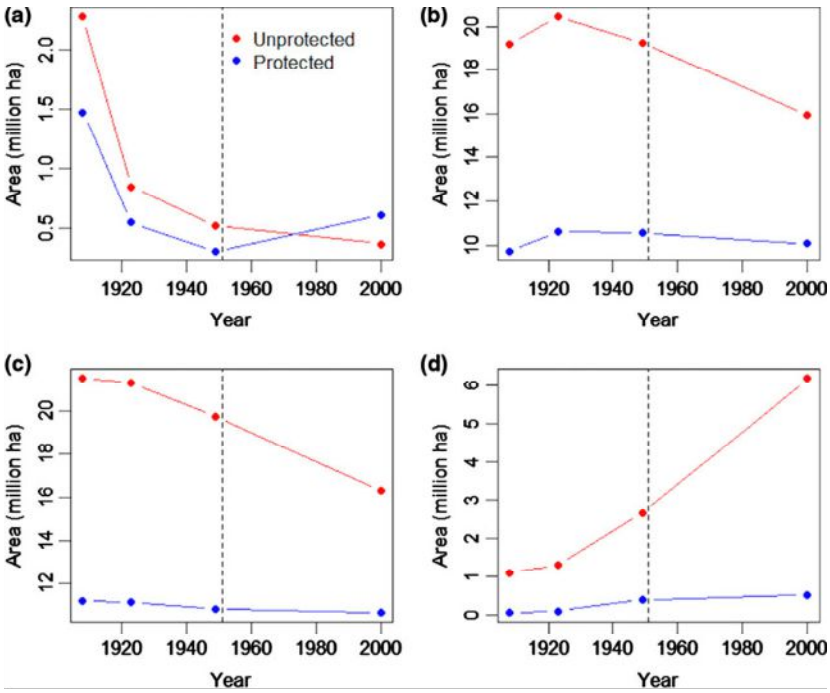


Fig. 4 The trend in LULCC between 1908 and 2000 for the EAM watershed: land covers are separated into (a) forest; (b) savanna; (c) forest and savanna combined; and (d) crop. Land covers currently within legally protected areas are indicated by blue lines and unprotected areas in red. The weighted mean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

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

			1908–1923		1949–2000	
Name	Area (ha)	Date established	Rate of change in forest area per total area (ha ha^{-1} yr^{-1})	Rate of change in total carbon storage (Mg ha^{-1} yr^{-1})	Rate of change in forest area per total area (ha ha^{-1} yr^{-1})	Rate of change in total carbon storage (Mg ha^{-1} yr^{-1})
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	5913	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	4562	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 Forest Reserve	17 481	1930	0.0197	4.35 (3.84 to 4.52)	0.0086	2.15 (2.14 to 7.06)
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)

(0.4–1.5) Pg C (13%; Figs 2, 3 and 5; Table 1), or 1.0 (0.9–1.2) Pg C (14%) using harmonized categories. The committed carbon emission was over fourfold 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 harmonized values) than the second half (4.3 [−2.9 to 11.6] Tg C yr^{-1} between 1949 and 2000 using harmonized 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; Fig. 5; Table 1) or 0.8 [0.4–1.2] Pg C (using harmonized categories) between 1908 and 2000; similarly dominated by committed emission from the first half of the twentieth century (14.6 [5.4–23.9] 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 subsample 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 (0.88–0.99) 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 mountain-

