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Richer histories for more relevant policies: 42 years of tree cover loss and gain in Southeast Sulawesi, Indonesia

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Abstract

Understandings of contemporary forest cover loss are critical for policy but have come at the expense of long-term, multidirectional analyses of land cover change. This is a critical gap given (i) profound reconfigurations in land use and land control over the past several decades and (ii) evidence of widespread 'woodland resurgence' throughout the tropics. In this study, we argue that recent advancements within the field of land change science provide new opportunities to address this gap. In turn, we suggest that multidecadal and multidirectional analyses of land cover change can facilitate richer social analyses of land cover change and more relevant conservation policies and practice. Our argument is grounded in a case study from Southeast Sulawesi, Indonesia. Using a novel analytical platform, Google Earth Engine, and open access to high-quality Landsat data, we map land cover change in Southeast Sulawesi, Indonesia, from 1972 to 2014. We find that tree cover loss constitutes the single largest net change over the period 1972–2014 but that gross rates of tree cover gain were three times higher than gross loss rates from 1972 to 1995 and equivalent to loss rates from 1995 to 2014. We suggest the smallholder tree crop economy likely produced both forest loss and *Imperata* grassland restoration in this region. This case points to the need to expand rather than collapse the baselines used to study carbon and biodiversity change in tropical regions. It also demonstrates the possible utility of applying such methods to other regions.

Keywords: Google Earth Engine, history, Indonesia, land cover change, policy

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Introduction

Dramatic changes in land use, land access and land control are fundamentally reconfiguring the social and natural fabric of rural areas throughout the Global South. The past few decades have seen a widespread shift from food to cash crop cultivation (Hecht, 2010), from relatively more centralized to relatively more decentralized forms of natural resource governance (McCarthy, 2004), and, for many people, from livelihood strategies primarily oriented around agricultural production to livelihood strategies constituted by a diversity of income sources, many of which are earned off-farm (Bryceson, 2002; Rigg, 2006).

These developments have profound and contradictory implications for land use and land cover change (LULCC) in tropical regions. Although the expansion of export-oriented commodities, particularly oil palm, soy and cattle, has been associated with significant forest cover loss (Gibbs *et al.*, 2010; Carlson *et al.*, 2013), there is evidence that many landscapes have been revegetated as smallholder-driven tree crop markets have formed. The development of off-farm economies has facilitated revegetation in some scenarios, not necessarily because land is abandoned, but because smallholders' land uses change in relation to other pursuits (Angelsen & Kaimowitz, 2001; Rudel *et al.*, 2002; Lambin & Meyfroidt, 2010). For example, Hecht & Saatchi (2007) found that the infusion of cash into rural areas via remittances from family members working internationally has supported widespread 'woodland resurgence' throughout El Salvador. Significant evidence now suggests that forest recovery is a more definitive of contemporary land cover changes in certain parts of Latin America and Asia than is forest clearance (Rudel *et al.*, 2002; Chazdon, 2014; Hecht, 2014).

Despite the diversity of change trajectories underway, work within the fields of remote sensing and land systems science continues to focus on refining estimates of forest cover loss, particularly recent rates of tropical forest cover loss. Information on either loss or gain over multidecadal time periods remains limited (for a valuable exception, see Gibbs *et al.*, 2010). Information on tropical tree cover gain historically is particularly lacking. We found very few studies that documented tree cover gain in the tropics and could not find any that did so before 1990. Only two of the top ten most cited studies on land cover change in Indonesia, the site of this study, extend beyond a 15-year time range, with very little work utilizing Landsat data that predates 1990. A valuable recent contribution documents four decades of forest cover loss for all of Borneo using satellite data from 1973, but does not include information on tree cover gain processes (Gaveau *et al.*, 2014).

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Limited information on long-term change limits both social and environmental analysis. In the Indonesian context, the most recent 15 years do not include the 1997–1998 fall of the Suharto dictatorship which set off a wave of changes in forest policy that still shape developments in forested landscapes (McCarthy, 2004). It does not capture land cover change associated with the demarcation of state forest reserves through the 1970s and 1980s, or the initial formation of timber, oil palm and cacao markets (Potter & Lee, 1998; Barr *et al*., 2002). It also does not capture the development processes which reordered rural societies and landscapes throughout the Suharto regime, including planned and spontaneous migrations, infrastructural developments, forced resettlements and a reorientation of many smallholder agricultural systems around more sedentarized, mechanized and input-dependent approaches (Li, 2007; Dove, 2011).

A fixation on recent forest loss also impedes conservation policy and practice. This is true in the broadest sense. A fixation on forests, particularly tropical forests, obscures the value of other anthropogenic environments (including working agroforests, old-growth grasslands, savannas and settlements) (Hecht, 2010). It is also true with more narrow reference to contemporary debates (e.g., the land sharing vs. land sparing literature). To significant extent, these debates presume the original baseline ecosystem against which tropical agriculture plays out has been a primary tropical forest. There is a need to expand our sense of the actual diverse contexts in which contemporary changes have unfolded by examining broader geographies and deeper histories.

Three recent advancements within land change science make it increasingly possible to fill these gaps, capturing gain and loss across large regions and multidecadal time periods. First, over the past ten years, there has been an unprecedented expansion in access to remotely sensed imagery. Landsat imagery was previously acquired on an at-cost and per-scene basis, a limitation which disincentivized long-term historical analyses in regions of little apparent forest cover change. In 2008, the USGS began to provide free access to all satellite imagery (Wulder *et al*., 2008, 2012). Analyses reliant on large stacks of Landsat imagery are newly feasible.

Second, in connection with the release of Landsat archives, the National Aeronautics and Space Administration (NASA) has developed the Global Land Survey (GLS) databases. The development of these databases for each of five reference years (1975, 1990, 2000, 2005 and 2010) was based on realizations that large-scale monitoring of land cover change depended on collections of satellite imagery that had been consistently corrected for radiometric and geometric distortions specific to the platform and sensor utilized in capturing the image (Hansen & Loveland, 2012). Landsat satellite imagery dates to the 1970s. Until recently, however, working with historical imagery required investment in complicated image correction procedures and created additional computing and storage burdens. The development of the 1975 dataset means that analysts now have access to high-quality historical imagery with limited need for preprocessing or prescreening.

Third, tremendous computing capacity and data storage leaps have been effected by the development of a cloud-based platform for earth observation analyses, Google Earth Engine (GEE). GEE hosts the entire Landsat data archive (including the GLS datasets) and stores these datasets within Google's data centers. GEE provides tools and an application program interface for summoning, processing and analyzing this imagery via Python and JavaScript. To reduce the processing time associated with heavy computing tasks, all analyses are also run in parallel across many machines in Google's cloud-based processing platform. These advancements make it possible to easily summon and analyze petabytes of data on the fly. This capacity enables analysis over long periods of time and across large areas. The potential of these technologies is evidenced by the work of Hansen *et al*., 2013, who piloted the use of GEE to produce global maps of tree cover loss and gain from 2000 to 2012 using high-resolution Landsat data.

In this study, we utilize these capacities to map tree cover loss and gain over a 42-year period in Southeast Sulawesi, Indonesia. We focus on Southeast Sulawesi for two reasons. First, Sulawesi has been the site of one of the most significant smallholder-led tree crop booms globally since the 1980s (Badan Pusat Statistik Sulawesi Tenggara, 2014; FAOSTAT, http://faostat.fao.org/). In this regard, Southeast Sulawesi speaks to many other regions throughout the tropics now organized around export-oriented smallholder tree crop economies. Second, as elsewhere in the tropics, most conservation attention has focused on environmental changes in forested lands. A longer history of land cover change in this region may inform other important sites of analysis and advocacy.

In this study, we aim to understand (i) historical rates of change and (ii) the extent to which tree cover loss has been coincident with tree cover gain. We do this by analyzing Landsat imagery from 1972 to 2014 using GEE. Our analysis is structured as follows. First, we outline the materials and methods that guide our land cover change analysis. Second, we present our results on 42 years of tree cover loss and gain in Southeast Sulawesi. Third, we synthesize these findings and analyze them in relation to this region's recent agrarian history. Fourth, we discuss the policy import of our conclusions in Sulawesi and beyond, suggesting the value of multidecadal and multidirectional land cover change analyses in other regions.

Our argument, in brief, is that an analysis of 42 years of land cover change in Southeast Sulawesi demonstrates significant tree cover gain as well as loss. This, we argue, points to the need to better understand and document the relatively more silent histories of tree cover gain also driving processes of social and environmental change throughout the tropics.

Materials and methods

Study area

The entire province of Southeast Sulawesi was used as our boundary for the land cover change analysis (Fig. 1). This includes Muna and Buton, two islands off the southern coast of the provincial mainland. Southeast Sulawesi is characterized by the same wet–dry climactic pattern characteristic of many tropical regions, and a diversity of land covers which range from peat swamp forest, to mangrove forest, to lowland forest to montane and karst forest (Whitten *et al.*, 1987).

Definitions

Tree cover is defined as vegetation >5 m in height and was classified into three categories per 60 m by 60 m pixel, an area corresponding to 0.36 ha: (i) <25% tree cover; (ii) 25–75% tree cover; and (iii) >75% tree cover. These categories represent our focus on assessing net tree cover change over time. We acknowledge that tree cover is only one of many variables relevant to a description of land cover. These land cover categories were also selected because without historical training data, it was considered impossible to accurately classify Landsat MSS/TM data more discretely. Loss and gain statistics represent pixels moving between tree cover categories across time periods (Table 1). These statistics do not differentiate between permanent and temporary loss or gain and refer to changes in land cover rather than land use.