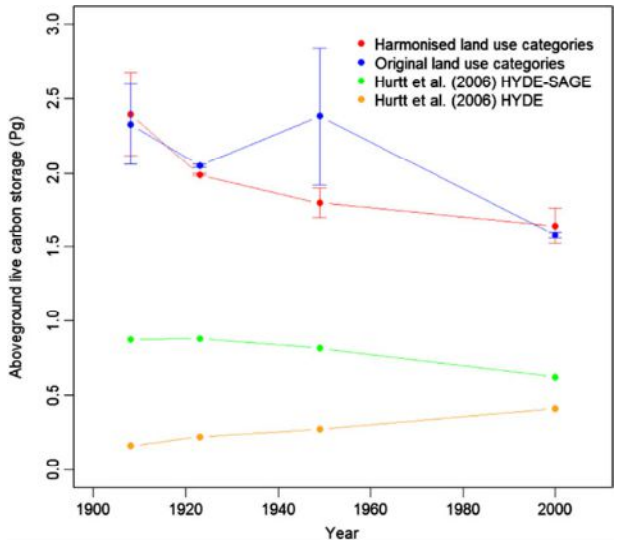


Fig. 5 The change in aboveground live carbon storage (±95% CI) within the Eastern Arc Mountain watershed during the 20th century; comparing our results to modelled outputs from HYDE and HYDE-SAGE (Hurtt *et al.*, 2006).

ous 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 (Newmark, 2002; Hall *et al.*, 2009). Historiographical studies also support our results and suggest that additional LULCC occurred prior to 1908 (see Appendix S2). 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 (Iliffe, 1971; Börjeson, 2004). 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 Appendix S2), 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 (Fig. 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% (7000 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 (Fig. 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 subsample 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 subsample 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; Laurance *et al.*, 2012; Pfeifer *et al.*, 2012; Green *et al.*, 2013). 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 underestimate 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 (Meyfroidt *et al.*, 2013; Coetzee *et al.*, 2014).

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.*, 2012, 2014), but larger than most globally derived estimates [Baccini *et al.* (2008, 2012), 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 (Fig. 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 postprocessing) 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 (Figs 1 and 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 to 14 km), 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, harmonized 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; Shantz & Marbut, 1923; Gillman, 1949) 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: (1) such shifts in classification are largely avoided when using our broader harmonized land cover categories; and (2) 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 his-

torical 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 criticized in the literature for the broad land cover categories used during the mapping process. Michelmore (1934) felt that land covers grouped together by Shantz & 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% (Newmark, 2002; Hall *et al.*, 2009). 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 postprocessing. 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 harmonized 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; Shantz & Marbut, 1923; Gillman, 1949, HTSL, 1997; 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 0.01–0.08 Pg 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 fertilization 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; Pan *et al.*, 2011; Mitchard & Flintrop, 2013). 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 fivefold. 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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References

Ahrends A, Burgess ND, Milledge SAH *et al.* (2010) Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proceedings of the National Academy of Sciences*, **107**, 14556–14561.

Alcamo J, Schaldach R, Koch J, Kölking C, Lapola D, Priess J (2011) Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa. *Environmental Modelling & Software*, **26**, 1017–1027.

Andam KS, Ferraro PJ, Pfaff A, Sanchez-Azofeifa GA, Robalino JA (2008) Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the National Academy of Sciences*, **105**, 16089–16094.

Baccini A, Laporte N, Goetz SJ, Sun M, Dong H (2008) A first map of tropical Africa's above-ground biomass derived from satellite imagery. *Environmental Research Letters*, **3**, 045011.

Baccini A, Goetz SJ, Walker WS *et al.* (2012) Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2**, 182–185.

Boesen J, Havnevik K, Koponen J, Odgaard R (1986) *Tanzania: Crisis and Struggle for Survival*. Scandinavian Institute of African Studies, Uppsala.

Bombelli A, Henry M, Castaldi S *et al.* (2009) An outlook on the Sub-Saharan Africa carbon balance. *Biogeosciences*, **6**, 2193–2205.

Börjeson L (2004) *A History Under Siege – Intensive Agriculture in the Mbulu Highlands, Tanzania, 19th Century to the Present*. Department of Human Geography, Stockholm University, Stockholm, Sweden.

Brown SL, Pearson T, Moore N, Parveen A, Ambagis S, Shoch D (2005) *Impact of Selective Logging on the Carbon Stocks of Tropical Forests: Republic of Congo as a Case Study*. Winrock International, Arlington.

Burgess ND, Butynski TM, Cordeiro NJ *et al.* (2007) The biological importance of the Eastern Arc Mountains of Tanzania and Kenya. *Biological Conservation*, **134**, 209–231.