Data sources and satellite image preprocessing

This analysis was conducted using Landsat satellite data. Our 1972 analyses used seven Landsat MSS scenes from the GLS 1975 image database: six of which were collected in the year 1972 and one from 1973. These images were provided preprocessed, that is, orthorectified and precalibrated by converting the raw values of pixels using top-of-atmosphere reflectance values. This provides systematic radiometric and geometric accuracy (within 250 meters for low-relief areas) (Hansen & Loveland, 2012).

For the 1995 and 2014 reference years, we used multidate image compositing for time series analysis to circumvent issues of cloud cover which often plague the tropics. This approach uses median pixel values for an area over multiple observations within a given time range. In data-poor environments such as Indonesia, creating relatively gap-free maps over large areas requires composites constructed with images from more than one year (Hansen *et al.*, 2008; Broich *et al.*, 2011; Potapov *et al.*, 2012). For this reason, 1995 and 2014 composite images were collected over two-two-year periods (1994–1996 and 2013–2015, respectively) utilizing over 150 individual images. The high data computing and storage demands from processing large stacks of imagery were facilitated by automated Landsat data processing and mosaicing in GEE (Hansen *et al.*, 2013). Composites were then prepared for analysis by (i) resampling images to 60-m resolution; (ii) converting raw digital values to top-of-atmosphere reflectance using values computed by Chander *et al.* (2009) (this calibration corrects for the amount of reflectance measured by different Landsat sensors and enables comparison between images from different time periods or satellites); and (iii) screening imagery for clouds. No prioritization was given to growing season imagery as there are no senescence or dormant seasonal periods in the study region.

Two other geospatial data layers aided analysis. Elevation data were generated at 90-m resolution using data from the Shuttle Radar Topography Mission (http://eros.usgs.gov/). Soil data were prepared by Cannon *et al.* (2007) based on maps produced by the Indonesian government's Pusat Penelitian Geologi (Geology Research Center) in Bandung, Indonesia, and consist of four broad classes, three of which (alluvial, limestone and mafic) have a known effect on tree distribution.

Training and classification

The land cover types in the 1972–1973, 1994–1996 and 2013–2015 (hereafter 1972, 1995 and 2014, respectively) were classified using a supervised support vector machine (SVM)

Fig. 1 Map of Indonesia, with Southeast Sulawesi Province highlighted.

Table 1 Land cover and land cover change typologies. These descriptors depict the three classes identified through this analysis. Descriptors have been selected to help us present results simply and directly. We use the phrase 'tree-dominant' to reflect the fact that not all land held in >75% tree cover is forest and that land held in other categories may also be considered forest in many cases. We acknowledge that land in <25% tree cover can represent a range of land covers, from old-growth grasslands to settlements to irrigated rice fields

Classification	Descriptor
>75% tree cover	Tree-dominant
25–75% tree cover	Mixed
<25% tree cover	Tree-sparse
From <25% to >25% or from 25–75% to >75%	Tree cover gain
From >75% to <75% or from 25–75% to <25%	Tree cover loss

algorithm that utilized nonparametric classifiers. SVM algorithms have been shown to perform well in places like Sulawesi where rugged topography often generates complex spectral dynamics as vegetation and illumination change with higher altitudes. SVM algorithms deal with this by fitting hyperplanes to different features guided by training samples (Kuemmerle *et al.*, 2008). SVM classification algorithms also excel at delineating forested from nonforested land covers (Huang *et al.*, 2008).

Each of the three time periods were separately trained and classified. Classifying change between time periods would involve classifying 27 different change categories (this analysis spanned three land cover classes and three time periods, meaning there are 3 × 3 × 3 possible directions of change). Given limitations in developing a representative training sample for each change class, we determined that a postclassification comparison was most appropriate for this analysis, that is, we assessed change *a-posteriori* after determining land cover in each image product separately. The training sample for each image was generated using human visual interpretation of a random sample of 5000 points across the entire study area. This number was selected based on past work which has demonstrated that classification accuracy tends to stabilize at roughly 500 points per class for an area the size of one Landsat scene (Kuemmerle *et al.*, 2009). QuickBird imagery was used to train human visual interpretation as were repeat field visits.

Validation

Validation was performed independently of mapping. For the 2014 Landsat composite image, QuickBird imagery from the time period 2013–2015 was randomly sampled, categorized and compared to classified products. Our pixel level accuracy was 90% across all three classes. Land cover classifications from 1972 and 1995 were assessed in two broad ways. First, archival maps were collected and qualitatively compared to the 1972 land cover classification. Data from this study were also compared to publicly accessible data on forest cover and forest cover change since 2000 (Cannon *et al.*, 2007; Miettinen *et al.*, 2011; Hansen *et al.*, 2013).