Coetzee BWT, Gaston KJ, Chown SL (2014) Local scale comparisons of biodiversity as a test for global protected area ecological performance: a meta-analysis. *PLoS One*, **9**, e105824.

Cowles HC (1910) Review of Die Vegetation der Erde. IX. Die Pflanzenwelt Afrikas insbesondere seiner tropischen Gebiete by A. Engler; O. Drude; Die Vegetation der Erde. X. Grundzüge der Pflanzenverbreitung in den Karpathen by A. Engler; O. Drude; F. Pax. *Botanical Gazette*, **50**, 468–470.

Defries R, Hansen A, Newton A, Hansen M (2005) Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecological Applications*, **15**, 19–26.

Earth Tools (2010) [Online]. Available at: http://www.earthtools.org/ (accessed 23 February 2010).

Ellis EC, Klein Goldewijk K, Siebert S, Lightman D, Ramankutty N (2010) Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, **19**, 589–606.

Engler A (1908–10) Die Pflanzenwelt Afrikas; insbesondere seiner tropischen Gebiete. Vegetation der Erde. *Band Allgemeiner Uberblick Uber Pflanzenwelt Afrikas und Ihre Existenzbedingungen*, **9**, 1–460.

Geldmann J, Barnes M, Coad L, Craigie ID, Hockings M, Burgess ND (2013) Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, **161**, 230–238.

Gillman C (1949) Tanganyika territory – vegetation types. *Geographical Review*, **Vol 39**, 7–37.

Gower ST (2003) Patterns and mechanisms of the forest carbon cycle. *Annual Review of Environment and Resources*, **28**, 169–204.

Grace J, Mitchard E, Gloor E (2014) Perturbations in the carbon budget of the tropics. *Global Change Biology*, **20**, 3238–3255.

Grainger A (2008) Difficulties in tracking the long-term global trend in tropical forest area. *Proceedings of the National Academy of Sciences*, **105**, 818–823.

Green JMH, Larrosa C, Burgess ND *et al.* (2013) Deforestation in an African biodiversity hotspot: extent, variation and the effectiveness of protected areas. *Biological Conservation*, **164**, 62–72.

Hall B, Motzkin G, Foster DR, Syfert M, Burk J (2002) Three hundred years of forest and land-use change in Massachusetts, USA. *Journal of Biogeography*, **29**, 1319–1335.

Hall J, Burgess ND, Lovett J, Mbilinyi B, Gereau RE (2009) Conservation implications of deforestation across an elevational gradient in the Eastern Arc Mountains, Tanzania. *Biological Conservation*, **142**, 2510–2521.

Hansen MC, Loveland TR (2012) A review of large area monitoring of land cover change using Landsat data. *Remote Sensing of Environment*, **122**, 66–74.

Hansen MC, Potapov PV, Moore R *et al.* (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–853.

Houghton RA (1994) The worldwide extent of land-use change. *BioScience*, **44**, 305–313.

Houghton RA, House JI, Pongratz J *et al.* (2012) Carbon emissions from land use and land-cover change. *Biogeosciences*, **9**, 5125–5142.

HTSL (1997) National Reconnaissance Level Land Use and Natural Resources Mapping Project. Final Report to the Ministry of Natural Resources and Tourism, Tanzania. In: *Forest Resources Management Project*. Hunting Technical Services Limited.

Hurlbert SH (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs*, **54**, 187–211.

Hurtt GC, Frolking S, Fearon MG *et al.* (2006) The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biology*, **12**, 1208–1229.

Iliffe J (1971) Agricultural change in modern Tanganyika: an outline history. In: *Issue 10 of Historical Association of Tanzania* (ed. Historical Association of Tanzania), pp. 1–47. East African Publishing House, Nairobi.

IUCN, UNEP-WCMC (2015) *The World Database on Protected Areas (WDPA)*. [Online]. UNEP-WCMC, Cambridge, UK. Available at: http://www.protectedplanet.net/ (accessed 5 May 2015).