Results

Dominant changes from 1972 to 2014

The loss of tree-dominant lands (i.e., those in >75% tree cover) constituted the single largest net change over the entire study period, declining from an estimated 81.6% to an estimated 54.0% of all land cover in Southeast Sulawesi from 1972 to 2014. However, gross rates of tree cover gain were three times higher than gross tree cover loss rates from 1972 to 1995 and roughly equivalent to loss rates from 1995 to 2014 (Fig. 2, Table 2a,b).

Tree cover loss

Tree cover loss in regions of >75% tree cover constituted roughly 90% of all loss in both time periods with loss concentrated in relatively few subdistricts (*kecamatan)*. Over 50% of forest cover loss occurred in just 12 and 13 of 68 subdistricts for the time periods 1972–1995 and 1995–2014, respectively. Tree cover loss was also overwhelmingly concentrated in known areas of lowland alluvial forest (i.e., forests at <400 m elevation on fertile alluvial soils) (Table S1). Tree cover loss tended to expand outward from lowland alluvial valleys or inward from lower coastal regions.

Tree cover gain

Tree cover gain during both time steps was driven by an increase in tree cover on previously tree-sparse lands. Over the time period 1995–2014, only 28.0% of tree-sparse lands experiencing tree cover gain were tree-sparse because they had been cleared over the time period 1972–1995. In other words, most tree cover gain during the time period 1995–2014 occurred on landscapes that had been held in <25% tree cover since at least 1972. Tree cover gain on tree-sparse and mixed lands was also overwhelmingly concentrated in the lowlands, particularly on the limestone soils of Muna and Buton islands from 1972 to 1995 although more evenly dispersed across alluvial, intermediate and limestone soil lowland zones from 1995 to 2014 (Table S1).

Discussion

Overview of land cover change analysis

In this paper, we document a much longer trajectory of gain and loss than ever before presented for this region. By utilizing Landsat MSS imagery from the GLS 1975 collection and wall-to-wall mapping with over 150 Landsat ETM+/TM images within Google Earth Engine, we document 42 years of change across 78.9%,

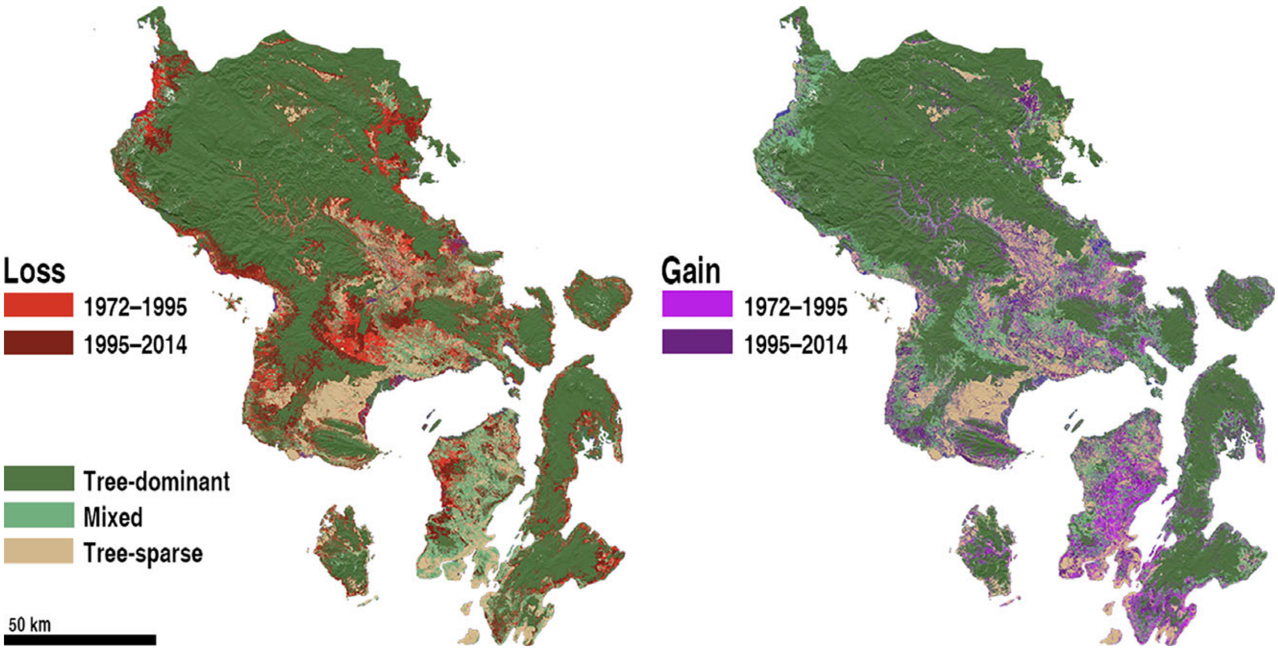

Fig. 2 Loss and gain from 1972 to 1995 and 1995 to 2014. Most tree cover loss occurred in areas previously dominated by tree cover (i.e., >75% coverage). Most tree cover gain during the time period 1995–2014 occurred on landscapes that had been held in <25% tree cover since before 1972.

Table 2 Tree cover loss and gain, 1972–2014. (a) Loss (b) Gain

	1972–1995				1995–2014			
	TD* to TS*	TD* to mixed	Mixed to TS*	All	TD* to TS*	TD* to mixed	Mixed to TS*	All
(a)								
Area loss (km^2)	944.2	1828.7	283.2	***3056.0***	801.4	4767.6	941.7	***6510.7***
Gross loss rate	0.16%	0.30%	1.10%	***0.48%***	0.17%	1.03%	1.05%	***1.17%***
Net loss rate	0.13%	0.25%	0.03%	***0.41%***	0.12%	0.72%	0.14%	***0.99%***
	1972–1995				1995–2014			
	TS* to mixed	TS* to TD*	Mixed to TD*	All	TS* to mixed	TS* to TD*	Mixed to TD*	All
(b)								
Area gain (km^2)	1329.5	675.2	252.5	***2257.1***	1877.6	109.0	230.8	***2217.4***
Gross gain rate	1.20%	0.61%	0.98%	***1.65%***	1.80%	0.10%	0.24%	***1.11%***
Net gain rate	0.18%	0.09%	0.03%	***0.30%***	0.28%	0.02%	0.03%	***0.34%***

All rates reflect an average yearly rate of change. Net rates of change refer to change relative to all categories of classified land. Gross rates of change are relative to prior classifications. For example, gross gain rates from tree-sparse to mixed land are calculated by dividing gain experienced over all land held in tree-sparse cover in either 1972 or 1995, respectively.
The numbers in bold italics refer to rates calculated across all categories. Gross loss rate across all categories in 1995 for example is derived by dividing loss across all categories over all land held in TD or mixed land as of 1972. Net loss rate across all categories in 1995 is derived by dividing loss across all categories over all land it was possible to classify during this time period. Similar is true of gross gain rates calculated in aggregate. *TD in this table refers to tree-dominant lands, that is, those with >75% tree cover and TS refers to tree-sparse lands, that is, those with <25% tree cover.

88.1% and 99.7% of the province's geographical extent in the years 1972, 1994 and 2014, respectively. Our results suggest significant loss of lowland forest since 1972. They demonstrate, however, that tree cover gain has also been an important component of ecosystem transformation.

These findings are broadly comparable with recent analyses of change reliant on wall-to-wall mapping or subsampling techniques. Comparable with our observation of a 0.99% net loss rate from 1995 to 2014, Miettinen *et al*. (2011) found an average annual rate of 1.1% and 1.2% forest cover loss in Sulawesi overall and in lowland evergreen forests, respectively, from 2000 to 2010. Similarly, our findings of loss and gain follow the geographic contours of those observed by Hansen *et al.* (2013) over a similar but shorter time period, 2000–2013. We report higher rates of tree cover loss than do Hansen *et al.* (2013) but this is logical given the inclusion of 1995–2000 in our analysis. This period included the Asian financial crisis, the fall of Suharto and the onset of decentralization – all of which shaped profound upheaval in Indonesian forests and significant forest clearance (Barr *et al*., 2002; Hansen *et al*., 2005; McCarthy, 2004).

Social and political context

Beyond documenting the multiple trajectories of change shaping tropical landscapes, a second goal of this study was to suggest how longer histories of land cover change may also support richer analyses of (i) what drives LULCC and (ii) what such changes imply, socially and environmentally. We make this point by offering a preliminary interpretation of our findings with reference to the recent agrarian history of the province's mainland.

Through the 1970s and 1980s, Tolaki peoples dominant in mainland Southeast Sulawesi generally practiced a long-fallow version of swidden agriculture supplemented by livestock production, swamp fishing and forest production collection (Tarimana, 1989; de Jong, 2011). Forested landscapes were often deliberately burned as part of this livelihood system to stimulate grass growth for livestock and to attract deer which could be hunted (ibid; Henley, 2002). *Imperata* grasslands could also emerge from repeated swidden cultivation in the same area. Once established, *Imperata* grasslands were difficult to reincorporate into swiddening systems given the labor demands required to extract grass roots from the soil (Garrity *et al*., 1996). This ecological transition likely compelled whole settlements to shift to new areas (Henley, 2002). In other cases, secondary forests regrew when settlements were abandoned to fallow lands or to seek better fortune elsewhere. Lowland forests were preferred but highland forests were also occupied and cultivated, particularly in times of disease, warfare or political violence (de Jong, 2011). Even where not occupied, forest product extraction and exchange connected the highlands to the lowlands for centuries (de Jong, 2011; Sutherland, 2015).