Jenkins CN, Joppa L (2009) Expansion of the global terrestrial protected area system. *Biological Conservation*, **142**, 2166–2174.
Joppa LN, Pfaff A (2009) High and far: biases in the location of protected areas. *PLoS One*, **4**, e8273.
Kaplan JO, Krumhardt KM, Ellis EC, Ruddiman WF, Lemmen C, Goldewijk KK (2011) Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene*, **21**, 775–791.
Kay AU, Kaplan JO (2015) Human subsistence and land use in sub-Saharan Africa, 1000 BC to AD 1500: a review, quantification, and classification. *Anthropocene*, **9**, 14–32.
Klein Goldewijk K, Verburg P (2013) Uncertainties in global-scale reconstructions of historical land use: an illustration using the HYDE data set. *Landscape Ecology*, **28**, 861–877.
Krausmann F, Erb K-H, Gingrich S *et al.* (2013) Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences*, **110**, 10324–10329.
Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, **28**, 205–241.
Laurance WF, Carolina Useche D, Rendeiro J *et al.* (2012) Averting biodiversity collapse in tropical forest protected areas. *Nature*, **489**, 290–294.
Lewis SL, Maslin MA (2015) Defining the anthropocene. *Nature*, **519**, 171–180.
Lewis SL, Lopez-Gonzalez G, Sonke B *et al.* (2009) Increasing carbon storage in intact African tropical forests. *Nature*, **457**, 1003–1006.
Leyk S, Boesch R, Weibel R (2005) A conceptual framework for uncertainty investigation in map-based land cover change modelling. *Transactions in GIS*, **9**, 291–322.
Lu GY, Wong DW (2008) An adaptive inverse-distance weighting spatial interpolation technique. *Computers & Geosciences*, **34**, 1044–1055.
Meiyappan P, Jain A (2012) Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years. *Frontiers of Earth Science*, **6**, 122–139.
Meyfroidt P, Lambin EF, Erb K-H, Hertel TW (2013) Globalization of land use: distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability*, **5**, 438–444.
Michelmore APG (1934) Letter to the Editor: vegetation succession and regional surveys, with special reference to tropical Africa. *Journal of Ecology*, **22**, 313–317.
Mitchard ETA, Flintrop CM (2013) *Woody encroachment and forest degradation in sub-Saharan Africa's woodlands and savannas 1982–2006.*
Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853–858.
Newmark WD (2002) *Conserving Biodiversity in East African Forests: A Study of the Eastern Arc Mountains*. Springer, Heidelberg.
NPW (2015) National Parks Worldwide. [Online]. Available at: http://www.nationalparks-worldwide.info/ (accessed 5 May 2015).
Pan Y, Birdsey RA, Fang J *et al.* (2011) A large and persistent carbon sink in the world's forests. *Science*, **333**, 988–993.
Pfeifer M, Burgess ND, Swetnam RD, Platts PJ, Willcock S, Marchant R (2012) Protected areas: mixed success in conserving east Africa's evergreen forests. *PLoS One*, **7**, e39337.
Pfeifer M, Platts PJ, Burgess ND, Swetnam RD, Willcock S, Lewis SL, Marchant R (2013) Land use change and carbon fluxes in East Africa quantified using earth observation data and field measurements. *Environmental Conservation*, **40**, 241–252.
Platts PJ, Burgess ND, Gereau RE *et al.* (2011) Delimiting tropical mountain ecoregions for conservation. *Environmental Conservation*, **38**, 312–324.
Platts PJ, Gereau RE, Burgess ND, Marchant R (2013) Spatial heterogeneity of climate change in an Afromontane centre of endemism. *Ecography*, **36**, 518–530.
Putz FE, Redford KH (2010) The importance of defining 'forest': tropical forest degradation, deforestation, long-term phase shifts, and further transitions. *Biotropica*, **42**, 10–20.
Ramankutty N, Gibbs HK, Achard F, Defries R, Foley JA, Houghton RA (2007) Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biology*, **13**, 51–66.
Rovero F, Menegon M, Fjeldså J *et al.* (2014) Targeted vertebrate surveys enhance the faunal importance and improve explanatory models within the Eastern Arc Mountains of Kenya and Tanzania. *Diversity and Distributions*, **20**, 1438–1449.
Saatchi SS, Harris NL, Brown S *et al.* (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, **108**, 9899–9904.
Shantz HL, Marbut CF (1923) The vegetation and soils of Africa. *American Geographical Society of New York*, **13**, 1–263.
Sloan S, Pelletier J (2012) How accurately may we project tropical forest-cover change? A validation of a forward-looking baseline for REDD. *Global Environmental Change*, **22**, 440–453.
Swetnam RD, Fisher B, Mbilinyi BP *et al.* (2011) Mapping socio-economic scenarios of land cover change: a GIS method to enable ecosystem service modelling. *Journal of Environmental Management*, **92**, 563–574.
Tucci M, Giordano A (2011) Positional accuracy, positional uncertainty, and feature change detection in historical maps: results of an experiment. *Computers, Environment and Urban Systems*, **35**, 452–463.
Verburg PH, Neumann K, Nol L (2011) Challenges in using land use and land cover data for global change studies. *Global Change Biology*, **17**, 974–989.
Wang Y, Bonynge G, Nugranad J *et al.* (2003) Remote sensing of mangrove change along the Tanzania coast. *Marine Geodesy*, **26**, 35–48.
van der Werf GR, Morton DC, DeFries RS *et al.* (2009) CO2 emissions from forest loss. *Nature Geoscience*, **2**, 737–738.
Whitlow R (1985) Vegetation mapping in Africa: a critique. *Singapore Journal of Tropical Geography*, **6**, 64–77.
Willcock S, Phillips OL, Platts PJ *et al.* (2012) Towards regional, error-bounded landscape carbon storage estimates for data-deficient areas of the world. *PLoS One*, **7**, e44795.
Willcock S, Phillips O, Platts P *et al.* (2014) Quantifying and understanding carbon storage and sequestration within the Eastern Arc Mountains of Tanzania, a tropical biodiversity hotspot. *Carbon Balance and Management*, **9**, 2.
World Bank (2010) World Bank Data Finder. [Online] World Bank. Available at: http://data.worldbank.org/ (accessed 24 February 2010).