Customary practices of diversified swidden agriculture – and attendant practices of settlement and resettlement – have by now fully disappeared from many regions. Forest extractions for timber have intensified. Swidden agriculture, particularly from the 1960s to 1980s, was forcibly discouraged by both official prohibitions and the burning of swiddeners' hillside settlements (Potter & Lee, 1998; unpublished data). Over 600 000 hectares of land were demarcated as state forests (Badan Pusat Statistik Sulawesi Tenggara, 2014), transferring use and ownership rights of these lands to the state and providing a juridical basis for excluding swidden agriculturalists from the forest (Peluso & Vandergeest, 2001). Many state forests, although nominally established for the sake of protection, have been used for logging and mining operations controlled by local elites with strong connections to the ruling regime (until 1998, Suharto's New Order dictatorship). In the lowlands, state development monies have supported the development of wet rice agriculture. Populations of transmigrants, typically poor, landless people from Java or Bali, were often allocated this land as a means of encouraging sedentarized agriculture and achieving rice self-sufficiency in Indonesia (in other regions, see, e.g., Li, 2007; Sunderlin & Resosudarmo, 1999).

Simultaneously, the smallholder agricultural economy has been reoriented around tree crop production, particularly cacao, cashew nut and coconut (Badan Pusat Statistik Sulawesi Tenggara, 2014). Cacao now dominates both revenues and land use within the province, comprising 49.7% of all trade revenues from primary production. In addition to being economically more significant than any other crop, for example, rice or coconut, cacao is more significant to the provincial economy than the entire mining, fishery and forestry sectors on their own (Badan Pusat Statistik Sulawesi Tenggara, 2014). Unlike other parts of Indonesia where export-oriented agriculture is dominated by corporate production and large-scale plantations, the average household growing cacao in Southeast Sulawesi holds just over 1.75 hectares of land in cacao (Direktorat Jenderal Perkebunan Sulawesi Tenggara, 2014).

Histories of Southeast Sulawesi's smallholder cacao economy suggest that it has developed both inside and outside forested landscapes. The trend, in general, has been for lowland state forests to *first* be used for logging or rattan extraction. Subsequent to these extractions (or alongside them), state forest lands have often been (i) parceled out to local people and migrants by the same elites that have already used the land for these operations and now seek to profit from land sales; (ii) claimed by individuals who assert their ancestral or *de facto* rights to the land; or (iii) officially reallocated to whole communities as a means of resolving long-standing conflicts and tensions. In all of these ways, forested lands (which in this analysis most aptly correspond to lands with >75% tree cover) have been enrolled into the smallholder tree crop economy (Ruf & Siswoputranto, 1995; Li, 2002, 2014; Gerard & Ruf, 2013).

Not all state forests actually contain trees, although many do. Some were *Imperata* grasslands designated for state reforestation programs or timber production (Potter & Lee, 1998). Some smallholders planted trees in these regions. Although less attractive in some regards than the fertile forest, grasslands were often in the flatlands close to settlements. These areas were often less strictly policed than the forested estate. Planting in forested lands was more likely to bring arrest and imprisonment. On land outside the domain of official state forest, too, many grasslands, home gardens and croplands were also converted to tree crop production (Ruf & Zadi, 1998; Kelley, 2013). Past work has suggested that grassland to cacao conversions were made more possible (i.e., less labor intensive and more profitable) by subsidized herbicides widely available through Indonesia's green revolution policies and programs (ibid).

Our data on land cover change – coupled to this social history – point to smallholder tree crop production as central but not fully determinative of loss and gain processes in the provincial mainland, particularly prior to 2005. A significant amount of land was held in <25% tree cover as of 1972, most of which was located in the alluvial lowlands along the banks of the Konaweha River. Southeast Asia has no significant occurrence of old-growth carbon-rich grasslands (Dixon *et al*., 2014). It is likely that most of these areas were active or former settlements characterized by the presence of *Imperata* grasslands. Left fallow, *Imperata* grasslands do not naturally revegetate (ibid). That 70% of all areas cleared as of 1972 are now held in 25–75% tree cover suggests that most such areas were actively rehabilitated.

Our evidence suggests, however, that the smallholder cacao economy also drove considerable forest clearance, likely more clearance than revegetation. Many people planted cacao in forests selectively logged to provide timber for export markets. Many other people obtained or reopened long-fallowed swidden plots that had regrown into dense secondary forests by the 1980s and 1990s. Three of the subdistricts that drove both loss and gain across both time steps lead the province in cacao production: Watubangga in the coastal lowlands and Lambuya and Ladongi in alluvial lowlands. Loss also predominantly occurred in tree-dominant lands in the alluvial lowlands, areas long considered ideal for agricultural pursuits given their fertility. Finally, to the extent that our data suggest high rates of forest clearance from 1995 to 2000, they correspond with the period of most significant land conversion for tree crops, particularly cacao (Direktorat Jenderal Perkebunan Sulawesi Tenggara, 2014).

The correspondence between smallholder cacao adoption and forest loss from 1995 to 2000 makes sense for at least two reasons. First, many decisions around land and resource management were decentralized in the wake of the Asian financial crisis and the overthrow of the Suharto regime. In the midst of administrative ambiguity about who had the right to allocate forest use rights, two things happened. First, smallholders took it upon themselves to open the forest, no longer afraid of the violent retribution promised them under the Suharto regime. Second, village elites and district officials began to sell forested land to migrants, capturing value from state lands before stability was recovered and they continued to be managed as such (McCarthy, 2004). Coinciding with this was the spectacular devaluation of the Indonesian rupiah during the Asian financial crisis. People trading crops on the global market and against the dollar made a windfall, driving further conversions and infusing cash into rural areas (Gerard & Ruf, 2013).

To substantiate the argument above and further suggest the value of long-term analyses in guiding an explanation of LULCC, Fig. 3 reconstructs LULCC dynamics in Lambuya subdistrict (a leader of loss and gain throughout both time steps), synthesizing oral histories and in-depth interviews collected by the first author over one year spent living in the region and four months' spent working in this specific district.

Policy import in Sulawesi and beyond

Our interpretation and our findings need to be substantiated with more discretely classified analyses of change in the current decade and with systematic collection of oral histories throughout the province. There is also a need to illuminate the specific agrarian histories that have rendered change pathways highly uneven across the region. However, to the extent that we are correct in our broad interpretation of change, our findings deepen existing accounts and approaches in at least three ways. First, our findings support the conclusion that multiple change trajectories are shaping tropical ecosystems (Rudel *et al*., 2005; Chazdon, 2014; Hecht, 2014). Although tree crops have been broadly treated and analyzed as a driver of deforestation (cacao, for example, is considered a 'deforestation crop' in Sulawesi and elsewhere, e.g., CI, 2004; Clough, 2009; Steffan-Dewenter *et al*., 2007), our findings suggest that in this case, Sulawesi's smallholder tree crop economy also helped to revegetate and reforest *Imperata* grassland ecosystems. This supports claims of tree crop-facilitated revegetation beyond Sulawesi (Rudel *et al*.,

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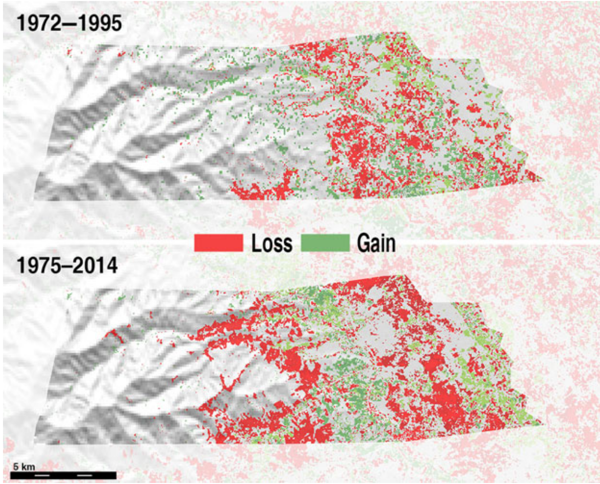

Fig. 3 Loss and gain from 1972 to 1995 and 1995 to 2014 in Lambuya subdistrict. This region has been inhabited by various settlements of Tolaki swiddeners predating Dutch occupation of the province in 1907. The lowlands have historically been used for sago palm groves, unirrigated rain-fed wet rice production, swidden rice cultivation and buffalo or cattle grazing. Since Dutch occupation, various Tolaki settlements have been relocated to the main road (where a colonial or government presence has existed) or have fled into the forest during at least three periods of political violence: (i) Dutch occupation (1907–1942); (ii) Japanese occupation (1942–1945); and (iii) the Darul Islam insurgency (~late 1950s to ~late 1960s). Since 1967, most land in this district has been declared state forest, with concrete poles established in many areas in the 1980s to visibly demarcate state lands. Tolaki swiddeners attempting to use forested lands for swidden rice production were forcibly evicted from the forest from the 1970s onward, often with swidden plots and houses burnt. This was driven by the desire of at least two local leaders who aimed to develop the area into an orderly village characterized by sedentary agriculture (at that time, intensive wet rice production; beginning in the 1980s, also commodity tree crop production). The area continued to be logged after most swiddeners had been evacuated: logging drove most loss from 1972 to 1995. Gain during this time was driven by Tolaki tree crop plantings in long-fallowed grasslands of the flatlands. At this time, most people planted cashew nut trees. When Suharto fell in 1998, village elites began to sell forested lands closer to the hills to Bugis migrants looking for land on which to grow cacao. District officials seized the chain saws being used to open the forest and the migrants temporarily returned to South Sulawesi. Migrants returned and clearing began again in 2004 in the sustained ambiguity surrounding resource decentralization. Many Tolaki planted cacao alongside Bugis migrants. Clearances for cacao drove forest cover loss as well as gain over the period 1995–2014. Gain during this time has also been driven by the fallowing and management of cashew nut farms. A second process driving tree cover loss during both time steps, particularly in the flatlands, has been the conversion of sago palm groves into irrigated wet rice fields. These lands have been opened by Bugis and Tolaki inhabitants as well as Javanese and Balinese inmigrants, allocated the land by the state through formal transmigration programs.