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. The 1908 land cover map: (a) shows the original map image, with our study area illustrated by a red outline; (b) shows the error corrected digitised map using original land cover categories; and (c) shows the error corrected digitised map using harmonised land cover categories.
Figure S2. The 1923 land cover map: (a) shows the original map image, with our study area illustrated by a red outline; (b) shows the error corrected digitised map using original land cover categories; and (c) shows the error corrected digitised map using harmonised land cover categories.
Figure S3. The 1949 land cover map: (a) shows the original map image, with our study area illustrated by a red outline; (b) shows the error corrected digitised map using original land cover categories; and (c) shows the error corrected digitised map using harmonised land cover categories.
Figure S4. The 2000 land cover map: (a) shows the error corrected digitised map using original land cover categories; and (b) shows the error corrected digitised map using harmonised land cover categories.

Figure S5. The modelled population of Tanzania between 1900 and 2000 (modelled population = −305287.934660931 + (477.954124067276 × Year) + (−0.249447122059476 × Year^2) + (0.0000434002810672193 × Year^3) [$P < 0.001$]).
Appendix S1. Geo-referencing and digitization procedure.
Appendix S2. History of forest protection for timber production and conservation in Tanzania.
Table S1. Land cover categories originally reported in maps and their coercion into the harmonised land cover categories (Forest, Savanna-spectrum, Crop, Other).
Table S2. The location of the published and unpublished data utilised for the creation of the carbon values and the land use categories and vegetation groups they were applied to.
Table S3. The derivation of final soil carbon values and 95% CIs.
Table S4. The median weighted total carbon values and 95% confidence limits for the study region.
Table S5. The key to the original land cover categories shown in Fig. 3.