2002, 2005; Klooster, 2003; Hecht & Saatchi, 2007; Lambin & Meyfroidt, 2010; Chazdon, 2014; Hecht, 2014; Schroth *et al*., 2015).

Second, our findings point to the need to expand rather than collapse the baselines used to understand biodiversity and carbon outcomes. Given the dominance of the cacao sector in Southeast Sulawesi, approaches to managing environmental change in Sulawesi have overwhelmingly focused on smallholders' agricultural practices, focusing in particular on the relative merits of simplified, monocultural production vs. diversified agroecological production *vis-à-vis* biodiversity and carbon (Bos *et al*., 2007; Steffan-Dewenter *et al*., 2007; Clough, 2009; Clough *et al*., 2011; Tscharntke *et al*., 2011). These analyses compare the merits of tree crop systems against a presumed tropical forest baseline. While it is true that carbon and biodiversity gains do not scale linearly with tree cover (new growth forests or agroforests are not comparable with old-growth forests of similar overall tree cover), our findings suggest the need to also understand tree crop systems *vis-à-vis* the carbon and biodiversity supported within *Imperata* grasslands. This suggestion is likely not only applicable to Sulawesi but to other regions of the tropics as well.

Third, our findings point to the intersectionality of multiple change drivers and suggest that histories of extraction build on one another. Spatially and temporally, our data suggest multiple processes of gain and loss playing out in relation to one another. Although we believe most tree cover gain has been driven by smallholder tree crop adoption, tree cover gain was also widespread in Asera where tree plantings for logging, pulp and paper production, and recently oil palm production, dominate. Similarly, tree cover loss in the mountainous northeast (associated with logging) and the coastal lowlands (associated with irrigated rice production) shaped loss dynamics across both time periods. Our data suggest that patterns of clearance can build on one another, pointing in particular to the connections between logging and cacao in this region. Analyses of change are often organized around a particular system of change (e.g., oil palm plantations, cattle ranching, smallholder tree crops). Our data suggest a promising next step would be to more deeply analyze how multiple systems and contexts of change intersect both spatially and temporally to shape environmental change.

Applying these techniques elsewhere will likely unearth other histories of tree cover gain in the tropics. A bias toward analyzing contemporary imagery can inadvertently overcapture tree cover loss relative to gain. Unlike stand felling, which appears in back-to-back remote-sensed images as a sudden change in spectral reflectance values, the changes associated with tree growth are much more gradual. Changes in spectral reflectance values are subtle in back-to-back images, and only profound when analyzed over longer periods of time given the long-term nature of growth. Spanning 42 uninterrupted years is part of what allowed us to capture a previously undocumented level of tree cover gain in this region.

Additionally, tree cover gain from household or smallholder tree planting produces a spatial pattern much less visible from the ground than do consolidated forest clearances, particularly those now emblematic of plantation and commodity crop expansion (e.g., a 3000 hectare clearance for oil palm) (Rudel, 2007). Utilizing open access to Landsat imagery and GEE to create relatively cloud-free wall-to-wall maps of Southeast Sulawesi allowed us to broadly survey change rather than focusing on regions of acute forest cover loss. In turn, we were able to capture areas of more dispersed activity, such as tree growth in the alluvial lowlands of the mainland, an area dominated by smallholder cacao, cashew and coconut production (Badan Pusat Statistik Sulawesi Tenggara, 2014).

We do not intend to overplay the historical value of new datasets and new approaches, either in terms of adding richness to analyses of change or in terms of adding visibility to historical processes of tree cover gain. It will not be possible to document such a long interrupted sequence of change everywhere. Landsat data, even within the GLS 1975 collection, remain poor for some regions. The best first cut available for many landscapes only begins in the 1980s. New techniques to composite multiple images do not circumvent the invisibilities imposed by consistent and heavy cloud cover in certain regions. An extra twenty years of land change visibility also do not push us closer to an understanding of the centuries of human activity which have built tropical ecosystems (Mann, 2005; Chazdon, 2014).

Even bearing in mind these important qualifications, we believe the broader argument of this article holds. Developments over the past several decades, including trade liberalization, export market formation and ongoing resource decentralization, are dramatically reconfiguring the relationship between markets, societies and landscapes. An as-yet unprecedented methodological opportunity exists for producing histories of land cover change in the midst of such reconfigurations. Where the possibility exists, new datasets and approaches might help us to get a handle on the diversity of land cover change trajectories shaping tropical histories and futures. They might also help us to deepen our sociological analysis of change, contributing new insights into conservation policy and practice.

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Supporting Information

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

Table S1. Net loss and gain by eco-type.